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Review

Natural zeolite as a supplementary cementitious material – A holistic review of main properties and applications

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ABSTRACT

Pozzolanic materials or industrial wastes can be used to partially replace cement, minimizing the carbon footprint of concrete structures. Zeolite, silica fume, fly ash, and metakaolin are some of the most frequently used supplementary materials that reduce the concrete's permeability and, therefore, play a significant role in improving its durability and strength. Among the available alternatives, the application of natural zeolite as a pozzolanic material, in concrete has increased in recent years. In particular, a range of studies have focused on including natural zeolite to produce mortar and concrete with a reduced cement content, and thus, environmental impact. Through a consistent and comprehensive blended evaluation method, this research aims to evaluate past studies that utilized natural zeolite for various concrete applications. A total of close to 2,000 papers were screened, and more than 60 of them were selected for relevance. Bibliometric mapping was used for keyword occurrences and zeolite-related details. This study provides a state-of-the-art review of research on natural zeolite through a critical analysis of various research studies carried out in the past. The ultimate goal is to provide an in-depth understanding of the effects of zeolite on the performance of concrete mixtures, in terms of workability, strength, and durability. Furthermore, the current challenges and future prospects of using natural zeolite have been outlined, paving the way to expand the use of this category of supplementary materials.

1. Introduction

Cementitious materials play a significant role in the construction and maintenance of civil infrastructures [1]. They are the backbone of countless projects, providing strength and durability for an extended service life. In the meantime, the concrete industry continuously explores strategies to enhance the properties of cementitious materials and reduce their environmental impact. This includes incorporating alternative fiber choices, nanomaterial additives, and supplementary cementitious materials (SCMs) to reduce carbon emission and improve strength and durability properties [2–5]. Noting that approximately 7 % of all carbon dioxide produced worldwide is from the cement industry [1,2], it is critical to consider various solid waste materials in practical applications, involving cementitious composite materials. Such waste (or byproduct) materials often include slag, fly ash, silica fume, nanomaterials, among others. They have motivated several research investigations to understand their contributions and introduce mixture design details that can properly utilize their broad spectrum of benefits [6–12]. Focusing on the SCMs that require minimum energy for production, naturally occurring alternatives, such as natural zeolite and limestone, offer unique choices, as their production only involves a relatively simple process of extracting and grinding. The following general benefits of partially replacing cement with SCM materials, including natural zeolites, can commonly be realized [11]: (1) Lower production costs compared to conventional Portland cement; (2) Drop in the energy usage and CO_2 emission; (3) Improvement in the mechanical properties of concrete products, especially over time; and (4) Enhanced durability and service life.

Natural zeolites have been employed in several industries, including wastewater treatment [13–15], gas purification [16,17], and

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construction [18,19], with a notable application of pozzolanic admixtures for concrete. For low water-to-binder ratio (w/b) concrete mixtures, incorporating a zeolitic additive with a high water absorption capacity (i.e., capable of absorbing up to almost 40 % of its weight [20]) can serve as an internal agent to reduce the permeability and enhance the durability of cement paste and concrete [21,22]. Natural zeolite is also used as an aggregate for producing lightweight concrete [23]. In addition, the concretes made with natural zeolite have been noted to provide enhanced resistance against sulphate attack [24,25] and freeze–thaw cycles [26].

In parts of Europe, including Germany, Switzerland, and France, a volcanic ash that contains 45 % zeolite originally deposited in the Black Forest is commonly used for concrete production [27]. Concrete structures made of high-strength materials, such as paving stones, slabs, and pipes, have all been produced using this concrete [27]. The attention to using zeolite as a pozzolanic material has recently increased in many other countries. However, the limited availability of natural zeolite resources and the presence of other cost-effective alternatives have limited its use in the concrete industry to only a few regions around the world [27]. A range of research studies have examined the impact of using natural zeolite on concrete characteristics and compared this pozzolanic material with similar products [28]. The durability has been noted to generally improve when natural zeolite was used instead of Portland cement, mainly due to their pozzolanic activities [28]. However, because natural zeolite comes in various types, structures, and purities [29], similar outcomes are not always expected from the experimental studies, out of which even contradictory observations have been occasionally reported.

Various percentages of natural zeolite have been studied in relation to their effects on concrete properties [30]. Most of the existing studies have focused on mechanical properties, alkali-silica reactions (ASR), and transport characteristics of zeolite-containing concrete and mortar mixtures. Even though there has been some worthwhile research, it is rare to find information on other durability details, such as resistance to sulfates. The performance of natural zeolite as a pozzolanic material has been compared to fly ash and silica fume [31,32]. In the study conducted by Poon et al. [31], zeolite was found to exhibit pozzolanic activities greater than fly ash but less than silica fume. A comparison between zeolite and silica vapor and pulverized fuel ash (PFA) was made by Chan and Ji [32]. Exploring how zeolite affected concrete performance, the referenced study concluded that silica vapor is more advantageous than zeolite in improving the load resistance and reducing the initial surface absorbency and the diffusion of chloride ions. Accordingly, Najimi et al. [33] looked into the impact of incorporating zeolite as a SCM on concrete's mechanical and durability characteristics. The referenced study explored acid-induced deterioration, rebar corrosion, drying shrinkage, and transport properties.

The main objective of the current study is to provide a comprehensive review of the most recent research efforts to explore the potential of natural zeolite as a partial substitute in concrete and mortar mixtures. Despite being a relatively new field of investigation, using zeolite in cementitious materials has gained considerable attention in the past few years, leading to a growing amount of relevant research. In this study, Section 2 provides an overview of the bibliometric analysis and science mapping utilized to ensure a quality review paper. This includes mapping of keywords, determination of occurrence and co-occurrence instances, data filtration, and data interpretation. The structure and main physical properties of zeolite have been discussed in Section 3, along with their key structural properties and chemical compositions. Subsequently, their potential applications have been investigated in detail. Section 4 has been dedicated to the main findings and discussions, capturing the effects of using zeolite on the main fresh and hardened properties of a variety of concrete and mortar mixtures. By reviewing all relevant keywords in the existing literature (such as zeolite, compressive strength, durability properties, and microstructure), the studies appropriate for review were decided. Therefore, this study offers a systematic review in conjunction with a bibliometric analysis to facilitate the identification of future research directions. Those details have been systematically discussed in Sections 4 and 5. This is expected to provide a robust understanding of the state of the knowledge in the field and highlight promising domains for further investigations. To the authors' best of knowledge, no similar comprehensive review is available in the literature on using zeolite as partial cement replacement for concrete and mortar applications.

2. Bibliometric analysis and science mapping

The term "bibliometric analysis" refers to techniques that use numerical and statistical tools to sort through and assess sizable collections of published literature in a particular field [34]. They are used for many different aspects, such as examining the theoretical foundations of a particular field and identifying novel trends in the publication of articles and journals, as well as collaboration patterns. The two main types of bibliometric analysis methods are science mapping and performance analysis. Performance analysis aims to quantify the general influence of research participants, such as authors, publishers, and institutions [35,36]. One of the most popular performance indicators is the number of publications and citations. The number of peer-review papers is often considered as a productivity measurement method, while the number of citations reflects the influence or impact of a particular research study or researcher. These metrics effectively synthesize the number of publications and citations into simplified and sophisticated measurements, such as the PageRank algorithm [37,38]. In addition, science mapping techniques (bibliometric mapping) emphasize examining the connections between the research components. The mapping of accumulated scientific knowledge is made possible by extracting meaning from copious amounts of unstructured data [39]. Additionally, science mapping methods can be used to find overarching themes by examining the relationships between different keywords in a sizable publications database. It is also possible to map the collaboration between academic institutions or researchers by looking at the authors of publications. The connections are then displayed as two-dimensional network maps, which are simple to read and understand and tend to group similar terms. Additionally, they can draw attention to intriguing features previously "hidden" or challenging to locate [40]. The synergistic effects can be maximized by combining performance analysis and science mapping techniques with bibliometric analysis. Donthu et al. [39] indicates that properly performed bibliometric studies can lay a foundation for advancing a field by aiding researchers to comprehend concepts completely, recognize knowledge gaps, produce new ideas, and place their planned contributions.

2.1. Bibliometric maps

This study aims to synthesize and assess the knowledge areas related to using zeolite in concrete and mortar mixtures. Hence, the investigations were carried out by combining "systematic review" criteria [41] with the "bibliometric analysis" method [42]. The bibliometric analysis was conducted on data methodically filtered, and the entire research framework—from data collection to the conclusion—was built on a systematic literature search. This comprehensive review utilized the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist [43].

Making a bibliometric map of keywords can help identify emerging trends and knowledge gaps in a field while also revealing the overarching theme of a large body of scientific literature. An easy way to connect different publications is through their keywords. If two or more articles share one or more keywords, it typically means a correlation between the publications, implying that they address similar research topics. Each publication may have either author-specified keywords or indexed keywords associated with it in the Scopus database. A fundamental step in creating bibliometric maps is quantifying the frequency and co-occurrence of all the unique items utilized in the database under study. Further explanations on the philosophy of visualization progress, including lines and dots and their relationship with occurrence and co-occurrence, are presented in the following sections.

2.2. Data filtration and interpretation

The selection criteria were based on the PRISMA statement [44]. In particular, the content released after 2000 was considered. At first, data from the database was extracted for a total of 1,969 records. Duplications were removed following a title and abstract scan, leaving a total of 150 articles. After reading the entire articles, 61 studies met the inclusion criteria. The only sources used for this study were original research publications. The study was then performed, and a thorough summary was produced. Fig. 1 depicts the criteria for inclusion and exclusion at each level (PRISMA statement).

Fig. 2 demonstrates the interest in zeolite among various countries. Due to the large amounts of zeolite available in Iran, China, and the United States, these three countries are noted to be most interested in this sector.

2.3. Bibliometric analysis

Creating a sizable database based on the literature is the first step in the bibliometric analysis process. To that end, this study made use of the Scopus search engine. Scopus offers a robust and sophisticated search feature, enabling users to quickly run queries based on various permutations of keywords, authors, publishing sources, years of publication, and other pertinent criteria. The selected keywords included zeolite, compressive strength, cement, mortar, mineral additive, durability,

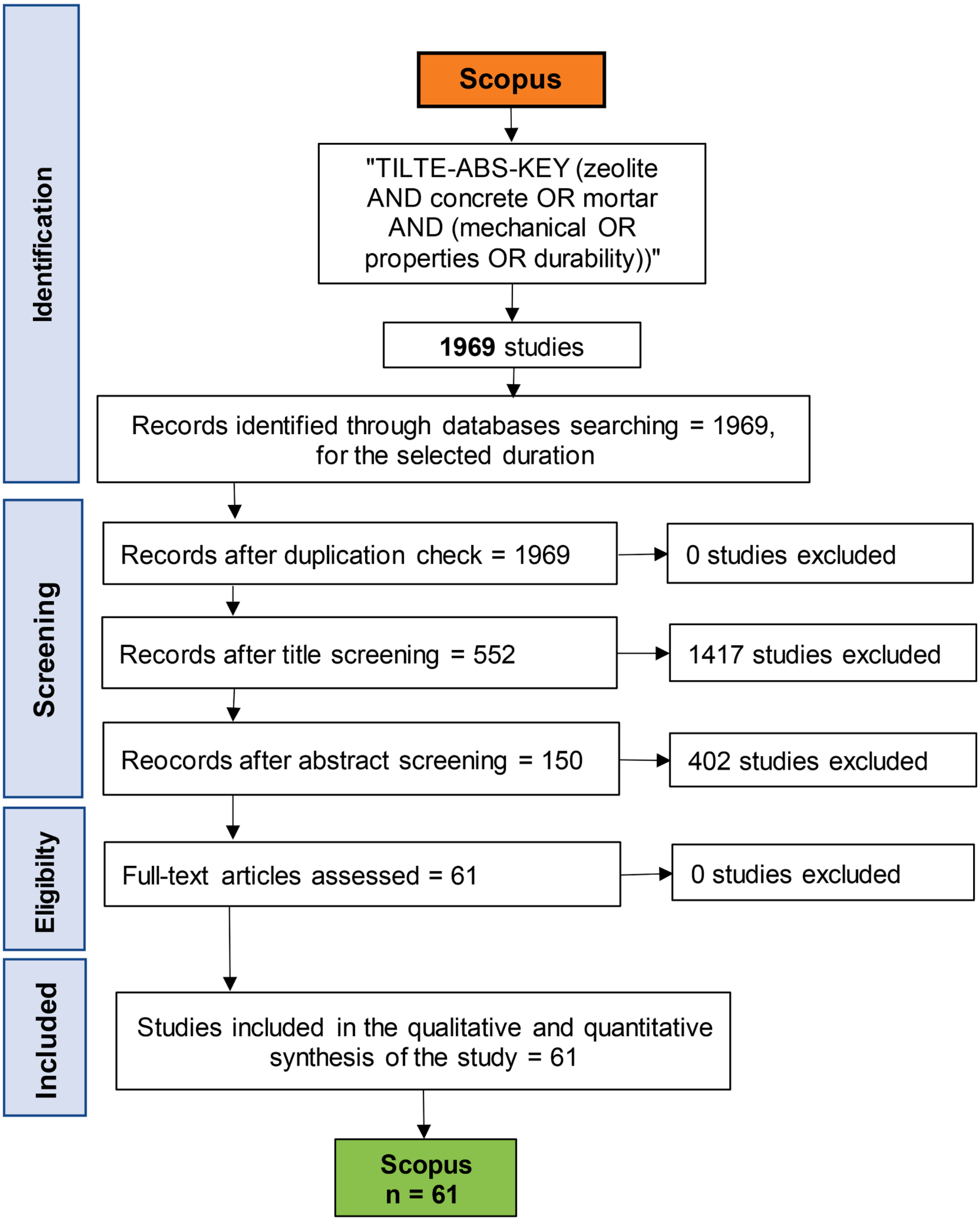

Fig. 1. PRISMA statement of the investigated studies.

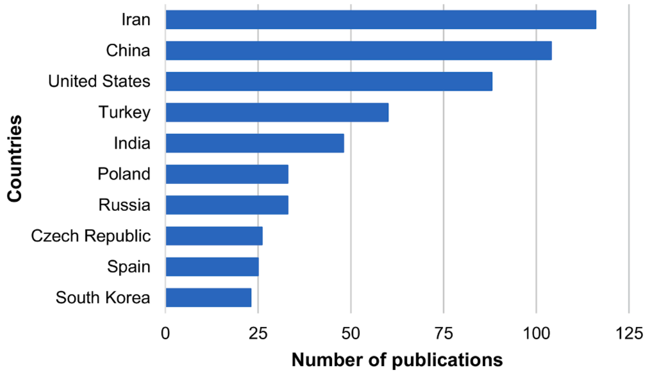

Fig. 2. Distribution of selected articles based on countries.

mechanical properties, pozzolanic activities, microstructure, and concrete. A CSV file was extracted with each search query's outcome. The user can choose the fields of a publication's metadata from Scopus. The fields downloaded for this study were title, DOI, publication year, authors' names and affiliations, citations, and publishers. A single CSV file was downloaded for each search query, and then they were merged into one file. The duplicates were removed based on the unique DOI field using the Excel tools. The completed database contained information on 1,969 publications in total.

Based on the principles for systematic reviews, this study's research goal, i.e., an overview of studies on using zeolite in cementitious composites, was established. All the selected publications had been released within the last 23 years, i.e., between 2000 and 2022. Fig. 3 depicts the historical trend in zeolite research. The initial metric that was examined was the temporal trend of publication outputs. Fig. 3 shows how a histogram that displays the number of publications per year was made with that objective in mind. As reflected in Fig. 3, the number of publications increased steadily from 2000 to 2013, with a growth pattern resembling a straight line. After 2013, there was a notable rise in relevant publications. As a result, it can be seen that over the past eight years, the trend has shown an exponential rise in the incorporation of zeolite into building materials, making it one of the popular topics. Such a trend is consistent with the global movement toward a net-zero built environment, especially through finding alternatives for cement.

Fig. 4 displays the distribution of the selected publications with respect to journals. The most frequently used zeolite-related articles are in the "Journal of Construction and Building Materials", which accounts for nearly half of all publications (30 searches). With 7 studies and 23 % of the total, "Journal of Building Engineering" is second on the list.

2.4. Bibliometric maps

Each component (word, author, etc.) is graphically depicted on the maps as a single circle. The circle size indicates how often each item occurs. Circles with a larger diameter represent higher occurrence values, while smaller circles represent lower occurrence values. There is a co-occurrence indicated by a line joining the two circles. More co-occurrences are indicated by a thicker line, reflecting a stronger co-occurrence. However, small line thicknesses are used to prevent the maps from becoming overly line-saturated. The various computed clusters are represented by the colors of the items in the visualization, meaning that nodes of identical color are grouped. The visual representations are produced using a minimal number of components due to page limitation, allowing for quick interpretation and comprehension. The interactive graphical user interface of bibliometric maps enables proper exploration through zooming, panning, and scaling. It also allows for including a greater number of items in a virtual, computer-generated environment.

The bibliometric analysis carefully examines the relationships between peer-reviewed papers, citations, co-citations, and keywords. With the help of bibliometric analysis, it is quick and easy to manage many papers and create an intelligent visualization that provides readers with a clear and concise categorization of research interest groups in a given subject. The network structure of the studies related to using zeolite in concrete and mortar mixtures was visualized using the VOS viewer during the keyword and network analysis of the bibliometric data. In total, 399 keywords were discovered in the 61 publications, 52 of which had more than three occurrences. The links in the occurrences were the ones targeted by using the most crucial keywords. The top 10 competing keywords are listed in Table 1 and presented in Fig. 5, which shows a co-occurrence mapping of the relevant keywords. The most frequently used keywords were "zeolite" and "compressive strength" with 30 and 28 repetitions, respectively.

The number of publications with two authors collaborating on a paper is known as their co-occurrence value. The database contains 19,916 unique authors. The first 62 authors from the list with the most publications are the only ones represented on the map. It should be noted that only publications in the analysis database are counted. The search may not have returned all of the authors of the reviewed publications. Nevertheless, a few of the 62 top authors share a co-occurrence of 0 with all 61 authors. That does not necessarily imply that those authors do not collaborate with others; instead, it just means that their most significant partnerships are with authors who are not in the other top 61. Items with zero co-occurrence produce isolated points in the bibliometric map that raise the overall error and degrade the map's accuracy. As a result, the authors with 0 co-occurrences are eliminated, leaving only 127 authors in the final map, where each author in the

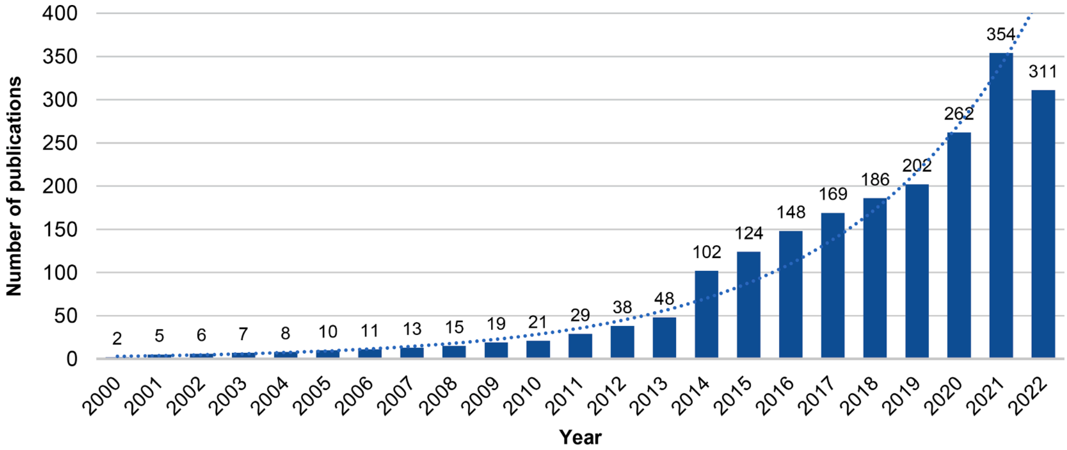

Fig. 3. Zeolite research trend over time.

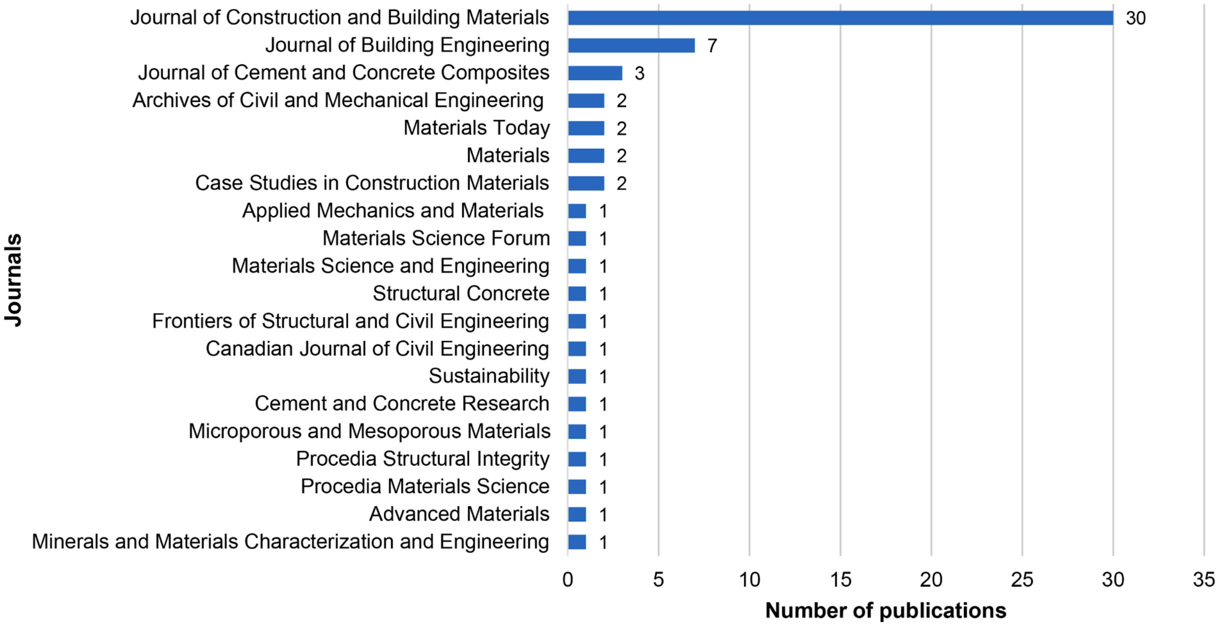

Fig. 4. Publication distribution per journal.

Table 1
Mapping summary of the top ten keywords.

Keyword	Occurrence	Total link strength
Zeolite	30	209
Compressive strength	28	145
Cement	17	112
Mortar	17	108
Mineral additive	10	79
Durability	8	61
Mechanical properties	8	79
Pozzolanic material	11	92
Microstructure	9	59
Concrete	8	53

network is linked to at least one other author. Fig. 6 displays the bibliometric map for authors. The clusters are formed based on how the nodes are connected, resulting in each cluster containing a unique network distinct from the others.

Despite the bibliometric study using a substantial number of publications, it exclusively relied on the Scopus database. More publications that affect the results may be found in other sizable scientific databases, such as the Web of Science. However, since the primary objective has been to propose a comprehensive picture, it should be possible to draw comparable conclusions from any sufficiently large database. Furthermore, some procedures are not easily automated and need human input, allowing users to affect the outcome using their knowledge [45]. To examine the literature in a specific field, data-driven bibliometric analysis has proven incredibly useful. In most instances, it can provide a preliminary viewpoint more effectively than manually reviewing the literature.

3. Content analysis

In the following sections, zeolite's main characteristics are investigated. The effects of zeolite addition as a pozzolanic component, internal hardener, aggregate, and air-generating agent are discussed in detail.

3.1. Key properties of natural zeolite

Natural zeolite is made of four-atom-shared hydrated crystalline aluminosilicates with 3D honeycomb structures made of TO_4 tetrahedral units (T: Si, Al) bonded to other tetrahedra [44]. The tetrahedra found in zeolites are classified as secondary building units (SBUs) due to their geometric configurations. The various ways polyhedra are formed through bonds between SBUs lead to different zeolite structures. About 40 different types of natural zeolite and seven groups of SBUs exist [46–48]. Table 2 presents the natural zeolite's mineralogical components and chemical composition, as referenced in the past studies [23,32,49–54]. Concrete properties with and without zeolite inclusion are provided in Table 3. This table shows the ratio of the change for compressive strength, chloride penetration, water penetration, frost resistance, and shrinkage [55].

The crucial factors in determining the zeolite properties are ion exchange, adsorption, dehydration, and rehydration processes, which are intricately linked to the zeolite's chemical structure and composition [51,56]. The extensive network of channels and cavities inside the zeolite structure allows cation exchange. Natural zeolites can exchange cations between 2 and 4 meq per gram, double those of bentonite clays [51]. A lack of positive charge results from Al^{3+}'s substitution of some Si^{4+} in the zeolite structure. Cations like Na^+ and K^+ located in voids within the structure balance out the net negative charge [56]. A process of ion exchange between Na^+ and a cation can occur when a zeolite is exposed to a solution with a high ionic concentration [56]. Zeolites can be divided into two groups based on their capacity for rehydration and dehydration. The first category includes natural zeolites, such as clinoptilolite, chabazite, and mordenite, which continuously lose weight as the temperature rises and do not undergo structural alterations or collapse during dehydration [56]. The second group experiences structural changes but does not continuously lose weight while heated. As temperature increases, structural alterations occur in the zeolite, leading to gradual degradations [23,50].

The chemical formula for natural zeolite is typically $Mx/n[(AlO_2)x(SiO_2)y]\cdot nH_2O$. The primary constituents of zeolites are SiO_2 and Al_2O_3. There are 45 known natural zeolites with different chemical compositions [51]. Among them, Clinoptilolite ($[Na,K,Ca]_6[Si,Al]_{36}O_{72}\cdot 20H_2O$) and mordenite ($[Ca,Na_2,K_2]Al_2Si_{10}O_{24}\cdot 7H_2O$), rich in silica, are the most commonly used for industrial purposes, such as odor control, water filtration, and molecular sieving [44,51,57]. However, impurities in natural zeolites can result in low purity levels, making them unsuitable for applications that require high-purity zeolites, such as petroleum

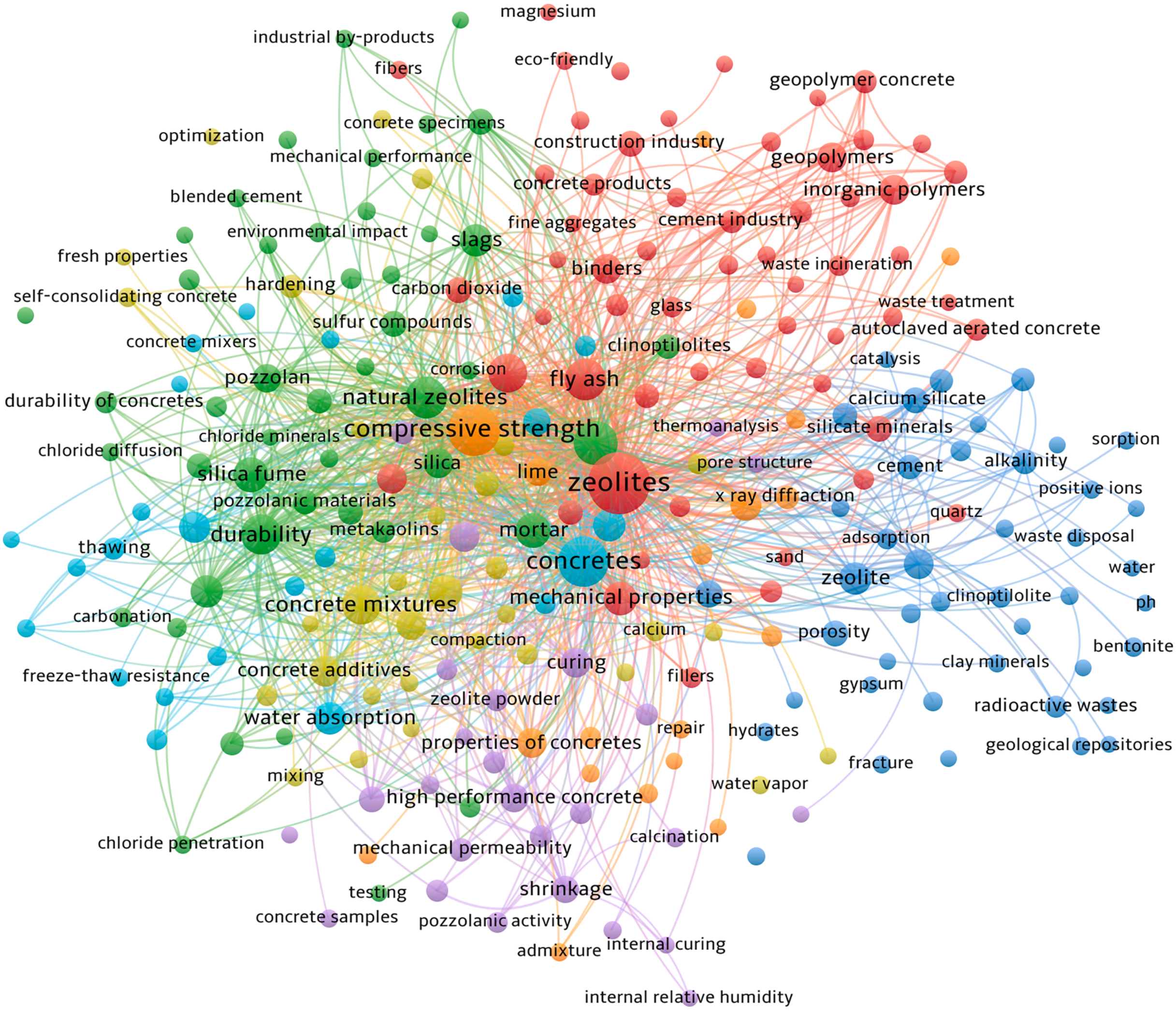

Fig. 5. Co-occurrence mapping of author keywords.

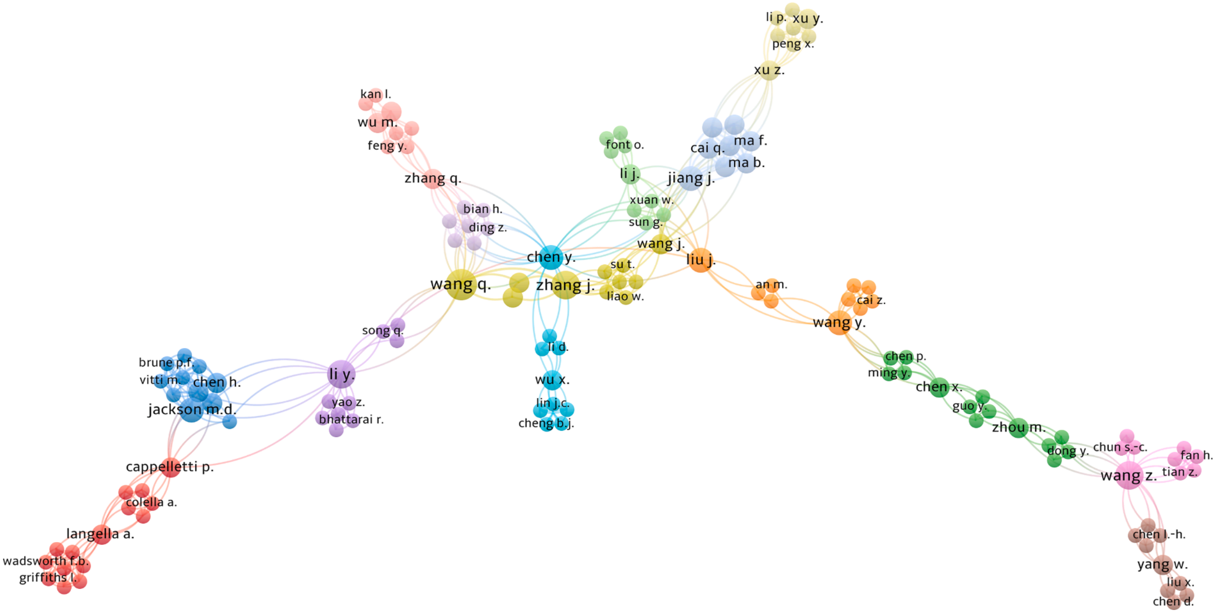

Fig. 6. Author collaborations map.

Table 2
Physical properties of ordinary Portland cement and zeolite.

Material	Specific surface area	Specific gravity	Density	Fineness	Initial setting time	Ref.
Cement	3519 (g/cm^2)	–	3.15 (g/cm^3)	–	–	[49]
	355 (m^2/kg)	3.1	–	–	–	[50]
	0.962 (m^2/kg)	–	3140 (kg/m^3)	11 %	125 (min)	[51]
	–	2.67	–	6.45 %	–	[23]
	3520 (cm^2/kg)	3.15	–	–	–	[32]
	339 (m^2/kg)	3.15	–	–	105 (min)	[52]
	3807 (cm^2/kg)	3.14		8.98 %	141 (min)	[53]
Zeolite	3980 (g/cm^2)	–	2.91	–	–	[49]
	750 (m^2/kg)	2.16	–	–	–	[50]
	1000 (cm^2/kg)	2.2	–	–	–	[54]

Table 3
Ratio of change in the compressive strength, chloride penetration, water penetration, frost resistance, and shrinkage of concrete after the addition of zeolite compared to the concrete mixtures made without zeolite [55].

Natural zeolite content (wt.% of cement)	2.5	5.0	7.5	10	15	20	30
Compressive strength	1.07	1.11	1.12	1.109	1.04	1.07	0.87
Chloride penetration	–	0.85	–	0.49	0.36	0.32	0.17
Water penetration	–	0.79	–	0.83	0.77	0.75	0.67
Frost resistance	2.37	2.49	2.89	3.32	–	–	–
Shrinkage	–	0.36	–	0.62	0.84	–	0.64

refinement and petrochemical production [55].

3.2. *Applications as pozzolanic materials*

Several papers have established the pozzolanic activity of natural zeolite [58–60]. Employing thermogravimetric and X-ray diffraction (XRD) analyses, Jana [58] showed that the pozzolanic reaction significantly reduced the calcium hydroxide content in the pastes containing clinoptilolite-type zeolite. A more significant reduction in calcium hydroxide occurred in the pastes with higher amounts of zeolite. Snellings et al. [61] and Perraki et al. [62–64] reported a similar trend for a type of heulandite-containing zeolite tuff. In general, the factors influencing the pozzolanic activity of natural zeolite appear to be the type of zeolite, the purity (i.e., the content of zeolite or active phase), the Si-Al ratio, the amount of soluble SiO_2, the external surface, and the content of exchangeable cations. EN 196-5 [65] assesses the pozzolanic activity of pozzolanic cements indicated in EN 197-1 [66].

According to EN 197-1, pozzolanic cement is categorized into two classes: CEM IV/A and CEM IV/B. The first type consists of a mixture of 65 % to 89 % clinker and additional components, such as silica fume, natural pozzolan, and fly ash. The percentage range drops to 45 % to 64 % in the second type. The zeolite microstructure was analyzed by scanning electron microscopy (SEM), as seen in Fig. 7. SEM images show the porous and platelet-like structure of the zeolite, suggesting a high water demand. The natural zeolite's particle size distribution was analyzed, with results shown in Fig. 8. The distribution shows that the zeolite particle size mostly ranges up to 200 μm.

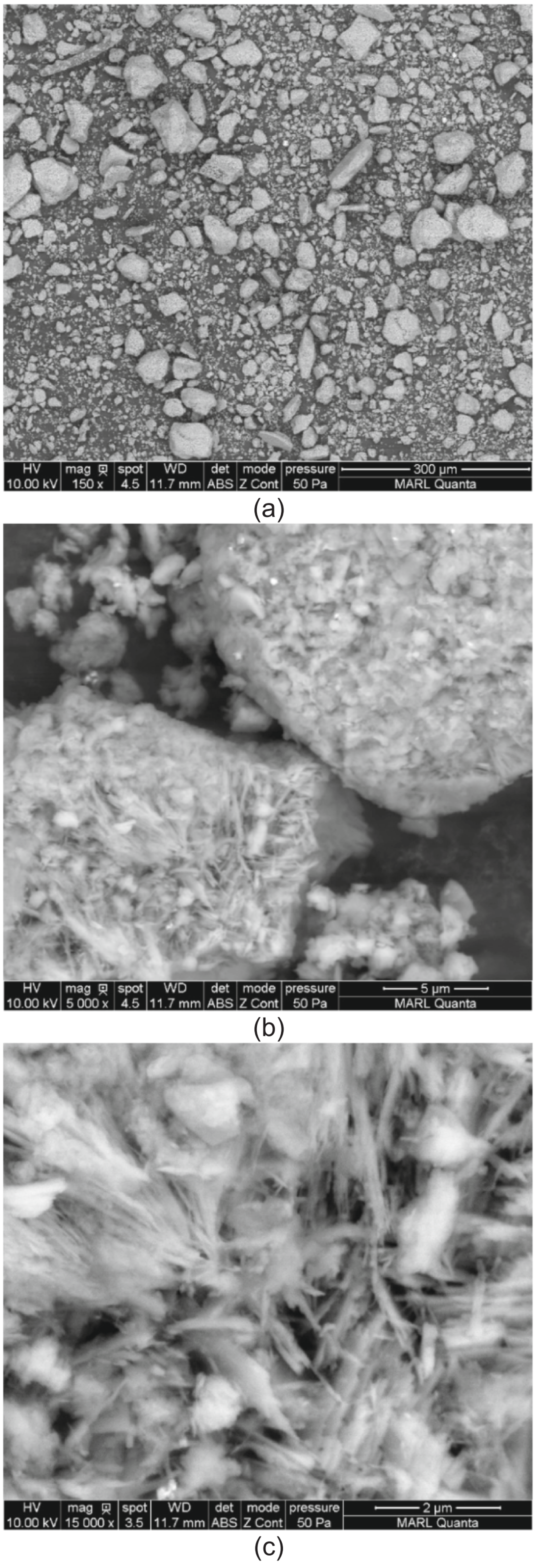

Fig. 7. SEM images of natural zeolite magnified by (a) 150X, (b) 5,000X, and (c) 15,000X [34].

3.3. *Applications as an internal curing agent*

Zeolites possess a porous structure, which includes micro, meso, and macro-scale pores, enabling them with a high ability to absorb and desorb water. Therefore, the concrete's internal relative humidity can be managed using natural zeolites. Autogenous shrinkage, the primary

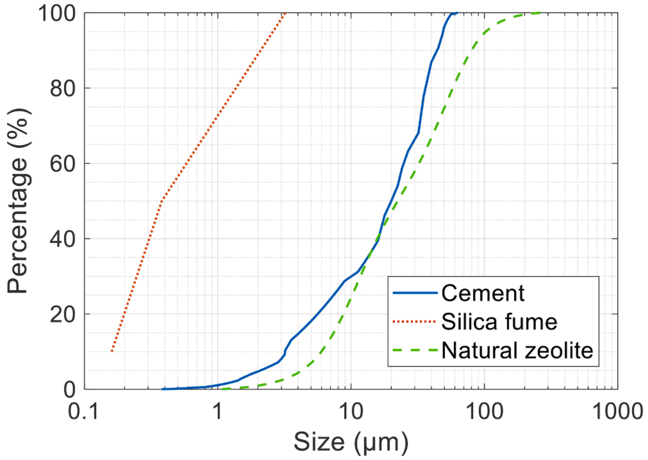

Fig. 8. Particle size distribution of natural zeolite in comparison with cement and silica fume [67].

reason for crack formation in concrete, is one of the most important phenomena at the beginning of concrete aging [68–71]. The water content in concretes with a low w/b (less than 0.25) and a high cement content is often insufficient for cement hydration. This leads to a continuous reduction in the mixture's internal relative humidity during the hydration process, causing the concrete to dry [72]. Low w/b ratios result in dense microstructures with small capillaries [73]. Therefore, surface tension in the capillary pores can cause autogenous shrinkage. Maintaining moisture in saturated capillaries is a proven method for preventing autogenous shrinkage [74]. Owing to the microstructure's density, the capillaries become too small for outside water to enter. Therefore, internal polymerization is viewed as a workable solution [75]. The high absorption capacity of zeolite particles allows them to act as water reservoirs distributed throughout the concrete, providing internal curing. At the beginning of the concrete mixing, capillary pores are formed with the water absorbed into these particles [76,77]. Consequently, the concrete's autogenous shrinkage is minimized because of preventing the dry-out process.

Tuan et al. [22] investigated how natural zeolites affected the autogenous shrinkage of ultra-high-performance concretes. After 28 days, the autogenous shrinkage of ultra-high performance concrete was reduced by 64 %, 74 %, and 77 % using 5 %, 10 %, and 12.5 % of natural zeolite, respectively. Similarly, Zhang et al. [75,76] reported that when pre-wetted zeolites were used as aggregates, the concrete's autogenous shrinkage was significantly reduced. At 28 days, the shrinkage of concrete made with natural zeolite was 42 % less than that of the control mix. Drying shrinkage is another typical form of shrinkage in concrete. This happens because the concrete's porous system allows water to evaporate, reducing the concrete's overall volume [78,79].

3.4. *Applications as aggregates and air-generating agents in concrete*

The concrete industry has utilized natural zeolites as foaming agents and lightweight aggregates. Natural zeolites can be added to concrete to improve thermal insulation performance while reducing unit weight [80,81]. In a study by Karakurt et al. [23], natural zeolites were used as aggregates. To produce autoclaved aerated concrete (AAC), natural zeolite (clinoptilolite) was used in percentages of 25, 50, 75, and 100 %. The referenced study found that replacing 50 % of the cement with natural zeolite produces an AAC structure with an ideal balance of compressive strength and unit weight, while improving the thermal insulation capacity. For use as a foaming agent in the creation of cellular concrete, natural zeolite was calcined for two hours at 500 °C. The aerated concrete had the highest compressive strength, owing to its high unit weight and low porosity. In addition to the outlined aspects, other properties of zeolites have made them useful in various concrete and mortar applications. These properties include large surface area, ion exchange capability, expansion at high temperatures, desorption of water at low humidity, and water reabsorption at high humidity.

4. Findings and discussions

A systematic review of the applications of zeolite in concrete mixtures has been summarized in Table 4. The details of material types, cement replacement dosages (as a weight percentage), number of curing days, conducted tests, and effects on concrete are all shown in this table. In this review study, three main components of the literature were examined based on the studies reviewed in the following sections: the effects of natural zeolite on concrete and mortar mixture properties, the rationale and motivation for using zeolite in concrete and mortar applications, and the critical aspects associated with the successful use of zeolite.

4.1. *Effects of zeolite on microstructural characteristics*

There has been a growing interest in investigating the influence of zeolite on concrete's microstructure. Specifically, when introduced into concrete mixtures, zeolite interacts with the cementitious matrix, leading to various microstructural changes. These changes may include alterations in the pore size distribution, the formation of new crystalline phases, and modifications to the interfacial transition zone (ITZ) between the cement paste and aggregates [30]. Understanding these alterations is crucial for assessing the long-term performance of zeolite-incorporated concrete. One of the key aspects of microstructural evaluation is the analysis of the pore structure. Zeolite, with its pozzolanic properties, can contribute to refining the concrete's pore structure. This refinement can lead to reduced porosity and improved resistance to permeability [21]. Researchers have employed mercury intrusion porosimetry and SEM techniques to quantify and visualize these changes [34].

Investigating the effects of zeolite, in terms of microstructural changes, is essential for understanding how it influences the strength and durability properties of concrete over time. Najimi et al. [33] reported findings on enhancing compressive strength, flexural strength, and resistance to various deterioration mechanisms, including chloride ion penetration and sulfate attack. The ITZ between aggregates and cement paste also plays a critical role in determining the overall performance of concrete. Zeolite incorporation may improve the ITZ by reducing the formation of detrimental products and enhancing the bond between aggregates and cementitious materials [34]. As the understanding of zeolite's impact on concrete microstructure continues to evolve, numerous avenues have emerged for future research. Investigating the synergistic effects of zeolite with other SCMs, exploring the role of zeolite in mitigating ASRs, and assessing microstructural changes under different curing conditions are among the research areas that require further investigation. The microstructural evaluation of zeolite-modified concrete is a vital aspect of research in this field, and it holds great potential for advancing the understanding of how zeolite influences the main properties and performance of concrete.

4.2. *Effects of natural zeolite on the properties of cement and concrete composites*

4.2.1. *Fresh and hardened states*

Compared to cement, zeolite typically requires more water in the mix, owing to to its high porosity and surface area. This, in turn, results in the reduction of the concrete's workability. Therefore, some studies suggest the use of natural zeolite with superplasticizers. However, it should be noted that some natural zeolites show a negligible effect on concrete workability. The types of zeolite minerals and the surface morphology and crystallinity of zeolites have different effects on the

Table 4
Overview of the past investigations on the application of zeolite in concrete and mortar mixtures.

	Material	Cement replacement dosage (%)	Number of days	Conducted tests	Main outputs	Ref.
1	Zeolite	25	3, 7, 28 90	Strength of the paste, degree of reaction of zeolite, and porosity of pastes	It increases the strength of the pastes made with a low w/b ratio and reduces their porosity after adding 25 % zeolite.	[23]
2	Zeolite, pulverized fuel ash, and silica fume	5, 10,15, 30	7 and 28	Compressive strength, slump, initial surface absorption, and chloride diffusion	Natural zeolite added to the concrete mixture significantly increased the compressive strength over time (by up to 30 %).	[32]
3	Natural zeolite, fly ash, and ground granulated blast furnace slag	Limestone: 5,10, 20, 30, 40, 45 and gypsum: 3	2, 7, 28, 180	Chemical and mineralogical analyses, compressive strength, and corrosion resistance	After 28 and 180 days, the compressive strength increased. The durability of concrete also improved.	[82]
4	Zeolite and fly ash	Fly ash: 0.4, 0.6, 0.8, and zeolite: 1, 2.5	28, 90, 180	Concrete strength, sorptivity property, and permeability	When the modified zeolite additive was used in optimal proportions between 0.6 and 1.0 %, the concrete strength was improved. Fly ash and modified zeolite additives were more effective when used together.	[83]
5	Natural zeolite	7.5, 15, 22.5, 30	7, 28, 90	Compressive strength, flexural strength, and depth of water penetration	Water penetration resistance was significantly improved by adding 22.5 % zeolite.	[84]
6	Natural zeolite	0, 5, 10, 15, 20, 25	28, 90, 270	Slump, compressive strength, water penetration, drying shrinkage, and freeze–thaw resistance	Due to its high surface area, a fresh concrete mix containing zeolite requires a higher superplasticizer dosage to achieve the targeted slump flow. The results also showed that using a superplasticizer and an air-entraining agent in zeolite concrete significantly affected water penetration, drying shrinkage, and resistance to freeze–thaw cycles.	[85]
7	Natural zeolite	10	1, 28, 56, 90, 180	Water absorption, water penetration, freeze–thaw resistance, and drying shrinkage	Favorable results were obtained for concrete containing zeolite, in terms of resistance to water penetration, freeze–thaw durability, and reduction of drying shrinkage.	[86]
8	Natural zeolite and silica fume	5, 10, 12.5, 15, 20	450	Activation energy value	Zeolite concrete's activation energy was higher than silica fume concrete's.	[87]
9	Natural zeolite	0, 8, 16, 24, 32, 40	28	XRF analysis for the chemical composition	Using natural zeolite is an appropriate approach to designing composite mixtures.	[88]
10	Silica fume and zeolite	7.5, 10	14, 28, 56 and 120	Fresh concrete evaluation, compressive strength, electrical resistivity, capillary water absorption, bulk water absorption, rapid chloride migration test, and microstructure analysis	A partial replacement of cement with silica fume by 7.5 % can compensate for the compressive strength loss.	[89]
11	Zeolite	10, 15	1, 3, 7, 14, 28, 90, 180 and 365	Durability of concrete based on wear resistance, tensile crack resistance, absorption, and frost resistance	Adding 5 % zeolite to the top layer of concrete paving blocks reduced absorption, increased tensile cracking resistance, and reduced wear. The addition of zeolite in concrete blocks after 28 cycles of freezing and thawing, when 3 % NaCl was used as a freezing solution, resulted in a 4-fold reduction in scaling. The decrease in shrinkage led to a reduced workability of shrinkage cracking in high-performance concrete (HPC) that included zeolites. In the case of the reference sample, the initial shrinkage cracks appeared at 1.3 days, while in HPC mixtures containing 10% and 15% zeolite, the shrinkage cracks only became visible after 6.8 days and 12.5 days, respectively.	[90]
12	Zeolite	5	7, 28	Water absorption, abrasion resistance, tensile splitting strength, and freeze–thaw	In paving blocks used as the highest layer, zeolite obtained from aluminum fluoride increased durability and longevity.	[91]
13	Zeolite	0, 14, 22	7	Compressive strength and flexural strength	The addition of zeolite led to a 4 % increase in compressive strength and an 18 % increase in flexural strength.	[92]
14	Natural zeolite and silica fume	10, 15	28,90	Thermogravimetric analyses, slump, compressive strength, water absorption, oxygen permeability, chloride diffusion, and electrical resistance	Natural zeolite was not as reactive as silica fume but demonstrated good pozzolanic reactivity. The performance of concretes containing zeolite was improved, and, in some cases, it rivaled or surpassed the performance of concrete made with silica fume.	[93]
15	Zeolite and silica fume	5, 10, 12.5, 15, 20	3, 7, 28, 90	Essential physical characteristics, mechanical properties, durability, and hygric and thermal properties	20 % zeolite content in the mixed binder was the most suitable option. Compressive strength, flexural strength, effective fracture	[94]

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Table 4 (*continued*)

	Material	Cement replacement dosage (%)	Number of days	Conducted tests	Main outputs	Ref.
					toughness, and specific fracture energy slightly dropped compared to the reference Portland cement concrete. However, it improved the resistance to cold, salt defrosting, and chemical agents.	
16	Zeolite	10, 20, 40, 60	28, 90, 360	Physical characteristics, mechanical properties, durability, hygric and thermal properties	Concrete with 20 % zeolite showed the best performance in the studied characteristics.	[25]
17	Zeolite	10	28	Compressive strength, water absorption, and density	Using synthetic zeolite derived from aluminum fluoride at low temperatures enhanced the durability.	[95]
18	Mineral additive Natural Zeolite	10	7,28	Compressive strength	In modified concrete, the compressive strength increased because of the active presence of SiO_2 and Al_2O_3 in zeolite additives.	[23]
19	Natural zeolite, soda lime, and glass powder	10, 15	28	Physical properties and porosity	Natural zeolite increased water absorption, adversely affecting durability.	[96]
20	Lightweight concrete with zeolitic aggregates	20	7, 28	Microstructural analysis	A correlation was established between the thickness of the interface zone, compressive strength, cement dose, and w/b ratio in lightweight structural concrete.	[97]
21	Natural zeolite	10, 20, 30, 40	28	Calcination above 500 ∘C	The use of natural zeolite in 10 % volume reduced bleeding and improved the consistency of the cement paste. Calcination at a temperature higher than 500 °C affected the quality of the rheological properties of cement paste.	[98]
22	Natural zeolite	10, 15, 20, 25	28	Microstructure behavior of unconfined strength, triaxial behavior, and permeability	The addition of zeolite reduced unconfined strength, elastic modulus, and peak strength in the early stages of curing.	[99]
23	Natural zeolite	20, 30, 40	7, 28	Rheological properties	Using zeolite in mortar decreased rheological properties (yield stress and plastic viscosity) but increased compressive strength over time.	[100]
24	Natural zeolite	0, 5, 10, 15, 20	28	Tensile properties	The tensile strength of concrete was improved after 10 % cement replacement with zeolite. Beyond this point, the strength decreased.	[101]
25	Natural zeolite	0, 5, 10	7, 28	Pore properties	Zeolite reduced the pore size in the microstructure of the cement paste by reducing the number of voids in the paste.	[102]
26	Natural zeolite	20	1, 2, 3, 5	Autogenous shrinkage	Zeolite caused self-desiccation and autogenous shrinkage mitigation.	[104]
27	Natural zeolite	10	28	Compressive strength, transport properties, and resistance to chloride penetration	Zeolite increased the resistance of concrete over time against water and ion penetration. A correlation was noted between properties, such as chloride diffusion coefficient, electrical resistance, and water penetration depth. The mixture with natural zeolite was more resistant to chloride penetration.	[103]
28	Natural zeolite	10	28	Shrinkage	Using zeolite decreased the 28-day dry shrinkage by 60 %.	[105]
29	Natural zeolite	30	28	Shrinkage	Using zeolite in concrete decreased both 28-day autogenous and drying shrinkage but improved the simultaneous limits of strength and shrinkage achieved.	[78]
30	Natural zeolite	15	28	Superhydrophobic properties	Using natural zeolite enhanced the microstructures of superhydrophobic mortar and decreased water absorption, leading to improved anti-corrosion performance.	[106]
31	Natural zeolite and 100 % micro-nano-bubble water	15	28	Durability and mechanical properties	Zeolite increased compressive strength over time. Also, there were 78 % increase in tensile strength, 254 % increase in electrical resistance, 83 % reduction in chloride penetration, and 49 % reduction in water absorption compared to the control mixture.	[84]
32	Calcined natural zeolite	20	7, 28	Characteristics of calcined natural zeolites	Compared to raw zeolite, compressive strength improved in mixed cement containing calcined natural zeolite because of the reduced porosity and refined pore structure of hardened cement materials.	[107]
33	Silica fume and natural zeolite	Optimum dosages	28	Internal curing capabilities	Hydration was improved due to the silica fume's high pozzolanic reactivity and the zeolite's internal curing capability.	[18]

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Table 4 (*continued*)

	Material	Cement replacement dosage (%)	Number of days	Conducted tests	Main outputs	Ref.
34	Natural zeolite	0, 5, 10, 15	7, 28, 90	Fresh properties, compressive strength, flexural strength, and abrasion resistance	Reducing the w/b ratio had a more significant effect on enhancing the mechanical properties than using natural zeolite. Observations showed a significant decrease in the width, length, and micro-cracks in the binder paste and interface zone for mixtures containing 10 % natural zeolite.	[67]
35	Calcined and natural zeolites	15, 30	7, 28, 91	Mechanical properties	Using calcined zeolites resulted in better compressive and flexural strengths than using natural zeolites. This was consistent at all curing stages.	[108]
36	Natural zeolite	30, 40, 50	7, 28	Pozzolanic activity, compressive strengths, and reaction rate	The pozzolanic activity of natural zeolites increased with each pre-treatment, either separately or together, after eight days of hydration.	[109]
37	Zeolite and waste	10	7, 28	Abrasion resistance and mechanical properties	Adding zeolite to concrete enhanced compressive strength and abrasion resistance. It effectively reduced the negative impact of fibers on chloride penetration. Combining zeolite and fibers proved to be more effective than using either alone.	[110]
38	Natural zeolite calcine	10	28, 90	Microstructure and freeze–thaw	The concrete's pore structure was improved with zeolite internal curing, and its frost resistance was enhanced after 150 cycles.	[111]
39	Natural zeolite	0, 5, 10, 20, 30	28	Compressive strength	Natural zeolite powder delayed the hydration process, resulting in a reduction in compressive strength.	[112]
40	Natural zeolite	0, 10	1, 28, 56 90, 180	Mechanical and durability properties	Using a combination of cement substitutes, such as zeolite and other chemical additives, increased the workability of concrete, improving the concrete's freeze/thaw resistance. It also reduced drying shrinkage and the depth of water penetration. Replacing cement with zeolite caused a temporary decrease in strength up to 90 days of hardening, but the compressive strength of concrete containing zeolite was higher than that of concrete without zeolite after 180 days.	[113]
41	Unburnt rice husk, fly ash, zeolite, and glass powder	15	28	Strength properties	The compressive strength of the concrete made with zeolite decreased, especially at an early age.	[86]
42	Zeolite powder	20	7, 28	Mechanical properties, volume stability (drying shrinkage and creep)	Zeolite powder increased the high-density calcium silicate hydrate (C–S–H) and reduced the cementitious mixture's low-density C–S–H content, reducing concrete creep.	[114]
43	Natural and calcined zeolites	15, 20, 30 of zeolite replacing quartz sand	28	Strength and shrinkage	Calcined zeolite decreased both 28-day autogenous and drying shrinkage. When used to replace sand partially, natural zeolite decreased the 28-day autogenous shrinkage.	[24,78]
44	Natural zeolite, silica fume, and fly ash	0, 10, 20	28	Fresh and hardened properties	Incorporating mineral admixtures and zeolite generally improved the mechanical and durability characteristics of the mixtures.	[115]
45	Zeolite and fly ash	0, 15, 20	7, 28	Slump and compressive strength	The addition of natural zeolite resulted in an increase in slump and a decrease in compressive strength over 7 and 28 days.	[116]
46	Natural zeolite	20, 10, 30	7, 28, 56, 90	Flexural strength and water absorption	The addition of natural zeolite resulted in a 30 % increase in water absorption. However, it also led to a 10 % decrease in flexural strength at 28 days.	[117]
47	Natural zeolite	20, 40, 50	28	Effects of natural zeolite addition on the properties of lime putty-based rendering mortars	The addition of zeolite increased water absorption and porosity. In addition, a higher content of zeolite (over 30 %) led to an increase in compressive strength.	[118,119]
48	Natural Zeolite	10, 20	28, 90	Salt crystallization resistance	Zeolite caused a significant reduction in thermal conductivity and volumetric heat capacity because of the lower density of zeolite compared to quartz sand and the greater porosity of lightweight zeolite. Using zeolite as aggregate significantly increased the water vapor absorption capacity.	[120]
49	Natural zeolite	20	28	Workability	Calcination decreased the surface area, leading to an improvement in the mixture's viscosity and yield stress, as well as an	[121]

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Table 4 (*continued*)

	Material	Cement replacement dosage (%)	Number of days	Conducted tests	Main outputs	Ref.
					improvement in workability and a reduction in the porosity of the mixture.	
50	Synthesis of zeolite from industrial wastes	20	1, 7, 28	Preparation of zeolite from the synthesis of industrial waste and its use in concrete	Zeolite improved 28-days compressive strength.	[122]
51	Zeolite	25, 50	7,28	Mechanical properties	Zeolite increased the flexural and compressive strengths of concrete over time.	[123]
52	Zeolite	10, 20	0 h, 0.5 h, 12 h, 1d, 3d, 7d, 14d, 28d	Internal curing performance	The pozzolanic reaction improved zeolite particles' water absorption and shortened the cement paste's humidity saturation period through internal curing. As the pozzolanic reaction progressed, the percentage of pores and water absorption in zeolite particles increased.	[124]
53	Zeolite	0–100 (with 10-day intervals)	28	Shrinkage	Zeolite directly affected the paste's drying shrinkage.	[125]
54	Zeolite	0, 5, 15, 20	7, 28, 90, 180	Mechanical properties and durability	Zeolite enhanced the properties, in terms of mechanical properties and durability.	[26]
55	Zeolite	0, 5, 15, 20	7, 28	The effect of zeolite on the properties of concrete	Density, compressive strength, and resistance to freeze–thaw cycles were improved.	[126]
56	Nano silica and zeolite	10	7, 28, 90	Mechanical properties and durability	Adding zeolite into concrete had a limited impact on the mechanical properties, but it notably reduced the rate of chloride penetration and improved electrical resistivity.	[127]
57	Zeolite	5, 10	3, 7, 28, 90	Rheological properties and hardness	Adding zeolite to mortar enhanced its flowability and adhesion, improving 90-day compressive strength.	[128]
58	Natural zeolite and recycled nylon granule	10, 15, 20	28	The effect of zeolite and steel fibers on the properties of concrete nylon granule	Adding steel fibers and natural zeolite enhanced the properties of concrete containing nylon granules.	[129]
59	Zeolite	10, 20	28	Microstructure and mechanical properties	Zeolite decreased the mechanical properties of cement mortar.	[130]
60	Zeolite	0, 5, 15, 20	28	Fresh and hardened properties	Including zeolite reduced the slump flow and water absorption of self-compacted concrete.	[131]
61	Zeolite	20	28	Various properties, including alkali-aggregate reactions	Zeolite improved the resistance properties and reduced the risk of alkali-aggregate reactions through pozzolanic reactions.	[118]

fresh state. Ahmadi and Shekarchi [94] studied the effects of natural zeolite substituted in different proportions as SCM in concrete mixtures. They noted that, as the amount of cement replaced by natural zeolite increased, more naphthalene-based superplasticizer was needed to keep the workability of the fresh concrete despite the increased viscosity caused by higher dosages of zeolite. A similar observation has been reported in [132].

Natural zeolite has proven to be a highly effective SCM. The high levels of reactive SiO_2 and Al_2O_3 in natural zeolite facilitate the reactions with the $Ca(OH)_2$ generated during cement hydration to form additional C-S-H gel and hydrated aluminates, improving the microstructure of the hardened cement. Improved mechanical properties, decreased permeability, reduced expansion from the ASR, and increased resistance to sulphate attack result from replacing cement with natural zeolite in cement and concrete composites. In addition, some research studies point out that zeolite exhibits insignificant effects on mechanical properties, while effectively improving concrete's durability [18].

4.2.2. *Mechanical properties*

Compared to the mixtures made with regular Portland cement, higher strengths have been reported for natural-zeolite-containing mixtures in late ages, but there is no consensus on how zeolite affects the concrete's mechanical properties during early ages. Tokushige et al. [133] found that, as mortars containing zeolite aged, their compressive strength significantly increased. By substituting 10 and 15 % cement and employing a w/b ratio of 0.5, Najimi [134] investigated the properties of concrete containing natural zeolite (clinoptilolite type) as SCM. After seven days of curing, it was found that the compressive strength of natural zeolite concrete was lower than that of the control mixture, whereas, after 28 days of curing, it was equal to or slightly higher than that of the control mixture.

Natural zeolite appears to perform better in mixed cementitious composites with lower w/b ratios, especially in terms of compressive strength. Natural zeolite was used as part of the cement in a study by Poon et al. [31], which also explored how the cement paste was affected by the w/b ratio. The simultaneous effects of silica fume and natural zeolite in concrete were compared by Ahmadi and Shekarchi [94]. They concluded that the control blend did not exhibit any superior properties at the early or late ages compared to the normal zeolite and silica fume concrete mixtures. When it came to increasing compressive strength, natural zeolite was less successful than silica fume. The 90-day results revealed that the performance of concrete mixes containing natural zeolite was comparable to that of mixtures containing 10 % and 12.5 % silica fume.

The compressive strengths of cement mortars containing two different natural zeolites, clinoptilolite and mordenite, were compared in a study by Kasai et al. [135]. Although the early compressive strength values for both clinoptilolite and mordenite mixed cement mortars with 10 % substitution were lower than those of control cement mortar, they increased after 28 days of curing. Clinoptilolite mixed mortar had higher compressive strength than mordenite mixed mortar. The referenced study attributed this distinction to clinoptilolite's lower water requirement than mordenite.

4.2.3. *Expansion caused by alkali-silica reactions*

One of the notable impacts of natural zeolites is to prohibit the expansion caused by ASRs. Due to the pozzolanic response and cation retention characteristics of natural zeolites, utilizing them can help avoid ASR by diminishing the accessibility of alkalis in the pore solution of solidified concrete, bringing down the pH and draining $Ca(OH)_2$ [135]. Even though zeolites can contain moderately expansive sums of alkalis, the effective soluble amount in most cases is relatively low. Moreover, the expanded alkali-binding capability of the hydration products (lower Ca/Si proportion of the C-S-H stage) assists with lowering the alkalinity. Compared to other pozzolanic materials, utilizing more zeolite appears to lead to less ASR development. The benefits of zeolite to improve ASR resistance can be further increased by warm treatment, chemical treatment, and further grinding [136–138]. However, as with other pozzolanic materials, an insufficient proportion of zeolite can increase the adverse effects of ASR [135,138,139].

The adequacy of natural zeolite in avoiding ASR expansion has been demonstrated in a few investigations. In a comprehensive study, Feng et al. [140] considered the impact of natural zeolite on avoiding ASR developments. The study found that natural zeolite viably diminished expansion. When 30 % natural zeolite was utilized as SCM, ASR did not occur in concrete, even by utilizing receptive aggregates. Based on the studies mentioned earlier, in some cases, a large amount of zeolite is required to control expansion due to ASR; however, high levels of zeolite can create practical issues. Noting that concrete made with natural zeolite generally requires more water or superplasticizer to keep the same slump as non-zeolite concrete, the initial strength of concrete may decrease as the percentage of zeolite increases [138].

4.2.4. Transport properties and resistance to acid and sulfate attacks

An increase in water absorption is anticipated because natural zeolite absorbs water more quickly than cement [32]. When natural zeolite was added, the depth of water penetration into the concrete mixtures made following EN 12390–8 was found to decrease. After 28 days of curing, the results showed that the depth of water penetration had decreased between 13 % and 40 % compared to the control mixtures. The performance further improved at 90 days of age. According to the tests on water absorption, natural zeolite-containing concrete mixtures absorbed more water than control concrete mixes. The different measurement methods used in each test may be the reason for this variation. Concrete mixtures containing natural zeolite had fewer pores because of their pozzolanic activity and $Ca(OH)_2$ consumption. On the other hand, the water uptake of the mixtures, particularly the paste on the surface of the concrete, impacted water absorption. Similar to the results of water permeability tests, natural zeolites reduced chloride ion permeability. Jana [59] and Feng et al. [140] reported a similar decrease in permeability values for chloride ions. However, the reduction observed using natural zeolites exceeded that of previous studies. This phenomenon can be explained by the considerable pozzolanic reactivity of the natural zeolites examined in the referenced study.

Pozzolans usually perform adequately well to prevent deterioration due to acid and sulphate attacks. Using natural zeolite with Portland cement in concrete increases resistance to aggressive ions from seawater, sulphate attack from the soil, and naturally acidic water. Jana [59] reported improved resistance to expansion caused by sulphate attacks in zeolite-containing mortar bars. Janotka et al. [141] focused on the chemical resistance of natural zeolite mixed cement mortar and its compressive strength. The relatively low resistance of cement-bentonite suspensions to aggressive underground media motivated Janotka and Stevula [142] to use zeolite as a partial substitute for bentonite. The study concluded that the compressive strength and durability of underground containment walls made with zeolite were higher than those made with bentonite alone.

4.2.5. Drying shrinkage and heat of hydration

The drying shrinkage of pozzolanic cement products was the subject of a study by Jana [59] to determine the effects of adding zeolite as an SCM at 10, 20, and 30 % replacement dosages. When Portland cement was replaced by 10 % or 20 % in the zeolite blends, drying shrinkage was comparable to or slightly higher than the control blend. The drying shrinkage was about 20 % greater than that of the control specimen when the zeolite content was increased to 30 %. In a separate study, Kasai et al. [135] investigated the drying shrinkage of mortars containing clinoptilolite and zeolites of the mordenite type. According to the referenced study, drying shrinkage occurred more quickly in the mortar mixtures containing clinoptilolite and mordenite than in the control mortar. In addition, more noticeable shrinkage was observed in the clinoptilolite mortar mixtures than in the mordenite mortar mixtures.

Recent studies have investigated the impact of natural zeolite on the temperature increase resulting from the hydration of cementitious materials. For example, in a report prepared by the NRC [142], the heat of hydration of chabazite and clinoptilolite pastes was investigated at 25 % and 50 % substitution levels. The heat generation rate was higher for the zeolite-containing paste samples than for the control samples before 10 h, but at later ages, the total heat generated was lower than that for the control mixture. Similarly, Sato et al. [143] and Krolo et al. [144] reported that the entire heat generation of control pastes was lower than that of zeolite-containing samples (clinoptilolite type) during the first 15 h; however, this changed to an increasing trend after 15 h. Furthermore, increasing the cement's substitution level with zeolite decreased the heat of hydration.

4.3. Challenges and future directions

Using natural zeolite as an admixture in concrete may decrease compressive strength due to the high water demand for mixing, which is attributed to the porous structure and high surface area of natural zeolite [22,23,145,146]. In addition, the drop of compressive strength, especially at an early age, is attributable to the w/b ratio. In any case, if a suitable amount of natural zeolite is chosen for concrete production, the benefits of applying them can outweigh the drawbacks. A few strategies to advance the use of zeolite in concrete production include considering other supplementary materials (e.g., carbon nanotubes [147,148], nano-silica [149–151], nano-titanium dioxide [152–154], and silica fume [33,155,156]). Typically, these materials are added to concrete mixtures to serve two vital purposes: First, since these materials contain fine or very fine particles, they can serve as fillers for minuscule spaces between large particles, increasing the concrete density. As a result, concrete's durability and strength can be improved. Second, they are recommended to decrease the requirements for superplasticizers and other additional mineral admixtures to mitigate potential practical limitations and cost considerations.

Using glassy surface materials, such as furnace slag, and substances possessing spherical structures, such as silica and fly ash, in conjunction with natural zeolites in producing zeolites may be a potential solution. By employing this strategy, a "ball bearing" effect between these spherical particles can occur in the concrete mixture, improving the concrete's flow characteristics [157–159]. Although there have been limited studies on the ability of concrete containing natural zeolite to remove contaminants, the acceleration of industrial developments highlights the potential for zeolite to reduce environmental pollution, in addition to minimizing the reliance on Portland cement. The outlined aspects can be subjects of future research and development.

5. Conclusions

In this study, an organized investigation was conducted to examine the applications of zeolite in concrete and mortar mixtures. Given that about 0.9 tons of CO_2 are emitted per ton of cement and another 0.1 tons per ton of concrete [160], the use of natural zeolites can be one of the solutions for reducing the cement required for the concrete industry [161–164]. Modifying concrete mixtures with the addition of natural zeolite can increase the concrete's strength and durability over time, allowing them to be successfully used in various construction projects. In addition, using ultrafine zeolite and carbonate aggregate powders instead of Portland cement clinkers (in the range of 20 %-25 %) reduces the alkali content soluble in water [165]. Water desorption in low- and high-humidity environments is another reason for considering natural zeolites. Humidity control solutions maintain indoor humidity to preserve historical objects in buildings, such as museums. Natural zeolites can also produce different forms of concrete, such as lightweight aggregate concrete and autoclaved aerated concrete [26,166]. A few studies have used natural zeolites to produce lightweight expanded aggregates [167–172]. Besides pozzolanic activity, other properties of zeolite are useful for targeted applications, owing to their high surface area, ion exchange capability, high temperature expansion, low moisture absorption, and high moisture resorption.

This study outlined several key areas with potential for future research and development. Firstly, further research into natural zeolite used in concrete, including optimal dosages, is suggested. Quantifying the environmental and economic benefits of zeolite-based concrete compared to conventional concrete mixtures is crucial for a movement toward sustainable construction practices. Additionally, it is critical to prioritize innovations in concrete technology, exploring new techniques and additives to enhance the constructability and performance of zeolite-containing concrete mixtures. Future research can also investigate zeolite's broader applications beyond permeability reduction, including thermal insulation, fire resistance, and chemical corrosion resistance. Recognizing the significance of standardization, efforts can also be made to establish industry-level standards for integrating zeolites into concrete and mortar. Lastly, long-term performance assessments of concrete structures made with zeolites are vital for understanding their benefits over time. Such new perspectives will directly assist with maximizing natural zeolite use, addressing sustainability challenges, and advancing eco-conscious construction practices.

CRediT authorship contribution statement

Mohammad Shekarchi: Writing – review & editing, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Babak Ahmadi:** Data curation, Methodology, Validation, Writing – review & editing. **Fazel Azarhomayun:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Behrouz Shafei:** Writing – review & editing, Supervision, Software, Resources, Methodology, Investigation. **Mahdi Kioumarsi:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, 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.

Data availability

Data will be made available on request.

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