Using Zeolite as a Partially Replaced Cement in Construction Materials: A Systematic Review of Properties

Alaa M. Hamad[1], Asma T. Ibraheem[2], Ahmed S. Ali[3], Azza H. Moubarak[4]

Authors affiliations:
1) Department of Civil Engineering, Al-Nahrain University, Baghdad, Iraq.
alaa.pciv22@ced.nahrainuniv.edu.iq
2*) Department of Civil Engineering, University of Al-Nahrain, Baghdad, Iraq.
asma.th.ibraheem@nahrainuniv.edu.iq
3) Department of Civil Engineering, University of Al-Nahrain, Baghdad, Iraq.
ahmed.s.ali@nahrainuniv.edu.iq

4) Department of Civil Engineering, Suez Canal University, Ismailia, Egypt
azza_moubarak@eng.suez.edu.eg

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Abstract

Concrete is considered the most important and widely used building material in the world of construction and building due to its durability, high efficiency in shaping, and relatively reasonable cost. The main component of concrete is cement, and one of the most important problems related to cement is the environmental problems associated with cement manufacturing, as the cement manufacturing process releases a large amount of carbon dioxide. Despite the essential role of concrete in construction, we cannot ignore its environmental impact. Some claim that exploring alternative materials or innovative building techniques would reduce the carbon footprint and enhance sustainability in the industry. Partial cement replacement with pozzolanic materials like zeolite is a key technique to reduce carbon dioxide emissions. Zeolite, which reduces permeability, is a typical concrete ingredient that strengthens and lasts. Recently, natural zeolite has become a prominent concrete pozzolanic component. For environmental preservation and sustainable development, various experiments were done on concrete with pozzolanic components partially substituting cement and compared to ordinary concrete. A partial replacement of cement with zeolite improves the properties of concrete up to a certain age and mixing ratio. More than 44 relevant articles from 2004–2024 were selected from 762 papers evaluated for this paper. This paper reviews natural zeolite research in real applications. Additionally, it provided a cutting-edge review of natural zeolite literature through a critical analysis of various previous investigations. It also helped to understand how zeolite influences concrete mixture workability, strength, and durability. Since zeolite is a major concrete ingredient, it should be promoted as a sustainable resource.

Keywords: Blended Cement, Cement, Construction Materials, Natural Zeolite, Specific Heat, Sustainable Zeolite, Thermal Conductivity, Thermal Diffusivity.

استخدام الزيوليت كبديل جزئي للأسمنت لمواد البناء: مراجعة منهجية للخصائص

علاء محسن حمد، اسماء ثامر إبراهيم، احمد سلطان علي، عزة حسن ابراهيم

الخلاصة:

تعتبر الخرسانة من أهم مواد البناء وأكثرها استخداماً في عالم البناء والتشييد نظراً لمتانتها وكفاءتها العالية في التشكيل وتكلفتها المعقولة نسبياً. المكون الرئيسي للخرسانة هو الأسمنت، ومن أهم المشاكل المتعلقة بالأسمنت هي المشاكل البيئية المرتبطة بتصنيع الأسمنت، حيث تطلق عملية تصنيع الأسمنت كمية كبيرة من ثاني أكسيد الكربون. وعلى الرغم من الدور الأساسي للخرسانة في البناء، إلا أننا لا نستطيع تجاهل تأثيرها البيئي. ويزعم البعض أن استكشاف مواد بديلة أو تقنيات بناء مبتكرة من شأنه أن يقلل من البصمة الكربونية ويعزز الاستدامة في الصناعة. ويعد استبدال الأسمنت جزئياً بمواد بوزولانية مثل الزيوليت تقنية أساسية لتقليل انبعاثات ثاني أكسيد الكربون. والزيوليت الذي يقلل من النفاذية هو مكون نموذجي للخرسانة يقوي ويدوم. وفي الآونة الأخيرة، أصبح الزيوليت الطبيعي مكوناً بوزولانياً بارزاً للخرسانة. وللحفاظ على البيئة والتنمية المستدامة، أجريت تجارب مختلفة على الخرسانة بمكونات بوزولانية تحل جزئياً محل الأسمنت ومقارنتها بالخرسانة العادية. ويؤدي الاستبدال الجزئي للأسمنت بالزيوليت إلى تحسين خصائص الخرسانة حتى عمر معين ونسبة خلط معينة. تم اختيار أكثر من ٤٤ مقالة ذات صلة من ٢٠٠٤ إلى ٢٠٢٤ من بين

٧٦٢ ورقة تم تقييمها في هذه الورقة. يتم تغطية الصفات الملموسة الأخرى في الموارد الأخرى. تستعرض هذه الدراسة أبحاث الزيولايت الطبيعي في التطبيقات الحقيقية. قدمت هذه الدراسة مراجعة حديثة لأدبيات الزيولايت الطبيعي من خلال التحليل النقدي لمختلف التحقيقات السابقة. والتي ستساعد على فهم كيفية تأثير الزيولايت على قابلية تشغيل الخليط الخرساني وقوته ومتانته. وبما أن الزيولايت هو عنصر ملموس رئيسي في تحسين الخرسانة، فيجب الترويج له كمورد مستدام.

1 Introduction

With their compact texture, the zeolite tuffs have compressive strengths ranging from 10 to 30 MPa, making them fairly robust. Philipsite and herschelite are the two main zeolite minerals. The zeolite minerals exhibit significant reactivity with lime and take on cementitious properties akin to pozzolans containing volcanic glass once the compact mass is crushed to fine particle size[1]. Zeolites are natural crystalline aluminosilicates with a three-dimensional honeycomb structure of TO_4 tetrahedral units (T: Si, Al) with four atoms. The tetrahedral present in zeolites is categorized as secondary building blocks because of their geometric arrangement[2]. Zeolite structures differ depending on how bonds between secondary building components generate polyhedral. There are around seven groups of secondary building units and about 40 different kinds of natural zeolit[3]. One type of these mineral components is natural zeolite. There are significant amounts of reactive SiO_2 and Al_2O_3 in natural zeolite (aluminosilicate mineral[4].By pozzolanic interaction with Ca $(OH)_2$, zeolite substitution can increase cement strength similarly to other pozzolanic materials. May decrease the porosity of the blended cement paste, stop unfavorable expansion caused by the alkali-aggregate reaction, and enhance the interfacial microstructure characteristics between the blended pastes of cement[4] [5] . It has been noted that natural zeolite has a higher pozzolanic activity than fly ash, but a lower one than silica fume.

2 Methodology

"Use of Zeolite as a Construction Material" has previously been identified as the review's general topic. The articles included in the analysis were published between 2004 and 2024. First, 762 records of data were taken out of the database. After a title and abstract scan, duplicate articles were eliminated, all articles were initially read, and they were removed as follows: After searching for articles with titles that were either exactly the same or had titles that had nothing to do with the research topic (for example, zeolite's uses in agriculture, water purification, and improving the properties of some weak soils) were thrown out. The remaining research abstracts were then read, and studies that used the same methodology and method of work were also thrown out. Research outside the framework of civil engineering in general and outside improving the properties of concrete in particular was excluded. In addition, focusing on quantity rather than quality may lead to the inclusion of less important articles that do not contribute significantly to the general understanding of the topic., leaving 282 articles in total. To give a thorough and systematic knowledge, further references were included to address difficulties related to qualities, treatments, applications, and standards. For the text analyses, the 55 articles were loaded into Microsoft Excel. An overview of the topic is provided via word clouds by giving the frequency of keywords and the program will give a larger volume for each word with a higher frequency through this analysis it is possible to know the importance of the research in which direction. Text analyses using Microsoft Excel can help automate the extraction of information from text, reducing the time required for human processing. Figure 1 shows a schematic diagram of the co-occurrences of related terms. The terms “zeolite”, “concrete”, “cement”, “silica”, “compressive strength”, “mechanical properties”, “mortar”, “durability”, and “fly ash” were the most frequently used, with corresponding numbers of 862, 581, 484, 315, 203, 195, 162, 139. Figure 2 shows the distribution of the years of publication of the collected research papers. An increasing and decreasing trend can be observed in the publication behavior. From 2004 to 2010 and 2014, only a few research papers were published. The year 2023 was the year with the highest number of publications. Figure 3 lists the countries that have conducted studies on zeolites and shows the interest of different countries in zeolites. These four countries are known to be the most interested in this field Iran, China, Turkey, and the United States. The distribution of the chosen journal-related articles is shown in figure 4. "Engineering" contains the most often used zeolite-related articles, accounting for almost 35.3% of all publications (491 searches). "Materials Science" comes in second on the list with 386 research and 27.7% of the total, followed by "Environmental Science" with 106 studies and 7.6% of the total.

Figure (1): Word cloud according to word frequency in the search

3 Results And Discussion

This study aims to evaluate the application of zeolite as a material for construction and pinpoint areas of unused research need. This section considers the types of zeolites used in concrete, its mechanical and physical characteristics, replacement approaches, and uses for both zeolite and composites. The gathered literature uses a variety of zeolite species from different locales.

3.1 Natural Zeolite Properties

With their compact texture, the zeolite tuffs have compressive strengths ranging from 10 to 30 MPa, making them fairly robust. Philipsite and herschelite are the two main zeolite minerals. The zeolite minerals exhibit significant reactivity with lime and take on cementitious properties akin to pozzolans containing volcanic glass once the compact mass is crushed to fine particle size [1]. Natural zeolites have been found all over the world. While offsite, paulingite, barrerite, and mazzite are rarer, clinoptilolite, mordenite, phillipsite, chabazite, stilbite, analcime, and laumontite are quite abundant types. Clinoptilolite is the most common naturally occurring zeolite and is extensively utilized worldwide. Natural zeolites are porous, hydrated aluminosilicate minerals that possess useful physicochemical qualities as sorption, molecular sieving, cation exchange, and catalysis. Natural zeolite is becoming more and more of a subject of study interest for environmental applications because of its characteristics and widespread occurrence. [6]. Zeolites are natural crystalline aluminosilicates with a three-dimensional honeycomb structure of TO_4 tetrahedral units (T: Si, Al) with four atoms. The tetrahedral present in zeolites is categorized as secondary building blocks because of their geometric arrangements [2].Zeolite structures differ depending on how bonds between secondary building components generate polyhedral. There are around seven groups of secondary building units and about 40 different kinds of natural zeolite [3].One type of these mineral components is natural zeolite. There are significant amounts of reactive SiO_2 and Al_2O_3 in natural zeolite (aluminosilicate mineral) [4].

By pozzolanic interaction with $Ca(OH)_2$, zeolite substitution can increase cement strength similarly to other pozzolanic materials. May decrease the porosity of the blended cement paste, stop unfavorable expansion caused by the alkali-aggregate reaction, and enhance the interfacial microstructure characteristics between the blended pastes of cement [5]. It has been noted that natural zeolite has a higher pozzolanic activity than fly ash, but a lower one than silica fume [4] Table 1 presents the physical characteristics natural zeolites and chemical composition, for past studies of zeolite.

Table (1): The Physical characteristics of zeolite and cement **[2]**

Cement							
Reference	[7]	[8]	[9]	[10]	[11]	[12]	[13]
Surface area	35٠ (m^2/kg)		33٠(m^2/kg)	38٠ (m^2/kg)	351(m^2/kg)	962 (m^2/kg)	355 (m^2/kg)
Specific gravity	3.15	2.67	3.15	3.14			3.1
Density					3150 (kg/m^3)	3140 (kg/m^3)	
Fineness		6.45 %				11%	
setting time			105(min)	141(min)		125(min)	
Zeolite							
reference	[11]	[14]	[13]				
Surface area	39٠ (m^2/kg)	1٠٠ (m^2/kg)	75٠ (m^2/kg)				
Specific gravity		2.2	2.16				
Density	2910 (kg/m^3)						
Fineness							
setting time							

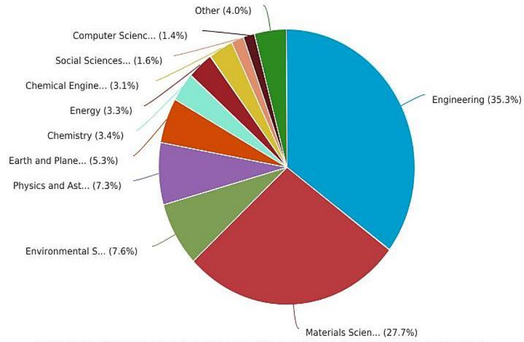

Figure (2): Papers' publication years.

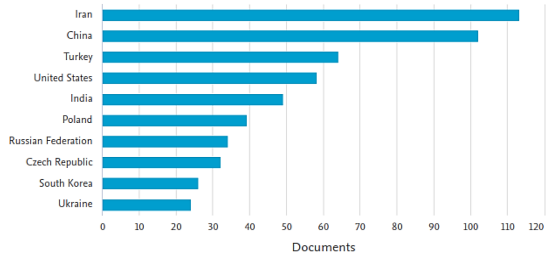

Figure (3): Lists the countries that have conducted zeolite studies.

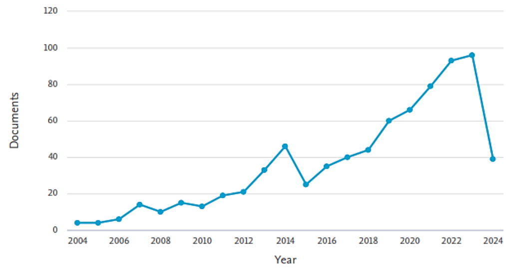

Figure (4): Distribution of publications by journal.

3.2 Preparation of concrete using zeolite as a substitute for part of the cement

Since reactive SiO_2 and Al_2O_3 are present in considerable quantities in natural zeolite, it is frequently employed as a cement blending ingredient in the cement industry. it is frequently employed as a cement blending ingredient in the cement industry. This mineral combination contributes to improving the quality of concrete [11]. Like any other pozzolanic ingredient, zeolite primarily increases the strength of concrete through the pozzolanic reaction with Ca

$(OH)_2$. When zeolite material is compared to other pozzolans, its reactivity is interesting [15]. Zeolite can be used in place of cement to improve the characteristics of concrete. By lowering the porosity of the blended cement paste, this mineral additive improved the produced concrete's interfacial transition zone microstructure qualities between the blended cement paste and the aggregate [16]. Zeolite can be used in place of cement in the recommended ratios to create concrete that is as strong as regular concrete. Because zeolite is naturally occurring, using it in concrete does not negatively impact the environment [17].

3.3 Assessment of studies on the use of zeolite materials in the production of concrete

It was found from the study that natural zeolite materials may be substituted for cement in building applications. This section reviews zeolite's uses in concrete mixes and includes information on material kinds; ratio of cement replacement, the length of the curing period, tested conditions, and how they affect concrete. Three main literature-related points were examined in this review research, the impact of natural zeolite on the characteristics of mortar and concrete mixtures, and the rationale and incentive behind utilizing zeolite as shown table 2

3.4 Tests of concrete enhancement with zeolite and discussion

Table 3 lists the parameters of the concrete, both with and without zeolite addition. The change in compressive strength, tensile strength, frost resistance, permeability, chloride penetration, electrical resistivity, and shrinkage is displayed in this table at 28 days.

Table (2): Summary of earlier studies on the use of zeolite in mortar and concrete mixes.

1	***Reference***	[18]
	Ratio of zeolite replacement %	6, 10, 15
	Days	7, 28
	Tests	Compressive strength, total absorption, tensile strength and abrasive resistance.
	Result	Concrete paver blocks made with zeolite provide unchanging strength, a long life, and sustainability. reduces microcracks and enhances water absorption and compressive strength.
2	Reference	[19]
	Ratio of zeolite replacement %	10, 20
	Days	0hr., 0.5hr., 12hr., 1day, 3day, 7day,14day, 28day
	Tests	Performance of internal curing
	Result	Through internal curing, the pozzolanic reaction reduced the humidity saturation period of the cement paste and enhanced the water absorption of the zeolite particles. As the pozzolanic process progressed, the percentage of porosity and absorption of water in zeolite grains increased.
3	Reference	[20]
	Ratio of zeolite replacement %	0, 5, 10, 15
	Days	7day, 28day, 90day
	Tests	Compressive strength test, flexural strength test, abrasion test, and fresh characteristics
	Result	Compressive strength test, flexural strength test, abrasion test, and fresh characteristics and mechanical characteristics were improved more significantly by reducing the w/b ratio than by employing natural zeolite. Observations of mixtures containing 10% zeolite a considerable decrease in microcracks.
4	Reference	[21]
	Ratio of zeolite replacement %	7.5, 15, 22.5, 30
	Days	7day, 28day, 90day
	Tests	Compressive strength test, flexural strength test, and the depth of water penetration test.
	Result	Adding 22.5 percent zeolite greatly increased the resistance to water penetration.
5	Reference	[22]
	Ratio of zeolite replacement %	10, 15, 20, 25
	Days	28
	Tests	Triaxial behavior, permeability, and unconfined strength microstructure behavior
	Result	Early in the curing process, the incorporation of zeolite decreased peak compressive strength, unconfined strength test, and elastic modulus of concrete.
6	Reference	[23]
	Ratio of zeolite replacement %	5 ,10 ,15

	Days	7day, 28day, 91day
	Tests	Mechanical properties tests.
	Result	Using natural zeolite, the mechanical characteristics of blends were enhanced. It was discovered that 10% was the ideal rate for natural zeolite.
7	Reference	[24]
	Ratio of zeolite replacement %	20, 10, 30
	Days	7, 28, 56, 90
	Tests	Water absorption and flexural strength
	Result	The amount of water absorbed increased by 30% when zeolite was incorporated. But after 28 days, it also caused a 10% drop in flexural strength.
8	Reference	[25]
	Ratio of zeolite replacement %	20, 40, 50
	Days	28
	Tests	Effect of adding natural zeolite on the characteristics of rendering mortars made with lime putty
	Result	Zeolite was added, which enhanced porosity and water absorption. Furthermore, a zeolite concentration greater than thirty percent increased the compressive strength.
9	Reference	[26]
	Ratio of zeolite replacement %	10, 20
	Days	28, 90
	Tests	Resistance to salt crystallization
	Result	Because lightweight zeolite has a higher porosity than quartz sand and a lower density than quartz sand, it significantly reduces the thermal conductivity and decreases heat capacity. The water vapor absorption capacity was greatly enhanced by using zeolite as the aggregate.
10	Reference	[27]
	Ratio of zeolite replacement %	(0–100) with 10-day intervals
	Days	28
	Tests	Shrinkage
	Result	Zeolite had a direct impact on the drying shrinkage of the paste.
11	Reference	[28]
	Ratio of zeolite replacement %	30, 40, 50
	Days	7, 28
	Tests	Reaction rate, compressive strengths, and pozzolanic activity
	Result	The pozzolanic activity of zeolites rose after each treatment, either separately or in combination, following eight days of hydration.
12	Reference	[29]
	Ratio of zeolite replacement %	10
	Days	28, 90
	Tests	Freeze–thaw and microstructure
	Result	Zeolite internal curing strengthened the concrete's pore structure and increased its resistance to frost after 150 cycles.
13	Reference	[30]
	Ratio of zeolite replacement %	0, 5, 10, 20, 30
	Days	28
	Tests	Compressive strength
	Result	The hydration process was slowed down by natural zeolite powder, which reduced compressive strength.
14	Reference	[31]
	Ratio of zeolite replacement %	0, 10
	Days	1, 28, 56 90,180
	Tests	Durability properties and mechanical
	Result	Combining cement alternatives like zeolite with additional chemical additives made the concrete more workable and enhanced its resilience to freeze-thaw cycles. Additionally, it decreased the depth of water penetration and drying shrinkage. Up to ninety days of hardening, adding zeolite instead of cement resulted in a brief reduction in strength; but, after 180 days, the compressive strength of the zeolite-containing concrete was greater than that of the cement-free concrete.
15	Reference	[32]
	Ratio of zeolite replacement %	10, 20, 30, 40

	Days	28
	Tests	Calcination test above 500 ∘C
	Result	The cement paste's consistency was enhanced and bleeding was decreased by adding 10% of natural zeolite. The rheological characteristics of cement paste were affected by calcination at temperatures over 500 ∘C.
16	Reference	[33]
	Ratio of zeolite replacement %	20, 30, 40
	Days	7, 28
	Tests	The properties of rheology
	Result	Over time, adding zeolite to mortar improved compressive strength while decreasing rheological characteristics (yield stress and plastic viscosity).
17	Reference	[34]
	Ratio of zeolite replacement %	10, 20
	Days	28
	Tests	Mechanical properties and microstructure
	Result	Cement mortar's mechanical properties were reduced by zeolite.
18	Reference	[35]
	Ratio of zeolite replacement %	10, 15
	Days	1, 3, 7, 14,28, 90, 180 and 365
	Tests	Concrete's durability as measured by its capacity to withstand frost, wear, tensile cracks, and absorption
	Result	According to test findings, the use of zeolite showed promise in increasing the compressive strength of high-performance concrete, fracture resistance, and self-shrinkage because of its synergistic internal curing and pozzolanic properties.
19	Reference	[36]
	Ratio of zeolite replacement %	15
	Days	28
	Tests	Superhydrophobic properties
	Result	Utilizing natural zeolite increased the superhydrophobic mortar's microstructures and reduced water absorption, which improved its anti-corrosion capabilities.
20	Reference	[37]
	Ratio of zeolite replacement %	0, 14, 22
	Days	7
	Tests	Flexural, compressive strength and density
	Result	Compressive strength increased by 4% and flexural strength increased by 18% with the addition of zeolite. And How well the created ultra-disperse modified zeolite-based additive works
21	Reference	[38]
	Ratio of zeolite replacement %	5, 10
	Days	3, 7, 28, 90
	Tests	Properties of rheology and hardness
	Result	Mortar's flowability and adhesion were improved by adding zeolite, which also increased the mortar's 90-day compressive strength.
22	Reference	[39]
	Ratio of zeolite replacement %	20
	Days	1day, 2day, 3day, 5day
	Tests	Autogenous shrinkage test
	Result	Zeolite reduced autogenous shrinkage and produced self-desiccation.
23	Reference	[40]
	Ratio of zeolite replacement %	20
	Days	7, 28
	Tests	Properties of calcined natural zeolites
	Result	The compressive strength increased in paste including calcined zeolite as compared to raw zeolite because the hardened cement materials' decreased porosity and refined pore structure improved.
24	Reference	[41]
	Ratio of zeolite replacement %	0, 5, 15, 20
	Days	7, 28
	Tests	Zeolite's effect on the characteristics of concrete

	Result	Its density of concrete improved the compressive strength also improved, and the cycle of freeze-thaw was enhanced.
25	Reference	[42]
	Ratio of zeolite replacement %	10, 15
	Days	28 ,90 ,236
	Tests	Compressive strength, resistance to acid attack, water absorption, and chloride diffusion
	Result	The highest positive results were when 10% zeolite was substituted for cement.
26	Reference	[43]
	Ratio of zeolite replacement %	5
	Days	7, 28
	Tests	Absorption of water, resistance to abrasion, strength in tensile splitting, and freeze-thaw
	Result	The top layer of paving blocks made of concrete contains zeolite, a material composed of aluminum fluoride that increases the blocks' lifetime and durability.
27	Reference	[44]
	Ratio of zeolite replacement %	10
	Days	28
	Tests	Shrinkage
	Result	By using zeolite, the dry shrinkage after 28 days was reduced by 60%.
28	Reference	[45]
	Ratio of zeolite replacement %	30
	Days	28
	Tests	Shrinkage
	Result	Zeolite was added to concrete, which enhanced the simultaneous limits of strength but reduced 28-day autogenous and drying shrinkage.
29	Reference	[46]
	Ratio of zeolite replacement %	0, 5, 10
	Days	7, 28
	Tests	Properties of Pore
	Result	Zeolite decreased the quantity of voids in the cement paste, which in turn decreased the pore size in the paste's microstructure.
30	Reference	[15]
	Ratio of zeolite replacement %	10
	Days	1day, 28day, 56day, 90day,180day
	Tests	Water pressure penetration test, freeze-thaw resistance test , drying shrinkage test, and absorption of water test.
	Result	Good results for freeze-thaw durability, drying shrinkage decrease, and penetration of water resistance were seen in concrete containing zeolite.
31	Reference	[47]
	Ratio of zeolite replacement %	10
	Days	28
	Tests	Transport properties of concrete, resistance to chloride penetration test, and compressive strength test.
	Result	Concrete's resistance to ion and water penetration has been improved over time by zeolite. Properties including the electrical resistance, water penetration depth, and chloride diffusion coefficient were shown to be correlated. Chloride seepage was more difficult to penetrate in a mixture including natural zeolite.
32	Reference	[48]
	Ratio of zeolite replacement %	10
	Days	28
	Tests	Water absorption, and Compressive strength, density
	Result	The durability was improved by employing low-temperature synthetic zeolite derived from aluminum fluoride.
33	Reference	[49]
	Ratio of zeolite replacement %	20
	Days	28
	Tests	Workability

	Result	Calcination reduced the surface area of the mixture, which improved its workability, reduced its porosity, and improved the yield stress of mixture.
34	Reference	[50]
	Ratio of zeolite replacement %	0, 5, 15, 20
	Days	7, 28, 90,180
	Tests	durability and mechanical properties
	Result	Zeolite improved its characteristics, particularly its mechanical properties and durability.
35	Reference	[17]
	Ratio of zeolite replacement %	0, 8, 16, 24, 32, 40
	Days	28
	Tests	XRF (X-ray fluorescence)
	Result	It is appropriate to use natural zeolite while creating composite mixtures.
36	Reference	[51]
	Ratio of zeolite replacement %	10, 20, 40, 60
	Days	28, 90, 360
	Tests	Mechanical characteristics durability, Physical characteristics, hygric properties, and thermal properties
	Result	Among the examined characteristics, mortar with twenty percent zeolite was the best.
37	Reference	[52]
	Ratio of zeolite replacement %	10
	Days	7day, 28day, 90day
	Tests	Mechanical properties of concrete and durability test
	Result	Concrete treated with zeolite showed a marked reduction in the rate of chloride penetration and an increase in electrical resistivity, while the mechanical properties of the material were unaffected.
38	Reference	[11]
	Ratio of zeolite replacement %	5,10,15,20,25
	Days	28,90,270
	Tests	Tests for water permeability, electrical resistivity, paste microstructure analysis, tensile splitting strength, compressive strength, and transition zone microstructure
	Result	The application of Zeolite modified the quality of pastes and the interfacial transition zone.
39	Reference	[53]
	Ratio of zeolite replacement %	0, ٧.5, 10, 15, 22.5, 25, 30
	Days	28day, 90day, 270day
	Tests	Water penetration test, slump test, drying shrinkage test, compressive strength test, and resistance to freezing and thawing
	Result	Concrete containing zeolite needs a dosage of superplasticizer to ensure the desired slump because of its large surface area. The findings also showed that the addition of an air-entraining agent and a superplasticizer to zeolite concrete had a major impact on the concrete's freeze-thaw cycles, drying shrinkage, and water penetration. And Zeolite with 22% showed a notable improvement in resistance to water penetration.
40	Reference	[54]
	Ratio of zeolite replacement %	0, 5, 15, 20
	Days	28
	Tests	properties that are both fresh and hardy
	Result	Zeolite inclusion decreased the self-compacted concrete's slump flow and water absorption.
41	Reference	[55]
	Ratio of zeolite replacement %	20
	Days	28
	Tests	Many properties such as alkali-aggregate reactions
	Result	Zeolite improved resistance characteristics and reduced the possibility of alkali-aggregate reactions through pozzolanic reactions.
42	Reference	[56]
	Ratio of zeolite replacement %	25
	Days	3day, 7day, 28day, 90day
	Tests	Paste test strength, zeolite test degree of reactivity, and paste test porosity.

	Result	After adding 25% zeolite, it decreases the porosity and strengthens pastes prepared with a low water binding ratio.
43	Reference	[8]
	Ratio of zeolite replacement %	10
	Days	7,28
	Tests	Compressive strength
	Result	Since zeolite additions contain active SiO_2 and Al_2O_3, the compressive strength of modified concrete improved.
44	Reference	[57]
	Ratio of zeolite replacement %	0, 5, 10, 15, 20 0.4, 0.6, 0.8, 1.0, 2.5
	Days	8, 90
	Tests	Concrete's permeability, strength, and absorption characteristics
	Result	zeolite works better than of fly ash in concrete.

Table (3): Lists the parameters of the concrete both with and without zeolite addition (**[6]**, **[7]**, **[8]** and **[11]**).

Zeolite replacement (% by weight)	Compressive strength (Percent of control) 28 days	Tensile strength	water permeability 28 days	Chloride penetration	Electrical resistivity 28 day	Frost resistance	Shrinkage
0	100	100	100	100	100	100	100
5	125	-	-	85	-	249	36
10	117	117	82	49	106	332	62
15	114	111	71	36	153		84
20	102	-	-	32	-		
25	95	-	-	17	-		

3.4.1 Enhancing effects of zeolite on the compressive strength of concrete

Reviewed the research that was collected and compared concrete reinforced with zeolite and concrete made from Portland cement, and it was found that there is no consensus about increasing or decreasing the compressive strength when enhancing the concrete with zeolite. In a study conducted by Ahmed and Ibraheem (2024) after 28 days of curing, the inclusion of zeolite increases the compressive strength, which demonstrates the benefit of zeolite in blended cement [18]. Markiv et al (2016) examined the natural zeolite containing concrete, natural zeolite concrete's compressive strength was less than that of the mixture without zeolite after 7 days of curing, but it was on a level with or slightly above, the mixture without zeolite after 28 days [15]. In a different investigation by Sedlmajer (2014), compressive strength values comparable to concrete containing Portland cement were only attained after 90 days of curing when zeolite was substituted for cement at a rate of up to 22%, the qualities of concrete made with zeolite plus small amounts of Portland cement can be exactly the same as concrete made with Portland cement alone [53]. The hydration process was slowed down by natural zeolite powder, which reduced compressive strength [58]. In another study conducted by Chan & Ji (1999) when zeolite, silica fume, and pulverized fuel ash were used to replace 10% of cement in concrete, the test results revealed that zeolite performed pulverized fuel ash, but did not reach the level of silica fume in terms of improving strength [7]. Silica fume worked better than natural zeolite. through a rise in compressive strength. The results of the 90-day experiment showed that the efficiency of blends of concrete using natural zeolite was substantially comparable to those with 10% and 12.5% silica fume [59]. Research by Kasai et al. examined the compressive forces of mortars made of cement including clinoptilolite and mordenite, two different types of natural zeolites, after 28 days of curing, the compressive strength values of the mixed cement mortars containing 10% substitution of clinoptilolite and mordenite rose, despite their initial lower values compared to the control cement mortar. The compressive strength of the clinoptilolite mixed mortar was greater than that of the mordenite mixed mortar. The study that was cited explained this difference by pointing out that clinoptilolite requires less water than mordenite [60].

Enhancing effects of zeolite on the workability of concrete The zeolite usually requires more water in the mixture than cement, because of its large porosity and surface area This ultimately causes the workability of the concrete to decrease. As a result, some research recommends combining superplasticizers with natural zeolite. However, it should be highlighted that certain natural zeolites have very little impact on the workability of concrete. Different zeolite mineral types, as well as zeolites' surface shape and crystallinity, have diverse effects on new concrete. the results of substituting natural zeolite in various amounts in concrete compositions. Even with the higher viscosity caused by zeolite ratio increases, more naphthalene-based superplasticizers were required to maintain the workability of the fresh concrete as the proportion of cement substituted by natural zeolite rose, these observations have been published in [59] and [58]. The concrete mixture became less workable when natural zeolite was added. An extra superplasticizer was used to make up for the loss of workability. The porous microstructure of natural zeolite is the reason for the increased water needed for concrete mixes that contain zeolite [15].

3.4.2 Enhancing effects of zeolite on the microstructure of concrete

Examining how zeolite affects the microstructure of concrete has attracted increasing attention. When zeolite is introduced to concrete mixtures, it interacts with the cementitious matrix, changing the microstructural composition in several ways. Among these alterations are modifications to the interfacial transition zone (ITZ) between the cement paste and aggregates, the size of pores distribution, and the emergence of new crystalline phases [61]. Determining how well zeolite incorporated concrete performs in the long-term requires an understanding of these changes. Pore structure analysis is one of the most important components of microstructural assessment. The pozzolanic qualities of zeolite can aid in enhancing concrete's pore structure, this modification may result in less porosity and better permeability resistance [62]. Scanning electron microscopy (SEM) and mercury intrusion porosimetry have been used by researchers to measure and illustrate these changes [2].Understanding the long-term effects of zeolite on the durability and compressive strength of concrete requires looking into its impact on microstructural alterations. Some researchers have highlighted the results on improving resistance to deteriorating processes, flexural strength, and compressive strength, such as sulfate assault and chloride ion penetration [63]. The overall performance of concrete is also significantly influenced by the cement paste and aggregates' interfacial transition zone (I.T.Z). By decreasing of harmful chemicals and strengthening the interaction between aggregates and cementitious materials zeolite inclusion may increase the interfacial transition zone [2]. Numerous directions for further investigation have developed as our understanding of how zeolite affects the microstructure of concrete continues to develop. Research has to be done in a number of areas, including evaluating microstructural changes under various curing conditions, examining zeolite's potential for synergy with other Supplementary cementitious materials (SCM), and examining zeolite's involvement in reducing alkali-silica reactions (ASR). An important part of this research is evaluating the characteristics of concrete containing zeolite, this might contribute to our knowledge of how zeolite influences the main properties and functioning of concrete. In a study conducted by Girskas et al. (2016), it was possible to determine that adding zeolite to concrete enhances the effectiveness of the air-entraining admixture (AEA) by analyzing the results of concrete density and compressive strength. Fine zeolite particles enhance the viscosity and cohesiveness of cement paste, which helps explain these events. These changes also affect the rheological properties and microstructure of the new cement paste, if a zeolite admixture is used, the amount of air-entraining additive can be reduced in the future when creating the concrete mix composition [48].

3.4.3 Enhancing effects of zeolite on the Freezing and thawing of concrete

Concrete deforms and mechanically breaks down when it is in a water-saturated state due to intricate physical processes that occur during periodic freezing and thawing. Comparing the concretes with and without zeolite, the ones with 10% zeolite showed greater resistance to damage from freezing and thawing [15]. It has to do with the secondary CSH gel that forms as a result of the pozzolanic reaction and lowers the capillary porosity of concrete that contains zeolite. According to another study, concrete with 10% zeolite added had superior resistance to freezing and thawing damage after 100 cycles than concrete without zeolite [51]. In-depth experiments using concrete pavement blocks with synthetic zeolite admixture in the upper layer revealed that following 28 freeze-thaw cycles, zeolite admixture reduced surface scaling four times. The durability and lifetime of concrete paving blocks are likely increased when a synthetic zeolite additive is made from aluminum fluoride manufacturing waste [43].Enhancing effects of zeolite on the water permeability of concreteReviewed the research that was collected and compared concrete containing zeolite and concrete made from Portland cement. In a study conducted by Ban et al., it was found that in concrete containing 10% zeolite aged 28 days, a decrease in chloride permeability was observed at 30 minutes and 24 hours compared to the control sample [64]. In another study, it was shown that adding modified zeolite reduces the continuity of the pore distribution of samples, which reduces the permeability of concrete [57]. It was found in a different investigation that concretes with natural zeolite had a much lower water penetration depth than reference concrete, the 10% zeolite mixture's permeability dropped, and the permeability improved even further when the zeolite content reached 15% of the cement's weight, for every chosen ratio of water to cementitious materials, the use of natural zeolite resulted in significant decreases in water permeability and capillary absorption. [11]. This discovery may be explained by the enhanced concrete pore structure that results from the grouting effect, pozzolanic interaction, and heterogeneous nucleation [65]. The use of 10% zeolite in concrete samples with 50 and 100% nanofiber water bubbles instead of plain water created a synergy that resulted in a 62.49 and 73.53% reduction in rapid chloride permeation [66].

Enhancing effects of zeolite on the water absorption of concreteWater absorption, which also provides information about the pore structure of concrete and indirectly accounts for porosity, are significant aspects that also impact how long concrete lasts. Test findings for concrete's water absorption and penetration depth are shown for a few research in this area. Water is absorbed by zeolite which is naturally more quickly than by cement, Hence, a rise in the absorption of water is expected., and the zeolite was effective in decreasing the initial surface absorption [7]. The depth at which water penetrated concrete mixes decreased with the addition of natural zeolite, in comparison to the control mixtures, it decreased by 13% to 40% after 28 days of curing. At

90 days of age, it drops even further. Ramezanianpour reported a similar [11], The tested concrete's capillary absorption was enhanced by the use of natural zeolite. When natural zeolite was added to Portland cement at a weight of 10%, capillary absorption dropped over 28 days. These gains grew as the replacement level reached 15%. Analogous patterns were noted at later ages (270 and 90 days). In a study conducted by Markiev et al., it was found that when comparing concrete containing zeolite with concrete without zeolite, concrete containing natural zeolite and superplasticizer had a higher water absorption rate during mixing, which was related to the water absorption capacity of natural zeolite. Concrete containing zeolite will inevitably absorb more water because it contains a higher proportion of zeolite than cement. After 28 days, the water penetration depth was measured, and the results showed that the water penetration depth was less than 20 mm, so the concrete could be considered waterproof. The concrete incorporating natural zeolite had a small water penetration depth (3.5 mm), a superplasticizer, and an air-entraining agent. This can be explained by the beneficial effects of air entrainment agents on the pore structure of concrete, the microstructure's pozzolanic reactivity with cement hydration products and natural zeolite [15]. Comparing the concretes studied in these investigations to those examined by Najimi et al. (2012), the latter found somewhat more water absorption and penetration depth at the same water-to-cementitious ratio [63].

3.4.4 Enhancing effects of zeolite on the resistance the acid and sulfate attacks

As was shown in the previous section (3.4.6), adding zeolite to concrete significantly improves its ability to reduce water absorption. According to Shekarchi et al., pozzolans often work well enough to prevent degradation brought on by sulfate and acid assaults [61]. Concrete's resistance to sulfate attack from the soil, naturally acidic water, and hostile ions from saltwater is increased when natural zeolite is mixed with Portland cement [2]. In a different investigation, Jana et al. (2007) found that mortar bars containing zeolite had enhanced resistance against expansion brought on by sulfate assaults [67].Chemical resistance was the subject of two more research by Janotka et al. (2003), this resistance is directly correlated with the compressive strength of cement mortar made from natural zeolite. Because bentonite cement suspensions have been reported to have relatively poor resistance to aggressive subsurface media that are more susceptible to sulfate assault, zeolite has been utilized in place of bentonite to some extent. According to the study, zeolite-built subterranean containment walls had greater compressive strength and durability than bentonite-only walls [68].

Enhancing effects of zeolite on the Drying shrinkage of concreteAmong the deformation characteristics of concrete, shrinkage plays a significant role in determining the durability and strength of buildings and infrastructures. We have reviewed research that includes the effect of adding zeolite on shrinkage in concrete and compared it with concrete made from Portland cement without adding zeolite. Jana carried out research to find out what happened when zeolite was used as a Supplementary cementitious material (SCM) at different ratio of 10, 20, and 30%. Products made using pozzolanic cement were examined for dry shrinkage. Drying shrinkage was either slightly greater or comparable to the control mixture when 10% or 20% Portland cement was replaced in the zeolite mixes. When the zeolite percentage was raised to 30%, About 20% more dried shrinkage occurred than in the control sample [67]. The study conducted by Markiv et al (2016), showed that applying natural zeolite significantly reduces shrinkage. The drying shrinkage of the zeolite-containing concrete was lower than that of the control concrete after 180 days It should be mentioned that the drying shrinkage of the zeolite-containing concrete was around three times smaller than that of the control concrete by not zeolite in cases with moisture loss up to 2.7%. The findings showed that, at a moisture loss of 4.5%, the dry shrinkage of the mixture containing zeolite was around six times less than that of the control concrete with no zeolite [15]. In a separate study, Milović et al. (2022) discovered that, regardless of the replacement amount, natural zeolite has a favorable impact on drying shrinkage reduction and that cement blends containing 10% natural zeolite yield the best results in terms of frost resistance [69]. In general, using natural zeolite in place of some cement increased the durability characteristics of concrete. The drying shrinkage was where the use of natural zeolite was most beneficial [63]. These outcomes are explained by natural zeolite's capacity for internal cure. It indicates that some water is absorbed by natural zeolite, a porous substance, when the concrete is still new, and that water eventually moves out of natural zeolite when the hardened concrete dries. This phenomenon has a lot of documentation when it comes to concrete compositions with lightweight particles [70].

4. Conclusion:

Zeolite has been proven to be a sustainable material when it is replaced as part of cement in concrete because it reduces the use of cement in concrete. Large amounts of carbon dioxide, one of the dangerous gases that pollute the environment, are known to accompany the manufacture of cement. Using natural zeolites can reduce the amount of cement required to make concrete. Concrete that undergoes adequate processing, material selection, and binders with different mixing ratios and W/C ratios exhibits superior mechanical properties and durability. Thus, concrete containing zeolite improves environmental impact and can enhance strength and durability up to the replacement ratio.

Most of zeolite's mechanical and physical properties are efficient. In some proportions, replacement types improve concrete and overcome the weaknesses of concrete; demand for it rises because it is eco-friendly and sustainable. Natural zeolite can also be used in autoclaved aerated and lightweight aggregate concrete. Long-term performance studies are needed to understand zeolite concrete's benefits and highlight innovative building techniques that leverage zeolites to create stronger, more durable structures while mitigating climate change This review will directly affect sustainability, natural zeolite use, and green building practices.

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