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ORIGINAL PAPER

Investigation mechanical characteristics and permeability of concrete with pozzolanic materials: a sustainable approach

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Abstract

Concrete is the most widely used construction material in the world. Therefore, the production of concrete with characteristics such as high strength and durability has received the attention of researchers. In alignment with sustainable development objectives, a pivotal focus within the construction industry has been the exploration of viable alternatives to conventional cement. In this study, the mechanical characteristics and permeability of the prepared samples containing pozzolanic materials (natural and synthetic) have been investigated by using the experimental method. To achieve the objectives of this research, six unique concrete mix formulations were developed, each incorporating silica fume, metakaolin (as a synthetic pozzolanic additive), and zeolite (as a natural pozzolanic substance). The performance outcomes of these mixes were then systematically evaluated against a baseline mixture that did not contain any pozzolanic components. Four distinct curing methods were employed: a humid environment (referred to as group A), a dry environment (designated as group B), and two corrosive environments (denoted as groups C and D). Compressive strength tests were conducted at 7, 14, 28, and 90 days, alongside indirect tensile strength tests at 28 and 90 days. Additionally, samples subjected to sulfuric solution (H_2SO_4) curing with a controlled pH of 1 at 90 days were compared against standard curing conditions. The permeability of the samples was evaluated through initial and final water absorption measurements, as well as penetration of water under pressure tests. Substituting 10% of the cement content with metakaolin and silica fume in the concrete mixing design enhanced the 28-day compressive strength under both humid and dry curing conditions, as compared to the control mixture. Incorporating a 10% substitution of cement with both natural and synthetic pozzolanic additives can beneficially preserve a portion of the compressive and tensile integrity that is otherwise diminished by sulfuric acid exposure, relative to the standard mix. Furthermore, this substitution enhances the mechanical robustness of the concrete. Replacing 10% of cement with natural and synthetic pozzolanic materials has a positive effect on maintaining part of the compressive and tensile strength loss due to sulfuric acid attacks compared to the control mixture, and the use of these materials improved the concrete's mechanical performance. The results indicate that incorporating pozzolanic materials (such as silica fume, metakaolin, and zeolite) leads to a reduction in initial water absorption compared to the control mix. Notably, this reduction is more pronounced in samples containing silica fume than in those containing metakaolin and zeolite.

Keywords Natural zeolite · Silica fume · Metakaolin · Pozzolan · Acid attack · Mechanical properties · Curing conditions

1 Introduction

Global warming and climate change are critical global issues. Industrial carbon dioxide (CO_2) emissions are the primary

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cause of global warming and ozone layer damage (Moein and Soliman 2022; Moein et al. 2023; Aghapour et al. 2019; Koushkbaghi et al. 2019; Tajasosi et al. 2023; Mousavinejad et al. 2023; Rabehi et al. 2023). Despite the Intergovernmental Panel on Climate Change (IPCC) urging zero greenhouse gas emissions by 2050, emissions continue to rise (Shahmansouri et al. 2021; Fathollahi-Fard et al. 2019). The construction industry is a major greenhouse gas producer, contributing around 50% of total emissions (Khasreen et al. 2009; Mohtasham Moein et al. 2024). Cement, a key component of concrete, consumes significant energy and releases 6–7% of CO_2 during production (IPCC 2006; Taylor et al. 2006). To promote sustainability, researchers propose using pozzolans—natural or synthetic materials—as supplementary cementitious materials in concrete (Mansoori et al. 2020; Tuan et al. 2011; Yazici et al. 2009; Beshkari et al. 2024; Saradar et al. 2024; Nabighods et al. 2023; Sadrmomtazi et al. 2012; Zareei et al. 2018). Regulations now recognize their potential as cement substitutes.

Concrete faces challenges like acid attacks, which involve the breakdown of hardened concrete by acids, particularly in environments like silos and sewage systems (Madhuri et al. 2021). The acidity of a liquid is indicated by its pH value; lower values mean higher acidity. Enhancing concrete's resistance to sulfate and alkali attacks can be achieved by reducing its permeability. Research shows that incorporating pozzolanic materials can decrease concrete's permeability (Madhuri et al. 2021; Najimi et al. 2012). Pozzolans also contribute to concrete's long-term durability and strength, while also curbing CO_2 emissions (Beshkari et al. 2024; Saradar et al. 2024; Nabighods et al. 2023).

Natural zeolite (NZ) is a noteworthy natural pozzolan. It possesses a three-dimensional structure surrounded by Si–O and Al–O tetrahedra (Feng and Peng 2005; Sabet et al. 2013). With honeycomb channels and pores measuring approximately 0.0004–0.0003 µm, NZ offers significant micro-porosity and favorable surface properties for civil engineering applications (Sabet et al. 2013; Boles et al. 1977; Mertens et al. 2009; Moshoeshoe et al. 2017). Historically, NZ has been used in construction, akin to other pozzolanic additives like silica fume (SF) and metakaolin (MK). SF exhibits excellent rheological properties, high pozzolanic activity, and effective filling ability (Sasanipour et al. 2019; Ahmad et al. 2014; Khayat and Aïtcin 1992; Al-Akhras 2006; Mohtasham Moein et al. 2022). MK, a thermally activated alumino-silicate available since the mid-1990s, reacts rapidly with water, yielding significant hydration products (Al-Akhras 2006; Sabir et al. 1996; Karahan et al. 2012).

Recent studies have focused on the impact of various pozzolans on concrete properties. Sivakumar et al. (2017) found that while glass fibers reduce the workability of self-compacting concrete (SCC) and do not enhance its compressive strength, they do improve tensile strength and flexibility when used in higher doses. The combination of MK and glass fibers, when used in appropriate amounts, markedly enhances the mechanical strength and longevity of SCC. Abdelli et al. (2017) observed that early compressive strength of cement mortar is boosted by MK, but this effect diminishes over time. Shen et al. (2017) noted that MK accelerates cement hydration and mitigates the adverse thermal effects on the microstructure of steam-cured high-strength concrete (HSC), with an ideal MK content of around 10%. Sabet et al. (2013) studied the impact of replacing cement with zeolite, fly ash, and silica fume on concrete durability. They found that zeolite reduced concrete fluidity more than silica fume and fly ash, necessitating increased superplasticizer use. Their research shows that using these pozzolans significantly increases compressive strength and electrical resistance while reducing water absorption. Rajasekar et al. (2018) investigated Ultra High Strength Concrete (UHSC) with recycled concrete aggregates and sugarcane bagasse ash as a natural pozzolan. They achieved UHSC strengths of approximately 160 MPa by replacing cement with this pozzolanic material at a 15% weight ratio, without adverse effects. Numerous studies have examined the incorporation of natural zeolite into concrete. Table 1 summarizes the outcomes of these studies, detailing the effects of varying zeolite proportions on concrete and the results from assorted tests on this concrete variant.

2 Significance of the investigation

In the last few decades, cement production has been one of the leading causes of increasing air pollution and environmental destruction. With the expansion of urbanization and the ever-increasing population, the demand for new structures as well as improved infrastructure and buildings increases. The total cost spent in the construction industry for new structures (residential and non-residential) was recorded at 11.4 trillion dollars in 2018, and it is predicted that this amount will reach 15.5 trillion dollars in 2030 (Moein et al. 2023; Maraveas 2020). Based on construction industry traditions, the growth of investment in this industry is directly related to the increase in the consumption of natural resources. In line with the goal of sustainable development, in recent years, many researchers have focused on using pozzolan as a part of cement, but there is still a gap in the issues. To deal with the aspects of concrete investigation that have received less attention, the present study seeks to gain more knowledge about concrete. Since concrete structures and elements may be attacked by acids during their lifetime, the present study investigates concrete containing pozzolan (synthetic and natural) in 4 different curing conditions (wet, dry, wet + acidic, and dry + acid). The topics examined in this study include: (1) investigating different percentages of pozzolan,

Table 1 A report of previous studies on natural zeolite (NZ)

No.	W/C	Test	Different percentages of natural zeolite (NZ)										References
			2.5%	5%	7.5%	8%	10%	12.5%	15%	20%	30%	40%	
1	0.45	CS	+ 7.13%	+ 7.70%	+ 11.41%		+ 13.26%						Nagrockiene and Girskas (2016)
		WA	− 3.11%	− 3.73%	− 54.51%		− 57%						
2	0.4	CS					+ 23.68%			+ 5.26%	+ 21.05%		Valipour et al. (2014)
		CP					− 72.80%			− 81.84%	− 81.39%		
3	0.45	CS					− 19.80%			− 25%		− 45.7%	Vejmelková et al. (2015)
4	0.55	CS							+ 14.74%				Bura and Kondraivendhan (2022)
5	0.5	CS					− 10.66%						Markiv et al. (2016)
6	0.5	CS							− 3.68%		− 24.47%		Najimi et al. (2012)
		WA							+ 15.84%		+ 12.64%		
		CP							− 72.53%		− 91.79%		
7	0.48	CS		+ 3.71%			+ 5.71%						Jokar et al. (2019)
		TS		− 4.30%			− 1.65%						
8	0.4	CS					+ 11.77%		+ 9.41%				Mohseni et al. (2017)
		WA					− 8.25%		− 26.82%				
		CP					− 31.20%		− 36.46%				
9	0.40	CS		+ 14.38%			+ 15.81%		+ 23.01%	+ 25.18%			Ahmadi and Shekarchi (2010)
		WA		− 20.91%			− 17.49%		− 22.81%	− 23.57%			
		CP		− 2.4%			− 56%		− 59.2%	− 64.8%			
10	0.32	CS					+ 3.35%			− 8.47%			Sabet et al. (2013)
		WA					− 17.22%			− 17.22%			
		CP					− 46.42%			− 64.28%			
11	0.45	CS		− 1.75%			− 13.25%		− 9.72%	− 16.8%			Ranjbar et al. (2013)
12	0.59	CS		+ 19.02%			+ 13.94%		− 6.31%	− 37.9%			Ahdal et al. (2022)
13	0.3	CS									+ 9.83%	− 2.72%	Madhuri et al. (2021)
		TS									− 9%	− 45.3%	
		CP									− 38.9%	− 21.9%	

Table 1 (continued)

No.	W/C	Test	Different percentages of natural zeolite (NZ)										References
			2.5%	5%	7.5%	8%	10%	12.5%	15%	20%	30%	40%	
	0.4	CS									− 36.68%	− 49.6%	
		TS									− 29.4%	− 38%	
		CP									− 3.01%	− 0.15%	
14	0.27	CS		+ 7.56%			+ 8.60%		+ 14.19%		+ 5.28%		Chan and Ji (1999)
15	0.5	CS		+ 9.69%			+ 16.86%		+ 26.17%	+ 21.50%			Nasr et al. (2019)
16	0.45	CS		+ 0.97%		− 11.95%	− 3.90%						Eskandari et al. (2015)
		TS		+ 18.37%		− 14.48%	0						
		CP		− 28.88%		− 44.90%	− 48.88%						
	0.4	CS		− 23.07%		− 33.77%	− 14.82%						
		TS		− 5.80%		+ 9.67%	+ 4.51%						
		CP		− 19.30%		− 18.70%	+ 14.48%						
17	0.35–0.39	CS	+ 81.46%	+ 90.10%	+ 130.8%	+ 151.8%							Nagrockienė et al. (2017)
		WA	− 59.68%	− 64.68%	− 68.43%	− 71.90%							

CS compressive strength, *TS* tensile strength, *WA* water absorption, *CP* chloride penetration

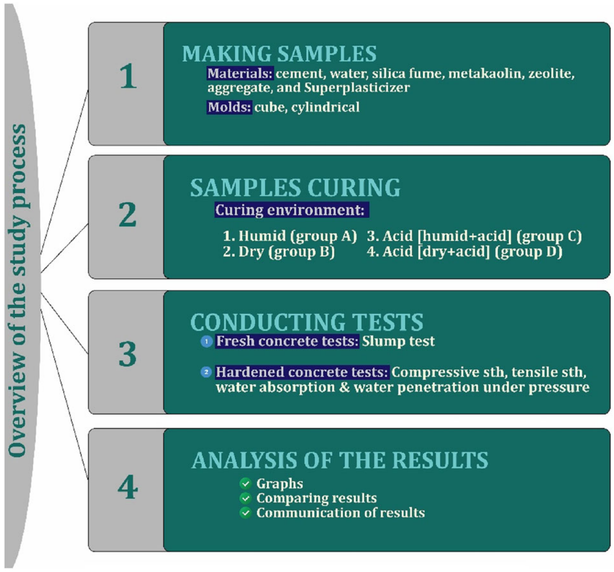

Fig. 1 The overview of the study process

(2) comparing the performance of mixtures containing different pozzolans with the control mixture, (3) comparing the performance of mixtures under different curing conditions, (4) comparing the performance of mixtures under curing in standard and acidic conditions, (5) examining mixture resistance (compressive and tensile), (6) examining initial and final water absorption in different ages, (7) examining water permeability under pressure, 8. Monitoring the resistance of mixtures from 7 to 90 days. Figure 1 provides an overview of the study's overarching process.

3 Experimental program

3.1 Materials

Materials used in this study include cement, aggregate (sand and gravel), pozzolan (metakaolin, silica fume, and natural zeolite), water, and superplasticizer. In this study, type I cement according to ASTM C150 (ASTM Committeee 2016) was considered. Table 2 shows the chemical characteristics of used cement. River sand utilized in this study exhibits a water absorption rate of 1.1% and a particle size distribution with a maximum dimension of 9.5 mm, which follows ASTM C33 standards (ASTM International 2016). The specific mass of the consumed gravel in the Saturated Surface Dry (SSD) condition was equal to 2611 kg/m^3 and its water absorption was 2.4% and had a maximum aggregate size of 25 mm. The particle size distribution of the aggregates used is following the ASTM C33 (ASTM International 2016) standard. Figure 2 shows a view of the consumed aggregate particle size distribution. In this study, three types of pozzolans (metakaolin, silica fume, and natural zeolite) were used. Table 2 shows the specifications of the pozzolans. The superplasticizer used in this study is polycarboxylate-based and has a specific gravity of 1.2 ± 0.05 gr/cm^3. The specifications of the superplasticizer are reported in Table 3.

3.2 Mixing design

Table 4 shows the characteristics of different mixtures in this study. To achieve the goals of this research, a total of 6 different mixtures were considered. Metakaolin, silica fume, and zeolite have been replaced as pozzolanic materials with 10% of the cement used. Also, natural zeolite pozzolans have been replaced with cement with 7.5 and 5% weight percentages. In one mixture, silica fume and zeolite were substituted for cement to determine the impact of the combination of natural and synthetic pozzolanic materials on the compressive strength test results. The ratio of water to cement materials for all samples was considered a constant value equal to 0.5.

Figure 3 shows how to name different mixtures. In this regard, the first mixture was considered the control mixture. The second mixture, M10, contains 10% metakaolin. The third mixture, S10, contains 10% silica fume. Mixtures 4 (Z10), 5 (Z7.5), and 6 (Z5) contain 10, 7.5, and 5% of natural zeolite, respectively. Finally, a mixture called Z5S5 (5% natural zeolite + 5% silica fume) was considered to investigate the combined effect of silica fume and natural zeolite on compressive strength.

In order to make the samples in the laboratory, aggregates are first mixed with water in a mixer. Then, the desired mixture of cement and pozzolan is added, and the remaining water along with the superplasticizer is added to the mixture. The resulting mixture was mixed for 4 min. Finally, the concrete is poured into cubic and cylindrical molds, and the vibration compaction process is performed on the samples according to the standard.

3.3 Curing

Figure 4 shows a view of this study's methods of curing the mixtures. After making the mixing designs, the samples are kept in the mold for 24 h in laboratory conditions, then they are divided into 4 curing groups.

- Curing group A includes mixtures that were cured in a humid environment (in a water pool at a temperature of 20 ± 2 °C).
- Curing group B includes mixtures that were cured in a dry environment (in a laboratory environment at a temperature of 25 °C).
- Curing group C includes mixtures that were cured for 28 days in a humid environment and then cured in a sulfuric acid solution with pH = 1 for 90 days.

Table 2 Chemical properties of type I cement and pozzolans

Composition	Cement	Silica fume (S)	Metakaolin (M)	Natural zeolite (N)
SiO_2	21.55	89.22	52.2	70.96
Al_2O_3	5.56	1.2	42.5	14.52
Fe_2O_3	3.46	2.12	1.4	2.44
CaO	63.95	1.87	0.2	3.52
MgO	1.85	1.61	0.21	0.74
K_2O	0.53	1.06	0.33	2.25
Na_2O	0.37	56	0.12	3.75
SO_3	2.01	–	0	–
TiO_2	0.01	–	–	–
LOI	0.12	2.6	0.97	1.28

	Cement	Silica fume (S)	Metakaolin (M)	Natural zeolite (N)
Chemical composition (%)				
SiO_2	21.55	89.22	52.2	70.96
Al_2O_3	5.56	1.2	42.5	14.52
Fe_2O_3	3.46	2.12	1.4	2.44
CaO	63.95	1.87	0.2	3.52
MgO	1.85	1.61	0.21	0.74
K_2O	0.53	1.06	0.33	2.25
Na_2O	0.37	56	0.12	3.75
SO_3	2.01	–	0	–
TiO_2	0.01	–	–	–
LOI	0.12	2.6	0.97	1.28
Physical properties				
Specific surface (m^2/g)	0.328	17.43	3.87	0.316
Specific gravity	3.16	2.19	2.54	2.33

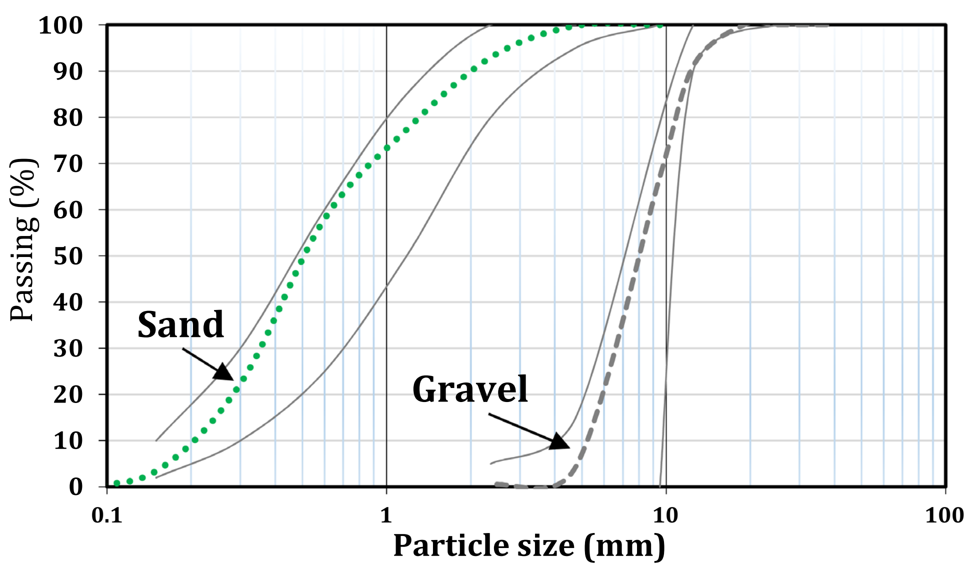

Fig. 2 Particle size distributions of the sand and gravel

Table 3 Specifications of the superplasticizer

Technical features				
Physical state	Color	Specific weight	Chemical base	Amount of chloride
Liquid	Light brown	1.2 ± 0.05 g/cm^3	Polycarboxylates	Insignificant

Table 4 Specifications of mixed designs

No.	Mix ID	Cement (kg/m^3)	Metakaolin (kg/m^3)	Silica fume (kg/m^3)	Natural zeolite (kg/m^3)	Water (kg/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)	Gravel/sand	SP (kg/m^3)	Slump (cm)
1	Control	350	0	0	0	175	1003	872	1.15	0	9
2	M10	315	35	0	0	175	1003	872	1.15	1.05	8
3	S10	315	0	35	0	175	1003	872	1.15	0.875	8.5
4	Z10	315	0	0	35	175	1003	872	1.15	0.7	9.5
5	Z7.5	323.75	0	0	26.25	175	1003	872	1.15	0.525	9
6	Z5	332.5	0	0	17.5	175	1003	872	1.15	0.35	8.7
7	Z5S5	315	0	17.5	17.5	175	1003	872	1.15	0.7	9

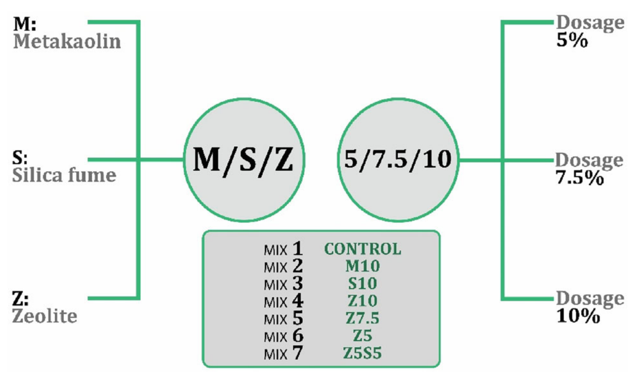

Fig. 3 Methods of naming mixtures

- Curing group D includes mixtures that were cured in a dry environment for 28 days and then cured in sulfuric acid solution with pH = 1 for 90 days.

Due to the reaction of acid with concrete samples, the concentration of acid decreased over time. To prevent this, the pH of the solution was controlled weekly and maintained within the range of 1 by adding acid.

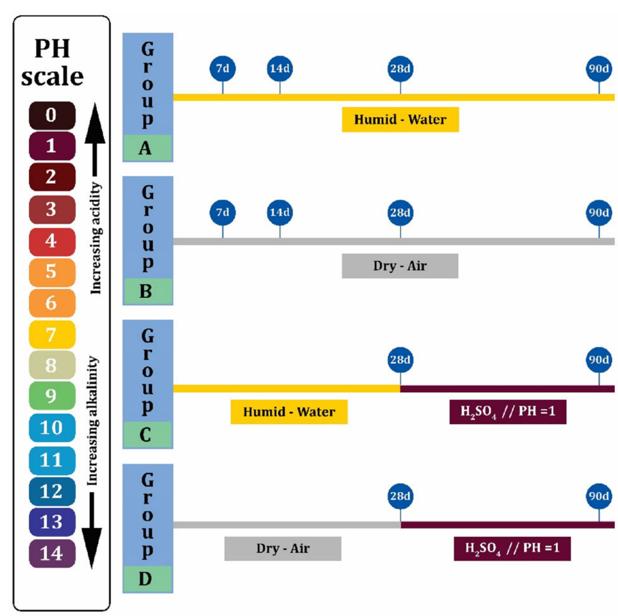

Fig. 4 Curing methods

3.4 Tests

The slump test was performed according to the ASTM C1611 (2018) standard (Fig. 5), and the compressive strength test was performed according to the ASTM C39 (2003) standard on cubic samples with dimensions of 100 × 100 × 100 mm. The splitting tensile strength test was performed according to the ASTM C496 (2004) standard on cylindrical samples with dimensions of 300 × 150 mm. According to ASTM C642 (2013), the water absorption test was performed on cubic samples with dimensions of 100 × 100 × 100 mm. Also, following the BS EN 12390-8 (2003) standard, a water penetration test under pressure was performed using cylindrical samples with dimensions of 300 × 150 mm. Figure 6 provides a clearer guide on how to perform the tests and the ages of the test concrete samples. Figure 7 shows a view of the molds and samples used in the tests.

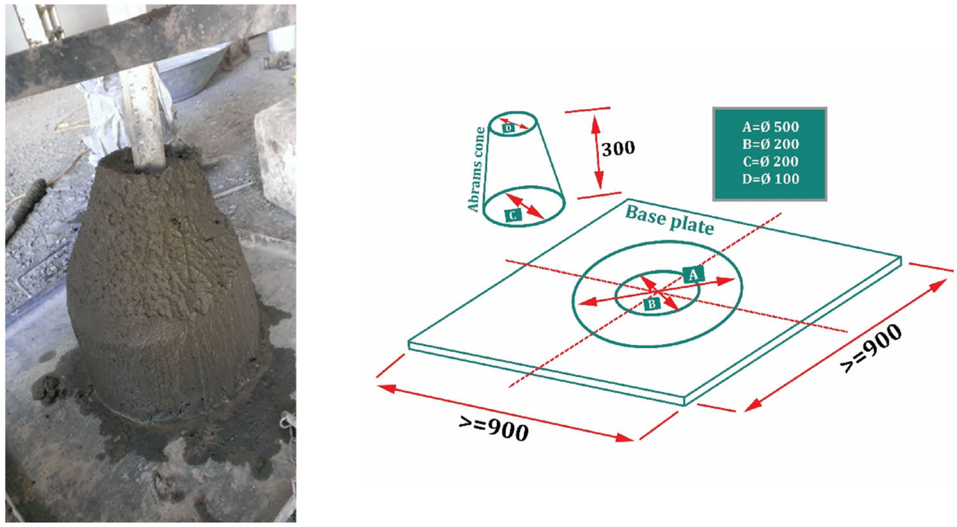

Fig. 5 Slump test

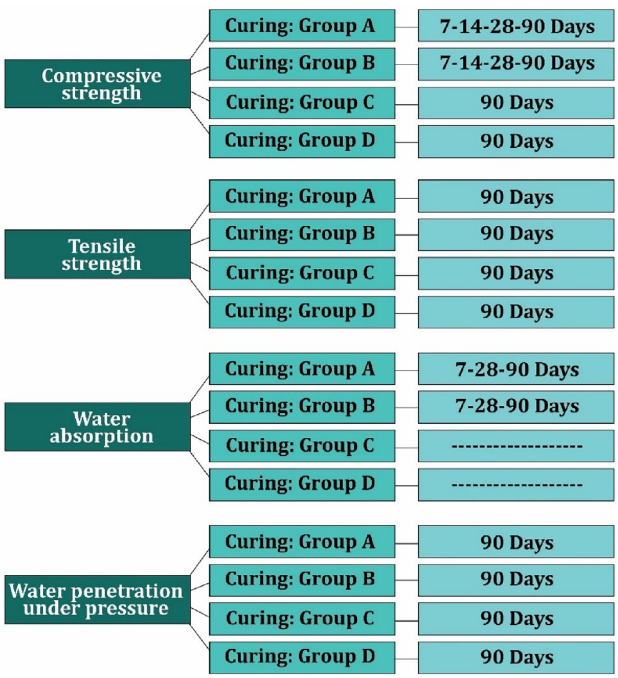

Fig. 6 Test details

Fig. 7 Molds and samples used in tests

4 Results and discussion

4.1 Slump

The results of the slump test for the control mixture and the mixtures containing pozzolanic materials according to the amount of superplasticizer are presented in Table 4. Also, Fig. 8 shows a view of the different mixtures' slump results. According to the results, among the mixtures containing 10% pozzolanic materials, the lowest amount of superplasticizer required to reach the slump of the control design (9 cm) corresponds to the sample containing 10% zeolite (Z10). Figure 9 compares the results of utilizing various pozzolans (zeolite, silica fume, metakaolin, and fly ash) from previous research with the current study. In the samples containing zeolite with an increasing percentage of zeolite replacement, the amount of superplasticizer required to maintain the slump has increased, which can indicate zeolite's negative effect in increasing the friction between particles as well as its relatively higher water absorption. In general, the presence of pozzolanic materials such as silica fume and metakaolin absorbs more water than cement due to their smaller particles, and this reduces the fluidity of fresh concrete, which requires much more superplasticizer to compensate. This is especially true for samples containing silica fume due to the very high specific surface area of silica fume particles compared to cement particles. This difference increases the amount of superplasticizer required to achieve the desired smoothness by increasing the percentage of zeolite consumption.

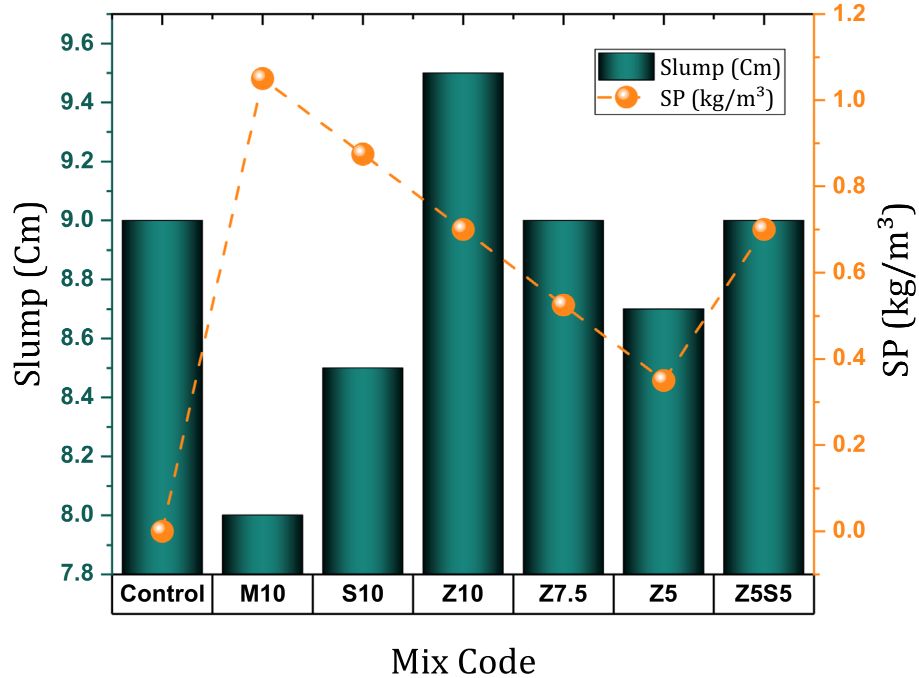

Fig. 8 Slump test results and consumable superplasticizer

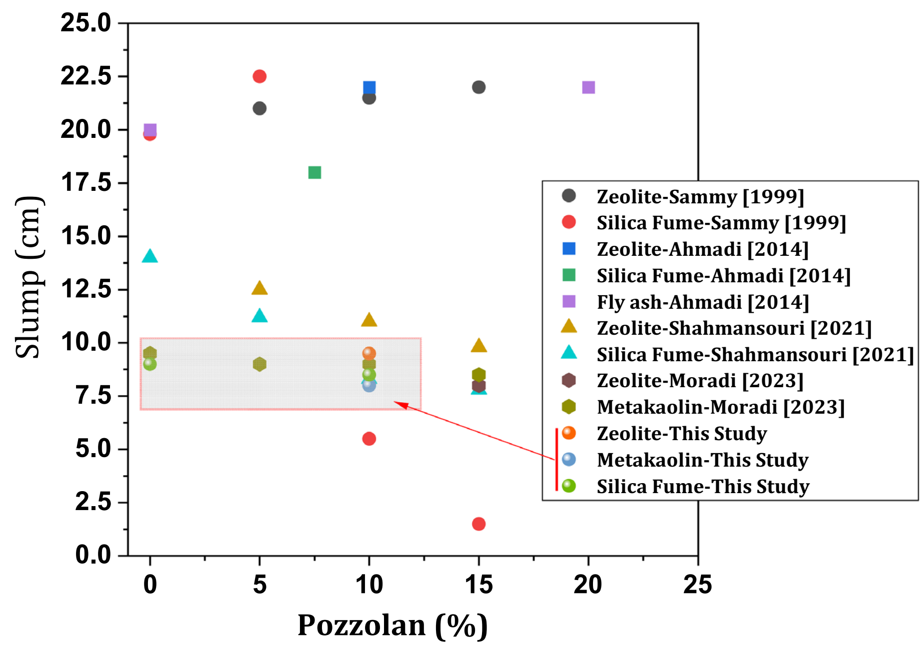

Fig. 9 The effect of various pozzolans on the slump test results in prior research (Shahmansouri et al. 2021; Chan and Ji 1999; Ahmadi et al. 2014; Moradi et al. 2023)

4.2 Water absorption

Table 5 and Fig. 10 show the results of the different mixtures' initial and final water absorption at 7, 28, and 90 days. The results of the initial water absorption test show that, in the normal curing method (humid curing = group A), replacing 10% of cement with silica fume or metakaolin will decrease the initial water absorption compared to the control sample, so that the initial water absorption of the mixture of M10 and the S10 mixture is lower than the control sample at 7, 28 and 90 days. The examination of the results also shows that using 10% zeolite (Z10) as a substitute for cement in the normal curing method will reduce the initial water absorption compared to the control sample at 90 days; while at 7 and 28 days, the initial water absorption of this sample has not changed much compared to the control sample. By increasing the replacement percentage of zeolite in the concrete mixture, an increase in initial water absorption was obtained for the mixtures cured under normal conditions (group A) at 7, 28, and 90 days. For the normal curing method, the lowest initial

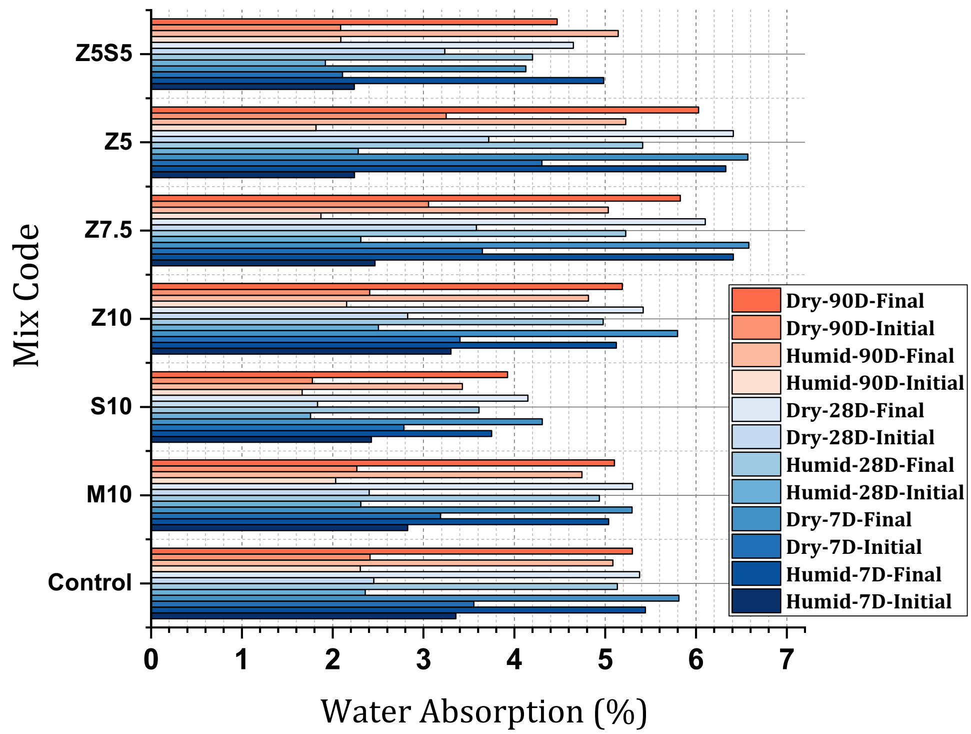

Fig. 10 Results of the different mixtures' water absorption

Table 5 Results of the different mixtures' water absorption

No.	Mix code	Humid curing (Group A)						Dry curing (Group B)					
		WA						WA					
		Initial 7 days	Final 7 days	Initial 28 days	Final 28 days	Initial 90 days	Final 90 days	Initial 7 days	Final 7 days	Initial 28 days	Final 28 days	Initial 90 days	Final 90 days
1	Control	3.356	5.443	2.359	5.132	2.304	5.085	3.553	5.811	2.452	5.380	2.412	5.299
2	M10	2.824	5.039	2.310	4.937	2.033	4.744	3.187	5.296	2.401	5.300	2.266	5.101
3	S10	2.426	3.749	1.756	3.611	1.663	3.428	2.785	4.308	1.833	4.148	1.777	3.925
4	Z10	3.302	5.123	2.503	4.977	2.153	4.816	3.401	5.795	2.827	5.418	2.406	5.188
5	Z7.5	2.465	6.410	2.309	5.225	1.871	5.033	3.648	6.583	3.581	6.101	3.055	5.828
6	Z 5	2.241	6.327	2.281	5.413	1.815	5.225	4.304	6.571	3.718	6.410	3.249	6.028
7	Z5S5	2.238	4.983	2.107	4.125	1.92	4.201	3.233	4.651	2.089	5.143	2.088	4.471

WA water absorption

water absorption at all ages is related to the sample containing silica fume.

The water absorption results of mixtures cured in a dry environment (group B) at 7, 28, and 90 days can be seen in Table 5 and Fig. 10. In this regard, replacing 10% of the used cement with pozzolanic materials such as silica fume, metakaolin, and zeolite will reduce the initial water absorption compared to the control design. The decrease in water absorption for the sample containing silica fume is more than the sample containing metakaolin and zeolite. Among the mixtures containing 10% pozzolanic materials, the sample containing silica fume (S10) has the lowest final water absorption, which of course can be due to the higher pozzolanic activity of silica fume and the smaller size of its particles compared to metakaolin and zeolite. The results also show that, in the mixtures cured under normal conditions, the mixture containing metakaolin and zeolite has almost the same final water absorption compared to the control mixture. Naturally, the amount of water absorption for the sample containing zeolite is slightly higher than the sample containing metakaolin. Examining the results obtained

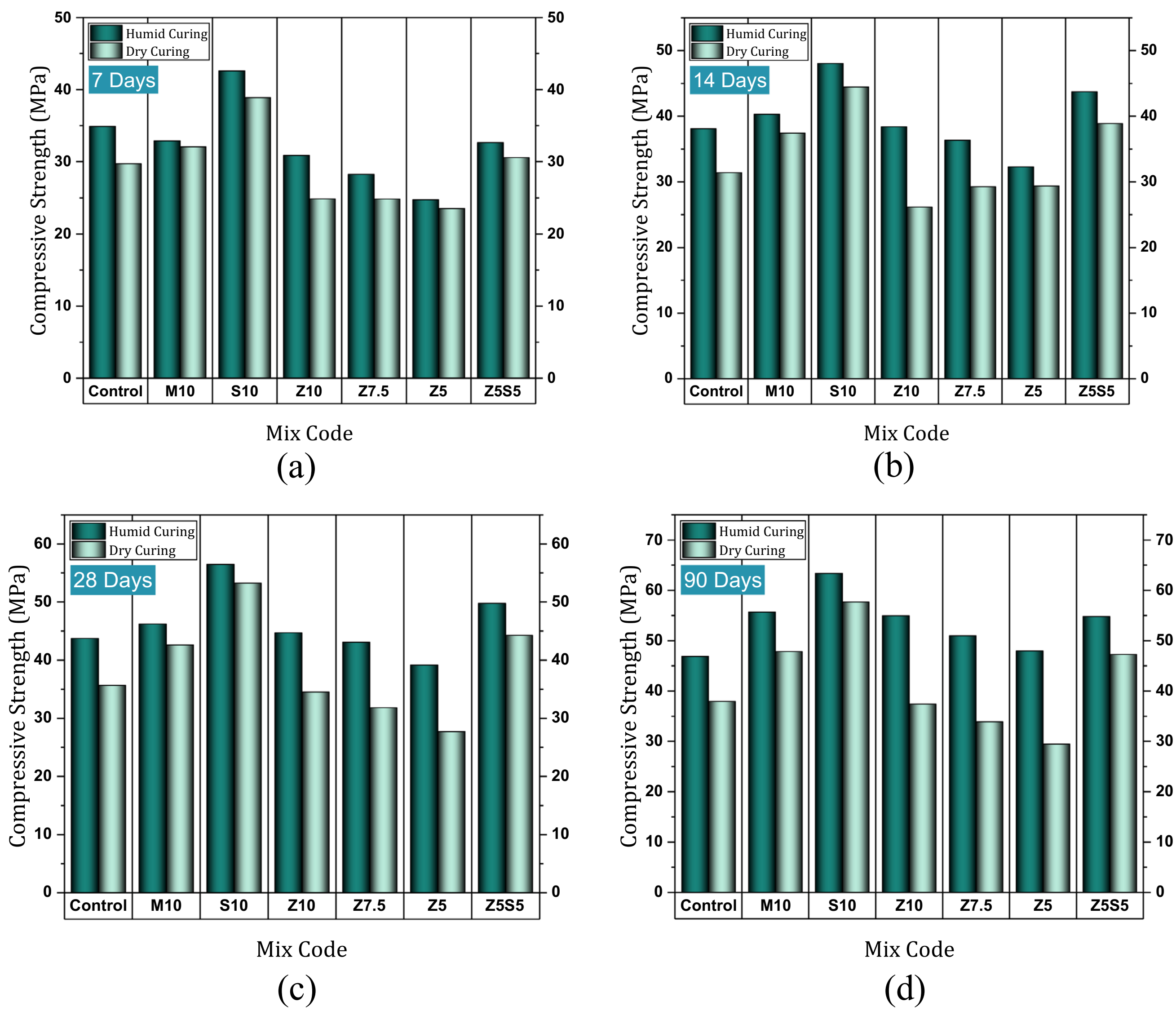

Fig. 11 Compressive strength of different mixtures **a** 7 days, **b** 14 days, **c** 28 days, **d** 90 days

by other researchers regarding the effect of pozzolanic materials on the amount of water absorption of concrete mixtures shows that, according to the nature of pozzolanic reactions, the use of cement substitutes reduces the amount of lime and improves the concrete's permeability (Mansoori et al. 2020; Singh and Singh 2016; Ramezanianpour 2014; Tahmouresi et al. 2021; Saradar et al. 2020). The final water absorption results for the samples processed under normal conditions (group A) show that, with the increase in the percentage of zeolite, the final water absorption decreases at 28 and 90 days.

4.3 Compressive strength (7, 14, 28 and 90 days)

Figure 11 shows the compressive strength results of the mixtures at 7, 14, 28, and 90 days. The obtained results show that, in general, the compressive strength of humid curing (normal curing) is higher than the dry curing method. This can be due to a better hydration process (completion of hydration process) in humid curing conditions. Also, Fig. 12 shows the improvement of compressive strength during curing in a humid environment (group A) compared to a dry environment (group B). In addition, Fig. 13 presents the comparison of the compressive strength of mixtures containing pozzolan with the control mixture.

4.3.1 Compressive strength (7 days)

The different mixes' compressive strength at 7 days is evident in Fig. 11a. The biggest difference between the 7-day compressive strength results of the two curing methods is related to the mixture containing 10% pozzolanic zeolite (Z10). By

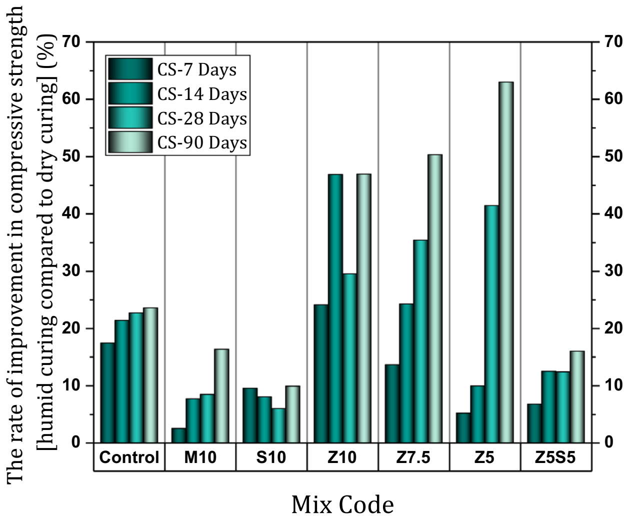

Fig. 12 Compressive strength (comparison of humid and dry curing conditions)

changing the curing method from dry to humid (from B to A) for this mixture, the 7-day compressive strength increases by 24.11% (Fig. 12). The results also show that changing the curing method had the least effect on the 7-day compressive strength of the sample containing 10% metakaolin (M10), so this mixture's 7-day compressive strength under normal curing is about 2.5% higher than the dry curing. In general, by increasing the replacement percentage of zeolite in the concrete mixture (from 5 to 10%), the effect of changing the curing method (from dry to normal) on the 7-day compressive strength increases. In the mixture containing 5% zeolite (Z5), with the change of curing method from dry to normal, the compressive strength will increase by 5.21%. This amount for the sample containing 7.5% zeolite (Z7.5) equals 13.6%. Substitution of 5, 7.5, and 10% of Portland cement with natural zeolite pozzolan reduces the compressive strength compared to the control mixture. Increasing the replacement percentage of natural zeolite pozzolan (from 5 to 10%) in the concrete mixture has resulted in a relative improvement of the 7-day compressive strength, which can be attributed to the filler effect of this material and the improvement of the concrete mixture's structure. Figure 13a shows that, in the normal curing method, only the sample containing 10% silica fume (S10) has a higher 7-day compressive strength than the control sample. In the dry process method, the mixture containing silica fume (S10) had the best results for 7-day compressive strength, so the compressive strength of this mixture is about 31% higher than the control mixture. The results also show that replacing different amounts of 5%, 7.5%, and 10% of cement with zeolite reduces the 7-day compressive strength in both dry and normal curing methods compared to the control mixture. So that the greatest reduction occurred during 5% replacement (Z5) and the lowest reduction occurred during 10% replacement (Z10). The sample containing the combination of zeolite and silica fume (Z5S5) had a lower 7-day compressive strength in normal curing and a higher 7-day compressive strength in dry curing compared to the control mixture. Replacing a part of zeolite with silica fume and using these two pozzolanic materials will improve the performance of the sample in the 7-day compressive strength test compared to the sample containing only zeolite. This can be due to the much stronger pozzolanic activity of silica fume compared to zeolite.

4.3.2 Compressive strength (14 days)

The results of the compressive strength test at 14 days show that the highest compressive strength for both dry and humid curing methods is related to the replacement of 10% silica fume (S10) (Fig. 11b). As expected, the results show that the 14-day compressive strength of the normal curing method (group A) for all samples is better than the results of the dry curing method (group B). The highest increase in 14-day compressive strength as a result of changing the curing method from dry to normal is related to the mixture containing 10% zeolite (Z10) (Fig. 12). The amount of compressive strength improvement in the Z10 mixture due to changing the curing method was equal to 46.9%. This amount for similar samples containing silica fume (S10) and metakaolin (M10) is equal to 7.7 and 8%, respectively. The control mixture's 14-day compressive strength cured by the humid method is 21.4% higher than the control mixture cured by the dry method (Fig. 13b). Comparing the results of compressive strength at 7 and 14 days shows the effect of pozzolanic activity, especially in mixtures containing metakaolin and silica fume, on improving compressive strength. This confirms the slower pozzolanic reaction of natural zeolite pozzolan compared to metakaolin and silica fume. So that the pozzolanic reaction, natural pozzolans take place slowly, and accordingly, they need a longer curing time than normal concrete in order to achieve the desired strength. Mixtures M10 and S10, which contain 10% pozzolan, in both dry and normal curing modes have resulted in higher 14-day compressive strength than the control mixture. So that the increase in 14-day compressive strength of both M10 and S10 mixtures that were cured in a dry environment is more than the control mixture cured in a humid environment. This issue also applies to the sample containing the combination of zeolite and silica fume (Z5S5). All the samples containing only zeolite pozzolan in the dry curing method have a lower 14-day compressive strength than the control mixture.

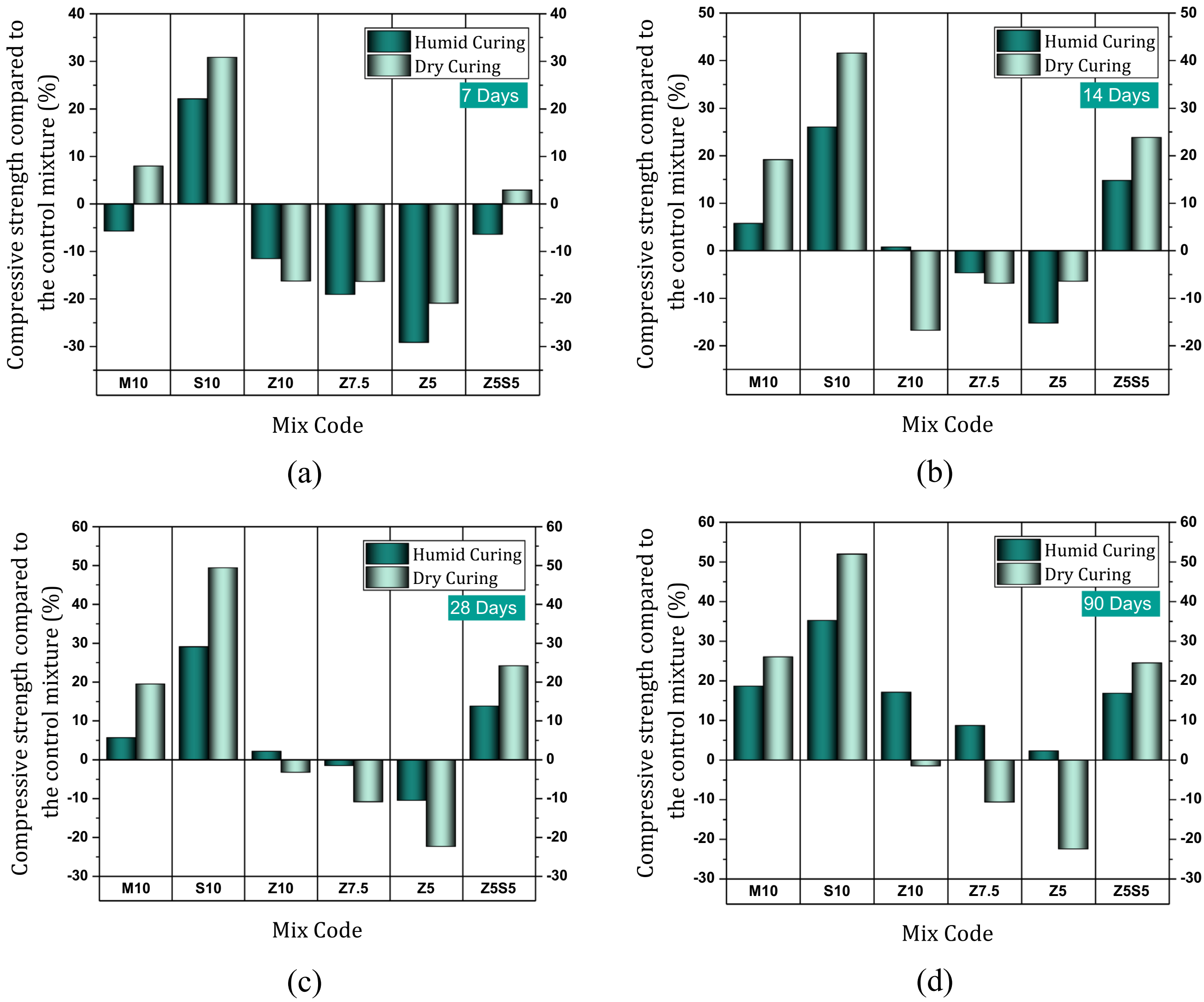

Fig. 13 Comparison of compressive strength of mixtures containing pozzolan with the control mixture

4.3.3 Compressive strength (28 days)

According to Fig. 11c, the results show that the highest 28-day compressive strength in both dry and normal curing methods is related to the mixture containing 10% silica fume (S10). Examining the results shows that, similar to the results obtained from the compressive strength test at 7 and 14 days and as expected at 28 days, all the mixtures obtained better compressive strength under the normal curing method (group A) than the dry curing method (group B). The biggest difference between the 28-day compressive strength of the two curing methods is related to the mixture containing 5% zeolite (41.5%), and with the increase in the replacement percentage of zeolite, the difference in the two curing methods' 28-day compressive strength has decreased. The results also show that the lowest difference between the 28-day compressive strength of the two dry and normal curing methods is related to the mixture containing 10% silica fume (6%). This value is 22.7% for the control mixture (Fig. 12). The difference between the 28-day compressive strength of the samples containing pozzolanic materials and the control mixture for the two dry and normal curing methods is shown in Fig. 13c. According to the results of 28-day compressive strength and its comparison with the results at 7 and 14 days, two issues can be investigated: (1) the effect of natural pozzolanic zeolite and (2) its comparison with synthetic pozzolanic materials (silica fume and metakaolin). The results show that, in general, the concrete mixtures containing silica fume and metakaolin (synthetic pozzolanic materials) at the early ages of 7 and 14 days, and at 28 days, have higher compressive strength than the control mixture. While the results obtained for the mixtures containing natural pozzolan show zeolite, the replacement of this pozzolan instead of cement until 28 days has led to a decrease in compressive strength compared to the control mixture. It seems that in the long run, zeolite can play a more impactful and colorful role in concrete. Sičáková et al. (2017) also mention this point in their study. The lower specific surface area and lower active silica content are possible reasons for the slow activity of pozzolanic zeolite. This issue leads to a decrease in the pozzolanic reaction process and leads to a decrease in the cement's hydration rate by absorbing part of the concrete water. Also, replacing 10% metakaolin or silica fume in the concrete mixing plan will improve the 28-day compressive strength in both normal and dry curing methods, compared to the control mixture. In the sample containing zeolite and silica fume combination (Z5S5), the 28-day compressive strength increased compared to the control mixture of both curing methods compared to the control mixture. According to Fig. 13c, the performance of the Z5S5 mixture shows that the increase in the compressive strength of this mixture (compared to the control mixture) is better in dry than humid curing.

4.3.4 Compressive strength (90 days)

Figure 11d presents the results of the 90-day compressive strength test for the control mixture and other prepared samples containing pozzolan. The results show that, at 90 days, as well as at 7, 14, and 28 days, the highest compressive strength is related to the mixture containing 10% silica fume (S10). According to Fig. 12, in mixtures containing zeolite (Z10, Z7.5, and Z5) the greatest difference between the compressive strength resulting from humid curing and dry curing is revealed at 90 days. Also, with an increase in the replacement percentage of zeolite, the effect of pozzolan on the development of compressive strength in dry curing decreases. Changing the curing method from dry to normal increases the 90-day compressive strength of the control mixture by 23.6%. This value is equal to 16.36% and 9.9% for the mixtures containing 10% metakaolin (M10) and the mixture containing 10% silica fume (S10), respectively. In the normal curing method, the 90-day compressive strength of all mixtures containing pozzolanic materials is higher than the control design (Fig. 13d). While the results related to the compressive strength at 7, 14, and 28 days show that the mixtures containing zeolite pozzolan at these ages cured by the usual method gave a lower compressive strength than the control mixture overall. This shows the low pozzolanic activity of zeolite compared to metakaolin and silica fume. The pozzolanic reaction of most natural pozzolans, including natural zeolite, is slow compared to synthetic pozzolanic materials such as silica fume and metakaolin, and accordingly, samples containing zeolite need a longer curing time than ordinary concrete to achieve the desired resistance. Therefore, the possible reason for the growth of strength by curing up to 90 days in the usual way is the slow pozzolanic reaction of zeolite, which has helped improve the internal structure and increase the concrete's compressive strength. According to Fig. 11d, the compressive strength of all samples containing zeolite in dry curing is lower than the control mixture.

4.3.5 The general trend of compressive strength from 7 to 90 days

Figure 14 shows the general trend of the compressive strength of the cured mixtures in groups A and B from 7 to 90 days. The results show that the greatest increase in compressive strength from 7 to 90 days is related to the mixture containing 5% zeolite (Z5), so the compressive strength of this mixture has increased by about 94% as the mixture ages from 7 to 90 days; the comparison of mixtures containing 10% pozzolan also shows that the mixture containing silica fume (S10) has a higher compressive strength growth from 7 to 90 days compared to the mixtures containing zeolite (Z10) and metakaolin (M10). In the dry curing method, the greatest increase in compressive strength due to the increase in the age of the mixture from 7 to 90 days is related to the mixture containing 10% zeolite (Z10). So that the compressive strength of this mixture has increased by 50.2% from 7 to 90 days. The values for mixtures containing 10% silica fume (S10) and 10% metakaolin (M10) are 48.2% and 49%, respectively.

4.3.6 Correlation between compressive strength results (from 7 to 90 days)

Figure 15 shows the correlation between the compressive strength of mixtures at different times. Figure 15a shows that there is a correlation between the mixtures and the compressive strength of the mixtures cured in the humid environment (group A). The R^2 value obtained for different mixtures confirms the acceptable correlation between the compressive strength results. In terms of statistical practice, an R^2 higher than 0.7 indicates an acceptable model (Rahmati et al. 2022; Bodt et al. 1997; Mohtasham Moein et al. 2019, 2023). Figure 15b also indicates a favorable correlation between the compressive strength results of curing mixtures in a dry environment (group B).

4.4 Tensile strength

Figure 16 shows the tensile strength results of different mixtures at 28 and 90 days. According to the graphs presented in Fig. 16, except for the Z5 mixture, the tensile strength of the sample cured in normal conditions (group A) is better compared to the same sample cured in dry conditions (group B). Figure 17 shows the trend of the tensile strength of the mixtures cured in the humid environment compared to the dry curing environment for 28 and 90 days. The biggest difference between the tensile strength of normal and dry

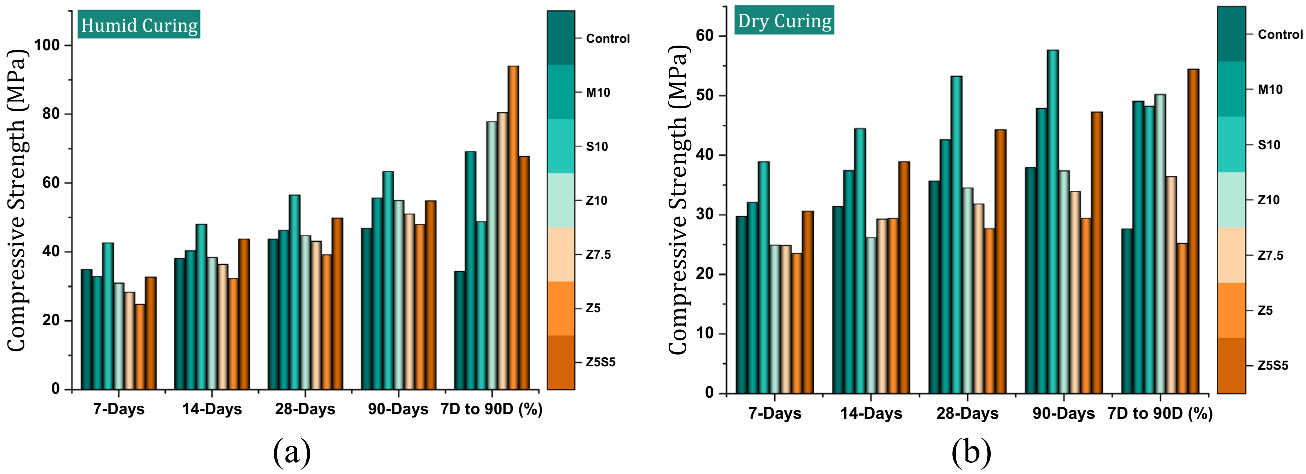

Fig. 14 Compressive strength process from 7 to 90 days **a** humid curing, **b** dry curing

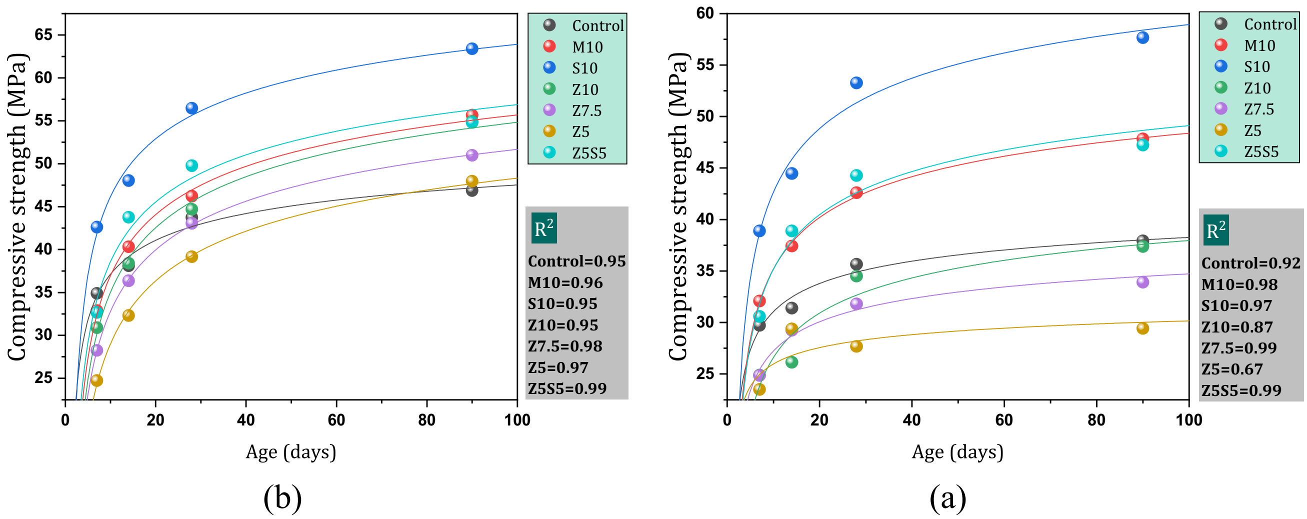

Fig. 15 Correlation between compressive strength results **a** humid curing, **b** dry curing

methods is related to the sample containing 10% zeolite (Z10), so for this mixture, by changing the curing method from dry to normal, the tensile strength increases by 32.8%. This value for samples containing 10% silica fume (S10) and 10% metakaolin (M10) is equal to 22.2% and 23.4%, respectively; for the sample containing 5% zeolite (Z5), by changing the curing method from dry to normal, the tensile strength decreased by 1.2%. Also, changing the curing method from dry to normal improved the tensile strength by 10.6% for the control sample.

Figure 18 compares the tensile strength of the 28- and 90-day mixtures containing pozzolanic materials compared to the control mixtures. Figure 18 shows that, in the normal curing method, replacing 10% of the used cement with silica fume pozzolanic materials, metakaolin, and zeolite will improve the tensile strength. The highest increase in tensile strength compared to the control sample is related to the sample containing silica fume (S10). Also, the examination of the results shows that in the normal curing method, the tensile strength of the mixture containing 10% zeolite has increased the most compared to the control mixture, and the tensile strength of the sample containing 5% zeolite (Z5) has decreased by 4% compared to the control mixture. In the dry curing method (group B), the samples containing 10% metakaolin (M10) and 10% silica fume (S10) have better tensile strength than the control mixture, while the tensile strength of the sample containing 10% zeolite (Z10) in this the curing method is 2.4% lower than the control mixture. In the dry curing method, by reducing the replacement percentage of zeolite, the tensile strength increased compared to the control mixture, so the tensile strength of the sample containing 5% zeolite (Z5) has increased by 7.5% compared to the control mixture.

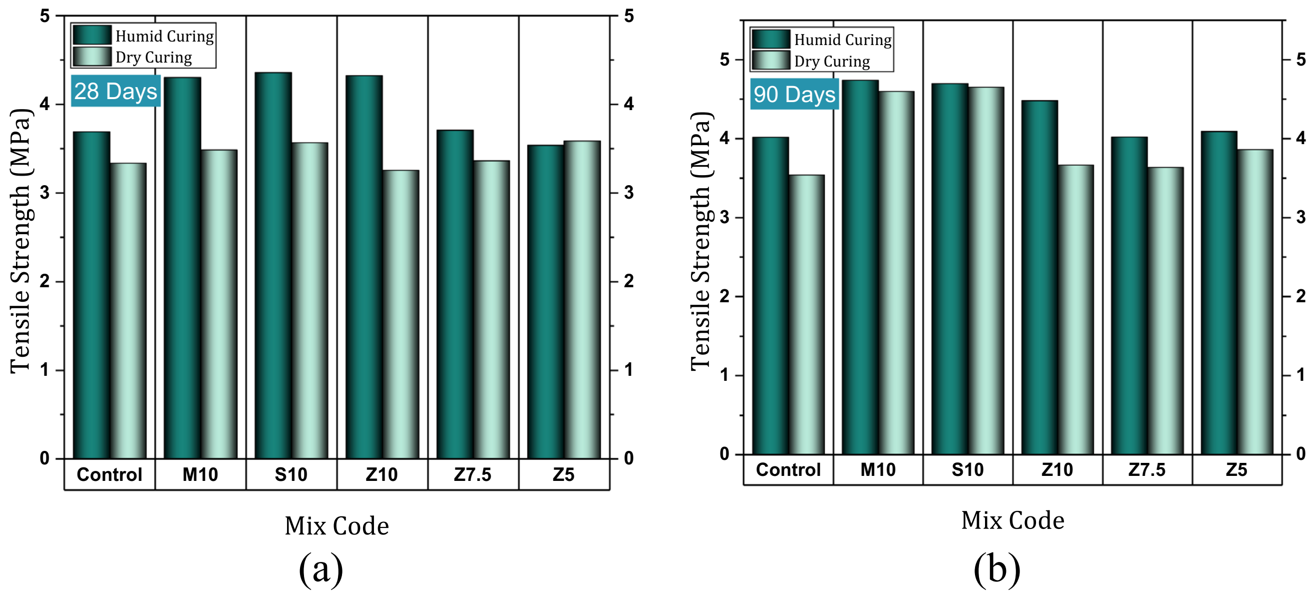

Fig. 16 Tensile strength results of different mixtures **a** 28 days, **b** 90 days

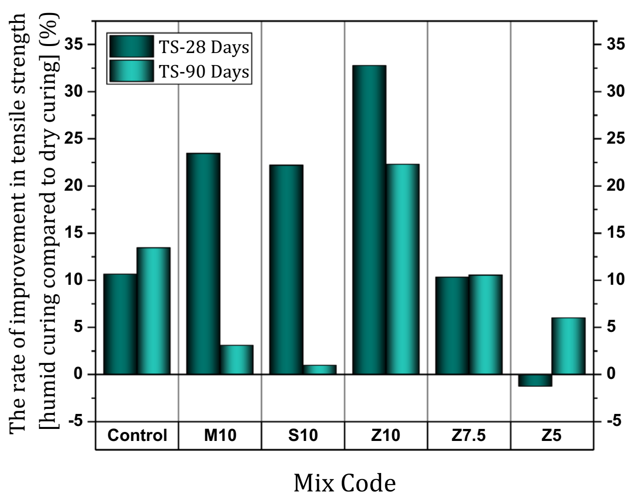

Fig. 17 Tensile strength of mixtures cured in a humid environment (group A) compared to a dry curing environment (group B)

The results show that in both curing methods (A and B), the samples containing silica fume (S10) and metakaolin (M10) have better tensile strength than the mixture containing zeolite and the control mixture. The results also show that, by changing the curing method from dry to normal, mixtures containing silica fume have the least amount of change in 90-day tensile strength compared to other mixtures. This value is 3% for the mixture containing metakaolin and about 1% for the mixture containing silica fume. While the 90-day tensile strength of the mixture containing 10% zeolite increases by 22.3% by changing the curing method, this value is equal to 10.5 and 6% for the mixtures containing 7.5% (Z7.5) and 5% (Z5) zeolite, respectively.

All the mixtures containing pozzolanic materials in both dry and normal curing methods have resulted in higher tensile strength than the control mixture. In the normal curing method, the highest increase in 90-day tensile strength compared to the control mixture is related to the mixing scheme containing 10% metakaolin (M10). The results show that among the mixtures containing zeolite (Z10, Z7.5, and Z5), the mixture containing 5% zeolite in the dry curing method recorded a greater increase in tensile strength compared to the control mixture.

4.5 Correlation of compressive and tensile strength/normal curing (group A and B)

Based on the general exponential relationship referenced in most international authoritative sources such as ACI 318, Eq. (1) between compressive and tensile strength is generally established, but the coefficients of this relationship (n and K) differ in different researches.

$$f_{spt} = K(f_{c'})^n \tag{1}$$

In Eq. (1), f'_c is the 28-day characteristic compressive strength under standard conditions, and f_{spt} is the splitting tensile strength of 28 days under standard conditions. K and n are also among the constants of the equation. Table 6 shows a report of the K and n constants based on different studies.

Figure 19 shows the relationship between compressive and tensile strength and compares it with the formulas proposed in Table 6. The results of the correlation between

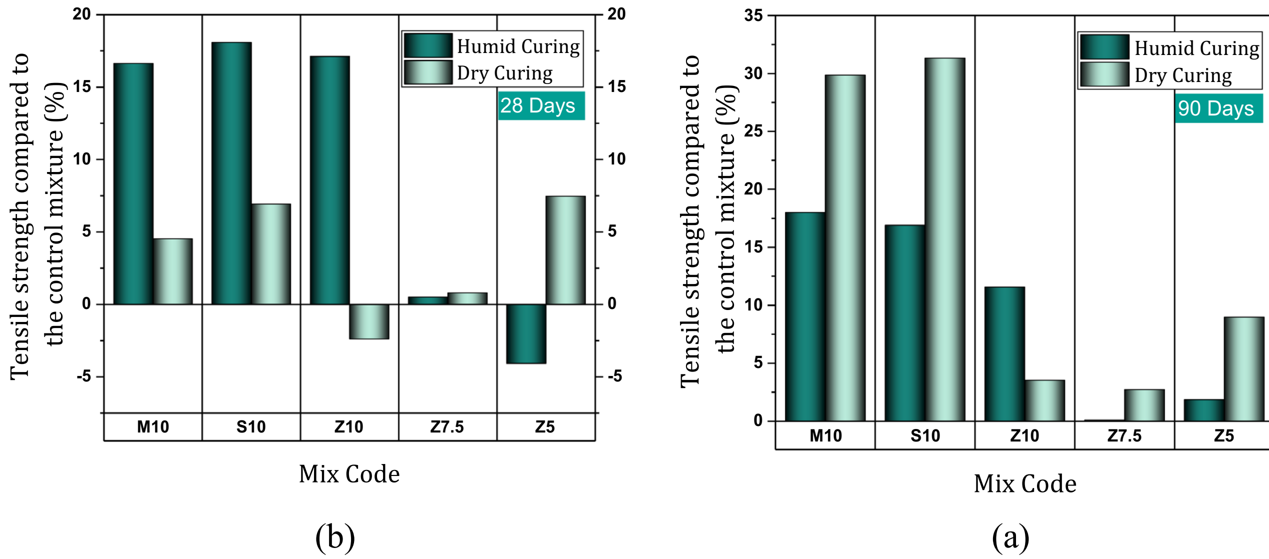

Fig. 18 Tensile strength results of mixtures containing pozzolan compared to the control mixture **a** 28 days, **b** 90 days

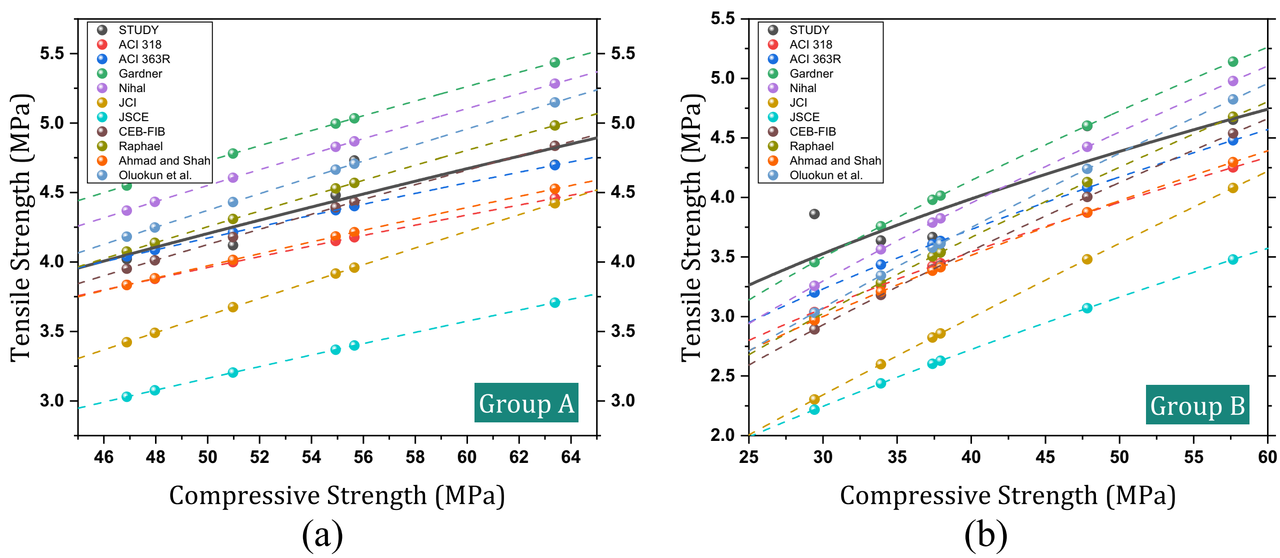

Fig. 19 Relationship between compressive and tensile strength **a** humid curing (group A), **b** dry curing (group B)

the compressive and tensile strengths compared to the ACI 318 relationship show the upper-hand results in such a way that, on average, compared to the ACI relationship, the estimated relationship obtained from the experimental results was 5.36% higher. The ACI relationship, which is used for standard conditions and normal concrete, provides a lower estimate than the experimental data for normal conditions in this part of the study. In this regard, we can point out two possible cases that can be responsible for this trend (1) better bonding between aggregates due to the addition of pozzolan, (2) internal curing due to the moisture retention of zeolite.

4.6 Compressive and tensile strength results after exposure to acidic environments

4.6.1 Compressive strength/acidic environment

The performance of samples cured in a sulfuric acid environment (with pH equal to 1) was investigated to better understand the resistance of concrete mixtures containing pozzolanic materials (such as silica fume, metakaolin, and zeolite) against acid attacks. For this purpose, compressive and tensile strength tests for samples cured in group C (28 days of curing in humid conditions and continued curing in acid) and group D (28 days of curing in dry conditions and

Table 6 Constant coefficients of the relation of compressive and tensile strength based on different sources

No.	Sources	K	n
1	ACI 318 (1994)	0.56	0.5
2	ACI 363R (Russell et al. 1997)	0.59	0.5
3	Gardner et al. (1988)	0.47	0.59
4	Nihal (Arioglu et al. 2006)	0.387	0.63
5	JCI (Sato et al. 2008)	0.13	0.85
6	JSCE (Uomoto et al. 2008)	0.23	0.67
7	CEB-FIB (Commitee for The Model Code 1990 1990)	0.3	0.67
8	Raphael (1984)	0.313	0.667
9	Shah and Ahmad (1985)	0.462	0.55
10	Oluokun et al. (1991)	0.294	0.69

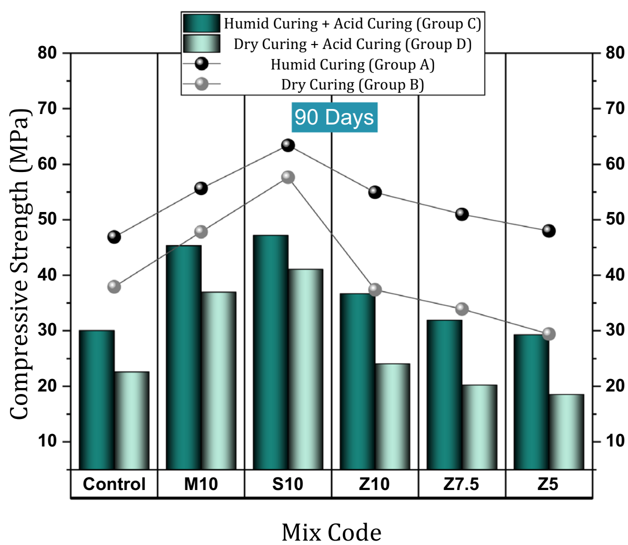

Fig. 20 Compressive strength of the mixtures in acidic conditions

continued curing in acid) were evaluated, and the loss of compressive and tensile strength was measured for each sample. Figure 20 shows the compressive strength test results of the cured mixtures (groups C and D) in acidic environments. The highest compressive strength after curing in an acidic environment under the normal curing method (group C) corresponds to the sample containing 10% silica fume (S10). Concrete samples are drawn in Fig. 21 to measure the lost compressive strength after being placed in an acidic environment. According to Fig. 21, the sample containing 10% metakaolin (M10) had the lowest decrease in compressive strength after exposure to the acidic environment. In general, replacing 10% of cement with pozzolanic materials such as silica fume, metakaolin, and zeolite will improve concrete sample performance in an acidic environment. In this regard, the performance of the sample containing zeolite compared

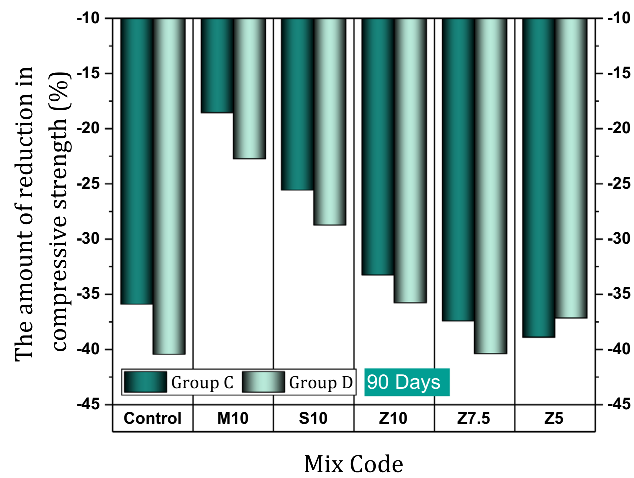

Fig. 21 The amount of drop in compressive strength exposed to acid

to the samples containing silica fume and metakaolin showed a weaker performance and resulted in a greater drop in compressive strength. In a study, Roy et al. (2001) also mentioned the positive effect of using different pozzolanic materials on the performance of concrete exposed to acidic environments. Although generally, silica fume shows higher durability than metakaolin, the available documents have significant differences, including in the ratio of water to cement materials, as well as the replacement percentage of additives (Kosmatka et al. 2002). Kosmatka et al. (2002), while investigating the performance of pozzolan-containing concrete against sulfuric acid attacks, reached the conclusion that, by increasing the replacement percentage of pozzolanic materials with cement, the performance of concrete against acid attacks improves. Extensive studies have also been conducted in order to improve the durability of concrete in harmful environments containing acidic agents. The results of the research show that, due to the vulnerability of cement hydration materials such as lime crystals and C–S–H gel against sulfuric acid attacks, avoiding cement materials as much as possible will improve performance in an acidic environment. In general, pozzolanic materials can play a positive role in reducing the severity of corrosion and preventing the reduction of concrete's compressive strength. Examining the Z10, Z7.5, and Z5 mixtures shows that increasing the replacement of zeolite from 5 to 10% reduces the intensity of compressive strength reduction.

4.6.2 Tensile strength/acidic environment

Figure 22 shows the tensile strength results of different concrete mixtures exposed to acidic environments. The highest tensile strength after exposure to an acidic environment (for curing groups C and D) is related to the mixture containing 10% metakaolin (M10). Also, the results show that,

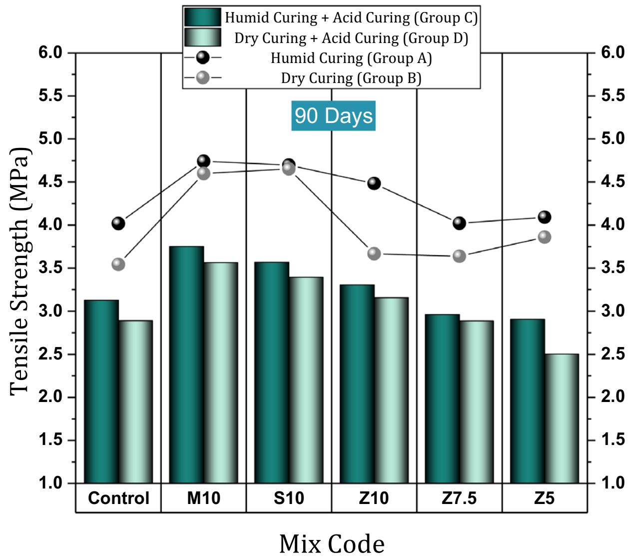

Fig. 22 The mixtures' tensile strength in acidic conditions

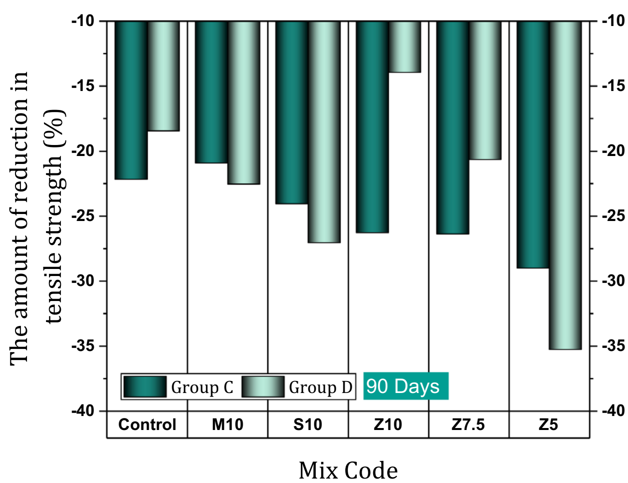

Fig. 23 The decrease in tensile strength when exposed to acid

among the mixtures containing 10% of cement substitutes, the lowest acid tensile strength is related to the mixture containing zeolite. In the samples containing zeolite, the tensile strength increases with the replacement percentage of zeolite. Figure 23 shows the decrease in the concrete mixture's tensile strength due to acid exposure. The highest tensile strength drop is related to the sample containing 5% zeolite (Z5). The comparison of the samples containing 10% pozzolanic materials instead of cement also shows that the highest drop in tensile strength is related to the sample containing zeolite. In general, comparing the results of the mixtures containing pozzolanic materials with the results of the control sample shows that, in the normal curing method (group C), only the sample containing metakaolin (M10) shows a lower tensile strength loss than the control mixture. Replacing 10% of mixed cement with natural and synthetic pozzolan materials such as zeolite, silica fume, and metakaolin has a positive effect on compressive and tensile strength, and the use of these materials improves concrete performance against sulfuric acid attacks. This applies to both dry and normal curing methods (group C and D).

4.7 Correlation of compressive and tensile strength/acid curing (groups C and D)

With the intensification of unfavorable conditions and the effects of an acidic environment, it is observed that the compressive and tensile strength decrease, but it should be noted that the speed of their resistance decrease (compressive and tensile) is different. Strength reduction occurs faster for tensile strength compared to compressive strength. This decrease in tensile strength compared to compressive strength can be attributed to acid infiltration in the border area of aggregate transfer and a decrease in aggregate bond strength with cement matrix. On the other hand, the formation of calcium sulfate resulting from the acid reaction with the cement matrix helps to reduce the drop in compressive strength to some extent, and these two possible factors can be considered effective for this reduction overall. According to the ACI relationship, the increase in the distance of tensile strength results due to the increase in compressive strength can raise the possibility of strengthening the internal porosity due to the formation of sulfate. Figure 24 shows that the ACI relationship provides a higher estimate than the mathematical relationship obtained from the results of the mixtures located in acidic environments, which is 4.47% higher on average.

4.8 Water penetration under pressure

After curing the samples by two methods, dry and normal, until 90 days, the permeability test was performed on the samples. Table 7 shows the results of permeability under pressure of different mixtures. Concrete's degree of permeability under the effect of water movement with pressure is an inherent characteristic of concrete, which depends on parameters such as placement and geometric order and the characteristics of the constituent particles of concrete. This issue is controlled by the density and porosity of the paste and the cement's hydration and transition area. Capillary holes and gel holes are distributed in the hydrated paste. The gel holes are very small and at the same time, they form a free network that has very low permeability, while there are capillary voids with larger spaces between cement particles. Therefore, better permeability (lower) in concrete is directly related to the reduction of capillary voids. Concrete samples can have a lower permeability if (1) the pozzolanic materials in them have a high degree of hydration, and (2) the distribution of pozzolanic particles in the mixture is such that they can fill the holes as much as possible.

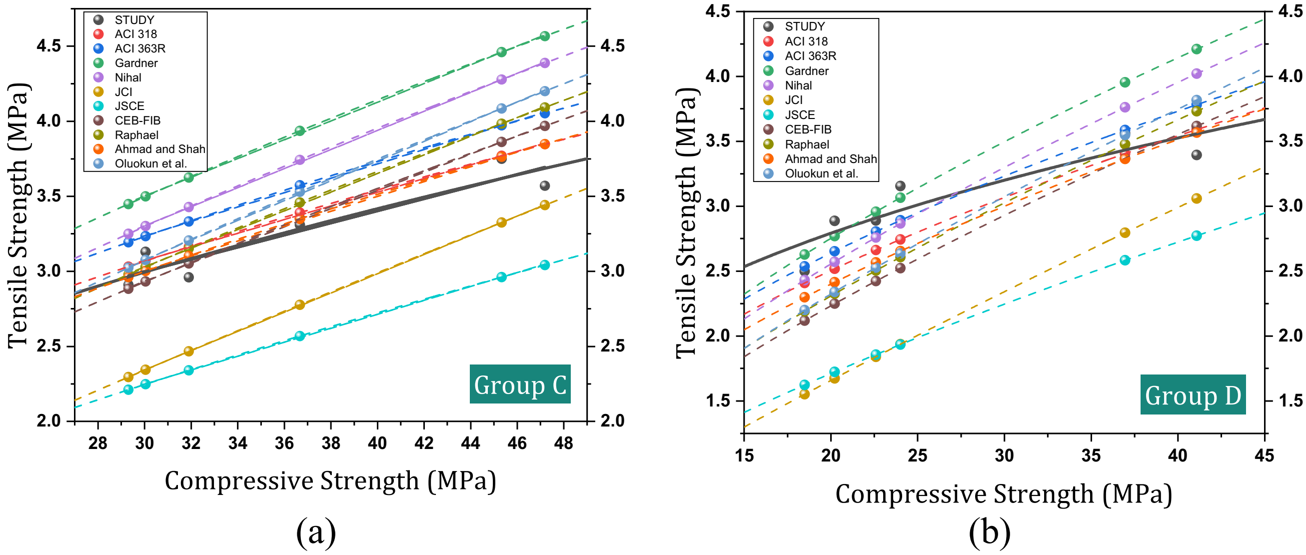

Fig. 24 Relationship between compressive and tensile strength **a** humid + acid curing (group C), **b** dry + acid curing (group D)

Table 7 The results of permeability under pressure of different mixtures

No.	Mix code	Curing			
		Group A	Group B	Group C	Group D
		Water penetration (mm-72h)		Water penetration (mm/min)	
1	Control	56	65	70	85
2	M10	16	19	7	12
3	S10	5	7	25	34
4	Z10	41	46	45	55
5	Z7.5	43	49	50	62
6	Z5	52	57	61	73

Figure 25 shows the results of permeability under pressure of different mixtures (cured in groups A and B). According to Fig. 25, the sample containing 10% silica fume (S10) has lower permeability under pressure compared to similar samples containing metakaolin and zeolite. This issue can be due to the higher degree of pozzolanic activity of silica fume, compared to metakaolin and zeolite, which leads to less porosity both in the cement paste and in the transfer zone. Also, the comparison of the sample results containing zeolite shows that increasing the replacement percentage of zeolite will reduce the porosity of concrete and thus reduce the permeability under pressure in both dry and normal curing methods. Figure 26 shows the results of permeability under the pressure of different mixtures (cured in groups A and B) compared to the control mixture. According to Fig. 26, replacing 10% of cement with silica fume (S10) resulted in a 91% decrease in permeability under pressure compared to the control sample. This value for the sample containing

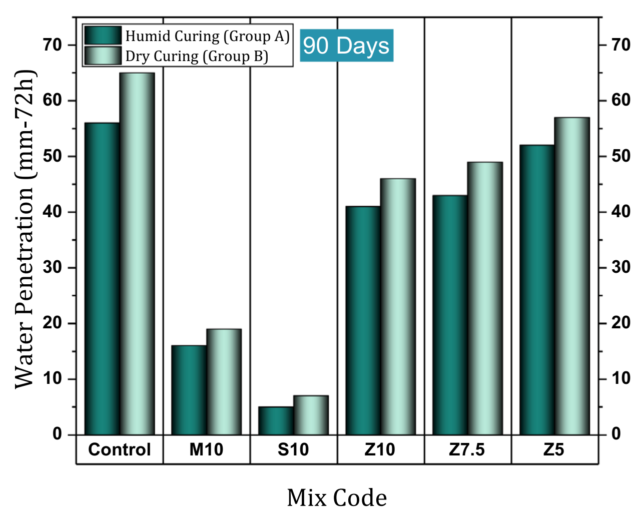

Fig. 25 The results of permeability under pressure of different mixtures (groups A and B)

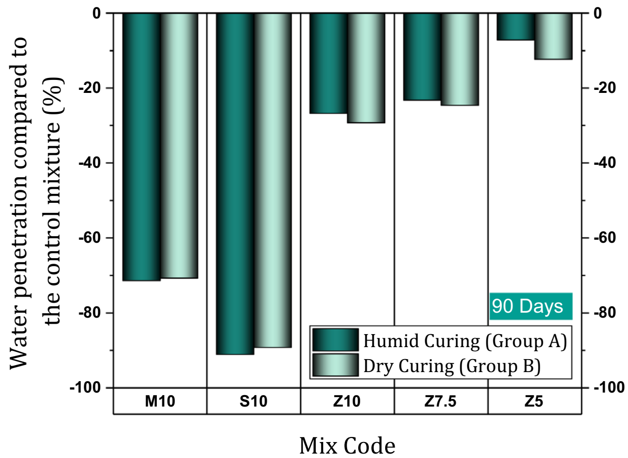

Fig. 26 Comparison of permeability under pressure of different mixtures with the control mixture (groups A and B)

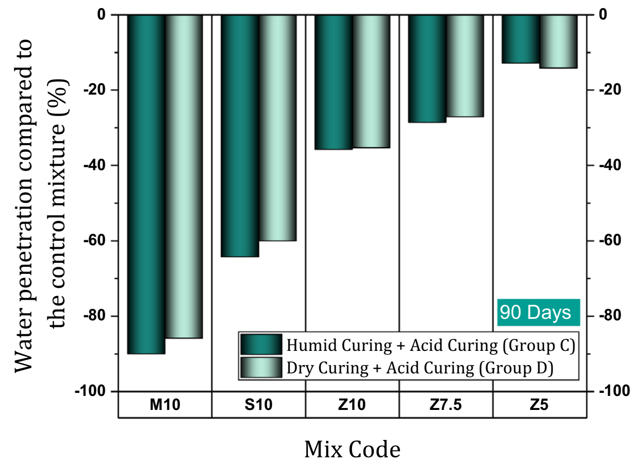

Fig. 28 Comparison of permeability under pressure of different mixtures with the control mixture (groups C and D)

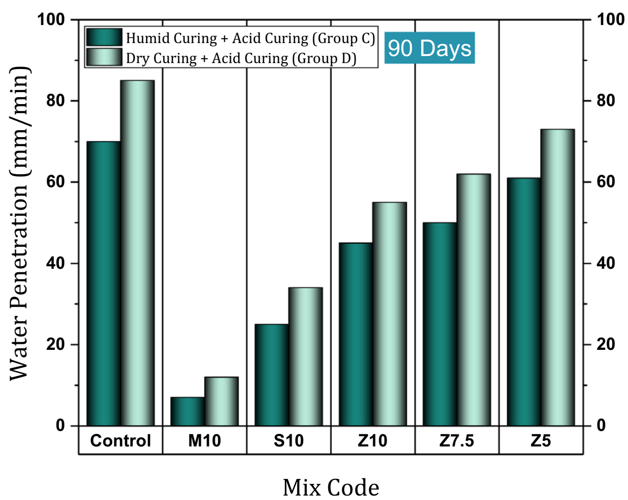

Fig. 27 The results of permeability under pressure of different mixtures (groups C and D)

10% metakaolin (M10) and the sample containing 10% zeolite (Z10) is equal to 71.4 and 26.8%, respectively. The sharp decrease in the permeability under pressure in the sample containing silica fume can be attributed to its strong pozzolanic activity, as well as the particles' high fineness and the ability to create relatively high density in the internal structure of concrete.

Water permeability under pressure has also been done for samples cured up to 28 days in two dry and normal environments and cured up to 90 days in an acidic environment (groups C and D). Figure 27 shows the results of permeability under pressure of different mixtures (cured in groups C and D). Figure 28 shows the results of permeability under the pressure of different mixtures (cured in groups C and D) compared to the control mixture. It is necessary to explain that, due to the damage to the samples' surface texture in the acidic environment and the emergence of penetration channels due to the chemical reaction, the impermeability of the samples has been greatly reduced. Also, the water passed through the samples with a significant flow intensity. Therefore, for this category of samples, instead of measuring the water permeability depth, the water permeability rate has been measured in cc/min. The lowest value of water penetration rate under pressure among all the samples and in both dry and normal curing modes corresponds to the sample containing 10% metakaolin (M10). A possible reason for this issue can be that the sample containing metakaolin is less damaged in an acidic environment than other samples. The comparison of samples containing 10% of cement substitutes shows that the highest rate of water penetration under pressure is related to the sample containing zeolite, and the rate of water penetration increases as the percentage of zeolite substitution decreases.

4.9 Performance evaluation of pozzolan

Table 8 displays the findings from the present research and previous studies regarding the effect of pozzolan on concrete strength and durability. Research indicates that the inclusion of pozzolan in cement structures, attributed to the pozzolanic characteristics of these materials, establishes a foundation for enhanced C–S–H quality and the enhancement of the interfacial transition zone (ITZ) between cement paste and aggregates. This, in turn, results in improved compressive and tensile strength as well as flexural.

Pozzolans contain silica and alumina that react with calcium hydroxide (a byproduct of cement hydration) to form calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H). These hydration products are less soluble in acids than calcium hydroxide, thus providing better resistance to acid attack.

Table 8 Effect of pozzolans on different parameters of concrete

Ref.	Characteristic	Target	Curing	Effects
Boukhelkhal et al. (2019)	Compressive strength	Metakaolin (M)	Air [28 days]	M 5% = 6.41% ↓ M 10% = 7.69% ↓ M 15% = 11.53% ↑
			Water [1 day] + air [27 days]	M 5% = 13.29% ↑ M 10% = 10.75% ↑ M 15% = 17.72% ↑
			Water [3 day] + air [25 days]	M 5% = 15.22% ↑ M 10% = 6.24% ↑ M 15% = 14.01% ↑
			Water [7 day] + air [21 days]	M 5% = 0 M 10% = 8.5% ↓ M 15% = 19.49% ↓
			Water [28 days]	M 5% = 1.08% ↑ M 10% = 9.23% ↑ M 15% = 9.52% ↑
This study		Metakaolin (M)	Water [28 days]	M 10% = 5.67% ↑
			Water [90 days]	M 10% = 18.70% ↑
			Air [28 days]	M 10% = 19.51% ↑
			Air [90 days]	M 10% = 26.09% ↑
		Silica fume (S)	Water [28 days]	S 10% = 29.09% ↑
			Water [90 days]	S 10% = 35.19% ↑
			Air [28 days]	S 10% = 49.40% ↑
			Air [90 days]	S 10% = 52% ↑
		Zeolite (Z)	Water [28 days]	Z 10% = 2.17% ↑
			Water [90 days]	Z 10% = 17.17% ↑
			Air [28 days]	Z 10% = 3.22% ↓
			Air [90 days]	Z 10% = 1.44% ↓
Boukhelkhal et al. (2019)	Flexural strength	Metakaolin (M)	Air [28 days]	M 5% = 16.36% ↓ M 10% = 32% ↓ M 15% = 24.54% ↓
			Water [1 day] + air [27 days]	M 5% = 5.45% ↓ M 10% = 1.48% ↓ M 15% = 3.96% ↑
			Water [3 day] + air [25 days]	M 5% = 9.92% ↑ M 10% = 7.08% ↑ M 15% = 8.97% ↑
			Water [7 day] + air [21 days]	M 5% = 3.36% ↑ M 10% = 2.52% ↑ M 15% = 0.42% ↓
			Water [28 days]	M 5% = 4.33% ↑ M 10% = 1.57% ↓ M 15% = 1.57% ↓
This study	Tensile Strength	Metakaolin (M)	Water [28 days]	M 10% = 16.63% ↑
			Water [90 days]	M 10% = 18% ↑
			Air [28 days]	M 10% = 4.52% ↑
			Air [90 days]	M 10% = 29.84% ↑
		Silica fume (S)	Water [28 days]	S 10% = 18.09% ↑
			Water [90 days]	S 10% = 16.89% ↑

Table 8 (continued)

Ref.	Characteristic	Target	Curing	Effects
			Air [28 days]	S 10% = 6.92% ↑
			Air [90 days]	S 10% = 31.33% ↑
		Zeolite (Z)	Water [28 days]	Z 10% = 17.12% ↑
			Water [90 days]	Z 10% = 11.57% ↑
			Air [28 days]	Z 10% = 2.39% ↓
			Air [90 days]	Z 10% = 3.5% ↑
Boukhelkhal et al. (2019)	Acid attack (strength loss)	Metakaolin (M)	Water [7 day] + 8 immersion-drying cycles [56 days] + acid [until 360 days]	**$MgSO_4$**: Control = 45.92% ↓ M 5% = 34.25% ↓ M 10% = 17.59%↓ M 15% = 13.88% ↓ **Na_2SO_4**: Control = 15.59% ↓ M 5% = 15.27% ↓ M 10% = 11.26% ↓ M 15% = 13.10% ↓ **HCl**: Control = 19.26% ↓ M 5% = 25.29% ↓ M 10% = 16.17% ↓ M 15% = 17.20% ↓
Chen et al. (2024)	Acid attack (mass loss)	Silica fume (S)	Erosion solution [5 days] + air [1 day] = 1 drying-wetting cycle 5 drying-wetting cycles = *1 cycle period*	**Acid rain (H_2SO_4, HNO_3)**: *1 cycle/* Control = 0.221% ↑ S 3% = 0.383% ↑ S 7% = 0.561% ↑ *2 cycles/* Control = 1.36% ↓ S 3% = 1% ↓ S 7% = 0.73% ↓ *3 cycles/* Control = 2.10% ↓ S 3% = 1.84% ↓ S 7% = 1.31% ↓
Chen et al. (2024)	Acid attack (compressive strength loss)	Silica fume (S)	Erosion solution [5 days] + AIR [1 day] = 1 drying-wetting cycle 5 drying-wetting cycles = *1 cycle period*	**Acid rain (H_2SO_4, HNO_3)**: *1 cycle/* S 3% = 1.75% ↑ S 7% = 5.42% ↑ *2 cycles/* S 3% = 1.58% ↑ S 7% = 5.08% ↑ *3 cycles/* S 3% = 2.07% ↑ S 7% = 6.05% ↑
This study	Acid attack (compressive strength loss)	Metakaolin (M)	Water [28 days] + acid [62 days]	**H_2SO_4**: Control = 35.89% ↓ M 10% = 18.55% ↓
			Air [28 days] + acid [62 days]	**H_2SO_4**: Control = 40.43% ↓ M 10% = 22.72% ↓
		Silica fume (S)	Water [28 days] + acid [62 days]	**H_2SO_4**: Control = 35.89% ↓ S 10% = 25.55% ↓

Table 8 (continued)

Ref.	Characteristic	Target	Curing	Effects
			Air [28 days] + Acid [62 days]	**H_2SO_4**: Control = 40.43% ↓ S 10% = 28.78% ↓
		Zeolite (Z)	Water [28 days] + acid [62 days]	**H_2SO_4**: Control = 35.89% ↓ Z 10% = 33.24% ↓
			Air [28 days] + Acid [62 days]	**H_2SO_4**: Control = 40.43% ↓ Z 10% = 35.76% ↓
This study	Acid attack (tensile strength loss)	Metakaolin (M)	Water [28 days] + acid [62 days]	**H_2SO_4**: Control = 22.17% ↓ M 10% = 20.90% ↓
			Air [28 days] + acid [62 days]	**H_2SO_4**: Control = 18.43% ↓ M 10% = 22.52% ↓
		Silica fume (S)	Water [28 days] + acid [62 days]	**H_2SO_4**: Control = 22.17% ↓ S 10% = 24.05% ↓
			Air [28 days] + acid [62 days]	**H_2SO_4**: Control = 18.43% ↓ S 10% = 27.04% ↓
		Zeolite (Z)	Water [28 days] + acid [62 days]	**H_2SO_4**: Control = 22.17% ↓ Z 10% = 26.27% ↓
			Air [28 days] + acid [62 days]	**H_2SO_4**: Control = 18.43% ↓ Z 10% = 13.93% ↓

Additional C–S–H and C–A–H enhance the mechanical strength of concrete, increasing its durability against physical and chemical damage. Secondary hydration products from the pozzolanic reaction fill capillary pores and microcracks, reducing permeability and enhancing resistance to acid penetration.

5 Conclusions

Based on the results, the following conclusions are drawn:

1. Substituting part of zeolite with silica fume and using these two pozzolanic substances at the same time improves the performance of the sample in the 7-day compressive strength test by 13.6% compared to the sample containing zeolite alone.
2. Samples containing 10% metakaolin and silica fume had higher 14- and 28-day compressive strengths (at least 7.7%) compared to the control mixture in both dry and humid curing conditions.
3. Changing the curing method from dry to humid had the greatest effect on the 90-day compressive strength of the samples containing zeolite, and by reducing the percentage of zeolite substitution in the mixing plan, the difference in the 90-day compressive strength of the two dry and humid curing methods increased.
4. In the dry curing method, the greatest increase in compressive strength due to the sample's aging from 7 to 90 days was related to the sample containing 10% zeolite, which reached 52.7%.
5. In the humid curing method, replacing 10% of the used cement with pozzolanic materials (silica fume, metakaolin, and zeolite) improved the 28-day tensile strength. The highest increase in tensile strength compared to the control mixture was related to the sample containing silica fume by 7.8%.
6. Replacing 10% of cement with pozzolanic materials (such as silica fume, metakaolin, and zeolite) improved the concrete sample's performance in an acidic environment compared to the control mixture. This improvement by 10.3, 17.3, and 2.7%, respectively, for S10, M10, and Z10 mixtures compared to the control mixture compensated for the loss of compressive strength. In the meantime, the performance of the sample containing zeolite was weaker compared to the samples

containing silica fume and metakaolin and resulted in a greater drop in compressive strength (33.2%).

7. The positive effect of pozzolans replacing cement on the resistance to an acidic environment and the compressive strength of the samples located in the desired environment were evident. This issue was more tangible for the samples containing zeolite in 10% replacement so the samples containing 7.5 and 5% zeolite (Z7.5 and Z5) had a greater drop in compressive strength than the control design. This quality loss was reported as 37.4 and 38.9%, respectively, for samples containing 7.5% and 5% zeolite (Z7.5 and Z5).
8. Increasing the replacement percentage of zeolite from 5 to 10% in the concrete mixing design increased the initial water absorption for samples cured under humid conditions at all ages. This increase reached 47% at 7 days and decreased to a maximum of 18.8% at 90 days. In the humid curing method, the lowest initial water absorption at 90 days was related to the sample containing silica fume at the rate of 1.66%.
9. Increasing the replacement percentage of zeolite led to a decrease in water permeability under pressure in both dry and humid curing methods. This reduction measured at least 7.1% in humid curing and at least 12.3% in dry curing.
10. The water pressure penetration test results for the samples after acidic exposure show that the lowest value of the pressure water penetration rate in both dry and humid curing modes was related to the sample containing 10% metakaolin (7 mm/min for humid curing and 12 mm/min for dry curing).

Author contributions Mohammad Reza Heyran Najafi: Software, Validation, Formal analysis Ashkan Saradar: Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing -original draft, Writing - review & editing, Visualization, Supervision Mohammad Mohtasham Moein: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization Moses Karakouzian: Writing - review & editing, Visualization.

Data availability The dataset analyzed in the present study is accessible and can be shared upon request.

Declarations

Conflict of interest The authors declare no competing interests.

References

Abdelli K, Tahlaiti M, Belarbi R, Oudjit MN (2017) Influence of the origin of metakaolin on pozzolanic reactivity of mortars. Energy Procedia. https://doi.org/10.1016/j.egypro.2017.11.201

ACI 318 (1994) Building code requirements for structural concrete and commentary. ACI Struct J 552

Aghapour AH, Yazdani M, Jolai F, Mojtahedi M (2019) Capacity planning and reconfiguration for disaster-resilient health infrastructure. J Build Eng. https://doi.org/10.1016/j.jobe.2019.100853

Ahdal AQ, Amrani MA, Ghaleb AAA, Abadel AA, Alghamdi H, Alamri M, Wasim M, Shameeri M (2022) Mechanical performance and feasibility analysis of green concrete prepared with local natural zeolite and waste PET plastic fibers as cement replacements. Case Stud Constr Mater. https://doi.org/10.1016/j.cscm.2022.e01256

Ahmad S, Adekunle SK, Maslehuddin M, Azad AK (2014) Properties of self-consolidating concrete made utilizing alternative mineral fillers. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2014.06.096

Ahmadi B, Shekarchi M (2010) Use of natural zeolite as a supplementary cementitious material. Cem Concr Compos. https://doi.org/10.1016/j.cemconcomp.2009.10.006

Ahmadi B, Sobhani J, Shekarchi M, Najimi M (2014) Transport properties of ternary concrete mixtures containing natural zeolite with silica fume or fly ash. Mag Concr Res. https://doi.org/10.1680/macr.13.00224

Al-Akhras NM (2006) Durability of metakaolin concrete to sulfate attack. Cem Concr Res. https://doi.org/10.1016/j.cemconres.2006.03.026

Arioglu N, Canan Girgin Z, Arioglu E (2006) Evaluation of ratio between splitting tensile strength and compressive strength for concretes up to 120 MPa and its application in strength criterion. ACI Mater J. https://doi.org/10.14359/15123

ASTM (2003) ASTM C39-03: standard test method for compressive strength of cylindrical concrete specimens. West Conshohocken

ASTM (2004) ASTM C496-04: standard test method for splitting tensile strength of cylindrical concrete specimens. West Conshohocken

ASTM C1611/C1611M-18 (2018) Standard test method for slump flow of self-consolidating concrete. ASTM International

ASTM-C642 (2013) ASTM C642-13 standard test method for density, absorption, and voids in hardened concrete. Annual Book of ASTM Standards

ASTM Committee C01.10 (2016) ASTM C150/C150M-16 standard specification for Portland cement. In: Annual book of ASTM Standards volume 04.01

ASTM International (2016) ASTM C33/ C33M-16 standard specification for concrete aggregates. ASTM International

Beshkari M, Amani B, Rahmati K, Mohtasham Moein M, Saradar A, Karakouzian M (2024) Synergistic effects of pozzolan and carbon fibers on the performance of self-consolidating concrete under plastic shrinkage and dynamic loading. Innov Infrastruct Solut 9:160. https://doi.org/10.1007/s41062-024-01440-6

Bodt BA, Ostle B, Turner K, Hicks C, McElrath G (1997) Engineering statistics: the industrial experience. Technometrics. https://doi.org/10.2307/1270788

Boles JR, Flanigen EM, Gudes AJ, Hay RL, Mumpton FA, Surdam RC (1977) Mineralogy and geology of natural zeolites. Mineralogical Society of America, New York. https://doi.org/10.1515/9781501508585

Boukhelkhal A, Azzouz L, Kenai S, Kadri EH, Benabed B (2019) Combined effects of mineral additions and curing conditions on strength and durability of self-compacting mortars exposed to aggressive solutions in the natural hot-dry climate in North African desert region. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2018.11.233

British Standards Institution BSI, BS EN 12390-8:2000 (2003) Depth of penetration of water under pressure, En 12390-8:2009 (E)

Bura AR, Kondraivendhan B (2022) An accelerated carbonation and its effect on concrete containing natural zeolite. Innov Infrastruct Solut. https://doi.org/10.1007/s41062-022-00796-x

Chan SYN, Ji X (1999) Comparative study of the initial surface absorption and chloride diffusion of high performance zeolite, silica fume and PFA concretes. Cem Concr Compos 21:293–300. https://doi.org/10.1016/S0958-9465(99)00010-4

Chen X, Wu X, Bian X, Wu Q, Cheng S, Ren C (2024) Evaluating the physicochemical properties of pervious recycled aggregate concrete incorporating pozzolanic additives under acid rain attack. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2023.134507

Commitee for The Model Code 1990 (1993) CEB Bulletin No. 213/214: CEB-FIP Model Code 90. Thomas Telford Ltd. Thomas Telford Bookshop Institution of Civil Engineers

Eskandari H, Vaghefi M, Kowsari K (2015) Investigation of mechanical and durability properties of concrete influenced by hybrid nano silica and micro zeolite. Procedia Mater Sci 11:594–599. https://doi.org/10.1016/j.mspro.2015.11.084

Fathollahi-Fard AM, Govindan K, Hajiaghaei-Keshteli M, Ahmadi A (2019) A green home health care supply chain: new modified simulated annealing algorithms. J Clean Prod. https://doi.org/10.1016/j.jclepro.2019.118200

Feng NQ, Peng GF (2005) Applications of natural zeolite to construction and building materials in China. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2005.01.013

Gardner NJ, Sau PL, Cheung MS (1988) Strength development and durability of concretes cast and cured at 0 C. ACI Mater J. https://doi.org/10.14359/2289

IPCC (2006) Carbon dioxide capture and storage: special report of the Intergovernmental Panel on Climate Change

Jokar F, Khorram M, Karimi G, Hataf N (2019) Experimental investigation of mechanical properties of crumbed rubber concrete containing natural zeolite. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2019.03.063

Karahan O, Hossain KMA, Ozbay E, Lachemi M, Sancak E (2012) Effect of metakaolin content on the properties self-consolidating lightweight concrete. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2011.12.112

Khasreen MM, Banfill PFG, Menzies GF (2009) Life-cycle assessment and the environmental impact of buildings: a review. Sustainability. https://doi.org/10.3390/su1030674

Khayat KH, Aïtcin PC (1992) Silica fume in concrete-an overview. In: American Concrete Institute, ACI Special Publication. https://doi.org/10.2208/jscej.1995.508_1

Kosmatka SH, Kerkhoff B, Panarese WC (2002) Design and control of concrete mixture. Portland Cement Association, Skokie

Koushkbaghi M, Alipour P, Tahmouresi B, Mohseni E, Saradar A, Sarker PK (2019) Influence of different monomer ratios and recycled concrete aggregate on mechanical properties and durability of geopolymer concretes. Constr Build Mater 205:519–528. https://doi.org/10.1016/j.conbuildmat.2019.01.174

Madhuri PV, Kameswara Rao B, Chaitanya A (2021) Improved performance of concrete incorporated with natural zeolite powder as supplementary cementitious material. Mater Today Proc. https://doi.org/10.1016/j.matpr.2021.06.089

Mansoori A, Mohtasham Moein M, Mohseni E (2020) Effect of micro silica on fiber-reinforced self-compacting composites containing ceramic waste. J Compos Mater. https://doi.org/10.1177/0021998320944570

Maraveas C (2020) Production of sustainable construction materials using agro-wastes. Materials 13:262. https://doi.org/10.3390/ma13020262

Markiv T, Sobol K, Franus M, Franus W (2016) Mechanical and durability properties of concretes incorporating natural zeolite. Arch Civ Mech Eng. https://doi.org/10.1016/j.acme.2016.03.013

Mertens G, Snellings R, Van Balen K, Bicer-Simsir B, Verlooy P, Elsen J (2009) Pozzolanic reactions of common natural zeolites with lime and parameters affecting their reactivity. Cem Concr Res. https://doi.org/10.1016/j.cemconres.2008.11.008

Moein MM, Soliman A (2022) Predicting the compressive strength of alkali-activated concrete using various data mining methods. In: Canadian Society of Civil Engineering annual conference. Springer Nature, Singapore, pp 317–326. https://doi.org/10.1007/978-981-19-1004-3_26

Moein MM, Saradar A, Rahmati K, Rezakhani Y, Ashkan SA, Karakouzian M (2023) Reliability analysis and experimental investigation of impact resistance of concrete reinforced with polyolefin fiber in different shapes, lengths, and doses. J Build Eng. https://doi.org/10.1016/j.jobe.2023.106262

Mohseni E, Tang W, Cui H (2017) Chloride diffusion and acid resistance of concrete containing zeolite and tuff as partial replacements of cement and sand. Materials. https://doi.org/10.3390/ma10040372

Mohtasham Moein M, Mousavi SY, Madandoust R, Naser Saeid HNS (2019) The impact resistance of steel fiber reinforcement concrete under different curing conditions: experimental and statistical analysis. J Civ Environ Eng 49(1):109–121. https://ceej.tabrizu.ac.ir/article_8961.html

Mohtasham Moein M, Saradar A, Rahmati K, Hatami Shirkouh A, Sadrinejad I, Aramali V, Karakouzian M (2022) Investigation of impact resistance of high-strength Portland cement concrete containing steel fibers. Cem Mater High Perform Concrete 15:1–30. https://doi.org/10.3390/ma15207157

Mohtasham Moein M, Saradar A, Rahmati K, Ghasemzadeh Mousavinejad SH, Bristow J, Aramali V, Karakouzian M (2023) Predictive models for concrete properties using machine learning and deep learning approaches: a review. J Build Eng. https://doi.org/10.1016/j.jobe.2022.105444

Mohtasham Moein M, Rahmati K, Saradar A, Moon J, Karakouzian M (2024) A critical review examining the characteristics of modified concretes with different nanomaterials. Materials 17:409. https://doi.org/10.3390/ma17020409

Moradi N, Tavana MH, Habibi MR, Amiri M (2023) Investigation of mechanical properties and permeability of concrete containing metakaolin, zeolite, and fly ash with two and three compounds. J Struct Constr Eng 9:100–121

Moshoeshoe M, Silas Nadiye-Tabbiruka M, Obuseng V (2017) A review of the chemistry, structure, properties and applications of zeolites. Am J Mater Sci 2017:196–221. https://doi.org/10.5923/j.materials.20170705.12

Mousavinejad SHG, Saradar A, Jabbari M, Moein MM (2023) Evaluation of fresh and hardened properties of self-compacting concrete containing different percentages of waste tiles. J Build Pathol Rehabil. https://doi.org/10.1007/s41024-023-00329-8

Nabighods K, Saradar A, Mohtasham Moein M, Mirgozar Langaroudi MA, Byzyka J, Karakouzian M (2023) Evaluation of self-compacting concrete containing pozzolan (zeolite, metakaolin & silica fume) and polypropylene fiber against sulfate attacks with different PH: an experimental study. Innov Infrastruct Solut 9:1. https://doi.org/10.1007/s41062-023-01309-0

Nagrockiene D, Girskas G (2016) Research into the properties of concrete modified with natural zeolite addition. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2016.03.133

Nagrockienė D, Girskas G, Skripkiūnas G (2017) Properties of concrete modified with mineral additives. Constr Build Mater 135:37–42. https://doi.org/10.1016/j.conbuildmat.2016.12.215

Najimi M, Sobhani J, Ahmadi B, Shekarchi M (2012) An experimental study on durability properties of concrete containing zeolite as a highly reactive natural pozzolan. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2012.04.038

Nasr D, Behforouz B, Borujeni PR, Borujeni SA, Zehtab B (2019) Effect of nano-silica on mechanical properties and durability of self-compacting mortar containing natural zeolite: experimental investigations and artificial neural network modeling. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2019.116888

Oluokun FA, Burdette EG, Deatherage JH (1991) Splitting tensile strength and compressive strength relationship at early ages. ACI Mater J. https://doi.org/10.14359/1859

Rabehi R, Rabehi M, Omrane M (2023) Physical–mechanical and fresh state properties of self-compacting concrete based on different types of gravel reinforced with steel fibers: experimental study and modeling. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2023.131758

Rahmati K, Saradar A, Mohtasham Moein M, Sardrinejad I, Bristow J, Yavari A, Karakouzian M (2022) Evaluation of engineered cementitious composites (ECC) containing polyvinyl alcohol (PVA) fibers under compressive, direct tensile, and drop-weight test. Multiscale Multidiscipl Model Exp Design. https://doi.org/10.1007/s41939-022-00135-8

Rajasekar A, Arunachalam K, Kottaisamy M, Saraswathy V (2018) Durability characteristics of ultra high strength concrete with treated sugarcane bagasse ash. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2018.03.140

Ramezanianpour AA (2014) Cement replacement materials; properties, durability, sustainability, 1st edn. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-36721-2

Ranjbar MM, Madandoust R, Mousavi SY, Yosefi S (2013) Effects of natural zeolite on the fresh and hardened properties of self-compacted concrete. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2013.05.097

Raphael JM (1984) Tensile strength of concrete. ACI 81:158–164. https://www.semanticscholar.org/paper/Tensile-Strength-of-Concrete-Raphael/15434632e55300d7ea822b82400b369a5bf30978

Roy DM, Arjunan P, Silsbee MR (2001) Effect of silica fume, metakaolin, and low-calcium fly ash on chemical resistance of concrete. Cem Concr Res. https://doi.org/10.1016/S0008-8846(01)00548-8

Russell HG, Anderson AR, Banning JO, Cook JE, Frantz GC, Hester WT, Moreno J, Mastin BR, Moore WC, Nilson AH, Perenchio WF, Aitcin PC, Anderson FD, Black RW, Cantor IG, Drake KD, Guennewig TG, Luther MD, Ohwiler CR, Russell MT (1997) State-of-the-art report on high-strength concrete reported by ACI Committee 363. Concrete 92:1–2

Sabet FA, Libre NA, Shekarchi M (2013) Mechanical and durability properties of self consolidating high performance concrete incorporating natural zeolite, silica fume and fly ash. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2013.02.069

Sabir BB, Khatib JM, Wild S (1996) On the workability and strength development of metakaolin concrete, concrete for environmental enhancement and protection, pp 651–656

Sadrmomtazi A, Sobhani J, Mirgozar MA, Najimi M (2012) Properties of multi-strength grade EPS concrete containing silica fume and rice husk ash. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2012.02.049

Saradar A, Nemati P, Paskiabi AS, Moein MM, Moez H, Vishki EH (2020) Prediction of mechanical properties of lightweight basalt fiber reinforced concrete containing silica fume and fly ash: experimental and numerical assessment. J Build Eng. https://doi.org/10.1016/j.jobe.2020.101732

Saradar A, Rezakhani Y, Rahmati K, Johari Majd F, Mohtasham Moein M, Karakouzian M (2024) Investigating the properties and microstructure of high-performance cement composites with nano-silica, silica fume, and ultra-fine TiO_2. Innov Infrastruct Solut 9:84. https://doi.org/10.1007/s41062-024-01407-7

Sasanipour H, Aslani F, Taherinezhad J (2019) Effect of silica fume on durability of self-compacting concrete made with waste recycled concrete aggregates. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2019.07.324

Sato R, Sogo S, Kanazu T, Kishi T, Noguchi T, Mizobuchi T, Miyazawa S (2013) JCI guidelines for control of cracking of mass concrete 2008. In: Proceedings of the International Committee of the SCMT Conferences on Sustainable construction materials and technologies, Kyoto, pp 18–21

Shah SP, Ahmad SH (1985) Structural properties of high strength concrete and its implications for precast prestressed concrete. J Prestressed Concr Inst. https://doi.org/10.15554/pcij.11011985.92.119

Shahmansouri AA, Yazdani M, Ghanbari S, Akbarzadeh Bengar H, Jafari A, Farrokh Ghatte H (2021) Artificial neural network model to predict the compressive strength of eco-friendly geopolymer concrete incorporating silica fume and natural zeolite. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.123697

Shen P, Lu L, Chen W, Wang F, Hu S (2017) Efficiency of metakaolin in steam cured high strength concrete. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2017.07.006

Sičáková A, Špak M, Kozlovská M, Kováč M (2017) Long-term properties of cement-based composites incorporating natural zeolite as a feature of progressive building material. Adv Mater Sci Eng. https://doi.org/10.1155/2017/7139481

Singh N, Singh SP (2016) Carbonation and electrical resistance of self compacting concrete made with recycled concrete aggregates and metakaolin. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2016.06.009

Sivakumar VR, Kavitha OR, Prince Arulraj G, Srisanthi VG (2017) An experimental study on combined effects of glass fiber and metakaolin on the rheological, mechanical, and durability properties of self-compacting concrete. Appl Clay Sci. https://doi.org/10.1016/j.clay.2017.07.015

Tahmouresi B, Nemati P, Asadi MA, Saradar A, Mohtasham Moein M (2021) Mechanical strength and microstructure of engineered cementitious composites: a new configuration for direct tensile strength, experimental and numerical analysis. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2020.121361

Tajasosi S, Saradar A, Barandoust J, Mohtasham Moein M, Zeinali R, Karakouzian M (2023) Multi-criteria risk analysis of ultra-high performance concrete application in structures. Civ Eng 4:1016–1035. https://doi.org/10.3390/civileng4030055

Taylor M, Tam C, Gielen D (2006) Energy efficiency and CO_2 emissions from the Global Cement Industry. IEA

Uomoto T, Ishibashi T, Nobuta Y, Satoh T, Kawano H, Takewaka K, Uji K (2008) Standard specifications for concrete structures-2007 by Japan Society of Civil Engineers. Concr J. https://doi.org/10.3151/coj1975.46.7_3

Valipour M, Yekkalar M, Shekarchi M, Panahi S (2014) Environmental assessment of green concrete containing natural zeolite on the global warming index in marine environments. J Clean Prod. https://doi.org/10.1016/j.jclepro.2013.07.055

Van Tuan N, Ye G, Van Breugel K, Copuroglu O (2011) Hydration and microstructure of ultra high performance concrete incorporating rice husk ash. Cem Concr Res. https://doi.org/10.1016/j.cemconres.2011.06.009

Vejmelková E, Koňáková D, Kulovaná T, Keppert M, Žumár J, Rovnaníková P, Keršner Z, Sedlmajer M, Černý R (2015) Engineering properties of concrete containing natural zeolite as supplementary cementitious material: strength, toughness, durability, and hygrothermal performance. Cem Concr Compos. https://doi.org/10.1016/j.cemconcomp.2014.09.013

Yazici H, Yardimci MY, Aydin S, Karabulut AŞ (2009) Mechanical properties of reactive powder concrete containing mineral admixtures under different curing regimes. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2008.08.003

Zareei SA, Ameri F, Bahrami N (2018) Microstructure, strength, and durability of eco-friendly concretes containing sugarcane bagasse ash. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2018.06.153

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