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ORIGINAL PAPER

The effect of adding zeolite and silica fume on properties of hardened ordinary and high strength concretes with cement grades 32.5, 42.5, and 52.5

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Abstract
In this paper, the effects of replacing natural zeolite and industrial by-products of silica fume with a portion of cement on ordinary and high-strength concretes with a compressive strength of 35 and 50 MPa were investigated. Twenty-four concrete mix designs, with three different grades of cement with compressive strengths of 32.5, 42.5, and 52.5 MPa, were considered. The percentage of zeolite replacement was 10, 20, and 30%, and silica fume was 7.5% by weight of cement. The compressive and tensile strength tests were performed at the ages of 28, 56, and 90 days, and as well as the XRD, DTA, TGA, and DTG tests were performed. The test results indicated that although the compressive strength of concrete containing zeolite in 28 days was less than that of normal concrete, the 56 and 90-day strengths of concretes containing up to 20% zeolite were almost equal to or even more than that of ordinary concrete, and the desired strengths were achieved. Also, the addition of 7.5% silica fume had a positive effect on compressive strength, and even in combination with 30% zeolite, it had compensated for the decrease in strength. The addition of up to 20% zeolite for ordinary concrete increased tensile strength by 10%. For high-strength concrete, the addition of 20% zeolite along with 7.5% silica fume showed a 25% increase in tensile strength compared to the reference samples. XRD test was also performed on zeolite and confirmed the purity of the compounds of this material.

Keywords Zeolite · Silica fume · Compressive strength · Tensile strength · High strength concrete · XRD

Introduction

Concrete is the most critical material used in the construction industry, which it has high compressive strength, good compatibility with steel in reinforced concrete structures, and ease of formability, but has the disadvantage of environmental degradation and energy consumption (Li 2011; Bhuyan et al. 2019). The construction industry will be more sustainable if use material with less energy consumption or solid wastes as a construction material (Packrisamy and Jayakumar 2022). Therefore, to reduce the use of Portland cement in concrete and reduce environmental pollution, natural pozzolanic materials and industrial waste should be used as part of cement in concrete and reduce the harmful effect of siliceous and alkaline aggregate (Soltani et al. 2018). Concretes are divided in terms of strength as ordinary strength concrete (OSC) (with a compressive strength of less than 40 MPa), high-strength concrete (HSC) (with a compressive strength of up to 100 MPa), high-performance concrete (HPC) (containing supplementary cementitious material such as silica fume and special aggregates), and concretes containing pozzolans (strengthened and durable concrete) (Lotfi Eghlim et al. 2019). The main difference between ordinary concrete and high-strength concrete is the level of quality control and monitoring (Sarıdemir et al. 2017; Hemmati et al. 2015). The most crucial usage of high-strength concrete is for road pavement, construction of high-rise buildings, construction of large span bridges, and improving the durability of bridge decks by increasing

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the strength of concrete from 40 to 70 MPa (Arowojolu et al. 2019). Pozzolans have low adhesion values, but in the presence of moisture and chemical reaction with calcium hydroxide at normal temperatures, form compounds with cementitious properties and improve the impermeability and strength of concrete (Kamal et al. 2021). Activated additives mineral powder are kiln slag, silica fume, fly natural ash pozzolans (terrace, pumice, zeolite, and metakaolin) (Ali et al. 2022). Zeolite has a three-dimensional structure and is an aluminosilicate material that forms holes of regular size in molecular dimensions (Lotfi Eghlim et al. 2019). Tosheva (1999) has also studied the synthesis of zeolites using fly ash derived from coal. De Luca et al. (2004) also investigated zeolites as solid materials that have tiny pores and cavities and have many industrial and laboratory applications as solid catalysts, filters, adsorbents, and gas separators due to movement. Silica fume is a highly reactive pozzolan that, by replacing 7 to 10% with cement weight in concrete, can improves the compressive strength, bond strength, and abrasion resistance (Qureshi and Barbhuiya 2016). Dalvand et al. (2014) studied the properties of silica fume on impact strength of different concretes. Ahmadi and Shekarchi (2010) obtained the test result of water absorption, slump, compressive strength at 90 days, oxygen penetration, chloride diffusion, and electrical resistance of concrete. Utilization of natural pozzolan improves workability and reduces water absorption and porosity of concrete (Zeyad and Almalki 2021). Although the portion replacement of zeolite with cement reduced the slump of concrete and needed more water, by using a superplasticizer, it was possible to produce concrete with high strength (80 MPa) and suitable slump (18 cm) by replacing 10% zeolite (Najimi et al. 2012). Deborah (2009) also examined the effect of modified zeolite. Perraki et al. (2010) studied the effects of zeolite in different parts of Greece and Thrace, where the amount of zeolite replacement was 10, 20, and 30% of cement weight, and performed various experiments on cement mortar. The result showed that zeolite had a good pozzolanic activity of 0.555 g of calcium hydroxide per gram of zeolite (according to Chapel experiments). Madandoust et al. (2013) studied the strength and durability properties of concrete containing zeolite and metkaolin using 20% replacement of zeolite and metakaolin pozzolans in mixed designs. In a study conducted in Hong Kong by Chan and Ji (1999), the effect of ground fly ash, silica fume, and zeolite on the compressive strength of concrete samples and compared with reference concrete samples made of ordinary Portland cement was investigated. It was observed that in all cases, the replacement of silica fume, zeolite, and fly ash increased the compressive strength of 28 days of concrete. Valipour et al. 2014investigated that 20% zeolite was an optimum replacement increased the compressive strength and durability of concrete, in addition contributes to the global warming index reduction compared to reference concrete. The optimum percentage of natural pozzolan replacement with cement in concrete is 20% (volcanic tuff) that improve the compressive strength of concrete (Ceylan 2021). Zeolite improved the water penetration, chloride ion penetration, drying shrinkage, and corrosion rate of concrete (Najimi et al. 2012). Zeolite replacement with cement in concrete showed lower water absorption value and has positive affected on compressive strength of concrete (Mohseni et al. 2017). By increasing the amount of silica fume in concrete as cement substitution, workability and autogenous shrinkage of concrete decreased but in short-term mechanical properties of concrete such as compressive and tensile strength increased (Mazloom et al. 2004). Incorporation of silica fume in concrete as a cement replacement increased the compressive and tensile strength of concrete and the result showed as well that the optimum replacement percentage of silica fume is not constant but it depends on water to cement ratio (Bhanja and Sengupta 2005). In an experimental study by Ashraf et al. (2022), 10% silica fume substitution with cement has positive impact on compressive strength and pore structures of concrete and enhance resistance against sulfate attack, as well as environmental analysis showed that this replacement reduced carbon emission 23%

Table 1 Chemical composition of cement types

Oxides	Percentage (%)		
	I- 525	I- 425	I- 325
CaO	62.9	62.11	63.5
SiO_2	21.3	20.1	20.90
Al_2O_3	4.7	4.12	4.5
Fe_2O_3	3.9	3.33	3.8
K_2O	0.5	0.92	0.45
MgO	2.9	3.09	2.7
MnO	0.21	0.2	0.22
P_2O_5	0.08	0.07	0.06
SrO	0.19	0.19	0.18
SO_3	2.1	2.46	2.0
L.O.I (loss on ignition)	1.7	3.5	1.5

Table 2 Chemical composition of zeolite

Oxides	Percentage (%)
CaO	1.53
SiO_2	68.33
Al_2O_3	10.98
Fe_2O_3	0.94
K_2O	1.6
MgO	1.15
Na_2O	2.37
SrO	0.15
SO_3	0.18

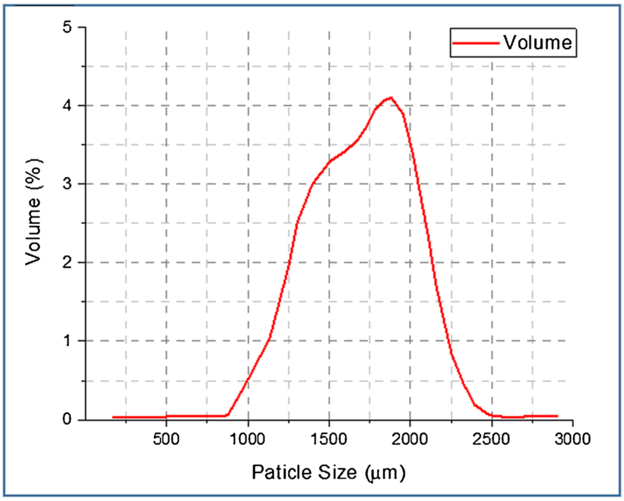


Fig. 1 Particle size distribution of zeolite based on PSA test

than the reference mix. Concrete containing 5% silica fume and 1.5% coir fiber improved the tensile strength and shear strength of samples 47% and 70%, respectively, than the reference mix (Ali et al. 2022).

Najimi et al. (2012) investigated the compressive strength of concrete cubic specimens (150 mm) with a water-to-cement ratio of 0.5, and the compressive strength decreased by increasing the amount of zeolite replacement compared to the reference specimens, but later on, this reduction decreased over time. Erfanimanesh and Sharbatdar (2020) investigated the mechanical and microstructural characteristics of geopolymer paste, mortar, and concrete containing local zeolite and slag activated by sodium carbonate. Ahmadi and Shekarchi (2010) showed that zeolite and silica fume reduced water absorption in concrete but with the increasing amount of silica fume water absorption has a downward trend. Also, the research by Madandoust et al. (2013) on the water penetration depth of concrete at 28 and 90 days showed that 20% replacement of zeolite and 20% replacement of metakaolin improved this parameter. In a study by Poon et al., using two water-to-cement ratios (0.25 and 0.30), the compressive strength of concrete containing zeolite at 3 and 7 days was slightly reduced. At the age of 28, 90, and 180 days, the compressive strength of the samples was almost equal to the reference samples (Poon et al. 1999). Vejmelkova et al. (2003) studied the mechanical properties of high-performance concrete containing 10, 20, 30, and 40% of cement replacement by zeolite. Najimi et al. (2012) investigated some mechanical properties and durability of concrete. They investigated the concretes containing partial replacement of 15 and 30% of zeolite and compared them with reference concrete. They obtained the results that zeolite effectively affected water penetration, chloride ion penetration, corrosion rate, and creep. Kushnir et al. (2021) investigated the durability of high-strength concrete containing natural zeolite using an accelerated corrosion method, and a pull-off test for rebar. According to the results, after 28 days, the highest compressive strength was achieved for the mix design containing 10% zeolite with water to cement ratios of 0.25 and 0.30. Still, in the rest of the mix designs, the compressive strength of samples decreased compared to the reference sample. Lotfi Eghlim et al. (2019) examined the effect of natural zeolite pozzolans on the mechanical, reliability, and structural properties of normal and high-strength concretes. With the increase of cement replacement by zeolite, the strength

Table 3 Particle size distribution of zeolite based on PSA test

Size (μm)	Volume (%)	Size (μm)	Volume (%)	Size (μm)	Volume (%)	Size (μm)	Volume (%)
0.105	0.00	1.096	0.95	11.482	3.41	120.228	0.80
0.120	0.00	1.259	1.14	13.183	3.51	138.038	0.59
0.138	0.00	1.445	1.39	15.136	3.62	158.489	0.42
0.158	0.00	1.660	1.67	17.378	3.73	181.970	0.28
0.182	0.00	1.905	1.96	19.953	3.83	208.930	0.18
0.209	0.00	2.188	2.24	22.909	3.90	239.883	0.11
0.240	0.00	2.512	2.48	26.303	3.92	275.423	0.06
0.275	0.00	2.884	2.68	30.200	3.86	316.228	0.01
0.316	0.00	3.311	2.84	34.674	3.73	363.078	0.00
0.363	0.00	3.602	2.96	39.811	3.51	416.869	0.00
0.417	0.08	4.385	3.05	45.709	3.21	478.630	0.00
0.479	0.20	5.012	3.11	54.481	2.86	549.541	0.00
0.550	0.34	5.754	3.17	60.256	2.47	630.957	0.00
0.631	0.46	6.607	3.21	69.183	2.08	724.436	0.00
0.724	0.57	7.586	3.24	79.433	1.70	831.764	0.00
0.832	0.67	8.710	3.29	91.201	1.36	954.993	0.00
0.955	0.80	10.000	3.34	104.713	1.06	1098.478	0.00
1.096		11.482		120.226		1258.925	

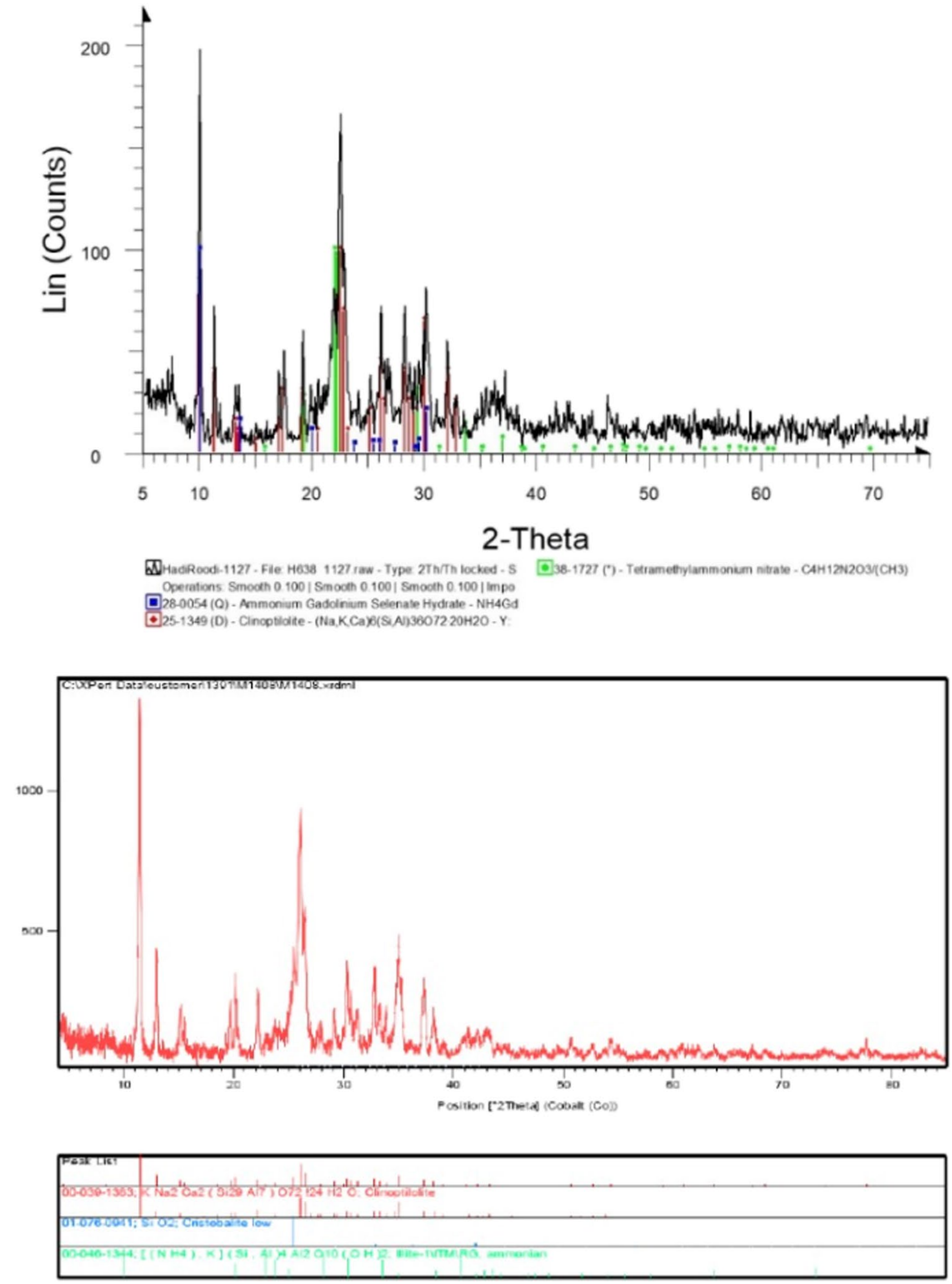


Fig. 2 Results of XRD test of zeolite

decreased with a uniform slope. Ramezanianpour (2014) studied the effect and role of zeolite pozzolans on the durability of concrete. The compressive strength of specimens containing different percentages of natural zeolite substitution increased by 8–10% compared to reference specimens after 28 days. In a study, Nafees et al. (2022) stated that when we use silica fume as a partial replacement of cement in concrete, the amount of cement and water is two governing parameters in developing the compressive strength of concrete. Substitution of zeolite with cement in concrete increased the strength and decreased the permeability compared to the reference samples (Lotfi Eghlim et al. 2019; Gowram and Beulah 2021).

The most of previous research was concentrated on replacing zeolite with ordinary cements with compression strength equal to 32.5 MPa (grade 32.5) to obtain the concrete mechanical strengths and other properties. The compressive strength of concretes containing ordinary cements (grade 32.5) and up to 20% zeolite replaced showed less than about 35 MPa as ordinary concrete. So far, no research was conducted to use zeolite with high strength grade cements (grades 42.5 and 52.5) to have two main characteristics sustainable concrete material plus to obtain higher compressive strength up to 50 MPa for specific structural applications to reduce the structure dimensions. In this experimental paper,

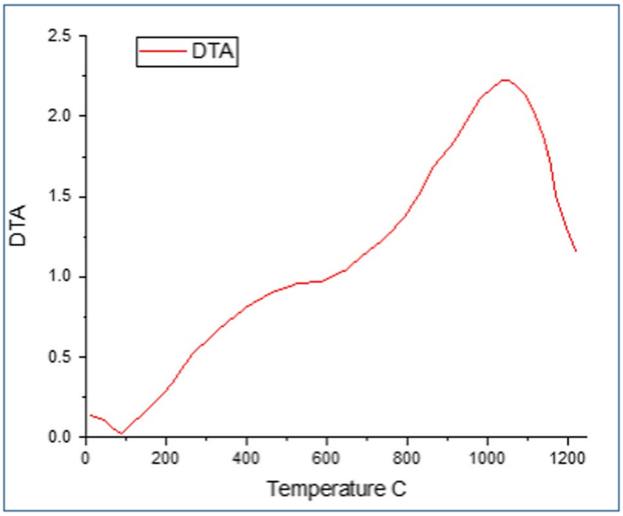


Fig. 3 Results of the DTA test of zeolite

zeolite as a natural pozzolan and silica fume as industrial waste with different percentages as partial replacement of cement were used to reduce the produced CO_2 in cement industry, and also high grade of Portland cement was used in concrete to help reducing the cement consumption and consequently reducing CO_2 and achieving high strength concretes.

Research method

Material

The types of cement used in this research were type 1 with three different grades of 32.5, 42.5, and 52.5 MPa. The chemical composition of three types of cement was determined by XRF spectroscopy analysis, and the results are shown in Table 1. By using the X-ray energy of the reflection or the wavelength, the values of the trace elements can be determined in parts per million PPM, and the principal oxides can be defined in terms of weight percentage. In addition, natural zeolite has been used and replaced with cement in mixed designs. XRF analysis of zeolite or chemical composition (clinoptilolite) is shown in Table 2, and the total weight percentage of Fe_2O_3, Al_2O_3, and SiO_2 is 80.25%.

As a result, according to (Standard ASTM C618 2008), this type of natural zeolite can be part of natural pozzolans, class N. Also, due to the high specific surface area and water absorption of this material, it can cause an increased weight loss due to heat (L.O.I). The value of L.O.I according to ASTM C 618 should be less than 10, where the applied temperature is up to 750 °C. This zeolite is calcined at a temperature of 1200°C. Therefore, for consumed zeolite, the value of L.O.I obtained was 12.78, which is an acceptable value. The most parts of zeolite are Sio_2 and Al_2O_3, and other compositions had the limited effects of the general behavior of zeolite. According to the results of the PSA test, the particle distribution size of zeolite was shown in Fig. 1 and Table 3, and the size of zeolite grains varied in a specific interval from 0.417 to 363.778 micrometers. In addition, more than 90% of the particles were between 1 and 100 microns in size. As a result, the porous between cement particles in the concrete can be filled by zeolite particles (filler role). Also, the porous of zeolite particles (1–100 microns) can be filled by silica fume particles that are smaller than zeolite particles. The results of the XRD test on natural zeolite are shown in Fig. 2.

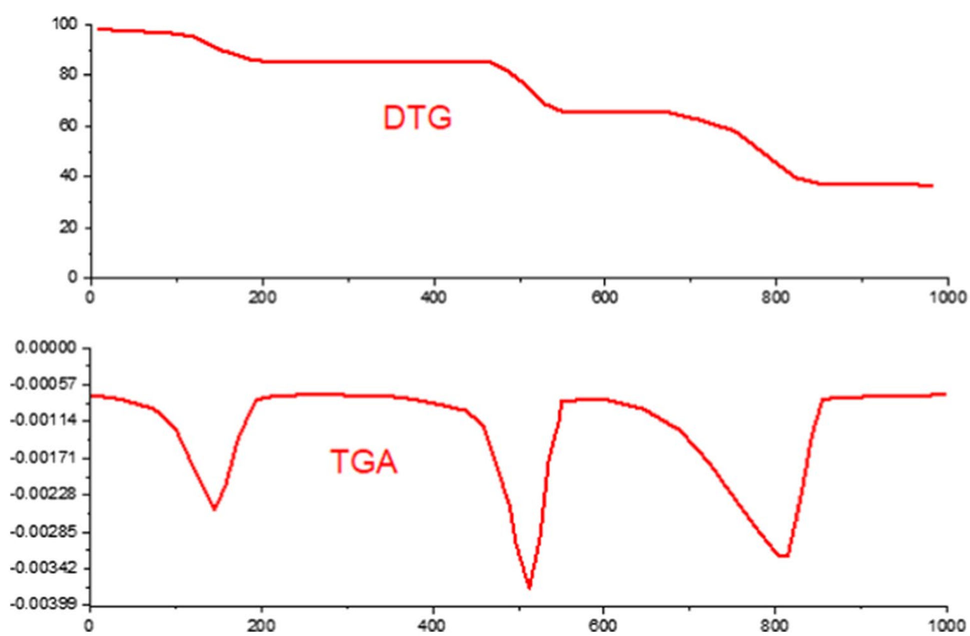


Fig. 4 Comparison between TGA graphs and DTG analysis results

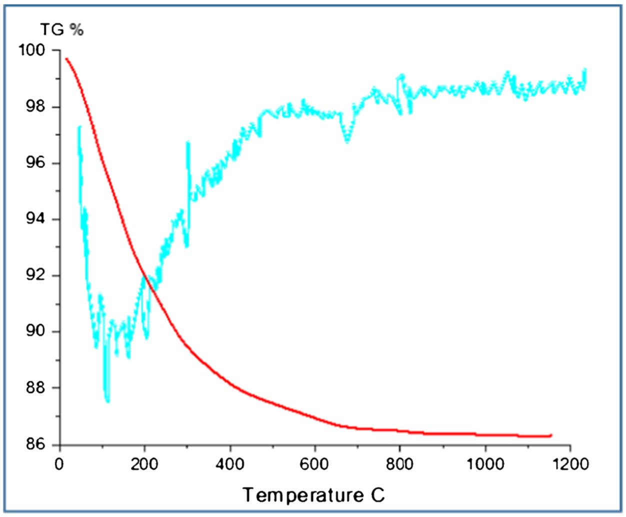


Fig. 5 Results of TGA and DTG experiments of zeolite

Figure 3 presents the DTA analysis of zeolite. The principle of this method is to measure the temperature difference between the reference sample and the target sample, although both samples are heated in the same thermal process. The sharp peak of the diagram can represent the type of thermal event that occurred. For example, we can see the crystalline structure and melting changes as sharp peaks, while chemical reactions and thermal decomposition as vast peaks.

From the surface of the below graph, helpful information can be obtained from the thermal interval, and the heat for the reaction can be calculated. According to Fig. 3, the change in the crystal structure in the tested zeolite is not visible. Because the DTA curve has no sharp peaks. The first temperature change was due to the gradual loss of water absorption. The second change occurs at a temperature of 1000 °C that is due to the outflow of molecular water from the zeolite structure. Figure 4 shows the results obtained from thermal gravimetric analysis (TGA); it is the simplest method of thermal analysis, which is based on measuring the weight of the sample during heating. This method provides excellent and helpful information when the material decomposes during heating or reacts with gasses around its environment. The thermal gravimetric analysis curve (physical changes of a material due to heat) can be used in two ways. One is to determine the temperature at the beginning and end of thermal analysis, and the other way is the amount of weight loss due to weight change in each stage written as a percentage. The vertical axis always represents the percentage change in weight and the horizontal axis represents the temperature on a degree Celsius scale.

The thermal weighing analysis is a technique that uses regular thermal changes to measure the mass changes of materials. Mass changes can be caused by various processes such as chemical composition changes, weathering, evaporation, sublimation, adsorption, desorption, reclamation, and oxidation. Among these processes, the most attention is paid to determining the thermal stability of materials and chemical composition, predicting the useful life of the material and evaluating the thermal kinetics, and the reactivity of materials with gasses.

According to Fig. 5, most weight loss is occurred at lower temperatures of 300 °C due to the evaporation of surface adsorption water and the conversion of a series of molecules into gas or vapor phases; for example, ammonium compounds (NH4), which are found in illite ores as a byproduct, are seen in zeolite analysis. This amount of weight loss is about 10%, which is approximately close to the calculated L.O.I. As a result, at higher temperatures, a significant amount of thermal weight loss in zeolite is not observed, which indicates the high purity of this pozzolan material. That means zeolite has retained its chemical and physical properties, has not changed to another material, and is generally a sign of the high stability of these pozzolans. In the TGA test, it will be difficult to separate the temperatures of two thermal accidences in the weight change curve in terms of temperature due to their proximity to each other.

Also, in thermal weighting curves, the temperature at the beginning and end of a thermal accidence cannot be readily determined. For these two reasons, by adding an electronic device to the thermal weighing device, the

Table 4 Coarse and fine aggregates specifications

Aggregate	Water absorption in SSD (%)
Gravel	0.8
Sand	2

Table 5 Cumulative percentage of passed aggregate as per Iranian national method of concrete mix design

Cumulative percentage of passed sand (national concrete mix design code)				
Maximum aggregate size (19 mm)				
Sieve #	Sieve (mm)	A19	B19	C19
3.4	19	100	100	100
5.8	12.5	83	84	90
3.8	9.5	62	75	84
4	4.75	38	55	70
8	2.38	23	40	56
16	1.19	14	27	43
30	0.6	8	18	31
50	0.3	4	11	20
100	0.15	1	5	10
Finesse modulus		5.5	4.69	3.86

Table 6 Sieve analysis of aggregate

Cumulative percentage of passed aggregate (national method of concrete mix design)						
Maximum aggregate size (19 mm)						
Sieve #	Sieve (mm)	Retained	Corrected retained	Absolute (%)	Cumulative retained (%)	Cumulative passed (%)
3.4	19	0	0	0	0	100
5.8	12.5	200	200	8.34	8.34	91.66
3.8	9.5	501	501	20.9	29.24	70.76
4	4.75	507	507	21.1	50.34	49.66
8	2.38	532	532	22.1	72.44	27.56
16	1.19	155	155	6.46	78.9	21.1
30	0.6	153	153	6.37	85.27	14.73
50	0.3	54	54 + 23	3.21	88.48	11.52
100	0.15	120	120	5	93.48	6.52
Pan		155	155	6.45	100	0
Total weight		2377	2400	100		
Finesse modulus		5.06				
Total weight		2400 gr				

derivative of the weight curve in terms of temperature can be drawn. This method is called derivative thermogravimetry (DTG). Figure 4 also presents the results obtained from the DTG and TGA analyses for the zeolite in this research.

In the sample in Fig. 5, the more the emitted wave is absorbed by the material, the lower the percentage of the transmitted wave to the receiver. On the other hand, if there is no wave absorption, all the transmitted waves on the sample will be completely transmitted to the receiver device. That means the curve will be a straight line.

Silica fume is a byproduct waste that was partially replaced as pozzolan with cement in this research. The aggregates specification and sieve analysis result are shown in Tables 4, 5, and 6 and Fig. 6 as per the (Iranian National Method of Concrete mix design (3th Edition) 2018). But by considering the same density for aggregate particles, the granulation curve can be calculated based on weight (Standard ASTM C136 2006). In this research, the granulation of the aggregate mix has been performed with and assuming 55% of sand and 45% of gravel, so the finesse modulus of 5.06 has been obtained for the whole mix. Urban potable water has been used for making samples.

Mix design

Generally, four mix designs of concrete in two categories of ordinary and high-strength are considered according to the national method of concrete mix design (third edition) and named D1, D2, D3, and D4. There are several sub-mix designs and each includes a reference mix design (without zeolite and silica fume) and several mix designs with different percentages of zeolite and silica

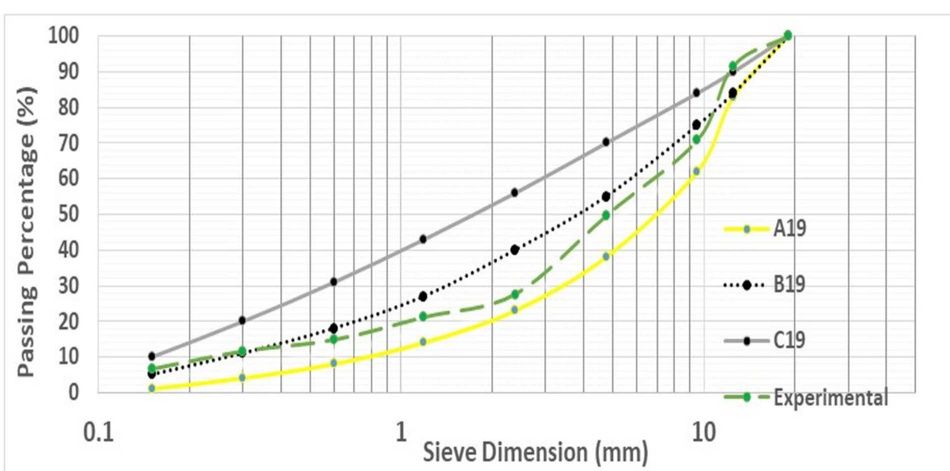


Fig. 6 Granulation curve of aggregates

Table 7 Mix design of concrete containing zeolite and silica fume (for 1 m^3)

Mix #	Mix ID	Compressive strength (MPa)	w/c	Cement type	Cement (kg)	Zeolite (%)	Zeolite (Kg)	Silica fume (%)	Silica fume (Kg)	Water (kg)	Aggregate (M3)	Aggregate (Kg)	Gravel (Kg)	Sand (Kg)
D1	D3300	35	0.4	1-325	490	0	0	0	0	210 + 23.6	0.62	1643	739.35	903.65
	D3310	35	0.4	1-325	441	10	49	0	0	210 + 24.15	0.614	1627.1	732.2	894.1
	D3320	35	0.4	1-325	392	20	98	0	0	210 + 23.05	0.607	1608.55	723.9	884.7
	D3330	35	0.4	1-325	343	30	147	0	0	210 + 22.9	0.6	1590	715.5	874.5
D2	D3400	35	0.5	1-425	400	0	0	0	0	201 + 25.1	0.66	1749	787.05	961.95
	D3410	35	0.5	1-425	360	10	40	0	0	201 + 24.75	0.65	1722.5	775.125	947.375
	D3420	35	0.5	1-425	320	20	80	0	0	201 + 24.9	0.6471	1714.8	771.66	943.14
	D3430	35	0.5	1-425	280	30	120	0	0	201 + 24.5	0.642	1701.3	765.6	935.8
D3	D5400	50	0.4	1-425	600	0	0	0	0	210 + 22.6	0.584	1547.6	696.5	851.2
	D5410	50	0.4	1-425	540	10	60	0	0	210 + 22.5	0.578	1532	689.4	842.6
	D5420	50	0.4	1-425	480	20	120	0	0	210 + 21	0.57	1510	680	831
	D5430	50	0.4	1-425	420	30	180	0	0	210 + 21.5	0.563	1492	671.5	821
	D5417	50	0.4	1-425	495	10	60	7.5	45	210 + 22	0.5573	1477	664.5	812.5
	D5427	50	0.4	1-425	435	20	120	7.5	45	210 + 21.5	0.564	1495	673	822
	D5437	50	0.4	1-425	375	30	180	7.5	45	210 + 21	0.556	1473	663	811
	D5407	50	0.4	1-425	555	0	0	7.5	45	210 + 22	0.58	1537	692	846
D4	D5500	50	0.4	1-525	525	0	0	0	0	215 + 24	0.605	1603.5	721.5	882
	D5510	50	0.4	1-525	472.5	10	52.5	0	0	215 + 23	0.6	1590	715.5	874.5
	D5520	50	0.4	1-525	420	20	105	0	0	215 + 23	0.59	1567	705	862
	D5530	50	0.4	1-525	367.5	30	157.5	0	0	215 + 22.1	0.584	1548	697	852
	D5517	50	0.4	1-525	433.13	10	52.5	7.5	39.4	215 + 22.8	0.592	1569	706	863
	D5527	50	0.4	1-525	380.6	20	105	7.5	39.4	215 + 22	0.584	1548	696.5	852
	D5537	50	0.4	1-525	328.13	30	157.5	7.5	39.4	215 + 22.3	0.578	1532	689.3	842.5
	D5507	50	0.4	1-525	485.6	0	0	7.5	39.4	215 + 23	0.6	1590	715.5	874.5

Table 8 Comparison of compressive strengths of mix design (D1) containing zeolite and type 1-325 cement after 28, 56, and 90 days

Mix ID	Zeolite (%)	Compressive strength 28 days (MPa)	Compressive strength 56 days (MPa)	Compressive strength 90 days (MPa)	Compressive strength ratio 56 to 28 days	Compressive strength ratio 90 to 28 days	Increase/decrease than reference (%) 28 days	Increase/decrease than reference (%) 56 days	Increase/decrease than reference (%) 90 days
D3300	0	47.04	52.17	54	1.11	1.14	0	0	0
D3310	10	49.75	58.26	59	1.17	1.19	5.76	11.67	12.6
D3320	20	45.4	54.25	58	1.195	1.28	-3.49	3.38	-10
D33300	30	45.07	46.84	51	1.04	1.13	-4.34	-10.2	-5

fume as a replacement for cement. The mix design for 35 and 50 MPa has been calculated, using the tables, formula, and proportion of material for concrete. The step-by-step method of concrete mix design calculation of targeted strength is described below to be a reference for researchers who want to work further to expand the research. According to Iranian National Standard No. 302, the aggregate with a maximum size of 19 mm has been selected and used in this study. Based on the Iranian Concrete code and determining the quality level of concrete production on-site, the ranking of the site is (A) category, the standard deviation the concrete with compressive strength of 50 MPa was estimated equal to 5 MPa. Equation (1) has been used to calculate the target compressive strength, which is 56.65 MPa.

$$f'_{cr} = f'_{c} + 1.34\ s$$
$$f'_{cr} = 0.9 * f'_{c} + 2.33\ s \quad (1)$$

f'_{cr} is the targeted compressive strength (MPa), f'_{c} is the initial compressive strength (MPa), and S is the standard deviation.

Due to the limitation of the maximum nominal size of aggregates, the largest aggregate size of 19 mm was selected and the softness modulus was considered to be 5.06. Based on the relevant table, cement grade (type I-425), targeted compressive strength, and aggregates shape (round or crushed), the water to cement ratio was selected as 0.35. Free water, which is the amount of water needed to hydrate the cement selected according to aggregates in saturated surface dry (SSD) case, the amount of cement in one cubic meter (350 kg), and slump of concrete (70 mm), calculated 195 kg/m^3. For cement, more than 350 kg/m^3, for every 10 kg of cement, 1 to 2 kg of more water should be added to the concrete matrix and the amount of cement must be calculated again. According to the amount of free water and the ratio of water to cement, the amount of cement in kilograms per cubic meter was obtained at 557 kg. so the amount of modified free water is equal to 210 kg, with cement equivalent to 600 kg. Assuming 1.5% for unintentional air volume, the density of cement 1-425, and free water the amount of saturated surface dry aggregate (SSD) volume is 0.584 cubic meters. Considering the density of aggregates of 2650 kg/m^3 and the percentage of sand and gravel of 55 and 45% respectively, so, the volume of aggregates in a saturated state can be obtained in kg/m^3. By considering the percentage of water absorption of sand and gravel, the amount of total water was 230 kg. In Table 7, all mix designs with compressive strength, water to cement ratio, type and amounts of cement, zeolite, silica fume, water, and aggregates for one cubic meter of concrete are calculated. The name of mix designs from left to right is based on the compressive

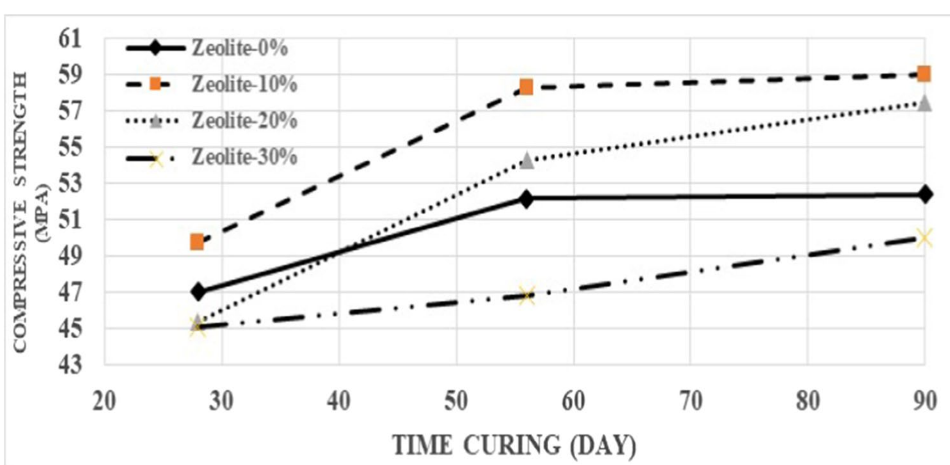


Fig. 7 Posture of increment of compressive strength of mix design (D1) containing zeolite and cement type 1-325 after 28 to 90 days

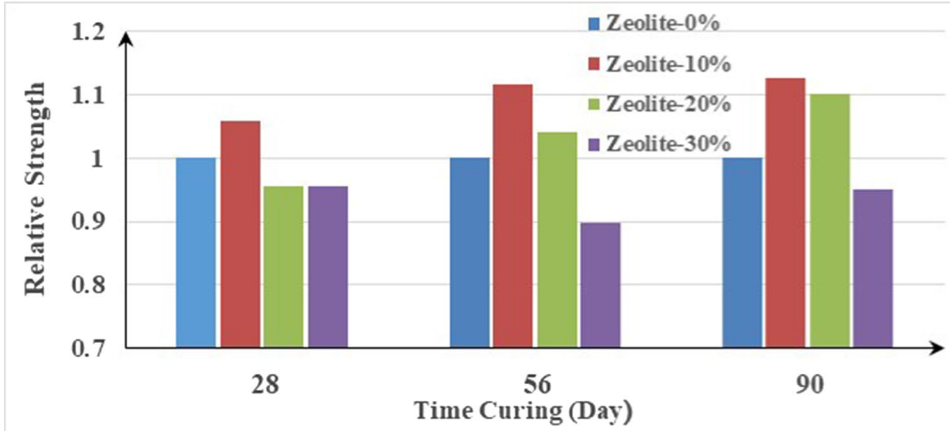


Fig. 8 Changes in relative compressive strength of mix design (D1) samples containing zeolite and cement type 1-325 compared to the reference sample after 28, 56, and 90 days

strength, type of cement, and the percentage of zeolite and silica fume. For example, D5427, the first number after D, which was 5, stands for 50 MPa; the second number, which was 4, stands for type cement I-425; the third number, which was 2, stands for 20% zeolite; and the fourth number, which was 7, stands for 7.5% silica fume.

Samples and experiments

For each mix design, the 100×100×100 mm cubes and 100×200 mm cylindrical samples were used, after 28, 56, and 91 days of curing in normal conditions, and after surface drying, their weight and dimensions were measured according to EN 12390-3 and ASTM C496 standard the compressive and tensile strength of samples were tested, respectively.

Results

Compressive strength

The compressive strength of concrete samples containing pozzolanic materials depends on various factors such as age and percentage of pozzolanic replacement. At an early age, the diluting effect of pozzolan can usually reduce the strength of concrete. The filling effect of a pozzolan can increase the compressive strength of concrete. At late ages, the decrease in strength can be due to the low performance of the desired pozzolan in concrete and the increase in strength can also be seen due to the development of the hydration process and secondary increment of C-H-S gel.

To obtain the average compressive strength for each mix design at any given time, three samples were tested and the results of the average values are given. The results of the D1 mix design which contained 10, 20, and 30% of zeolite and cement type I-325 are shown in Table 8 and Fig. 7. The 28, 56, and 90 days' compressive strength of these samples have been compared with reference and the percentage of increment of each sample contained zeolite at any age was calculated. In addition, Fig. 8 shows the increase of compressive strength of the D1 mix design, at the age of 28 to 56 days; D3310 and D3320 samples, which contained 10 and 20% zeolite, respectively, had the highest strength of than reference sample. D3310 and the reference samples experienced a slow increment of strength in 56 to 90 days, which indicates a relative decrease in the compressive strength growth rate than 28 to 56 days. Still D3320 sample from 56 to 90 days had a better strength growth rate than D3310 and reference samples, which indicates that the speed of

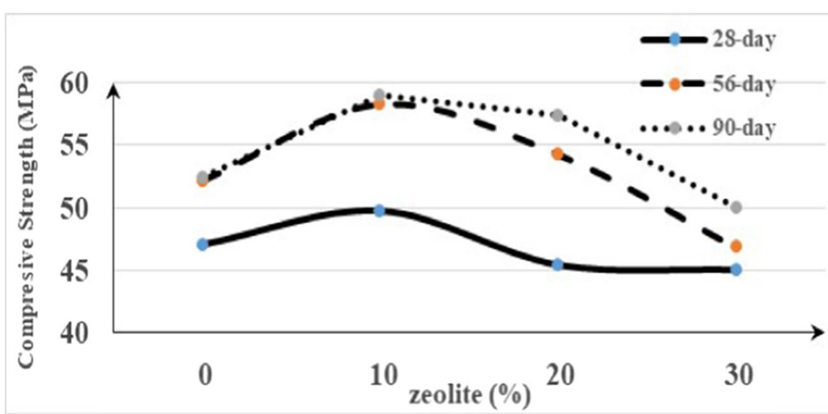


Fig. 9 Comparison of compressive strength of (D1) samples containing zeolite and cement I-325 with compressive strength of 35 MPa at different ages

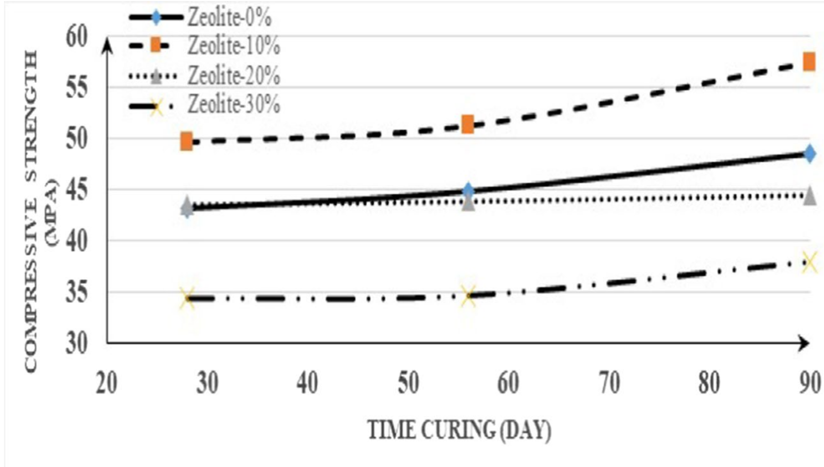


Fig. 10 Posture of compressive strength increment of the mix (D2) containing zeolite and cement type I-425 after 28 to 90 days

increasing the strength of samples was higher than the reference sample.

It was also observed that after 28 days, the samples containing 10% zeolite showed more compressive strength than the reference sample. After 56 and 90 days, both samples containing 10 and 20% zeolite had better strength than the reference sample. By the way, samples containing 10% zeolite had higher compressive strength than the reference and samples containing 20% zeolite. The changes in compressive strength of each sample at any age compared to the reference sample of mix design (D1) are shown in Fig. 9.

Based on the results obtained in Fig. 10, the 28-day compressive strength of the sample containing 10% zeolite had a strength of 5.76% compared to the compressive strength of the reference sample. Still samples with 20 and 30% zeolite replacement decreased the compressive strength. The compressive strength of the 56 days of samples with 10% and 20% zeolite increased by about 11.67 and 3.98%, respectively, compared to the reference sample, but for the sample with 30% zeolite, the compressive strength was still less than the reference sample. After 90 days, the concrete samples containing 10% zeolite have gained the highest strength, followed by the concrete sample containing 20% zeolite. The sample containing 10 and 20% zeolite had a compressive strength growth rate of about 11.67 and 10% compared to the reference samples respectively, but the sample containing 30% zeolite had a 5% decrease compared to the reference samples. Therefore, the concrete with a compressive strength of 35 MPa and using type I-325 cement (low strength) the maximum replacement of natural zeolite can be 20%. The results of (D2) mix design similar to (D1) but with cement type 1-425 are given in Table 9 and Figs. 10, 11 and 12. The compressive strengths at 28, 56, and 90 days were compared with reference samples, and the percentage of increment of each mix design has been calculated as well.

The results showed that the mix design containing 10% zeolite after 28 and 56 days had the same compressive strength compared to the reference sample, and after 90 days, the compressive strength of samples increased more than 28 and 56 days. This indicates the development of the pozzolanic reaction. Still the sample containing 20% zeolite after 28 and 56 days, the compressive strength was equal to the reference sample, but after 90 days, the compressive strength of the sample was much lower than the reference sample. The sample containing 30% zeolite decreased the compressive strength of the concrete than the reference sample in any age. The compressive strength of the sample containing 10 and 20% zeolite after 28 days increased by 15 and 0.7% compared to the compressive strength of the reference sample, respectively, and the sample containing 30% zeolite decreased the compressive strength by 20% than the reference samples.

Table 9 Comparison of compressive strengths of mix design (D2) containing zeolite and cement type I-425 after 28, 56, and 90 days

Mix ID	Zeolite (%)	Compressive strength 28 days (MPa)	Compressive strength 56 days (MPa)	Compressive strength 90 days (MPa)	Compressive strength ratio 56 to 28 days	Compressive strength ratio 90 to 28 days	Increase/decrease than reference (%) 28 days	Increase/decrease than reference (%) 56 days	Increase/decrease than reference (%) 90 days
D3400	0	43.2	44.9	48.6	1.04	1.125	0	0	0
D3410	10	49.7	51.2	57.4	1.03	1.16	15	14.3	18
D3420	20	43.5	43.85	44.5	1.008	1.023	0.7	-2	-8
D3430	30	34.4	34.67	37.91	1.009	1.102	-20.4	-22	-22

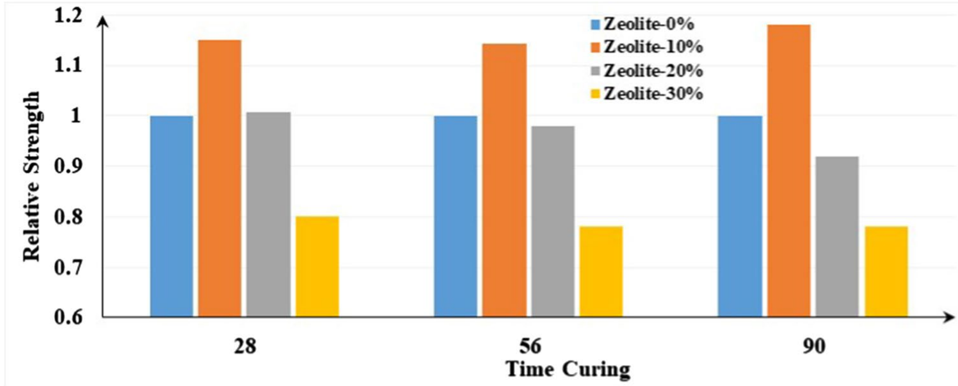


Fig. 11 Changes in relative compressive strength of mix (D2) containing zeolite and cement type I-425 compared to the reference sample after 28, 56, and 90 days

The compressive strength of samples after 56 days with 10% zeolite compared to the reference sample increased by 14.3% and samples with 20 and 30% zeolite decreased the strength of samples 2 and 20%, respectively. The compressive strength of samples containing 10% zeolite after 90 days increased by about 18%, compared to the reference sample and samples with 20 and 30% zeolite decreased by 8 and 22%, respectively, compared to the reference sample. The D3 and D4 mix designs were considered the same as D1 and D2 mix designs with different cement types, I-425 and I-525, to achieve high strength concrete with compressive strength of 50 MPa. The results of the compressive strength of the D3 mix (containing 10, 20, and 30% of zeolite and 7.5% silica fume) after 28, 56, and 90 days are given in Table 10 and Figs. 13, 14 and 15.

The results showed that the sample containing 10% zeolite after 56 days had good compressive strength compared to its 28 days, but after 90 days, the compressive strength decreased compared to 56 days. In any case, the compressive strength was less than the reference sample. The sample containing 20% zeolite after 28 days it had a much lower compressive strength than the reference sample, but after 56 days compared to its 28 days, had better compressive strength, and the compressive strength after 56 days was equal to the reference sample. This strength was increased slightly from 56 to 90 days of curing compared to the reference sample. As well as, the sample containing 10% zeolite and 7.5% silica fume had a significant compressive strength from 28 to 90 days; at an early age, the compressive strength was the same as the reference sample, but, over the time, it increased than the reference sample. The sample containing 20% zeolite and 7.5% silica fume had a slight increase in the early days but over the time from 56 to 90 days, became approximately equal to the reference samples. Therefore, the replacement compound of 10% zeolite and 7.5% silica fume with cement type I-425 was the optimum replacement for high-strength concrete. It was observed that after 28 days, D3 samples containing zeolite with 10, 20, and 30% achieved lower compressive strength than the reference sample. This is due to the zeolite's slow hydration compared to cement, and mostly, zeolite played the filler role in concrete. Meanwhile, the sample containing 7.5% zeolite has achieved much higher compressive strength than the reference sample. Indeed, it has increased compressive strength by 11.5% compared to the reference sample. Also, the samples containing 10 and 20% zeolite with 7.5% silica fume achieved a compressive strength almost equal to that of the reference sample, and

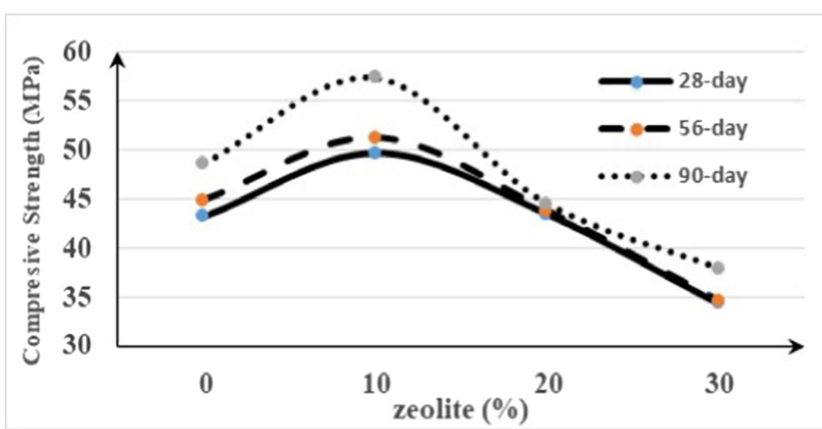


Fig. 12 Comparison of compressive strength of mix design (D2) samples containing zeolite and cement type I-425 with compressive strength of 35 MPa in different ages

Table 10 Comparison of compressive strengths of mix design (D3) containing zeolite and silica fume with cement type I-425 after 28, 56, and 90 days

Mix ID	Zeolite (%)	Silica fume (%)	Compressive strength 28 days (MPa)	Compressive strength 56 days (MPa)	Compressive strength 90 days (MPa)	Compressive strength ratio 56 to 28 days	Compressive strength ratio 90 to 28 days	Increase/decrease than reference (%) 28 days	Increase/decrease than reference (%) 56 days	Increase/decrease than reference (%) 90 day
D5400	0	0	58.3	61	63.5	1.05	1.09	0	0	0
D5410	10	0	48	57.33	58	1.2	1.21	-17.7	-6	-8
D5420	20	0	51	60	62	1.18	1.22	-12.5	-1.7	-2
D5430	30	0	48	46.3	50	1	1.04	-17.1	-24	-21
D5417	10	7.5	58	68.2	74	1.18	1.28	0	12	16.6
D5427	20	7.5	55.46	60.3	62	1.09	1.18	-4.8	-1	-2
D5437	30	7.5	47.5	52	52	1.1	1.1	-18.7	-15	-18
D5407	0	7.5	65	72.7	73	1.12	1.12	11.5	19	15

this is due to the high pozzolanic activity of the silica fume than zeolite, which partially compensates for the low activity of zeolite. It was observed that after 56 days, the compressive strength of the sample containing 10% zeolite was slightly less than the compressive strength of the reference sample. Still compressive strength of the sample containing 20% zeolite was almost equal to the reference, and this is due to pozzolanic activity of zeolite over time. In addition, the sample containing 30% zeolite has a much lower compressive strength than the reference sample.

The sample containing 7.5% silica fume due to high pozzolanic activity increased the compressive strength by about 20% compared to the reference sample. Samples containing 10% zeolite and 7.5% silica fume increased the compressive strength by 12% more than the reference samples. The samples containing 20% zeolite and 7.5% silica fume had less strength than the reference sample. It was also observed that after 90 days, the compressive strength of the sample containing 10% zeolite was less than the reference. Still compressive strength of the sample containing 20% zeolite was almost equal to the reference sample and the sample containing 30% zeolite had much lower compressive strength than the reference sample. The compressive strength results at 28, 56, and 90 days of mix design (D4) with the strength of 50 MPa (containing 10, 20, and 30% of zeolite and 7.5% silica fume replacement with cement type I-525) are summarized in Table 11 and Figs. 16, 17 and 18. The results of Table 11 and Figs. 17, 18 and 19 showed that the D4 sample containing 10% zeolite had a lower strength than the reference at 28 days, but over time, the difference in the strength of the samples and the reference decreased and after 56 days of curing, they had almost the same strength, but at the age of 90 days, the strength of samples was 4% less than the reference sample.

The compressive strength of samples containing 20 and 30% zeolite increased from 28 days to 90 days of curing but still was less than the reference samples. Samples containing 10 and 20% zeolite and 7.5% silica fume had good compressive strength than the reference sample after 28, 56, and 90 days of curing. The sample containing 30% zeolite and 7.5% silica fume had less compressive strength than the reference sample at all ages. Sample containing only 7.5% silica fume after 28 days of curing had better strength and increased over time. Indeed, the compressive strength of the sample after 56 and 90 days had higher strength than the reference. The reason for these events is the pozzolanic activity of silica fume and zeolite after 28 days. The consumption of free $Ca(OH)_2$ is due to the hydration of concrete matrix. After reaction with pozzolanic properties of silica fume and zeolite, secondary gel of CSH produced and the microstructure, and strength is improved and the resistance is increased. After 28 days of curing the D4 samples containing 10, 20, and 30% zeolite,

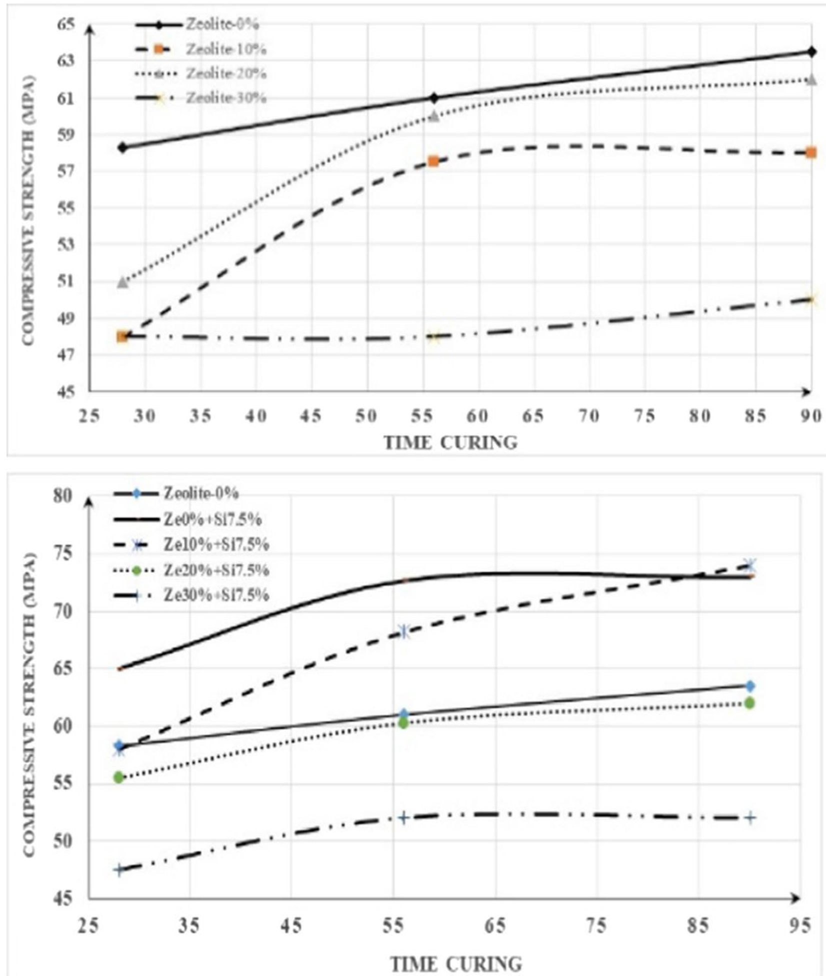


Fig. 13 Posture of increment of compressive strength of mix design (D3) containing zeolite and silica fume with cement type I-425 after 28 to 90 days

it was observed that these samples had lower compressive strength than the reference, which was due to the late activation of zeolite. For samples containing 10, 20, and 30% zeolite in the presence of 7.5% silica fume, they had a better strength growth rate, so the samples with 10 and 20% zeolite in the presence of 7.5% silica fume compared to the reference samples were 5 and 3.5 increased, respectively. In samples containing only 7.5% silica fume, the compressive strength increased 2% compared to the reference samples, and this was due to the high pozzolanic activity of silica fume. Samples containing 30% zeolite had a deficient compressive strength compared to the reference because 30% zeolite reduced the volume of cement in the concrete. This volume of cement replacement could not provide the target strength due to the late activation of zeolite.

It was observed that after 56 days, the compressive strength of the sample containing 10% zeolite was equal to the reference sample and the samples containing 20% and 30% zeolite had lower strength compared to the reference sample. Also, the compressive strength of samples containing 10 and 20% zeolite in presence of 7.5% silica fume was higher than the reference sample, which was due to the pozzolanic activity of zeolite and silica fume. The sample containing 7.5% of only silica fume had a significant compressive strength compared to the reference sample, which indicates the high pozzolanic activity of silica fume. After 90 days, samples containing 10% zeolite increased the compressive strength of samples 1.03 times compared to the reference sample. Figure 19 showed samples containing a combination of 10 and 20% zeolite and 7.5% silica fume and samples having only 7.5% silica fume, with higher compressive strength around 1.02, 1.03, and 1.07 time, respectively, compared to the reference sample.

Tensile strength (Brazilian method)

The tensile strength of each mixed design consists of two cylindrical specimens with a diameter of 100 mm and a height of 200 mm for 56 and 90 days were tested and the average strengths are given. First, the effect of different

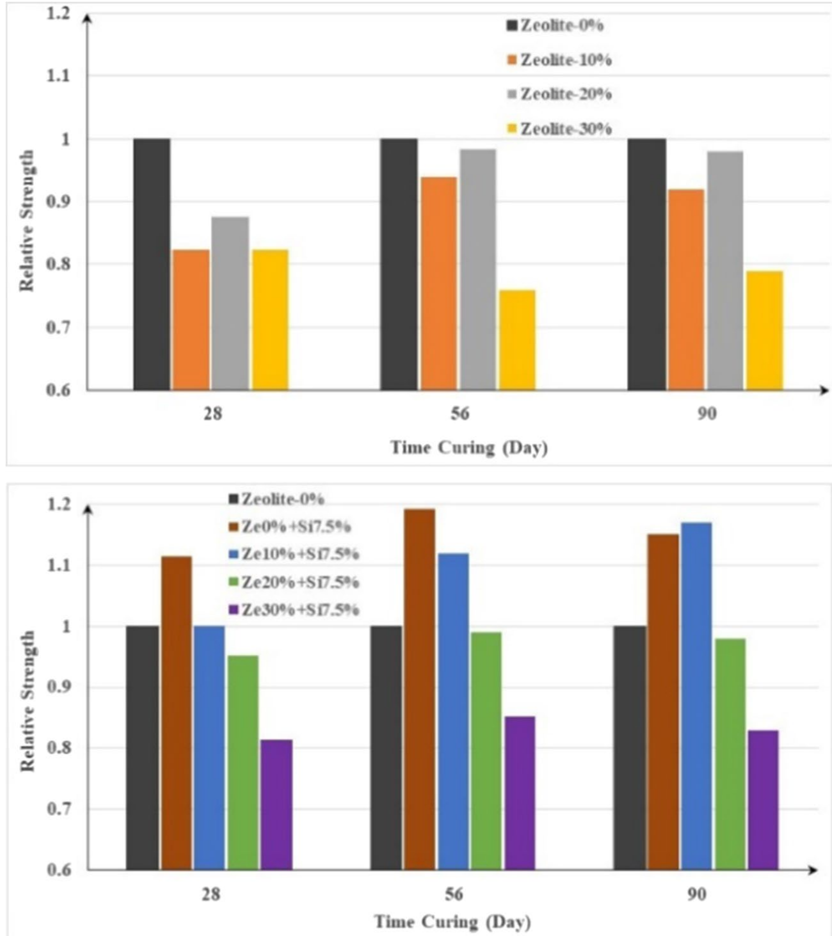


Fig. 14 Relative changes of compressive strength of mix design (D3) sample containing zeolite and silica and with cement type I-425 compared to the reference sample after 28, 56, and 90 days

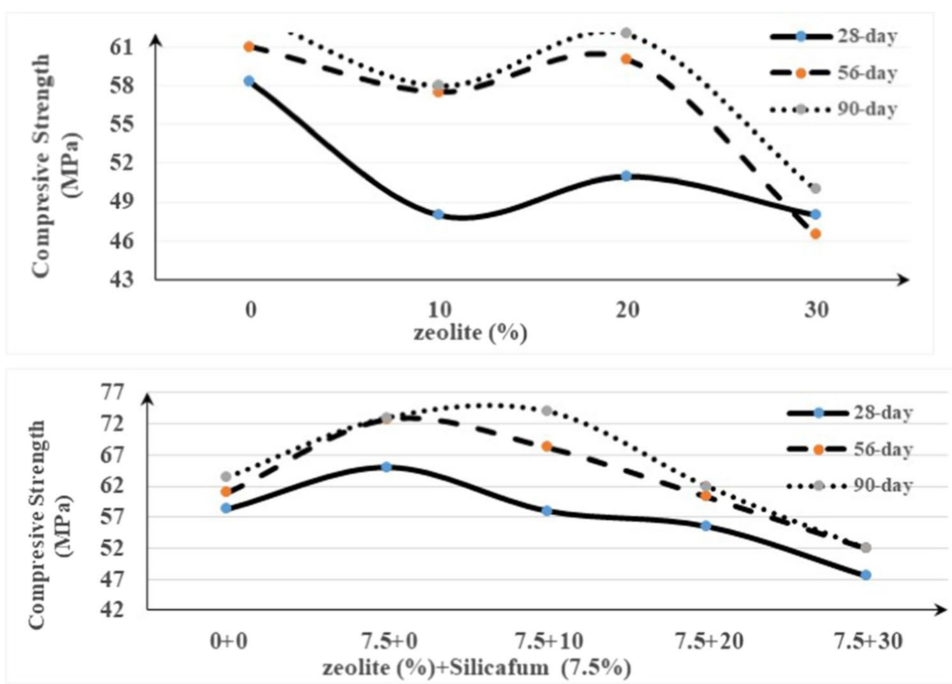


Fig. 15 Comparison of compressive strength of D3 design samples containing zeolite and silica fume (characteristic strength of 50 MPa with 1-425 cement (at different ages)

Table 11 Comparison of compressive strengths of mix design (D4) containing zeolite and silica fume with cement type I-525 after 28, 56, and 90 days

Mix ID	Zeolite (%)	Silica fume (%)	Compressive strength 28 days (MPa)	Compressive strength 56 days (MPa)	Compressive strength 90 days (MPa)	Compressive strength ratio 56 to 28 days	Compressive strength ratio 90 to 28 days	Increase/decrease than reference (%) 28 days	Increase/decrease than reference (%) 56 days	Increase/decrease than reference (%) 90 days
D5500	0	0	54	55.7	56.8	1.026	1.052	0	0	0
D5510	10	0	48.5	55.7	58.4	1.15	1.21	-11	0	3
D5520	20	0	46.4	50.66	54.4	1.092	1.17	-14	-9	-4
D5530	30	0	45.65	48.7	51.4	1.067	1.126	-15	-13	-9
D5517	10	7.5	65.41	56.85	58	1.008	1.03	5	2	2
D5527	20	7.5	56	57.6	58.4	1.03	1.043	3.7	3.4	3
D5537	30	7.5	49	51	51.7	1.041	1.06	-9	-8	-9
D5507	0	7.5	55	59	60.8	1.073	1.11	1.9	6	7

percentages of zeolite and the type of cement used on the mix designs D1 and D2 was investigated. The tensile strength results of the mix design D1 are given in Table 12 and Figs. 20, 21 and 22. From the results of Table 12 and Figs. 19, 20 and 21, it was observed that the samples containing 20% and 30% zeolite had lower tensile strength than the reference sample after 56-90 days of curing. The sample containing 10% zeolite after 56 days had lower tensile strength than the reference sample, but at 90 days gained much more strength almost 1.24 times than the reference sample.

In addition, the tensile strength of mix design D1 after 56 days, samples containing 10% zeolite had 13% less tensile strength than the reference samples. Also the samples containing 20 and 30% zeolite had almost the same tensile strength, but the tensile strength of this specimen was about 5% less than the reference sample. Cylindrical samples after 90 days, containing 10% zeolite, had increased 3.2% tensile strength compared to the reference sample, and samples containing 20 and 30% zeolite had almost the same tensile strength as the reference, and it was about 9% lower than the reference samples.

The tensile strength of mix design D2 is given in Table 13 and Figs. 22, 23 and 24. Observing the results of D2 mix design cylindrical specimens after 56 days of curing, containing 10 and 20% zeolite had 8.4 and 10% higher tensile strength than the reference specimen, respectively. Samples consisting of 30% zeolite decreased the tensile strength by about 6% compared to the reference specimen. According to the table (4-26) and figure (4-35) and observing the results of cylindrical samples of D2 mix design after 90 days, samples containing 10 and 20% zeolite had 23 and 10% higher tensile strength than the reference specimen, respectively. Samples consisting of 30% zeolite decreased the tensile strength by about 4% compared to the reference specimen.

It was also observed that the sample containing 10% zeolite had a tensile strength of 1.15 times higher than the reference sample from 56 to 90 days. The samples containing 20 and 30% zeolite had not developed the tensile strength from 56 to 90 days. However, the tensile strength of 20% zeolite was higher than the reference sample at any age, and the tensile strength of samples with 30% zeolite was less than the reference sample.

The tensile strength results of the D3 mix design are given in Table 14 and Figs. 25, 26 and 27. From the results shown in the table and related figures, it was observed that the sample containing 10 and 20% zeolite had higher strength than the reference from 56 to 90 days of curing and the percentage of increment was 41 and 1.14%, respectively. Samples containing 10 and 20% zeolite and 7.5% silica fume, from 56 to 90 days of curing, had higher strength than the reference sample.

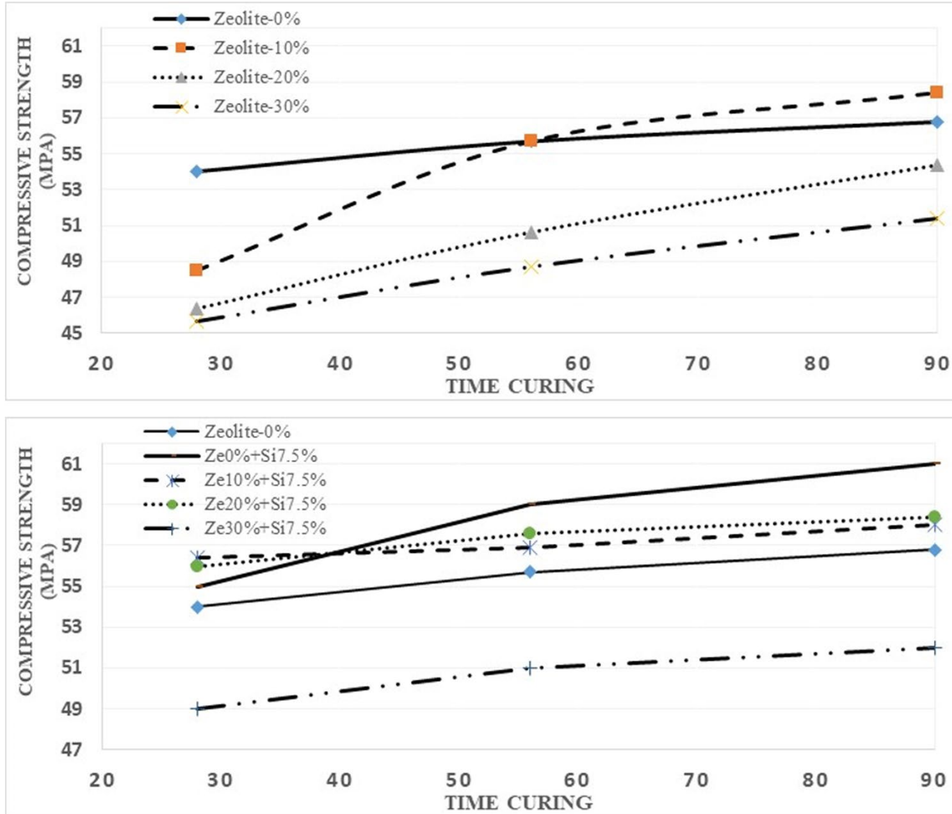


Fig. 16 Posture of increment of compressive strength of mix design (D4) containing zeolite and silica fume with cement type I-525 after 28 to 90 days

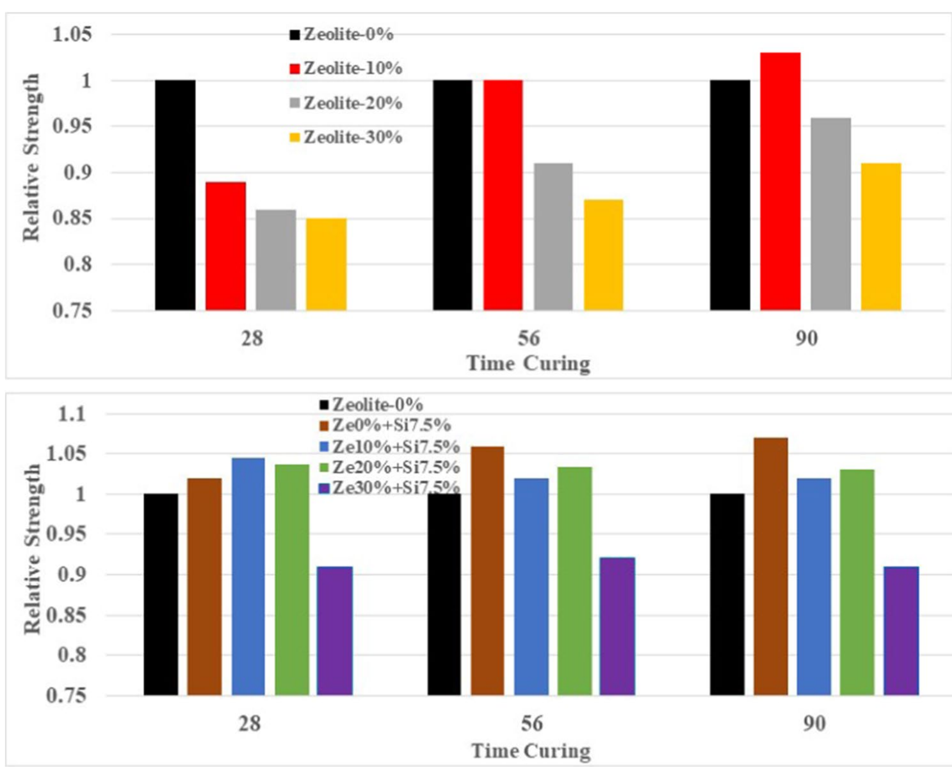


Fig. 17 Relative changes of compressive strength of mix design (D4) samples containing zeolite, and silica fume with cement type I-525 compared to the reference sample after 28, 56, and 90 days

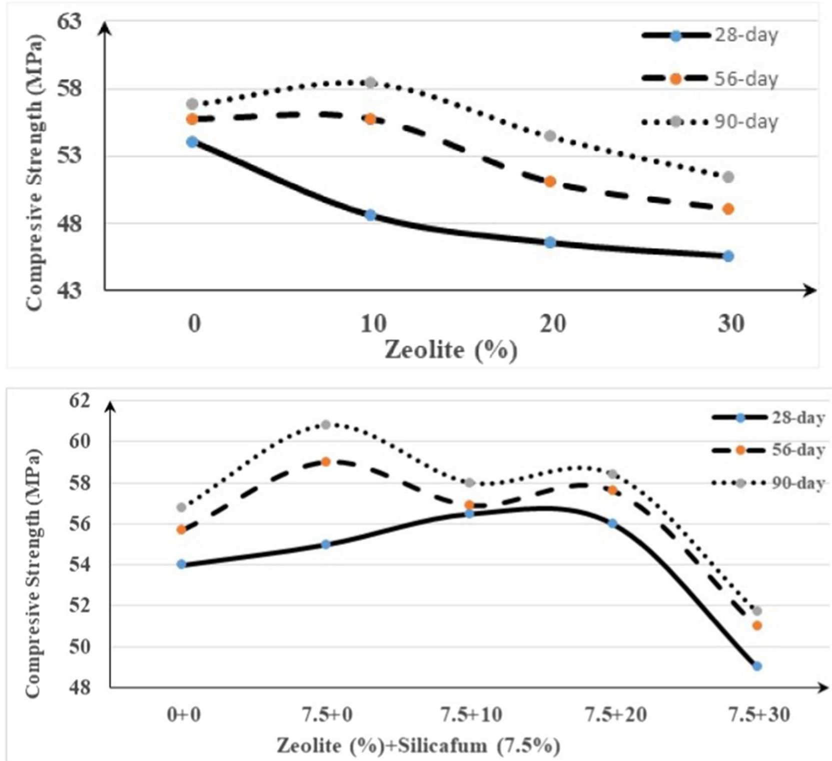


Fig. 18 Comparison of compressive strength of 50 MPa mix design (D4) samples containing zeolite and silica fume with cement type I-525 at different ages

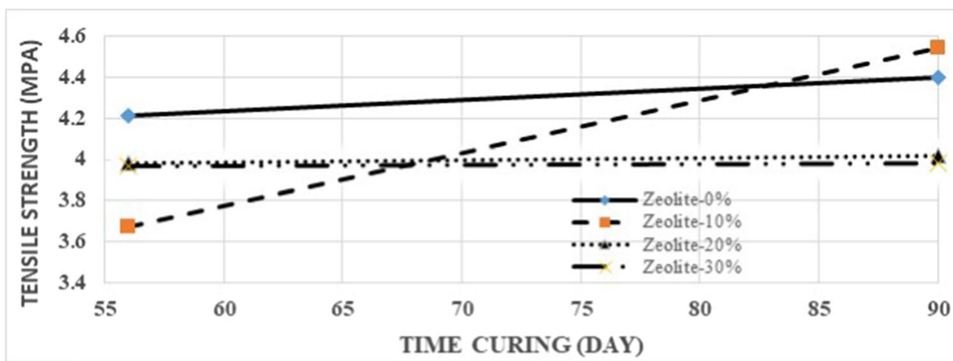


Fig. 19 Posture of increment of compressive strength of mix design (D1) after 56 to 90 days

Samples containing 10 and 30% zeolite had almost equal tensile strength and had 5% less strength than the reference samples. The sample containing 20% zeolite increased the tensile strength by 4.3% compared to the reference sample. The sample containing 10 and 20% zeolite and 7.5% silica fume and also the sample containing only 7.5% silica fume had higher tensile strengths of 7, 30, and 10% than the reference, respectively. It was also observed that samples

Table 12 Comparison of tensile strengths of mix design D1 with cement type I-325 after 56 and 90 days

Mix ID	Zeolite (%)	Tensile strength 56 days (MPa)	Tensile strength 90 days (MPa)	Ratio of 90/56 days	Increase/decrease than reference 56 days (%)	Increase/decrease than reference 90 days (%)
D3300	0	4.21	4.4	1.045	0	0
D3310	10	3.67	4/54	1.237	-13	3.2
D3320	20	3.97	4.02	1.01	-5	-8.6
D33300	30	3.97	3.98	1	-5	-9.5

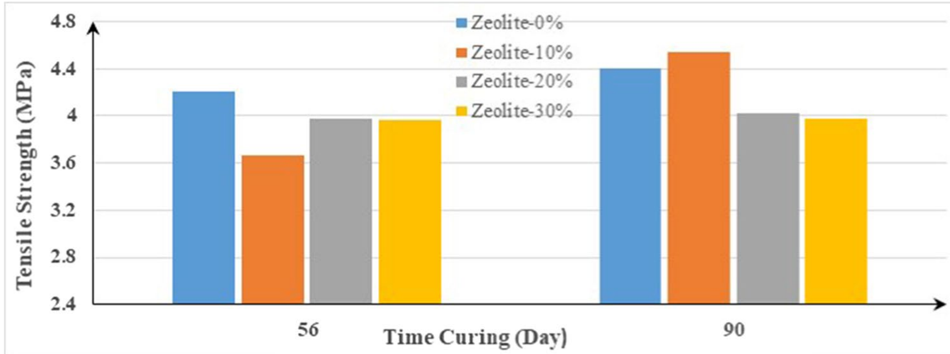


Fig. 20 Relative changes of tensile strength of mix design (D1) samples compared to the reference sample after 56 and 90 days

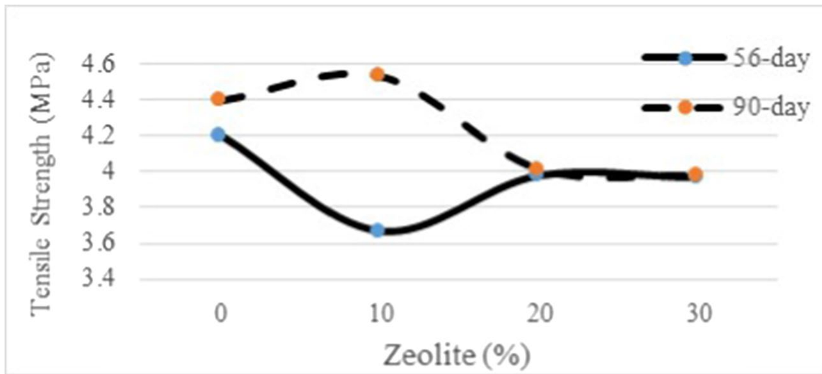


Fig. 21 Comparison of tensile strength of mix design (D1) samples at different ages

containing only 10 and 20% zeolite had higher tensile strengths of 23 and 11% than the reference samples, respectively. The tensile strength of the sample containing 30% zeolite was lower than the reference sample.

The tensile strength results of the D4 mix design are given in Table 15 and Figs. 28, 29 and 30. According to the results, samples containing 10 and 20% zeolite had the same strength and equal tensile strength from 56 to 90 days compared to the reference sample. The samples containing 20% zeolite increased the tensile strength by 3.4% than the reference samples, and the sample containing 30% of zeolite, although it had good strength from 56 to 90 days, in many cases after 56 to 90 days decreased the tensile strength by 23% than the reference samples. Also, the sample containing 10 and 20% zeolite and 7.5% silica fume after 56 days of curing had lower tensile strength than the reference sample, due to the strength after 90 days, the tensile strengths were higher than the tensile strength of the reference sample 3 and 28%, respectively. The sample containing 30% zeolite and 7.5% silica fume had a less strength growth from 56 to 90 days and had a lower tensile strength of 11% than the reference sample after 56 and 90 days, and the same way the samples containing 7.5% silica fume also had a slight strength growth from 56 to 90 days, but after 56 and 90 days,

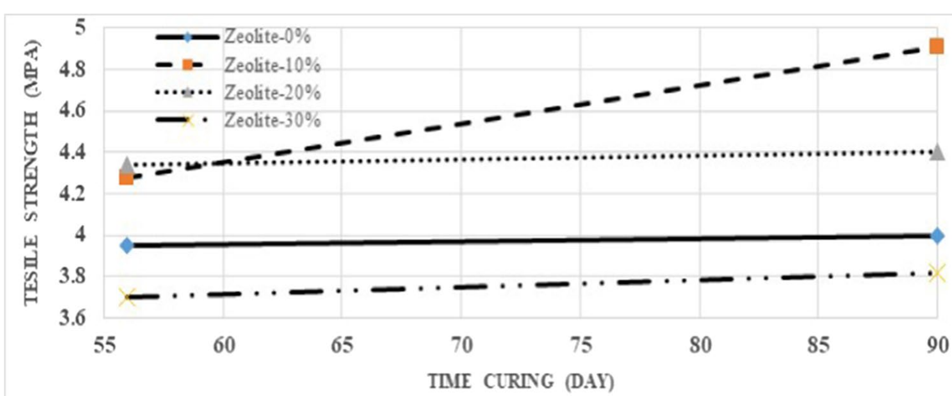


Fig. 22 Posture of increment of tensile strength of mix design (D2) from 56 to 90 days

Table 13 Comparison of tensile strengths of mix design D2 with cement type I-425 after 56 and 90 days

Mix ID	Zeolite (%)	Tensile strength 56 days (MPa)	Tensile strength 90 days (MPa)	Ratio of 90/56 days	Increase/decrease than reference 56 days (%)	Increase/decrease than reference 90 days (%)
D3400	0	3.95	4	1.013	0	0
D3410	10	4.28	4.91	1.15	8.4	23
D3420	20	4.34	4.4	1.014	10	10
D3430	30	3.7	3.82	1.032	-6	-4

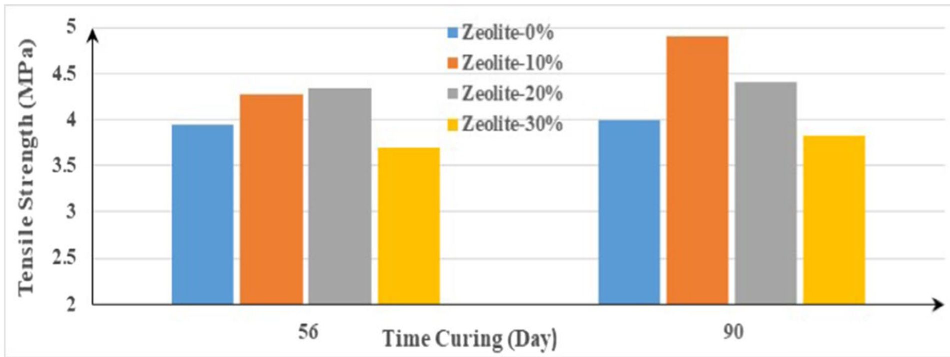


Fig. 23 Relative changes of tensile strength of mix design (D2) samples compared to the reference sample at 56 and 90 days

there was a positive and more minor difference between the tensile strength samples and the reference.

It was also observed that after 90 days, samples containing 10 and 20% zeolite had a tensile strength equal to the reference. Also, the sample containing 30% zeolite had an 8% lower tensile strength than the reference. The samples containing 10, 20, and 30% zeolite and 7.5% silica fume and samples containing only 7.5% silica fume increased the tensile strength by 14, 30, 11, and 16% compared to the reference sample, respectively.

The results of tensile strengths of four different mix designs (D1, D2, D3, and D4) particularly for optimum 20% zeolite show that some decreasing was observed at the 56-day age but the significant increasing or to be equal 56-day strength was observed for 90-day age samples, indicating the curing process of zeolite will be completed up to 90 day. Mix designs of D2 and D3 with 42.5 grade cement showed the better behavior under tensile strength and no decreasing or even increasing of tensile strength was observed for mixes with 10 and 20% zeolite. The adding silica fume was more effective to improve the tensile strength of mixes containing zeolite, and the improving up to 30% increasing was observed for mix designs D3 and D4 containing silica fume.

Formula between the compressive and tensile strength of mix designs

In the American Concrete Institution (ACI), the relationship between the compressive strength (f'_c) and the indirect tensile strength of concrete (f_t) is defined as $f_t = \gamma_c \sqrt{f'_c}$. According to (ACI 318-19 2019) and ACI 363, γ_c for ordinary and high-strength concretes is between 0.55 and 0.59. The relationship between compressive and tensile strengths is presented in Tables 16 and 17 for all mix designs

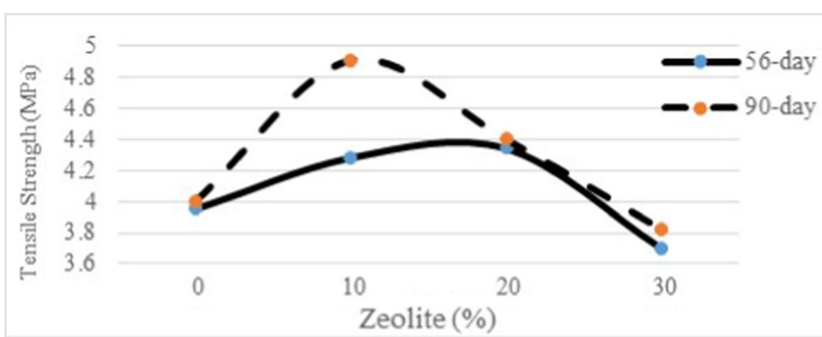


Fig. 24 Comparison of tensile strength of mix design (D2) samples at 56 and 90 days

Table 14 Comparison of tensile strengths of D3 with cement type I-425 after 56 and 90 days

Mix ID	Zeolite (%)	Silica fume (%)	Tensile strength 56 days (MPa)	Tensile strength 90 days (MPa)	Tensile strength ratio 90 to 56 days	Increase/decrease than reference (%) 56 days	Increase/decrease than reference (%) 90 days
D5400	0	0	4.15	4.46	1.075	0	0
D5410	10	0	3.9	5.5	1.41	-6	23
D5420	20	0	4.33	4.93	1.14	4.3	11
D5430	30	0	3.98	4.23	1.063	-4	-5
D5417	10	7	4.44	4.8	1.081	7	8
D5427	20	7	5.4	5.5	1.019	30	23
D5437	30	7	3.57	4	1.12	-14	-10
D5407	0	7	4.55	4.5	1	10	0

containing zeolite and silica fume in this study as $f_t = \gamma_i \sqrt{f'_c}$ and the value of γ_i is given for all mix designs. f'_c is the compressive strength of the cylindrical specimen and f_t is the Brazilian tensile strength. Compressive strength tests in this study were performed on 100 * 100 * 100 mm cubic specimens. The results of compressive strength were converted to the equivalent strength of a cylindrical specimen by dividing the sample strength of 100 * 100 * 100 mm by the 1.05. It becomes the compressive strength of 150 * 150 * 150 mm cubes and by subtracting 5 MPa from the cubic sample of 150 * 150 * 150 mm, the equivalent compressive strength of the cylindrical specimen (f'_c) is obtained. According to the results of Table 16, after 56 days of curing, with the addition of zeolite in mix design (D1) for all 10, 20, and 30% replacement percentages, the tensile strength was slightly reduced than the reference concrete. For mix design (D2), the addition of zeolite percentages increased the tensile strength of samples than the reference concrete. This increment was 12% for the sample containing 20% zeolite compared to the reference sample. In mix design (D3), the addition of 10% zeolite did not affect tensile strength compared to the reference, and the addition of 20 and 30% zeolite increased the strength by 6 and 13% compared to the reference concrete, respectively. Replacement of 20% zeolite along with 7.5% silica fume increased tensile strength by 30% more than the reference concrete. Finally, in mix design

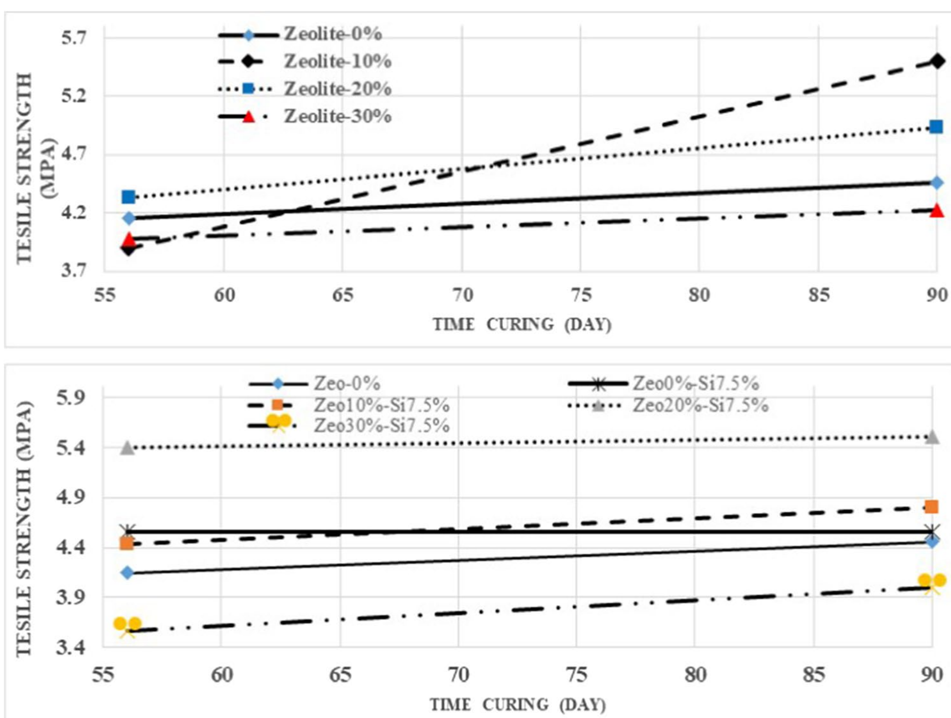


Fig. 25 Posture of increment of tensile strength of mix design (D3) from 28 to 90 days

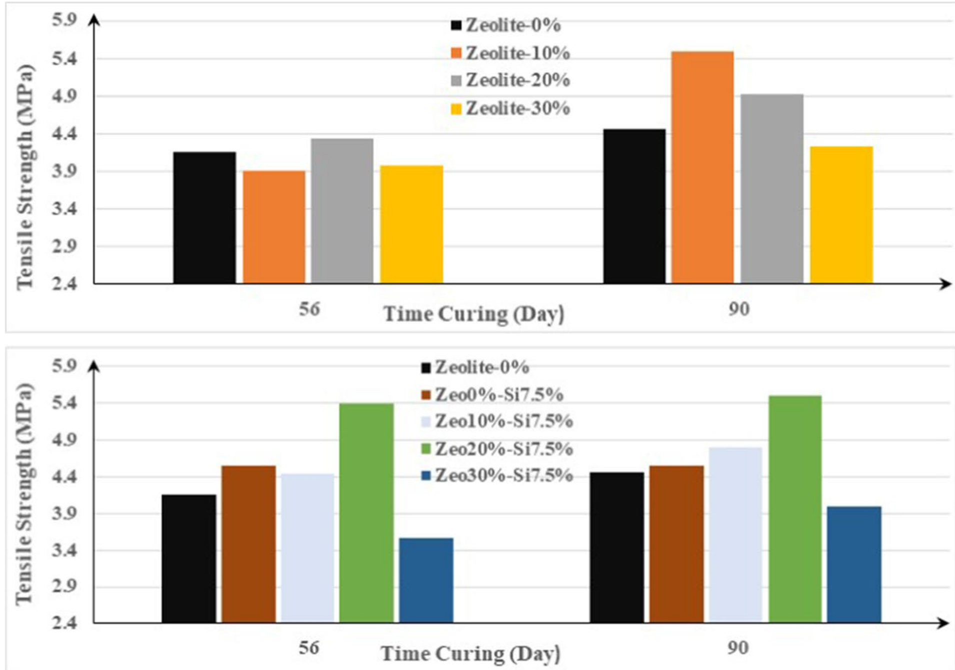


Fig. 26 Relative changes in tensile strength of mix design (D3) samples compared to the reference sample at 56 and 90 days

(D4), the addition of only zeolite has not affected the tensile strength of the samples, but the addition of different percentages of zeolite and silica fume increased the tensile strength so that the addition of 20 and 30% of zeolite and 7.5% of silica fume increased the strength 27% and 15% compared to the reference sample, respectively

According to the results of Table 17 after 90 days of curing, for mix design (D1), the addition of zeolite percentages did not increase the tensile strength of samples than the reference samples. In the mix design (D2), samples containing 10 and 20% zeolite increased the tensile strength of the samples 13 and 16% compared to the reference samples, respectively. Mix

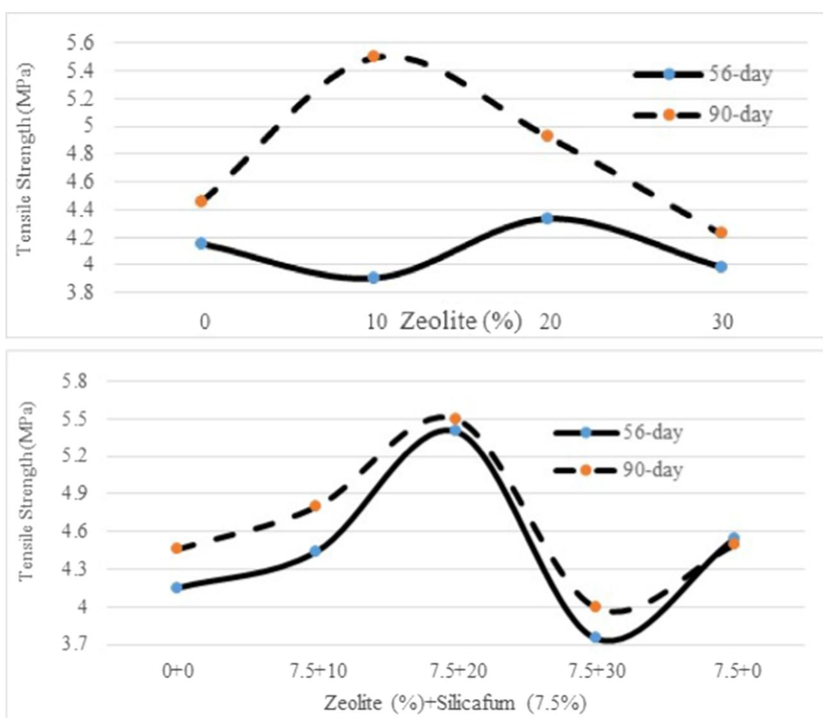


Fig. 27 Comparison of tensile strength of mix design (D3) samples at 56 and 90 days

Table 15 Comparison of tensile strengths of D4 with cement type I-525 after 56 and 90 days

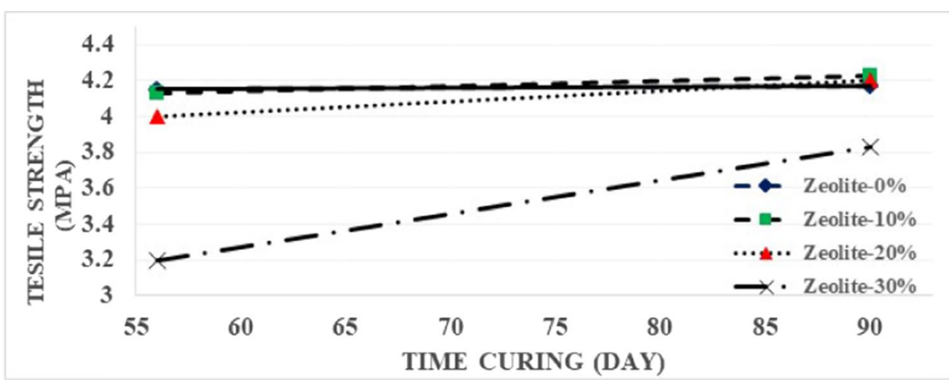
Mix ID	Zeolite (%)	Silica fume (%)	Tensile strength 56 days (MPa)	Tensile strength 90 days (MPa)	Tensile strength ratio 90 to 56 days	Increase/decrease than reference (%) 56 days	Increase/decrease than reference (%) 90 days
D5500	0	0	4.15	4.17	1.005	0	0
D5510	10	0	4.13	4.23	1.024	0	1.44
D5520	20	0	4	4.2	1.05	-3.6	0.7
D5530	30	0	3.2	3.83	1.20	-23	-8
D5517	10	7	4.27	4.76	1.115	3	14
D5527	20	7	5.2	5.42	1.02	28	30
D5537	30	7	4.58	4.62	1.009	10	11
D5507	0	7	4.63	4.82	1.043	11.6	16

design (D3), samples containing 10 and 20% zeolite increased the tensile strength of the samples by 30 and 12% compared to the reference samples, respectively, in the same way, the replacement of 20% zeolite and 7.5% silica fume increased the tensile strength of the samples 25% than the reference samples. Replacement of zeolite in mix design (D4) has not affected the tensile strength of concrete compared to the reference sample, but, compound replacement of 10, 20, and 30% of zeolite and 7.5% silica fume and 7.5% of only silica fume increased the tensile strength of concrete 13, 27, 15, and 10%, respectively, compared to the reference samples.

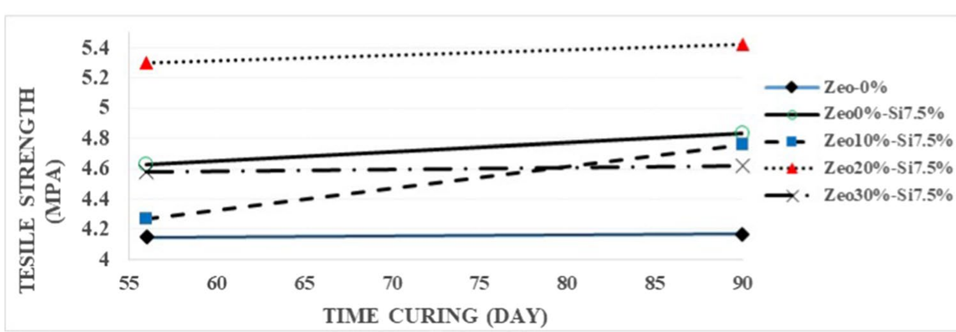
Proposed formula for compressive strength proportional to the time

Based on changes in compressive strength from 28 to 90 days shown for four mix designs in Section 3-1, the proposed formula for calculating the equivalent cylindrical compressive strengths of 56 and 90 days compared to 28 days is presented in Table 18. It should be noted that in these formulas, (f_c) represents the compressive stress of the equivalent cylindrical specimen, (t) represents the age of the specimens, the number after (z) indicates the

Fig. 28 Posture of increment of tensile strength of mix design (D4) from 56 to 90 days

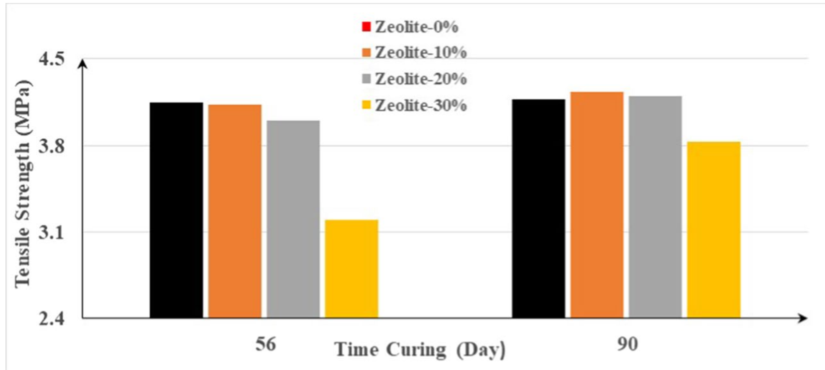


a) Only Zeolite

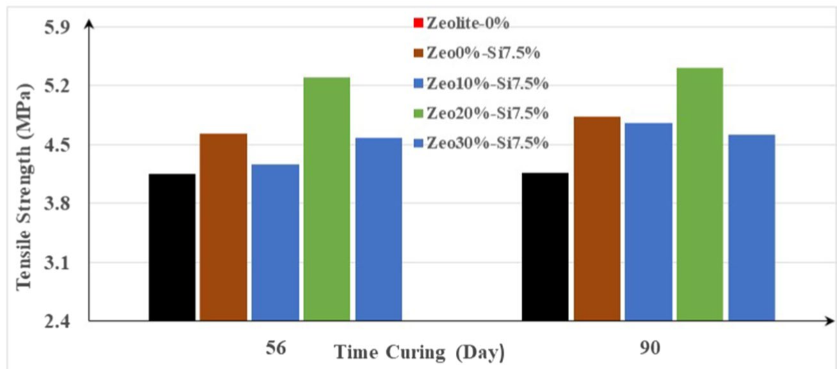


b) Zeolite and Silica Fume

Fig. 29 Relative changes of tensile strength of mix design (D4) samples compared to the reference after 56 and 90 days

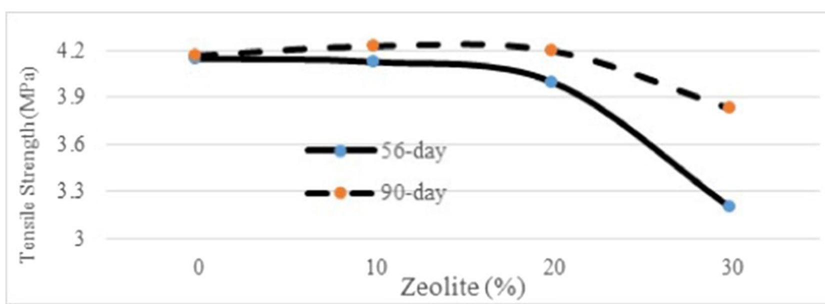


a) Only Zeolite

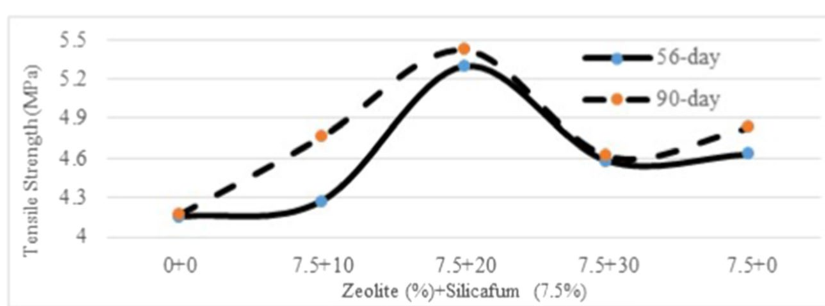


b) Zeolite and Silica Fume

Fig. 30 Comparison of tensile strength of D4 mix design samples after 56 and 90 days



a) Only Zeolite



b) Zeolite and Silica Fume

Table 16 Relationship between 56-days of compressive and tensile strength of mixed designs samples

Mix ID	Zeolite (%)	Silica fume (%)	Cement type	f'_{cu} (MPa)	f'_{c} (MPa)	$\sqrt{f'_c}$ (MPa)	f_t (MPa)	$\gamma_{i=}\frac{f_t}{\sqrt{f'_C}}$	$\frac{\gamma_i}{\gamma_{ref}}$
D3300	0	0	I-325	49.69	44.69	6.69	4.21	0.63	1
D3310	10	0	I-325	55.49	50.49	7.1	3.67	0.52	0.83
D3320	20	0	I-325	51.67	46.67	6.83	3.98	0.58	0.92
D3330	30	0	I-325	44.61	39.61	6.29	3.97	0.63	1
D3400	0	0	I-425	42.76	37.76	6.14	3.95	0.64	1
D3410	10	0	I-425	48.68	43.86	6.62	4.28	0.65	1.02
D3420	20	0	I-425	41.76	36.76	6.06	4.34	0.72	1.125
D3430	30	0	I-425	33.02	28.02	5.29	3.7	0.7	1.09
D5400	0	0	I-425	59	54	7.35	4.15	0.565	1
D5410	10	0	I-425	54.6	49.6	7.04	3.9	0.554	0.98
D5420	20	0	I-425	57.14	52.14	7.22	4.33	0.6	1.062
D5430	30	0	I-425	45	40	6.32	3.98	0.63	1. 12
D5417	10	7	I-425	65	60	7.75	4.44	0.573	1.01
D5427	20	7	I-425	57.43	52.43	7.24	5.4	0.75	1.33
D5437	30	7	I-425	49.5	44.5	6.67	3.57	0.535	0.95
D5407	0	7	I-425	69.2	64.2	8.01	4.55	0.568	1
D5500	0	0	I-525	53.05	48.05	6.93	4.15	0.6	1
D5510	10	0	I-525	53.05	48.05	6.93	4.13	0.6	1
D5520	20	0	I-525	48.25	43.25	6.58	4	0.61	1.017
D5530	30	0	I-525	46.4	41.4	6.43	3.2	0.5	0.84
D5517	10	7	I-525	54.14	49.14	7	4.27	0.61	1.017
D5527	20	7	I-525	54.86	49.86	7	5.3	0.76	1.27
D5537	30	7	I-525	48.57	43.57	6.6	4.58	0.69	1.15
D5507	0	7	I-525	56.19	51.19	7.15	4.63	0.65	1.08

Table 17 Relationship between 90-day compressive strength and tensile strength of samples for all mix designs

Mix ID	Zeolite (%)	Silica fume (%)	Cement type	f'_{cu} (MPa)	f'_{c} (MPa)	$\sqrt{f'_c}$ (MPa)	f_t (MPa)	$\gamma_{i=}\sqrt{\frac{f_t}{f'_C}}$	$\frac{\gamma_i}{\gamma_{ref}}$
D3300	0	0	I-325	49.9	44.9	6.7	4.4	0.65	1
D3310	10	0	I-325	56.2	51.2	7.16	4.54	0.64	0.97
D3320	20	0	I-325	56.7	51.7	7.2	4.02	0.56	0.87
D3330	30	0	I-325	54.7	49.7	7.05	3.98	0.56	0.93
D3400	0	0	I-425	46.3	41.3	6.43	4	0.62	1
D3410	10	0	I-425	54.7	49.7	7.05	4.91	0.7	1.13
D3420	20	0	I-425	42.4	37.4	6.12	4.4	0.72	1.16
D3430	30	0	I-425	36.1	34.4	5.87	3.82	0.65	1.05
D5400	0	0	I-425	60.48	55.48	7.45	4.46	0.6	1
D5410	10	0	I-425	55.24	50.24	7.09	5.5	0.78	1.3
D5420	20	0	I-425	59.05	54.05	7.35	4.39	0.67	1.12
D5430	30	0	I-425	47.62	42.62	6.53	4.23	0.65	1.08
D5417	10	7	I-425	70.48	65.48	8.09	4.8	0.6	1
D5427	20	7	I-425	59.048	54.048	7.35	5.5	0.75	1.25
D5437	30	7	I-425	49.53	44.53	6.67	4	0.6	1
D5407	0	7	I-425	69.53	64.53	8.03	4.5	0.56	0.94
D5500	0	0	I-525	54.1	49.1	7	4.17	0.6	1
D5510	10	0	I-525	55.62	50.62	7.11	4.23	0.6	1
D5520	20	0	I-525	51.81	46.81	6.8	4.2	0.62	1.04
D5530	30	0	I-525	49	44	6.6	3.83	0.58	0.97
D5517	10	7	I-525	55.2	50.2	7.09	4.73	0.67	1.13
D5527	20	7	I-525	55.62	50.62	7.11	5.42	0.76	1.27
D5537	30	7	I-525	49.2	44.2	6.65	4.62	0.69	1.15
D5507	0	7	I-525	57.9	52.9	7.27	4.83	0.66	1.1

Table 18 Proposed formula between compressive strength of samples at different ages

Categories	Mix ID	28-day compressive strength	Strength in (*t*) days	Proposed formula
D1	D3300	f_{c33}	f_{c33t}	"$f_{c33t}=f_{c33}\ (-7.05*10^{-5}\ t^2+10.54*10^{-3}\ t+0.8)$"
	D3310	f_{c33z10}	$f_{c33z10t}$	"$f_{c33z10t}=f_{c33z10}\ (-1.08*10^{-5}\ t^2+0.017\ t+0.69)$"
	D3320	f_{c33z20}	$f_{c33z20t}$	"$f_{c33z20t}=f_{c33z20}\ (-7.8*10^{-5}\times^2\ 0.014x+0.58)$"
	D3330	f_{c33z30}	$f_{c33z30t}$	"$f_{c33z30t}=f_{c33z30}\ (1.05*10^{-5}\times^2+7.96*10^{-3}x+0.97)$"
D2	D3400	f_{c34}	f_{c34t}	"$f_{c34t}=f_{c34}\ (1.94*10^{-5}\ t^2+0.113*10^{-3}\ t+0.98)$"
	D3410	f_{c34z10}	$f_{c34z10t}$	"$f_{c34z10t}=f_{c4z10}\ (4.48*10^{-5}\ t^2-2.5*10^{-3}\ t+1.03)$"
	D3420	f_{c34z20}	$f_{c34z20t}$	"$f_{c34z20t}=f_{c4z20}\ (2.75*10^{-6}\ t^2+6.3*10^{-5}\ t+1)$"
	D3430	f_{c34z30}	$f_{c34z30t}$	"$f_{c34z30t}=f_{c4z30}\ (4.7*10^{-5}\times^2-3.75*10^{-3}x+1.067)$"
D3	D5400	f_{c54}	f_{c54t}	"$f_{c54t}=f_{c54}\ (-7.9*10^{-6}\ t^2+2.4*10^{-3}\ t+0.944)$"
	D5410	f_{c54z10}	$f_{c54z10t}$	"$f_{c54z10t}=f_{c54z10}\ (-1.23*10^{-4}\ t^2+0.018x+0.63)$"
	D5420	f_{c54z20}	$f_{c54z20t}$	"$f_{c54z20t}=f_{c54z20}\ (-9.2*10^{-5}\ t^2+0.013\ t+0.66)$"
	D5430	f_{c54z30}	$f_{c54z30t}$	"$f_{c54z30t}=f_{c54z30}\ (2.2*10^{-4}\ t^2-1.9*10^{-3}\ t+1.04)$"
	D5417	$f_{c54z10si7.5}$	$f_{c54z10si7.5t}$	"$f_{c54z10si7.5t}=f_{c54z10si7.5}\ (-6*10^{-5}\ t^2+0.012\ t+0.71)$"
	D5427	$f_{c54z20si7.5}$	$f_{c54z20si7.5t}$	"$f_{c54z20si7.5t}=f_{c54z20si7.5}\ (-4*10^{-5}\ t^2+6.7*10^{-3}\ t+0.84)$"
	D5437	$f_{c54z30si7.5}$	$f_{c54z30si7.5t}$	"$f_{c54z30si7.5t}=f_{c54z30si7.5}\ (-6.2*10^{-5}\ t^2+9*10^{-3}\ t+0.82)$"
	D5407	$f_{c54z0si7.5}$	$f_{c54z0si7.5t}$	"$f_{c54z0si7.5t}=f_{c54z0si7.5}\ (-2.5*10^{-5}\ t^2+0.01\ t+0.76)$"
D4	D5500	f_{c55}	f_{c55t}	"$f_{c55t}=f_{c55}\ (-1.02*10^{-5}\ t^2+2.02*10^{-3}\ t+0.96)$"
	D5510	f_{c55z10}	$f_{c55z10t}$	"$f_{c55z10t}=f_{c55z10}\ (-6.7*10^{-5}\ t^2+0.01\ t+0.073)$"
	D5520	f_{c55z20}	$f_{c55z20t}$	"$f_{c55z20t}=f_{c55z20}\ (-1.45*10^{-5}\ t^2+5.07*10^{-3}\ t+0.89)$"
	D5530	f_{c55z30}	$f_{c55z30t}$	"$f_{c55z30t}=f_{c55z30}\ (-1.23*10^{-5}\times^2+3.7*10^{-3}\ t+0.92)$"
	D5517	$f_{c55z10si7.5}$	$f_{c55z10si7.5t}$	"$f_{c55z10si7.5t}=f_{c55z10si7.5}\ (3.9*10^{-6}\ t^2-5.06*10^{-5}\ t+1)$"
	D5527	$f_{c55z20si7.5}$	$f_{c55z20si7.5t}$	"$f_{c55z20si7.5t}=f_{c55z20si7.5}\ (-9.8*10^{-6}\ t^2+2.02*10^{-3}\ t+0.96)$"
	D5537	$f_{c55z30si7.5}$	$f_{c55z30si7.5t}$	"$f_{cz30si7.5t}=f_{cz10si7.5}\ (-1.59*10^{-5}\ t^2+2.95*10^{-3}\ t+0.933)$"
	D5507	$f_{c55z0si7.5}$	$f_{c55z0si7.5t}$	"$f_{cz0si7.5t}=f_{cz0si7.5}\ (-2.8*10^{-5}\ t^2+5.2*10^{-3}x+0.89)$"

percentage of zeolite, and the number after (si) indicates the constant percentage of silica fume used in mix designs.

Conclusion

Based on the compressive and tensile strength tests performed on 24 mix designs in 4 categories with different types of cement and replacement of zeolite percentages of 10, 20, and 30 and silica fume of 7.5%, the following results for ordinary and high strength concrete were achieved.

1. In ordinary concrete with compressive strength of 35 MPa and cement with a strength of 325 kg /cm^2 (mix design D1), samples containing 10 and 20% zeolite had better compressive strength than the reference sample at 28 and 56 days. Whereas the compressive strength of concrete with cement grade of 425 kg/cm^2 (mix design D2), the 56-day strength was almost the same as reference concrete
2. In high-strength concrete with a compressive strength of 50 MPa and cement strength of 425 kg/cm^2 (mix design D3), all samples containing 10, 20, and 30% zeolite at 28 days had lower compressive strength than the reference sample; over time, the samples containing 10 and 20% zeolite achieved almost the same strength as the reference concrete. For example, containing 7.5% silica fume at all ages has performed better strength than the reference samples, and the strength of the sample compared to the reference concrete after 28, 56, and 90 days of curing had a positive and better trend. Sample containing 10% zeolite and 7.5% silica fume after 28 days of curing had almost equal strength to the reference sample. Over time, the strength is much better than the strength of reference concrete due to the pozzolanic activity of zeolite and silica fume
3. In high-strength concrete with a strength of 50 MPa with cement strength of 525 kg/cm^2 (mix design D4), samples containing 10, 20, and 30% zeolite after 28 days had less compressive strength than the reference sample, but over the time, the samples containing 10% zeolite performed almost the same strength as the reference concrete and after 90 days of curing higher strength achieved than the reference sample. Samples containing 10 and 20% zeolite and 7.5% silica fume and samples containing only 7.5% silica fume, at all ages, had better strength than the reference sample

4. Tensile strength of samples containing 10 and 20% zeolite (D1 and D2 mix designs) after 56 days compared to reference samples had a growth of about 5 and 10%, respectively, while at 90 days, this growth rate was 9 and 23%, respectively
5. After 56 days, the tensile strength of 20% zeolite, 7.5% only silica fume, 10 and 20% of zeolite, and 7.5% silica fume, (mix design D3) samples had higher tensile strength 5, 10, 7, and 30% compared to the reference sample, respectively. After 56 and 90 days, tensile strengths of the sample containing 20% zeolite and 7.5% silica fume (mix design D4) were 28% higher than the reference sample
6. Based on ACI, the relationship between the compressive and tensile strength of concrete ($f_t=\gamma_c \sqrt{f'_c}$), the interval for coefficient (γ_c) is from 0.55 to 0.59, while based on the results obtained in this study, this coefficient was varied from 0.5 and 0.78 for 56 and 90 days of curing

Declarations

Conflict of interest The authors declare no competing interests.

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