Faghihmaleki and Nazari
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Laboratory study of metakaolin and microsilica effect on the performance of high-strength concrete containing Forta fibers

Hadi Faghihmaleki[1*] and Hossien Nazari[1]

*Correspondence:
h.faghihmaleki@gmail.com

[1] Faculty of Civil Engineering, Ayandegan Institute of Higher Education, Tonekabon, Iran

Abstract

In the present study aims to produce high-strength fiber concrete containing microsilica and metakaolin. Eight concrete mixing samples have been defined. The samples include the control concrete with ordinary Portland cement, replacing 10 percent of the weight of cement with microsilica. The amount of microsilica was kept constant in the next six designs. Three samples with the addition of Forta fibers at the rate of 0.2, 0.5, and 0.8 percent. Finally three samples with 0.5% Forta fibers and 8, 10 and 12% metakaolin were subjected to compressive, tensile and elastic modulus tests at the ages of 7 and 28 days. The addition of Forta fibers and the replacement of microsilica and metakaolin in concrete reduced the slump of concrete up to 5 cm. The highest compressive strength, tensile strength and elastic modulus at the age of 28 days of design 8 (concrete containing 10% microsilica, 0.5% Forte fibers and 12% metakaolin) are respectively equal to 73.6 MPa, 5.55 MPa and 37.49 MPa with The increase was 19.43%, 32.77% and 15.21% compared to control concrete without pozzolan and additives. Also, the relationship between compressive and tensile strength were presented. In total, all samples containing microsilica and fibers had a favorable effect on the resistance properties of concrete compared to the control design. The constant concern of bridge engineers, especially concrete bridges, is the production of concrete with high-strength and very low permeability in the face of their surroundings. Therefore, the result of this research can be a significant contribution to improving the quality of concrete used in bridge constructions.

Keywords: Forta fibers, High strength concrete, Concrete performance, Metakaolin, Microsilica

1 Introduction

The creation of high strength concrete has been one of the key areas of study for engineers and researchers looking to improve the performance and durability of concrete. Improvements in density, long-term mechanical qualities, strength at a young age, toughness, stable volume, or usable life in difficult settings are a few advantages of this concrete. Compressive strength, or the greatest resistance of the concrete sample to the applied pressure, is the primary distinction between high-strength and normal-strength concrete. The best possible usage of the raw materials used to create concrete with normal strength is a need for the creation of high-strength concrete.

When kaolin mineral resources are burned at temperatures between 500 and 900 degrees Celsius, metakaolin, a highly active pozzolanic substance, is created. There are 3 billion tons of kaolin deposits (Xi et al. 2016). Due to its favorable impact on the environment, metakaolin also guarantees the performance, mechanical characteristics, and durability of concrete. A siliceous substance that chemically combines with calcium hydroxide in the presence of water to produce cement compounds is known as metakaolin pozzolan. In this context, alkali activated metakaolin or metakaolin geopolymers have lately been employed to lessen the environmental consequences generated by the cement industry. The heat of hydration is reduced when pozzolans are used in place of cement (Environment et al. 2018).

In 2001, Zhang and Malhotra (Zhang and Malhotra 1995) studied how local metakaolin affected the characteristics of concrete and its resistance to sulfuric acid. This research examines the effects of adding two different kinds of local metakaolin to cementitious materials on the characteristics, strength, and longevity of concrete as well as how well it performs when combined with silica fume and regular concrete. In order to test the properties of fresh concrete in terms of weight, compaction, and slump factor as well as the properties of hardened concrete in terms of compressive strength, water absorption, and porosity, the experimental study was conducted in two stages. The first stage included 14 concrete mixtures of two types of metakaolin as well as silica fume with varying percentages of (8, 12, 15, and 20 percent) as a partial replacement by cement weight. The second phase is examining the impact of two varieties of metakaolin and contrasting it with silica fume as well as the kind of cement on concrete's resistance to acid assault. Sulfuric 3 percent by calculating the mass loss percentage and compressive strength percentage changes after immersion in acids for 30, 60, and 90 days. The findings indicate that Egyptian metakaolin may be regarded as a useful substance, much as silica fume. a pozzolanic mineral combination that benefits from the substitution of cement and metakaolin. When concrete has an ideal proportion of metakaolin and a water to cement ratio of 0.4, partial cement replacement of 15 to 20 percent boosts the strength of the concrete by 25 percent. It has the least water absorption and a greater pressure than the control. The resistance of concrete to sulfuric acid is improved by the combination of two additives, including 15% metakaolin and 20% silica fume. In a paper published in 2001, Poon et al. (Poon et al. 2001) discuss the findings of an experimental inquiry to determine the right quantity of metakaolin to use while making concrete and to look into how metakaolin affects the strength of concrete. Using regular Portland cement, reference concrete with a typical strength of 30 MPa was created, and different combinations were created by partially substituting metakaolin for the cement. By cement weight, the replacement rate for metakaolin was 5 percent, 10 percent, 15 percent to 20 percent. In order to draw helpful conclusions, several studies that demonstrate the impact of using metakaolin in place of cement are described in this article. The performance of concrete was increased by 15% when replacement cement containing metakaolin was used, according to the findings when compared to reference concrete.

In 2010, Vejmelkova et al. (Vejmelkova et al. 2010) investigated replacement in concretes with a water-cement ratio of 0.35. Cement that contains metakaolin or silica fume at 0, 5, 10, and 15 percent. Compared to concrete changed with silica fume, concrete modified with metakaolin performed better. Both types of mineral pozzolans decreased free drying shrinkage and stopped shrinkage cracks from widening. Additionally, they significantly decreased concrete chloride emissions. Concrete's compressive strength increased and chloride levels decreased when silica fume was added. Silica fume increased steel in concrete's resistance to chloride-induced corrosion. Concretes with silica exhibit remarkable resistance to damage from freezing and thawing.

According to a 2012 study by Dinakar (Hemalatha and Ramas 2017), the increase in metakaolin concrete's average strength is only noticeable while the concrete is still young; over time, it makes little difference in terms of strength. For metakaolin concrete, particularly at higher water-cement ratios, the improvement in compressive strength was greater (i.e. 0.4 and 0.5). At a water-cement ratio of 0.4, the highest compressive strength of 59.25 N/mm2 was found. Chloride ions penetrate metakaolin concrete substantially less deeply than control concrete. For concrete with a water-cement ratio of 0.32, 0.35, 0.4, and 0.5, respectively, the minimal chloride penetration depth reduction rate was 78%, 38%, 25%, and 25%. The concrete containing metakaolin with a water-cement ratio of 0.32 had the highest decrease rate of 95%. Ramezanianpour and Bahrami (Ramezanianpour and Bahrami Jovein 2012) conducted experimental study in 2012 to examine the impact of metakaolin, silica fume, and fly ash at high temperatures on the characteristics of high-strength cement mortar based on metakaolin, silica fume, and fly ash. After being exposed to temperatures of 50, 150, 300, 400, 500, 800, and 900^{0}C, the qualities of concrete were assessed for resistance to temperature rise. The mixes with replacement ratios of 9 percent, 6 percent, and 15 percent, respectively, produced results that demonstrated outstanding temperature resistance in all categories of maximum temperature. The negative impacts of using regular Portland cement have been reduced by the additional features of these supplemental cement components, which include a decrease in calcium oxide and an increase in silicon oxide and aluminum oxide. The results also shown that the value of common cement particles is impacted by how soft they are at high temperatures. The temperature resistance is improved by 152 percent when pozzolans used at high temperatures are optimally replaced with metakaolin at 9 percent. Compared to the control mixture, which contains 160 percent silica fume, the temperature resistance for mixes containing 6 percent silica fume is enhanced (Fig.). The combination containing 15% fly ash has a 153 percent resistance to temperature increase. Due to its proper consumption, silica fume demonstrated greater temperature resistance overall.

Additionally, Dinakar et al. (Dinakar Pradosh et al. 2013) show the impact of metakaolin composition on the mechanical characteristics and durability of high strength concrete in another research from 2013 (Dinakar Pradosh et al. 2013). They created concrete with a consistent water-cement ratio of 0.3 and a characteristic strength of 90 MPa by substituting 5, 10, and 15% of the cement with metakaolin. According to the findings, the replacement level of 10% is the ideal amount in terms of compressive strength. The strength reduced with replacement levels of 10%, although it remained higher than the control mixture. At 10% replacement, a compressive strength of 106 MPa was attained.

The values of tensile strength and elastic modulus have likewise shown this pattern. Additionally, the 28-day tensile strength, compressive strength, and modulus of these concretes increased by 5.15 percent.

In 2013, Nadeem et al. (Nadeem et al. 2013) examined the effectiveness of fly ash and metakaolin at high temperatures and for partial replacement of cement with metakaolin from 5 to 20 percent, fly ash from 20 to 60 percent, and temperature ranging from 27 °C to 800 °C. The test findings demonstrate that when temperature is raised from 27 °C to 800 °C, compressive strength for all mixes drops while the pass charge rises. After 400 °C, all compositions experience a significant decrease in strength and durability. So, in terms of loss of strength and durability, 400 degrees Celsius might be regarded as a crucial temperature.

In 2015, Jiang et al. (Jiang et al. 2015) carried out an experimental investigation on the effects of silica fume and metakaolin on the characteristics of freshly-poured and cured self-compacting concrete. Portland cement was substituted for silica fume and metakaolin in varying amounts of 5, 10, 15, 20 and 25 percent. For all of the examined samples, the water-cement ratio of 0.38 was maintained. The test results for compressive strength on the seventh, fourteenth, twenty-first, and twenty-eighth days of processing indicated that with 2 percent super-lubricant, new concrete performs well and lowers it. This test shown that compressive strength rises with curing day age. It was shown that silica fume had a greater compressive strength than metakaolin, and that after 28 days, the flexural strength and tensile strength of concrete containing 15% silica fume increased relative to the control mixture by 14.6 percent and 22.4 percent, respectively. In 2016, Gneyisi and Mermerdas (Gneyisi and Mermerdas 2007) studied the results of partially substituting metakaolin for cement in concrete. 5 percent, 10 percent, 15 percent, and 20 percent of the cement weight were replaced with metakaolin, respectively. The findings show that all metakaolin concrete combinations have greater strengths than regular concrete. Metakaolin is preferable than other mixes when used to replace 15% of the cement. By adding more metakaolin, the compressive and tensile strength of the material increased by 15%. In 2017, Hemalatha and Ramaswamy (Hemalatha and Ramas 2017) studied how nano- and micro-sized silica affected the way steel fibers and polypropylene bonded in fly ash mortar. As a partial substitute for regular Portland cement, fly ash was utilized in three different volumes of 40%, 50%, and 60% (by weight). The weight additions of nano and microsilica were 2% and 10%, respectively. The findings shown that when fly ash concentration is increased, the maximum tensile force of steel and polypropylene fibers falls. The effectiveness of mortar was decreased by the inclusion of nano and micro silica. It can be shown that the addition of 2% nanosilica and 10% microsilica at both the ages of 7 and 28 days enhanced the compressive strength of the combination containing 40% fly ash. Moreover, when 2% nanosilica is added to the mortar, the flow of concrete is reduced by around 5%. On the other hand, the current drops by around 8% when 10% of microsilica is added, and when nano and microsilica are employed at the same time, a nearly identical drop is seen.

Kashyap et al. (Kashyap et al. 2023) in 2023 assessed the durability performance of concrete mix with the addition of marble dust and Nano silica as partial replacement of cement. Concrete blends with 1%, 2%, and 3% Nano silica and 5%, 10%, and 15% marble dust powder were prepared at constant water to binder ratio of 0.4. The bulk density, water permeability, water absorption, carbonation depth, rapid chloride penetration test, and acid attack after curing for 28 days along with mineralogical and morphological tests were carried out. In the present study aims to Metakaolin and Microsilica effect on the performance of high-strength concrete containing Forta Fibers.

2 Methods

2.1 Aggregate

Cement, water, coarse and fine particles, and optional chemical and mineral additions make up concrete. Since aggregate makes about 75% of the volume of concrete, strong concrete needs high-strength and graded material. To minimize voids, it's crucial to have well-graded aggregate in the proper ratios of various sizes (Li et al. 2021; Li et al. 2023); (Siddique 2011). In reality, the granular ingredients that provide concrete the greatest volume and strength are the crushed stones, sand, and other materials (Siddique and Klaus 2009; Mansouri et al. 2022).

Another significant feature that the granulation test reveals is the aggregate's maximum size. The natural sand from the Tonekabon city's Cheshme Kileh river was employed in this investigation. More surface area is available for bonding other substances, such water and cement, thanks to the aggregate's rough outer surface. Because of this, sand (coarse grains) is considerably more suited for use in building, where stronger material bonding is required to produce concrete that is more resilient and long-lasting.

Figure 1's sand grading curve is impressive and offers excellent grading. Sand with a softness modulus of 2.9 and a maximum nominal size of 20 mm for corner sharpness. Sand with a softness modulus between 2.3 and 3.1 is good for concrete production. In actuality, the modulus of elasticity increases with grain size.

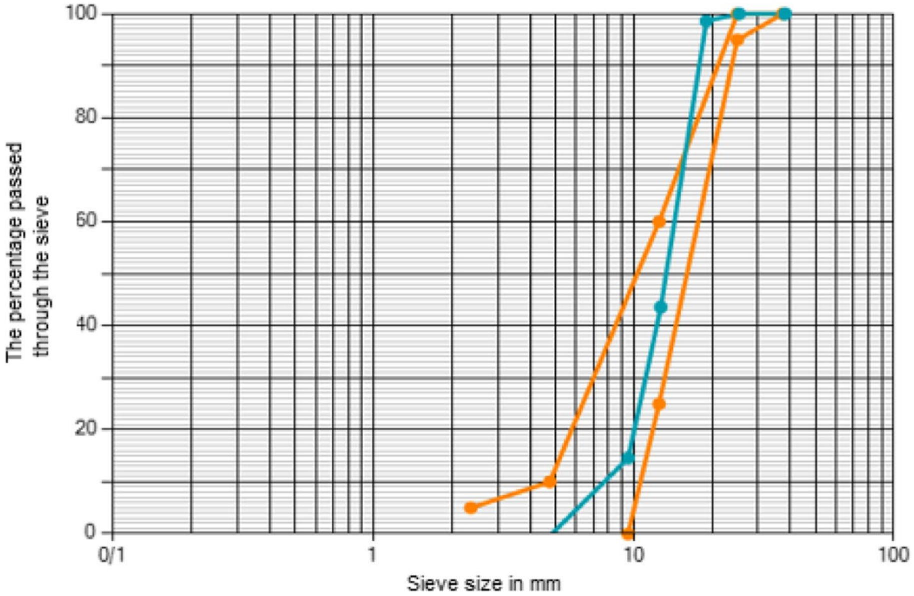

Fig. 1 Graining curve of the sand used in the research compared to the permissible limits of ASTM

Table 1 Technical specifications of metakaolin

Powder	Appearance
Pinkish cream color	Color
700 °C	baking temperature
325 Mesh	Grading

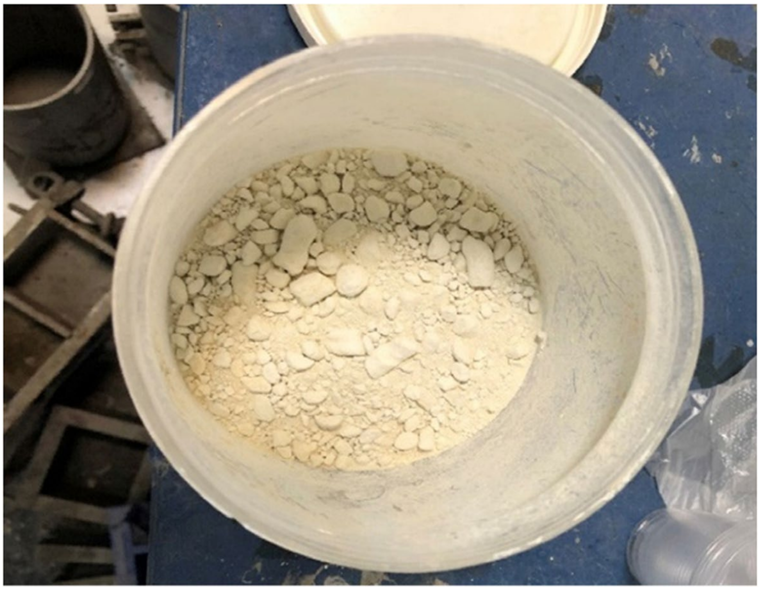

Fig. 2 The appearance of metakaolin

2.2 Cement materials

A geopolymer called metakaolin is useful for making inexpensive, lightweight, heat-resistant, and ecologically beneficial materials. A whitish, amorphous aluminum silicate is called metakaolin. The metakaolin utilized in this study was obtained from the Iran Imart Company and matched the technical requirements shown in Table 1 and Fig. 2.

One of the most effective and adaptable additives for concrete and cement products is microsilica (Jiang et al. 2021). With spherical particles smaller than 1 μm in diameter and an average diameter of roughly 0.15 μm, microsilica is an extremely tiny substance. This reduces it to a size that is around 100 times smaller than typical cement particles. It should make up between 6 and 15 percent of the weight of cement used, which may be decreased by the same percentage. In Figs. 3 and 4, you can see the microsilica that was employed.

The cement is Boroujerd Cement Company's Portland Type 2 cement. The proportion of aluminate phase in this cement gives it a mediocre level of resistance to sulfate attack. On the other hand, it may be utilized in nearly bulky concreting because of its medium hydration heat. At the age of 28 days, this cement has a minimum compressive strength of 440 kg/cm2. Table 2 provides a list of cement's physical characteristics. Additionally, Table 3 provides the chemical compositions of cement, microsilica, and metakaolin.

Fig. 3 Microsilica powder

Fig. 4 Appearance of microsilica powder

Table 2 Physical properties of cement

experiments	ASTM C150 standard requirements	Results
Specific weight (ton/m^3)	-	3.164
Water percentage of natural concentration	-	24
Initial capture time	Minimum 45 min	165
Final taking time	Minimum 6:15 h	0.3:00
Autoclave test expansion percentage	Maximum 0.8	0.03
28-day compressive strength (kg/cm^2)	Minimum 315	500

Table 3 Chemical compounds of cement, microsilica and metakaolin

Chemical compounds	Abbreviation	Cement %	microsilica %	metakaolin %
Silicon dioxide	$SiO2$	22.8	90	54.3
Aluminum oxide	$Al2O3$	5.7	1.2	38.3
iron oxide	$Fe2O3$	3.6	1.8	4.28
Calcium oxide	CaO	59.11	0.5	0.39
Magnesium oxide	MgO	2.38	0.6	0.08
Sodium oxide	$Na2O$	0.74	0.3	0.12
Potassium oxide	$K2O$	0.27	0.13	0.50
Sulfur trioxide	$SO3$	1.92	2.1	0.22

2.3 Lubricant

A thick, dark, chlorine-free liquid with the qualities of lubrication, concrete water reduction, and cement particle dispersion preserves the cohesiveness of concrete without diminishing its strength. Additionally, it enhances the slump and results in self-leveling concrete after being used in concrete (Parcesepe et al. 2023).

Due to the feature of increasing static electricity, this polycarboxylate ether-based substance disperses cement particles efficiently at the beginning of hydration, and its molecular chains firmly prohibit the re-aggregation of cement particles. This action results in smooth concrete with a very low water content and the permanent preservation of cement particles in a separate and dispersed state. A significant increase in concrete's compressive strength at various ages, a reduction in water mixing by up to 30 percent while maintaining fluidity, an increase in concrete's adhesion to steel and reinforcement, ease of pumping and a decrease in the need for concrete vibration, an increase in concrete's impermeability, a decrease in the water-to-cement ratio and a reduction in water and cement use, improved concrete efficiency, long-term slump maintenance, and an increase in concrete's impermeability are A lubricant, that is. Strong concrete preparation and creation, ready-made and prefabricated concrete industries, self-compacting concrete, use of super-reinforced structures and quick-concreting, creation of concrete with a high initial strength and long-term maintenance, and creation of floor mortars One of the applications for concrete lubricant is the construction of pieces with dense reinforcement. It typically consumes between 0.2% and 1% of the weight of the cement.

Table 4 Specifications of Forta fibers

Percentage elongation at break	Melting point °C	The maximum amount allowed in concrete is kg/m^3	Water absorption percentage	Density gr/cm^3	Thickness mm	Length mm
15	170	1	-	0.91	0.50	52

Fig. 5 Appearance of Forta fibers

2.4 Forta fibers

Forta polymer fibers are included into concrete or mortar as a supplementary reinforcement to lessen shrinkage and cracking and improve concrete's long-term durability (Aflakisamani et al. 2023). The fibers are mixed in with the other ingredients in a dry or fresh mixture. In order to build a high performance concrete reinforcing system, Forta, a colorful composite fiber derived from virgin copolymer and formed of fibrillated filaments, is used. It is used to boost concrete's hardness and fatigue resistance, reduce plastic shrinkage in hardened concrete, and improve impact resistance. These fibers are completely anti-alkali, non-magnetic, and non-corrosive. The maximum quantity of these fibers that may be used in concrete is 5 kg/m3. Forta fiber characteristics and appearance are illustrated in Table 4 and Fig. 5, respectively.

3 Concrete mixing plan

Cement should be used in greater quantities for high strength concrete than for standard strength concrete. Depending on the desired strength, these concretes might include anywhere between 420 and 650 kg/m^3 of cement. In comparison to concrete of normal strength, the size of the fine aggregate should rise as the quantity of cement increases. When compared to standard strength concrete, the quantity of cement used to manufacture cement hydration products is more when the fine aggregate size is increased since there is more space between the particles. More cement is used, which increases the heat of hydration and plastic shrinkage of new concrete, although it may be reduced by substituting minerals like metakaolin for some of the cement. In high strength concrete additives, silica fume may be used in lieu of up to 8% of the cement. Concrete's nano-scale holes are filled by silica fume particles because they are so tiny (less than one tenth the size of cement particles). In accordance with the water to cement weight ratio, a predetermined quantity of microsilica powder substitutes 10% of the weight of cement in all designs.

Based on the needed strength, which in this study is 0.32, it may be set for concrete with high strength in the range of 0.25 to 0.40. 40 MPa was thought to be the typical concrete strength. One of the prerequisites of high strength concrete is that there be less free space in the concrete, which may be achieved by decreasing the water to cement ratio. The effectiveness (flowability) of concrete is decreased by lowering this ratio. However, the use of chemical admixtures that reduce water may greatly enhance the flowability of concrete. The quantity of lubricant in the designs was established, and 0.85 percent of the weight of cement was taken into consideration, in light of the investigation into the ratio of water to cement components.

Forta fibers were added to designs 2, 3, and 4, respectively, by 0.2, 0.5, and 0.8 percent, in order to get the best consumption of these fibers to boost resistance. Forta fibers were consistently added to the concrete in plans 5, 6, and 7 at a rate of 0.5 percent owing to the fluctuating quantity of metakaolin. In designs 5, 6, and 7, respectively, 8, 10, and 12 percent of the weight of cement were used in lieu of the metakaolin powder. Table 5 provides specifics on the mixing ratios.

According on the sample's age, Table 6 lists the number of samples created to test the concrete's compressive and tensile strength. These samples' molds for compressive strength and tensile strength are each 15 cm cubes and 20 cm cylinders, respectively.

Table 5 Concrete mixing plan (kg/m^3)

Mixing plan number	1	2	3	4	5	6	7	8
The name of the mixing	Plain1	Plain2	F 0.2 SF 10	F 0.5 SF 10	F 0.8 SF 10	F 0.5 SF 10 MC8	F 0.5 SF 10 MC10	F 0.5 SF 10 MC12
Water to cement ratio	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Water	166/44	166/44	166/44	166/44	166/44	166/44	166/44	166/44
Cement	520	468	468	468	468	426.40	416	405.6
Metakaolin	-	-	-	-	-	41.6	52	62.4
Microsilica	-	52	52	52	52	52	52	52
coarse grain	898	898	898	898	898	898	898	898
fine grain	808	808	808	808	808	808	808	808
Forta fibers	-	-	1.8	4.55	7.2	4.55	4.55	4.55
super lubricant	4.42	4.42	4.42	4.42	4.42	4.42	4.42	4.42

Table 6 Total number of samples

The name of the mix	7-day pushing resistance	28-day compressive strength	28-day Tensile strength
Plain1	2	2	2
Plain2	2	2	2
F 0.2 SF 10	2	2	2
F 0.5 SF 10	2	2	2
F 0.8 SF 10	2	2	2
F 0.5 SF 10 MC8	2	2	2
F 0.5 SF 10 MC10	2	2	2
F 0.5 SF 10 MC12	2	2	2

Fig. 6 Strong concrete materials during mixing

The aforementioned studies produced two standard samples for each design, and the study findings represent the average of the two samples.

4 The method of making strong concrete

Samples are created in accordance with the weighted mix design. First, the fine and coarse aggregates, cement, metakaolin, and cement are precisely weighed. After mixing coarse and fine aggregates, cement, metakaolin, and microsilica are added and well mixed. Most of the water, which was properly measured, was poured to the dry mixture. Superlubricant was combined with the remaining water before being added. To ensure consistency, the whole mixture is vigorously stirred for 10 min (Fig. 6). A cube mold with dimensions of 150 mm in length, width, and height as well as a cylindrical mold with dimensions of 100 mm in diameter and 200 mm in height were both utilized for concreting. Before pouring concrete into the molds, the molds were fully coated in oil and cleansed of any dust particles. Then, the molds were filled with the mixed concrete. The

Fig. 7 Concreting in standard forms

Fig. 8 Samples made during processing in the water basin

rod crushed and totally compacted three layers of identical height 25 times. The surface of the samples is polished after concreting (Fig. 7). Molds were taken out and the hardened concrete was put in a water pool at room temperature for processing 24 h after the concrete had set (Fig. 8). The samples in the pond had a processing age of 7 and 28 days.

5 Strong concrete tests

5.1 Slump

Slump cone testing is done to verify the consistency or workability of the concrete mix as well as the quality and uniformity of the concrete produced in the laboratory or on the job site. The easiest and most affordable concrete performance test, the slump test yields findings right away. Concrete slump is also influenced by other elements, including addition volume, mixing techniques, and material characteristics. A slump cone, a non-absorbent base plate, a measuring ruler, and a compression rod are necessary pieces of equipment for the slump test. The mold's inside surface was cleaned and lubricated before to the test. The ready concrete mixture was poured into the mold in three almost equal layers, which were then set on a level, horizontal foundation plate. The round end of the hammering rod was used to provide 25 even blows to each layer on the mold's cross section. At the conclusion, extra concrete was scraped off and the concrete's surface was polished with a trowel. The cone was instantly and gradually raised vertically from the concrete, and a ruler was used to measure the concrete drop (Fig. 9).

5.2 Compressive resistance

One of the pieces of information required for the design of the construction is the testing of concrete's compressive strength. To guarantee the attainment of the grade of concrete taken into account in the design of the construction, the compressive strength is verified first by carrying out the mixing plan. Concrete's compressive strength is a characteristic that is influenced by a number of variables linked to the quality of the raw materials, mix design, and quality assurance procedures. After 7 and 28 days of treatment, the samples were taken out of the water, and any extra water was drained. After determining the sample's weight, it was loaded. Place the sample in the testing device's proper location so

Fig. 9 Concrete slump test

that the weight is delivered in a direction that is perpendicular to the direction of concreting (Fig. 10). The sample was positioned in the middle of the machine's base plate, and the results of the maximum load test were recorded.

5.3 Tensile strength

Concrete's capacity to bear stress is measured by its tensile strength. Concrete's tensile strength is measured using the units of force at each segment. Concrete has an excellent compressive strength but a weak tensile strength. When compared to the direct tensile test technique, the splitting tensile strength test method offers numerous benefits. For instance, it is significantly simpler to complete and test results are sent much more accurately.

Researchers have shown that the split tensile test, which can assess the real tensile strength of materials that are similar to concrete across a broad range of strain rates, is the most accurate of the three test techniques (direct tensile tests, split tensile tests, and flexural tests) ((Gneyisi and Mermerdas 2007). The samples were taken out of the water after 28 days of treatment, and extra water was drained. This was followed by loading.

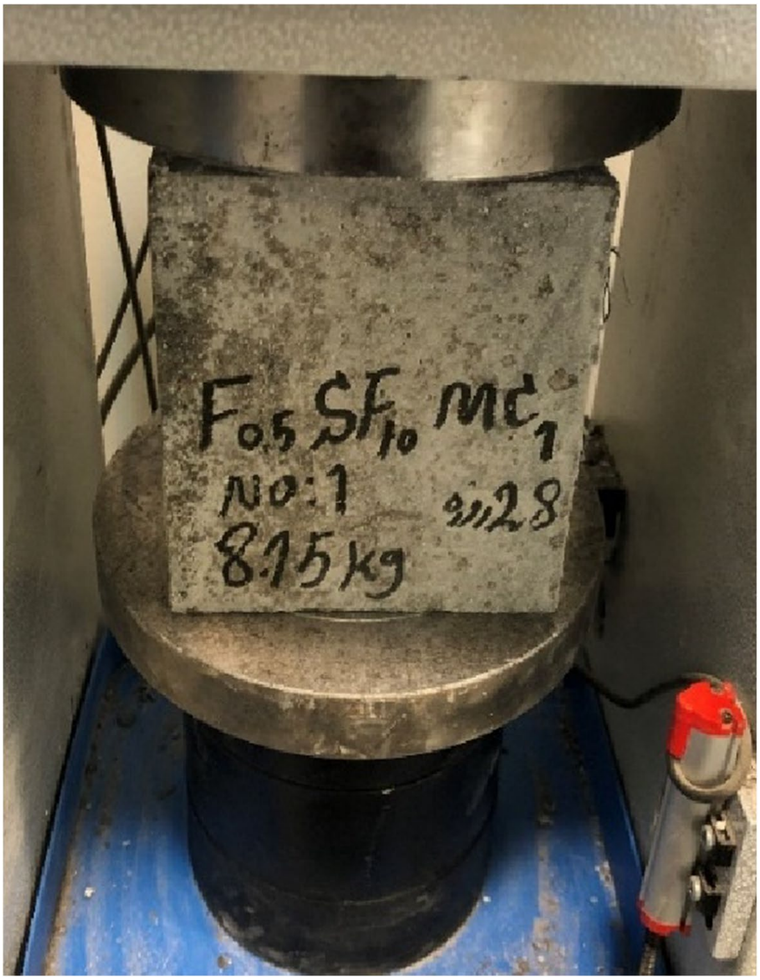

Fig. 10 The sample weighed inside the concrete breaker

With the aid of a steel rod and a bottom plate that was fully secured in the testing apparatus, the sample was positioned appropriately so that the load would be delivered counterclockwise to the direction of concreting (Fig. 11). The sample was positioned in the middle of the machine's base plate, and the results of the maximum load test were recorded. Then, using Eq. 1, the reduced tensile strength was determined.

$$\mathrm{T} = 2\mathrm{P}/\pi \mathrm{ld} \tag{1}$$

In Eq. 1:
T = Tensile strength of halving (kg/cm2).
P = maximum applied load (kg).
L = length of cylindrical sample (cm2).
d = diameter of cylindrical sample (cm)

5.4 Modulus of elasticity

The elastic modulus, which is essentially a function of the elastic moduli of the aggregates and cement and their ratios, is primarily connected to the compressive strength of concrete. The characteristics of the coarse aggregate have a significant role in determining the elasticity modulus of concrete. The aggregate modulus may be raised by utilizing coarser, harder aggregates with a greater modulus of elasticity or by enlarging coarse aggregates. At low stress levels, the concrete's modulus of elasticity is mostly constant, but as the stress increases, concrete cracking occurs and the modulus of elasticity begins to fall. Concrete's modulus of elasticity measures the material's hardness, which is a

Fig. 11 Cylindrical sample inside the concrete breaker

reliable predictor of resistance. Concrete may tolerate greater stress and become brittle with a higher elastic modulus. Concrete's modulus of elasticity, which measures how easily it can change form to make the most of its compressive strength, is a crucial factor. High-strength concrete constructions often have thinner walls and need a greater modulus of elasticity to maintain their hardness. Therefore, it is crucial to understand the elasticity modulus of high-strength concrete in order to avoid excessive deformation and maintain the required properties of concrete. Concrete typically has an elastic modulus between 30 and 50 GPa. Concrete's minimum elasticity modulus was recently defined by design requirements. The objective is to reduce excessive sway and distortion in tall structures. The slope of the stress–strain curve under uniaxial loading for high-strength concrete is used in Eq. 2 to get the static modulus of elasticity of concrete under tension or compression

$$\mathrm{E} = \left(3300\sqrt{\mathrm{F_C}} + 6900\right)(\gamma_C/23)^{1.5} \tag{2}$$

In Eq. 2:
E = The modulus of elasticity of concrete GPa.
FC = compressive strength of concrete MPa.
γC = specific mass of concrete KN/m3

6 Test results

6.1 Slump

Table 7 and Fig. 12 show the results of the slump test on newly laid concrete. The grade 520 and 468 kg/m^3 control concretes have slump loss in the range of 68 and 64 mm, respectively. Because microsilica replaced 10% of the regular Portland cement in type 2 reference concrete, the slump rose by 5.9% compared to type 1 reference concrete. This is what causes microsilica to absorb more water than ordinary cement alone.

As anticipated, the inclusion of fibers also caused the consistency of the concrete to rise while reducing the amount of slump. The amount of slump is lowered in designs using 0.2 percent, 0.5 percent, and 0.8 percent Forta fibers compared to type 1 control concrete by 13.3, 19.2, and 26.5 percent, respectively, and by 7.9, 14.1 and 21.9 percent compared to type 2 control concrete. Despite not being water absorbent, the fibers decreased the fluidity and, as a result, the drop of the concrete when they were added to the overall volume of the mixture.

Table 7 Slump results of concrete samples

The name of the mix	Slump (centimeter)
Plain1	6.8
Plain2	6.4
F 0.2 SF 10	5.9
F 0.5 SF 10	5.5
F 0.8 SF 10	5
F 0.5 SF 10 MC8	5.4
F 0.5 SF 10 MC10	5.3
F 0.5 SF 10 MC12	5

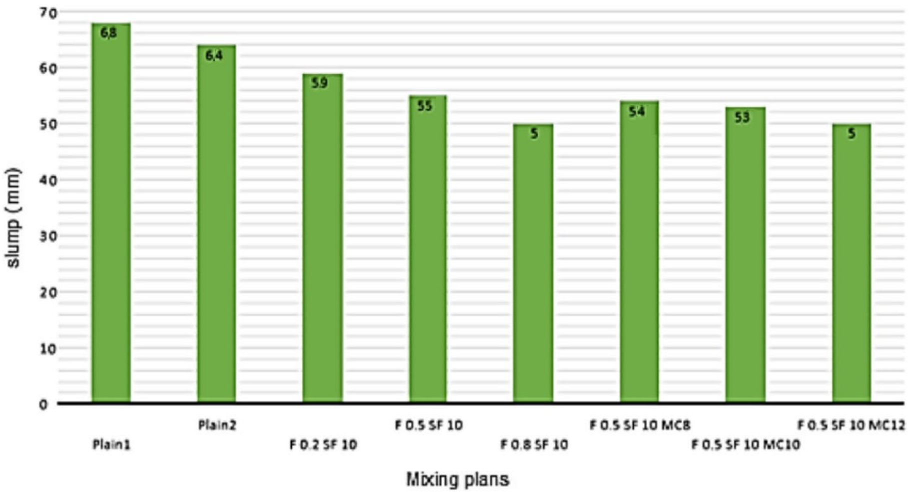

Fig. 12 Concrete slump

Table 8 Results of compressive strength (MPa)

The name of the mix	7-day pushing resistance	28-day compressive strength
Plain1	46.4	51.4
Plain2	47.7	53.13
F 0.2 SF 10	52.6	65.5
F 0.5 SF 10	55.3	66.5
F 0.8 SF 10	56.6	67.6
F 0.5 SF 10 MC8	67.3	71.6
F 0.5 SF 10 MC10	67.7	72.8
F 0.5 SF 10 MC12	67.9	73.6

In reality, it has a clear impact on the synergy of microsilica and metakaolin. By altering and increasing the proportion of metakaolin as a replacement for cement, the quantity of slump also reduced. Additionally, the recorded findings demonstrate that when cement is replaced with metakaolin by 8%, 10%, and 12%, respectively, 21.1, 22.1, and 26.5% dropped in comparison to control type 1 concrete, and 15.7, 17.3, and 21.9% decreased in comparison to type 2 control concrete. As a result, concrete with metakaolin and cement absorbs more water than concrete made with regular Portland cement.

In the study of Vejmelkova et al. (Jiang et al. 2015), concrete with 10% microsilica demonstrated a 5% decrease in slump. Plan 8 with a 12 percent metakaolin content had the largest 26.5 percent drop in slump rate. This high percentage demonstrates the significant effects of Forta fibers and microsilica, and the end result of this triple combination was a reduction in the fluidity of concrete in this size.

6.2 Compressive resistance

Due to the rise in curing age in all concrete designs, the compressive strength of concrete has been rising (Table 8). When compared to when it was 7 days old, the pressure sample of design 2 control grew by 11.74 percent at age 28. Plans 3 to 5 showed a 28-day concrete compressive strength increase of 24.52, 18.44, and 19.43 percent over its 7-day age. In designs 6 to 8, 28-day concrete's compressive strength rose 6.38, 7.53, and 8.39 percent in comparison to its 7-day age (Fig. 13). In concretes containing microsilica and Forte fibers, the rate of increase of compressive strength from 7 to 28 days of curing age has been quite amazing; these designs have less initial resistance than designs 6 to 8.

Due to the substitution of 10% by weight of microsilica with cement at the age of 28 days, the compressive strength of the concrete design 2 was 3.69 percent greater than the compressive strength of the design 1. In designs 3 to 5, the synergy of 10% microsilica with 0.2%, 0.50%, and 0.80% Forta fibers is 27.4%, 29.37%, and 31.51%, respectively, compared to the control sample of design 1. Additionally, 22/88, 24/76, and 26/82 increased compared to the control sample of design 2. By raising the amount of fibers to 0.8 percent, the compressive strength trend improved.

The compressive strength of concrete was significantly increased in plans 6 to 8 due to the synergistic effects of 10% microsilica, 5% Forta fibers, and 8%, 10%, and 12% metakaolin by weight of cement. As the amount of metakaolin rose from 8 to 12 percent, the trend of compressive strength increased. Comparing these designs to the control samples of design 1 and 2, the increase in compressive strength was 39.29, 41.63, and 43.19 percent, respectively, and 34.33, 36.58, and 38.08 percent, respectively. (Fig. 14).

Additionally, the 28-day compressive strength of concrete is 7.66, 9.47, and 10.67 in designs 6 to 8, which comprise a triple combination of microsilica, metakaolin, and Forta fibers, compared to designs 3 to 5 of concrete containing microsilica and Forta fibers.

Overall, the compressive strength of all the concretes with pozzolan and additives was greater than that of the control designs 1 and 2. Plan 8 (concrete containing 10%

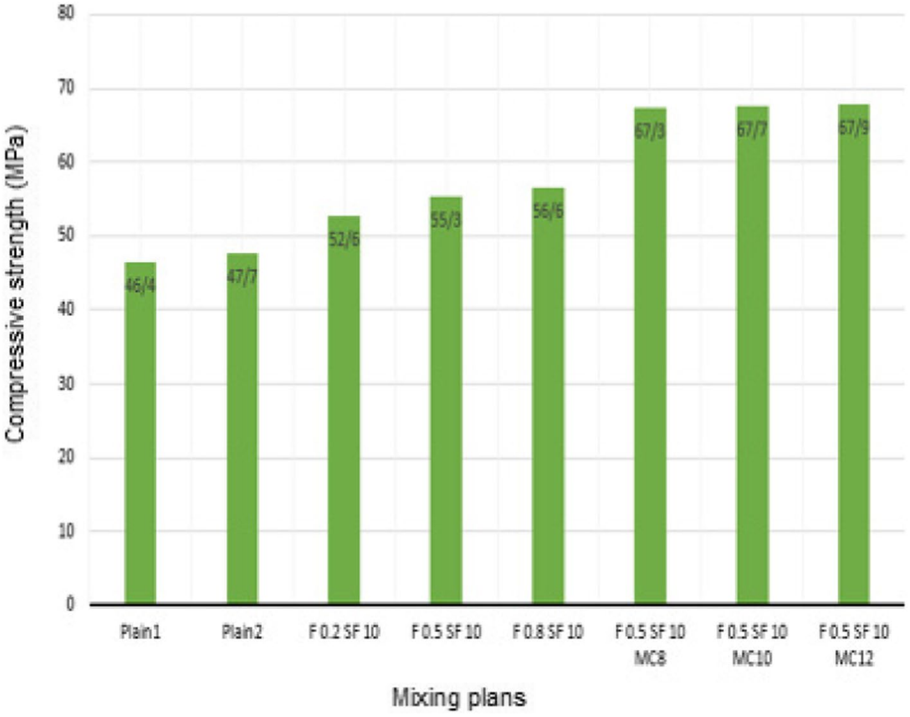

Fig. 13 7-day compressive strength of designs

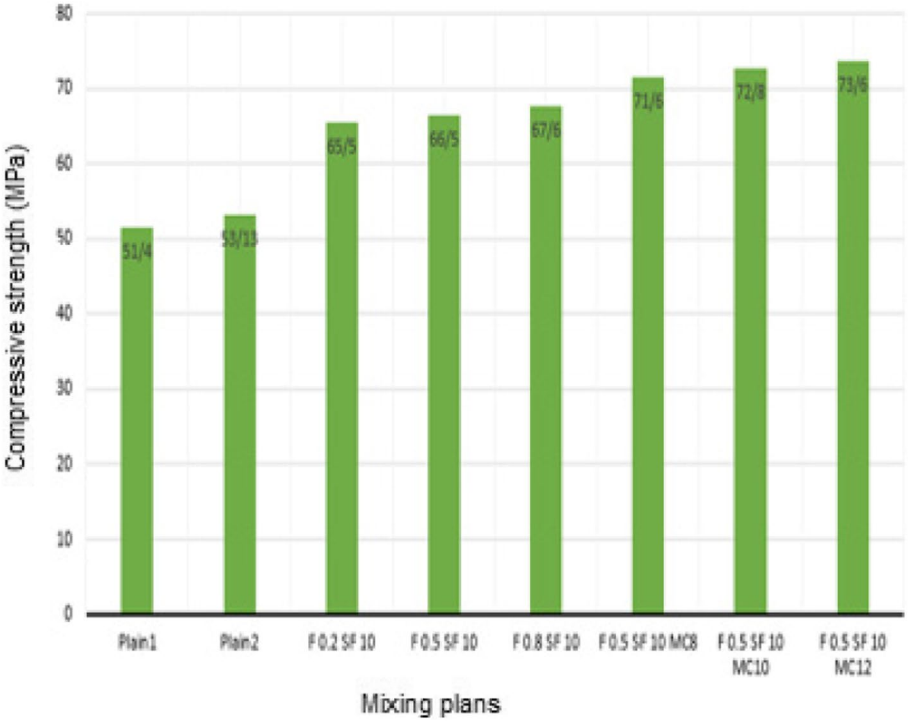

Fig. 14 28-day compressive strength of designs

microsilica, 5% Forte fibers, and 12% metakaolin) had the maximum compressive strength at 28 days old (73.6 MPa). The control concretes showed the lowest compressive strength as a result of the increase in strength. The maximum compressive strength of design 5's concrete, which contains 0.8 percent Forte fibers and 10% microsilica, is 67.6 MPa for designs 3 to 5.

In the study of Jiang et al. (Poon et al. 2001), the compressive strength of concrete increased when metakaolin was substituted for 15% of it. Additionally, in Zahiri and Nadaf's study (2019), the compressive strength of cement was increased to 52.5 MPa by substituting microsilica and nanosilica at rates of 8.3 percent and 2.4 percent, respectively. On the other hand, Hassanzadeh et al. (2022). produced a 10.855 percent improvement in compressive strength above control concrete at the age of 28 days of concrete by substituting metakaolin and microsilica for 17 percent of the cement ingredients at the rates of 8 and 9 percent, respectively. The strength of the high-strength concrete in the present study increased in comparison to the witness sample, which was realized, as predicted based on the research's findings. In this study, we found a 43.19 percent increase in compressive strength growth in the design of concrete containing 12 percent metakaolin, which is evidence of the synergy of the triple combination of microsilica, metakaolin, and Forta fibers. Compressive strength is increasing at a very rapid pace.

Table 9 Tensile strength results (MPa)

The name of the mix	28-day Tensile strength
Plain1	4.18
Plain2	4.30
F 0.2 SF 10	4.71
F 0.5 SF 10	4.77
F 0.8 SF 10	4.99
F 0.5 SF 10 MC8	5.11
F 0.5 SF 10 MC10	5.36
F 0.5 SF 10 MC12	5.55

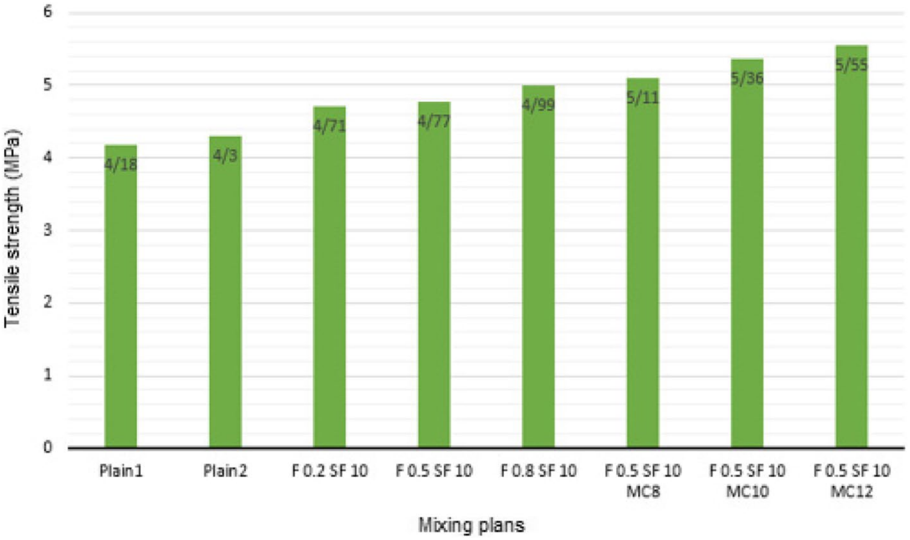

Fig. 15 Tensile strength at the age of 28 days of strong concrete

6.3 Tensile strength

Concrete's tensile strength consistently grew as the sample's compressive strength did (Table 9 and Fig. 15). Due to the substitution of 10% by weight of microsilica with cement, the tensile strength of concrete design 2 at 28 days was greater than that of design 1. The synergy of 10% microsilica with 0.2, 0.5, and 0.8% Forta fibers increased in designs 3 to 5 by 12.67, 14.11, and 19.37% compared to the control sample of design 1 and by 9/53, 10/93, and 19/04 compared to the control sample of design 2. Tensile strength was consistently on the rise as fiber percentage rose up to 0.8 percent.

In designs 6 to 8, the synergistic imapct of 10% microsilica, 0.5% Forta fibers and 8%, 10% and 12% metakaolin by weight of cement, the increase in tensile strength in comparison with the control sample of design 1, is 22.24, respectively. 28.22 and 32.77% and compared to the control sample of design 2, it was 18.83, 24.65 and 29.06%.

Overall, all the concretes with pozzolan and additives outperformed control designs 1 and 2 in terms of tensile strength. Design 8's concrete, which contains 10% microsilica, 5% Forte fibers, and 12% metakaolin, has the best tensile strength at 28 days old, 5.55 MPa. The control concretes showed the lowest tensile strength as a result of the increase in strength. The highest tensile strength of plan 5 concrete, which contains 0.8 percent Forta fibers and 10% microsilica, is 4.99 MPa for plans 3 to 5.

According to Dinakar's study (Hemalatha and Ramas 2017), concrete containing 10% metakaolin has a 15.5% improvement in tensile strength. According to the aforementioned studies, the rise in tensile strength seen in the current study's Forta fibers, microsilica, and metakaolin plan rose by 32.70 percent in the maximum condition. Forta fibers clearly have a part in the tensile strength of concrete.

6.4 Relationship between tensile strength and compressive strength

For quality assurance purposes, concrete's compressive strength is often tested. Using time analysis empirical correlation equations, tensile strength is calculated from compressive strength. Regression analysis was used to statistically determine the link between the 28-day tensile and compressive strength of concrete based on the findings of the strength of 8 different concrete mix designs.

The equation ($y = 0.278 \times ^{0.6856}$) is plotted in Fig. 16 with experimental data. The tensile strength of concrete is represented in terms of a coefficient of tensile strength in this equation (Eq. 3). The regression lines revealed a quite strong correlation. The correlation coefficient (R^2), which indicates how much of the total changes in the dependent variable can be obtained with the regression equation, in which the standard error equals 0.9077, between the splitting tensile strength and compressive strength with the dispersion of the 28-day test data is 0. The correctness of this ratio is shown by the coefficient of determination. Therefore, it is possible to depict the connection between tensile strength and compression using equations to the 0.5 power. As compressive strength increased after 28 days of curing, the link between compressive and tensile strength of concrete diminished. In actuality, the tensile strength of concrete really increases more slowly.

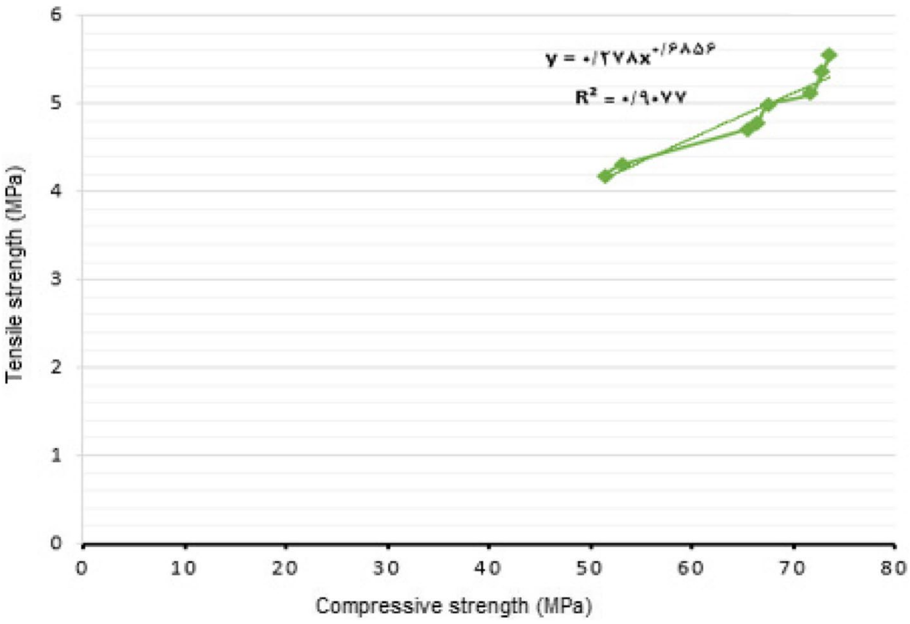

Fig. 16 Relationship between tensile strength and compressive strength of concrete

Table 10 Modulus of elasticity of 28-day concrete (GPa)

The name of the mix	Modulus of elasticity
Plain1	32.54
Plain2	33
F 0.2 SF 10	35.79
F 0.5 SF 10	36
F 0.8 SF 10	36.24
F 0.5 SF 10 MC8	37.08
F 0.5 SF 10 MC10	37.33
F 0.5 SF 10 MC12	37.49

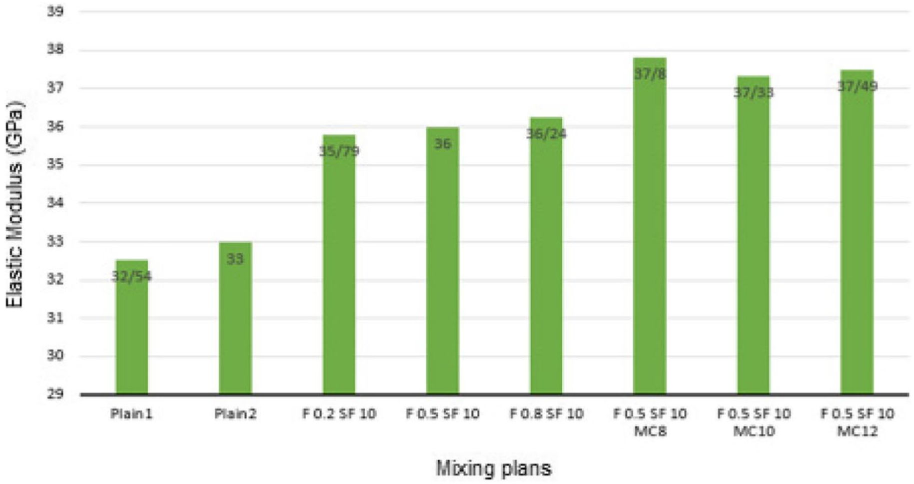

Fig. 17 Modulus of elasticity of concrete at the age of 28 days

$$f_t = 0.278 f_c^{0.6856} \mathrm{MPa} \tag{3}$$

In Eq. 3:

Ft = the tensile strength of the bisection.

F_C = compressive strength of concrete.

6.5 Modulus of elasticity

Although the elastic modulus rises as concrete's compressive strength rises, Table 10 and Fig. 17 demonstrate that the elastic modulus' rate of growth is less rapid than that of compressive strength, and the outcomes of strong concrete designs are generally comparable. In this case, 12 percent of metakaolin is the ideal proportion to get the highest elastic modulus.

In concrete samples, the compressive strength rose together with the elastic modulus. When the concrete was 28 days old, control design 2's elastic modulus was 1.41 percent greater than control design 1's elastic modulus. In designs 3 to 5, the synergy of 10% microsilica with 0.2%, 0.5%, and 0.82% Forta fibers, respectively, is 9.98%, 10.63%, and 11.37% higher than the control sample of design 1, and 8.45, 9.09, and 9.18% higher than the control sample of plan 2. The proportion of fibers has constantly increased together with the elastic modulus trend, reaching a maximum of 0.8 percent.

In designs 6 to 8, the synergistic impact of microsilica 10%, Forta fibers 0.5% and metakaolin 8%, 10% and 12% by weight of cement, the amount of increase in elastic modulus in comparison with the control sample of design 1, respectively, is 13.95. 14.72 and 15.21%, and in comparison with the control sample of design 2, it was 12.36, 13.12 and 13.6%. At the age of 28 days, design 8 (concrete involving 10% microsilica, 0.5% Forte fibers and 12% metakaolin) had the highest elastic modulus of 37.49 GPa.

According to Poon et al.'s study (Hemalatha and Ramas 2017), the elastic modulus rose with the addition of metakaolin up to 10% of the cement weight and declined with higher additions of metakaolin. The elastic modulus rose in the present study by raising the proportion of metakaolin to 12 percent, however this rise was only marginally faster than that of concrete. The ideal amount, therefore, might be thought of as increasing metakaolin up to 12%.

The equation ($y = 2315\sqrt{X} + 20{,}700$) is drawn in the figure with experimental data. In Eq. 4 and Fig. 18, the elastic modulus of concrete is indicated due to a coefficient of compressive strength. The correlation coefficient (R2) in this equation is equal to 0.9854. The coefficient of determination indicates the accuracy of this ratio. As compressive strength increased, the elastic modulus of the concrete after 28 days of curing steadily fell as well.

$$\mathrm{E} = 2315\sqrt{\mathrm{F_C}} + 20700\,\mathrm{MPa} \tag{4}$$

In Eq. 4:

E = elastic modulus of concrete.

$\mathrm{F_C}$ = compressive strength of concrete.

The starting value of the tangent for each mixing design is taken from the stress–strain diagram in order to determine the modulus of elasticity. The witness 1 and 2 concrete's stress–strain curve is shown in Figs. 19 and 20. Control designs 1 and 2 both failed

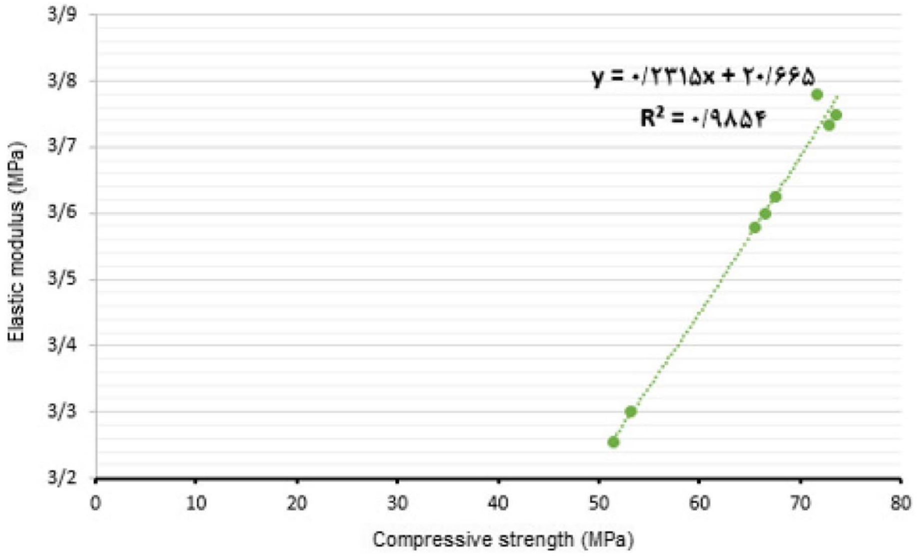

Fig. 18 Relationship between compressive strength and elastic modulus

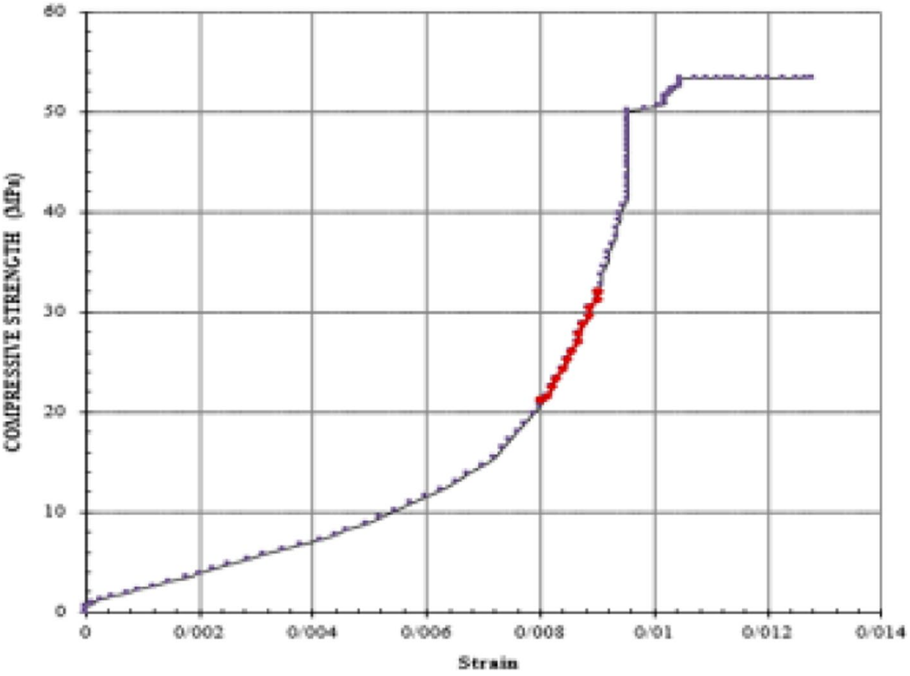

Fig. 19 Stress–strain diagram of plain 1 plan

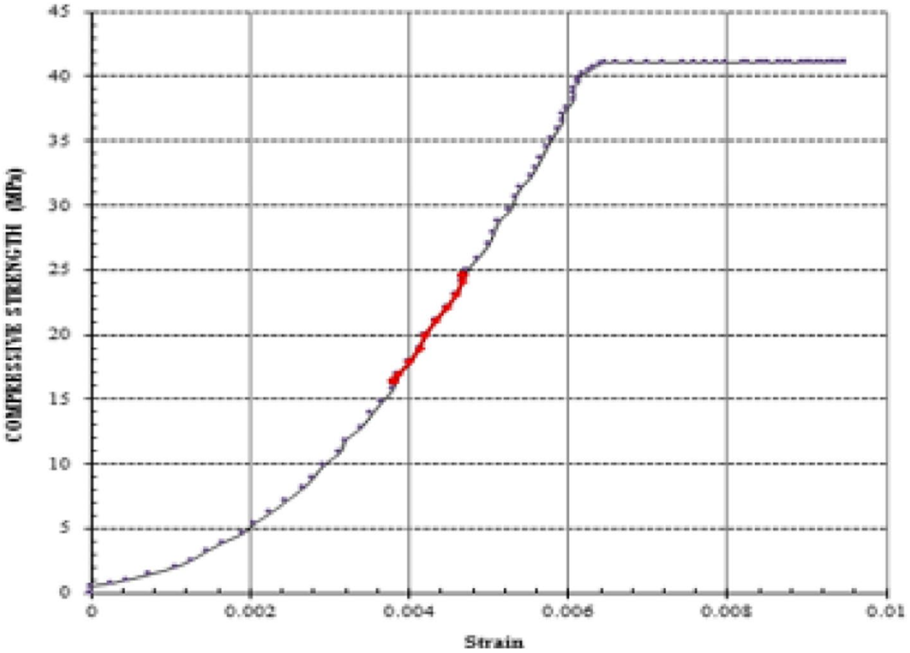

Fig. 20 Stress–strain diagram of plain2 plan

following bearing stresses of 51.4 MPa and 53.3 MPa, respectively, and only displacement occurred. It is clear how silica fume affects design 2's stress tolerance. When the stress (force applied to the concrete sample) is removed, the concrete returns to its initial condition, and the strain is no longer precisely proportional to the stress at the starting points of the stress–strain diagram. The concrete sample is then positioned at the yield point or elastic limit. The concrete sample is put under the most stress following the elastic condition at the red points, and it reaches its failure point at the end of the red points. Following that, the strain keeps increasing even as the stress reduces, and the sample continues to move under pressure.

In Figs. 21, 22 and 23, the synergistic action of Forta and microsilica fibers causes the sample to experience higher compressive stress in the strain stress curve because of the rise in compressive strength and as a consequence of the elastic modulus. Forta fibers provide a beneficial effect in preventing concrete from cracking and spalling when their elastic modulus improves as their number increases linearly. In reality, as fractures begin to appear, fibers like poly hold the individual parts of the concrete together, allowing the concrete to withstand greater stress and have a higher elastic modulus.

The combination of microsilica, Forta fibers, and metakaolin with an increased volume % also has a positive impact on the elastic performance of concrete in Figs. 24, 25 and 26. The stress–strain graphs for these designs show that they begin to deteriorate later than the Forta and microsilica fiber-containing systems. This demonstrates that for concrete with high strength, the ideal proportion of metakaolin may be 8 percent by weight of cement, since the results are relatively similar for metakaolin amounts of 10 and 12 percent. Additionally, excessive fiber volumes might cause concrete's compressive hardness to decline. Since the elastic modulus is quite similar to that of concrete with a volume of 0.8 percent when Forta fibers are used, it is preferable to use 0.5 percent of fibers instead. Forte fibers may cause a very modest increase in concrete porosity (over 0.5 percent),

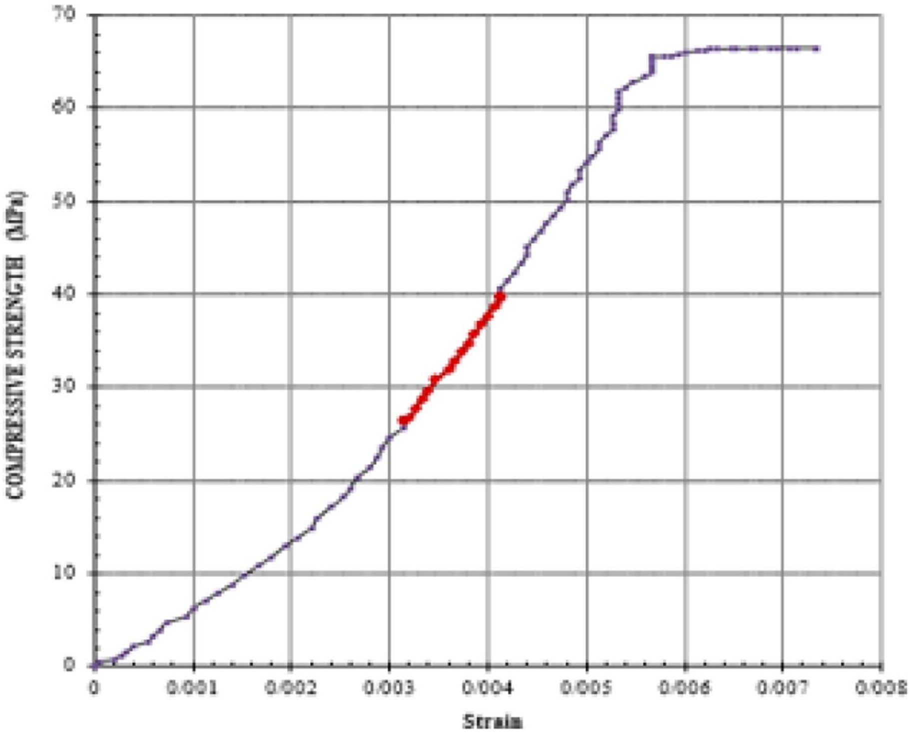

Fig. 21 Stress–strain diagram of F 0.2 SF 10 plan

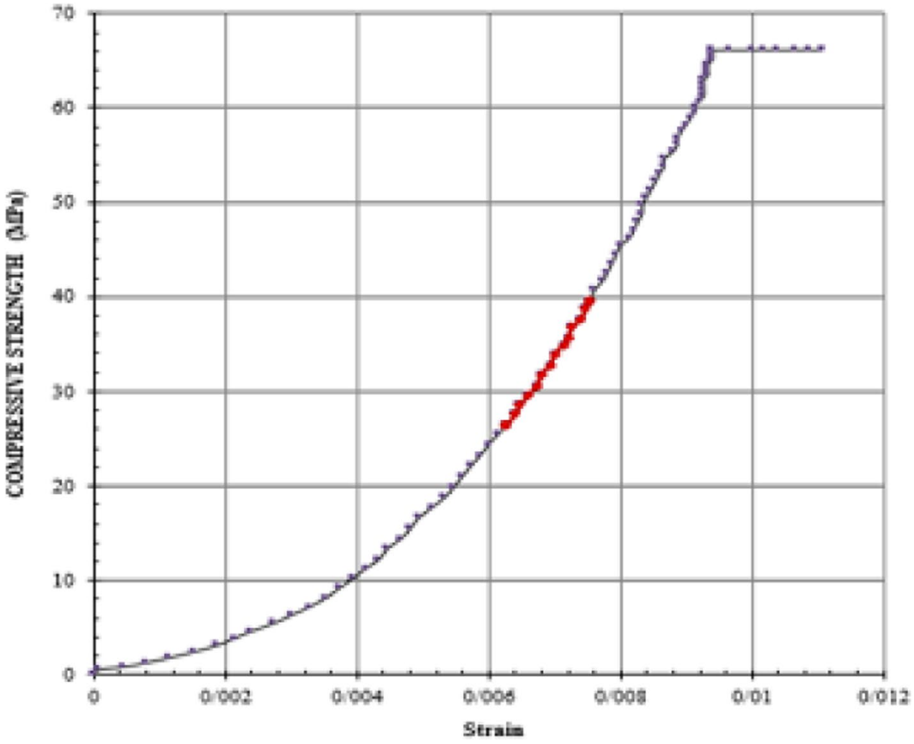

Fig. 22 Stress–strain diagram of F 0.5 SF 10 plan

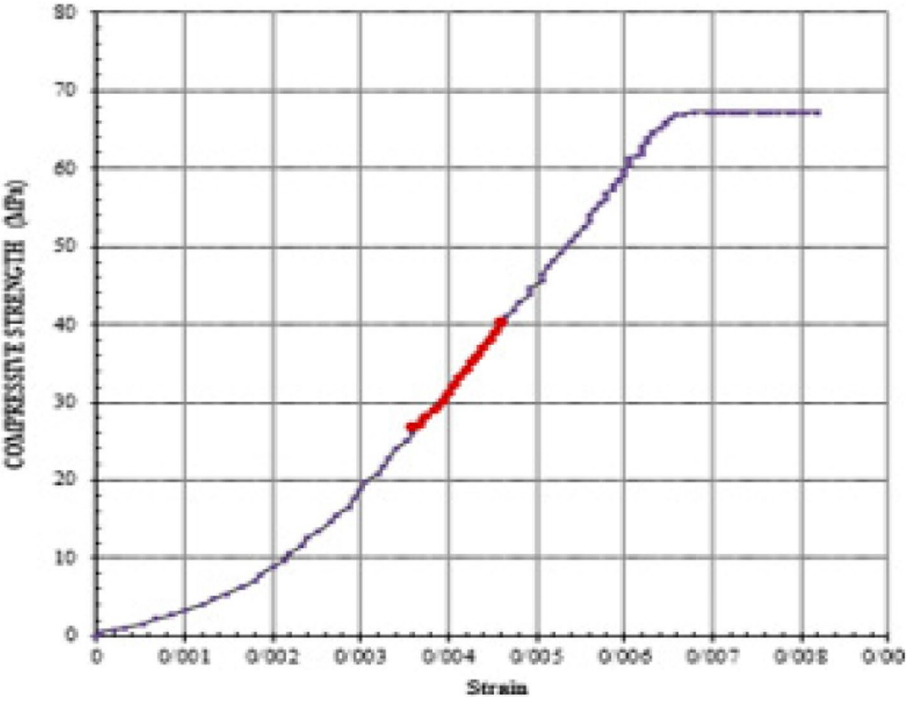

Fig. 23 Stress–strain diagram of design F 0.8 SF 10

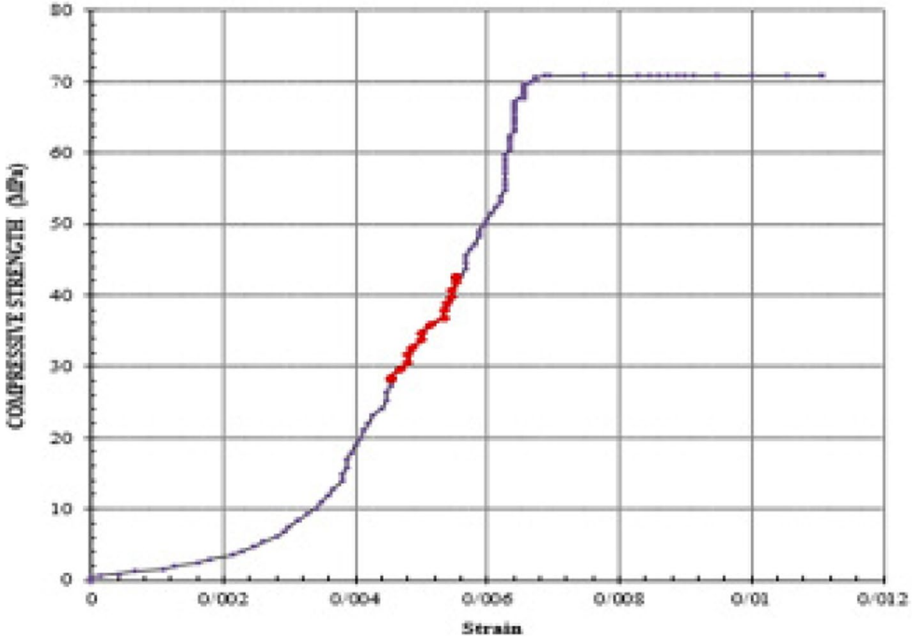

Fig. 24 Stress–strain diagram of design F 0.5 SF 10 MC8

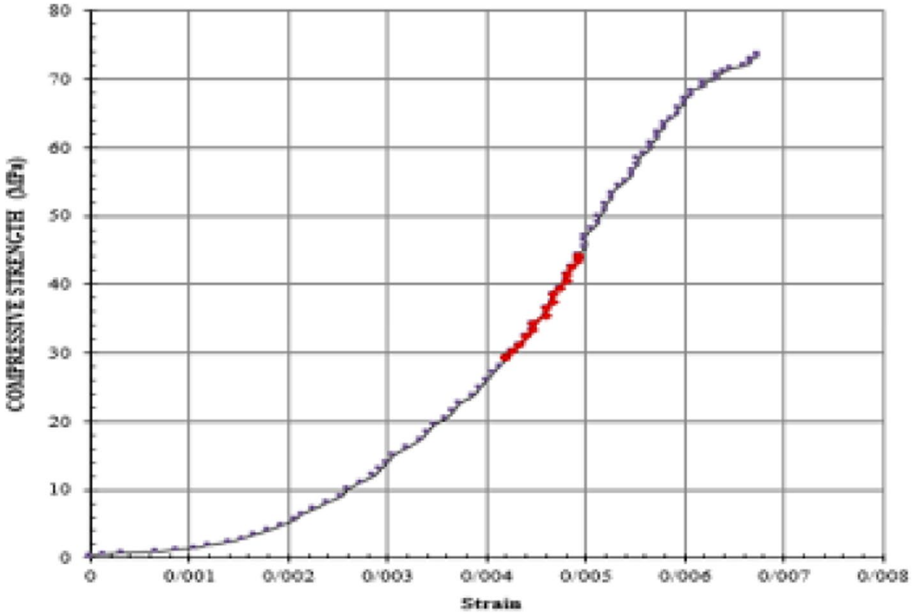

Fig. 25 Stress–strain diagram of 0.5 SF 10 MC10 design

which can also reduce elastic modulus. It was shown that, in contrast to composites with smaller fiber volumes, mixes with high fiber volume had more ductility before to failure during the compressive test. With an increase in metakaolin concentration, a linear rise in energy absorption capacity was seen. Additionally, since the fibers in concrete do not activate before the peak load point, the primary contribution of microsilica to

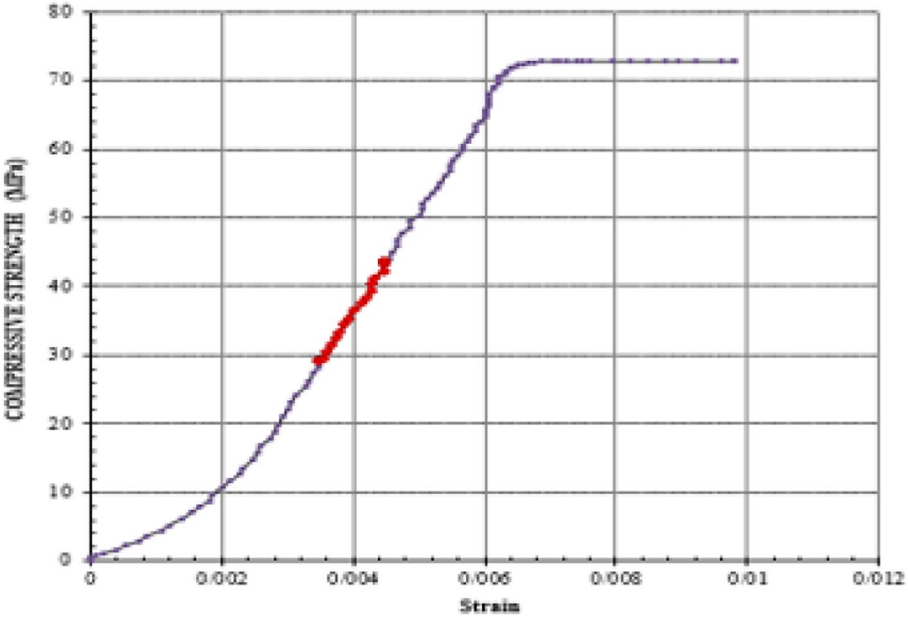

Fig. 26 Stress–strain diagram of 0.5 SF 10 MC12 plan

compressive strength (behavior after the peak load) is emphasized. The elastic modulus is greatly enhanced when all three additives, microsilica, Forta fibers, and metakaolin are used. Therefore, in terms of the elastic properties of high strength concrete, all three characteristics may be significant. Since calculating the elastic modulus in a laboratory setting is challenging and prone to inaccuracy. As a result, it is often assumed that the elastic modulus and compressive strength have an exact proportional connection, and that the elastic modulus eventually exhibits less fluctuations.

7 Results and discussion

In this study, it is crucial to attempt to decrease environmental pollution and produce economically viable concrete by substituting metakaolin and microsilica pozzolans for a portion of cement. In this study, it was also looked at how well the pozzolans microsilica and metakaolin work together. Forta fibers were utilized in addition to the pozzolans already stated in order to improve the tensile strength of concrete. Although the fibers have little to no impact on the compressive strength of concrete, the microsilica factor is very promising for pozzolanic concrete and this reduction in strength compensates. Reinforcing fibers are used to slow the growth of cracks in structures and improve the tensile strength and flexural strength of concrete.

8 Conclusions

From this study on the impact of partial replacement of cement with metakaolin and microsilica in concrete containing Forta fibers, we can conclude:

1. All strong concrete compounds regarded in this research have a common trend, that is, all strength points increase with the age of the sample and the volume of additive.

2. The efficiency (slump and setting time) increased in terms of the increase in the replacement level of metakaolin, silica fume, and Forta fibers.
3. The greatest quantity of slump reduction in concrete designs 5 (concrete containing 10% microsilica and 0.8% Forta fibers), and 8 (concrete containing 10% microsilica and 0.5% Forta fibers and 12% metakaolin) with an amount equal to 50 mm happened.
4. Metakaolin may be economically regarded better than silica fume because it is cheaper than silica fume, and it needed less superlubricant than silica fume.
5. The highest compressive strength at the age of 28 days of design 8 (concrete concluding 10% microsilica, 0.5% Forta fibers and 12% metakaolin) was equal to 73.6 MPa.
6. The highest tensile strength at the age of 28 days of plan 8 (concrete concluding 10% microsilica, 0.5% Forta fibers and 12% metakaolin) was equal to 5.55 MPa.
7. The highest elastic modulus at the age of 28 days of plan 8 (concrete concluding 10% microsilica, 0.5% Forta fibers and 12% metakaolin) was equal to 37.49 GPa.
8. Adding silica fume, Forta fibers and metakaolin has always had a positive impact on the strength of strong concretes and they reached desired result at the age of 28 days.
9. The optimal amount of Forta fibers in strong concrete is recommended between 0.5 and 0.8 percent and the optimal amount of metakaolin between 10 and 12 percent.

The results of this research showed that cement with metakaolin and microsilica in concrete containing Forta fibers can be very useful in bridge structures, especially the foundation and deck of concrete bridges.

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Authors' contributions
Prof. Faghihmaleki examined the necessity and importance of the research as well as the interpretation of the results and summarization of the data. Mr. Nazari did the laboratory work and also analyzed the results.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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