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Investigating the Effect of Silica Foam on the Mechanical Properties of Concrete Containing Recycled Glass Shards

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ABSTRACT

Recycled glass waste is one of the most attractive waste materials that can be used to create a concrete mix. Therefore, researchers focus on the production of concrete using recycled glass as an abrasive or as a pozzolanic material, but the use of recycled glass in the form of coarser particles to replace sand in concrete increases the alkali-silica reaction and this causes Unfavorable performance in the mechanical properties of concrete. To prevent this, micro silica is used to improve the strength and mechanical properties of concrete .In this research, after building the control mixing design, recycled glass was replaced with sand and silica foam as micro silica in four designs with a fixed ratio of 5% by weight of cement. The compressive strength test was performed at the ages of 7 and 28 days, and three samples were taken in each test, and a total of 24 cubic samples were tested. Tensile test, like compressive strength test, were tested at the ages of 7 and 28 days, which included two cylindrical samples in each test, and a total of 16 cylindrical samples were tested. The presence of silica foam in concrete causes adhesion and reduction of slump fluidity, and the highest slump fluidity was observed at 5% ratio. The result of testing the compressive strength and tensile strength of the concrete containing glass shards and silica foam had decreased in quality compared to the control mixing plan, which shows the unfavorable performance of coarse glass particles in the concrete structure.

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1. Introduction

Concrete is one of the most widely used materials in engineering structures [1]. The favorable physical and mechanical properties of concrete and the ease of its production have made concrete the most widely used material in the construction industry. The compressive strength of concrete and bearing high pressures is one of its characteristics [2]; In this way, it shows good resistance against sudden failures and compressive stresses other characteristics of concrete that can be mentioned are high energy absorption and fire resistance [3]. Although concrete works well in civil works, its components are made from natural sources.

Lack of natural resources and over-harvesting can cause great problems in the future. Therefore, an alternative to the materials used in concrete that reduces the damage to the environment is felt more than ever [4]. The volume of industrial and construction waste landfills is expanding [5]. According to the estimates made in the last few years, we

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have faced an increase of 9.2% of natural materials [6]. One of the ways to deal with this important issue is to recycle and reuse it. This will prevent the accumulation of waste materials. Glass is one of the waste materials that we see producing a significant amount of it all over the world. In 2004, the United Nations estimated the production of solid waste in the whole world to be about 200 million tons, of which more than 7% was glass waste [7]. Concrete containing glass shards is one of the modern innovations in the construction industry, which avoids problems related to their burial and recycling by using glass shards as a substitute for traditional aggregates. But concrete containing glass fragments may lose properties such as mechanical resistance and weather resistance compared to traditional concrete. In order to improve the properties of concrete containing glass shards, adding silica foam to it as a strength additive is investigated. Silica foam is a self-compacting filler material that, by adding it to concrete, reduces the porosity and weight of the concrete itself, and as a result improves the mechanical resistance and thermal properties and insulation of concrete.

Bhanja and Sengupta in 2005 [8], conducted experiments on a water ratio of 0.26 to 0.42 and a silica foam ratio of 0.0 to 0.3. and considered compressive, tensile and bending strength for all samples in this research. The obtained results show an increase in compressive and tensile strength with silica foam composition and that the percentage of substitution in the tests is not fixed at one percent but depends on the ratio of water to cement. Compared to split tensile strengths, flexural strengths showed more improvements. Evaldes and Vitoldas in 2021 [9], collected glass from a dump site and crushed it in a ball mill in two ways before and after cleaning, and then the glass shards were analyzed by a scanning electron microscope (SEM) and analyzed by energy dispersive X-ray spectroscopy (EDX).

The effects of waste glass powder before and after cleaning, hydation process of Portland cement were analyzed using semi-adiabatic calorimetric method. For further research, the boiler properties such as density, compressive strength and porosity of ordinary strength concrete with different amounts of glass powder were also investigated. In these tests, it was found that when 25% of the ordinary sand was replaced with waste glass powder after the cleaning process, a slight increase in compressive strength could be expected. Vaitkus and et al., in 2020 [10], in percentages of 0%, 7% and 10% compared to cement and a fixed ratio of 0.4 water to cement ratio. The designs were tested in compression, tension and cyclic loading of production. In addition, the density was determined to identify the difference in concrete microstructure due to the presence of silica fume. The results showed that silica foam significantly increases the performance of high-strength concrete in terms of pressure, stretch, bending and cyclic loading, and the design of 7% is the optimal value.

The use of glass in concrete can be done in two ways: glass shards as a substitute for part of the aggregate and glass powder as a substitute for part of the cement. One of the biggest concerns for replacing glass chips as part of the aggregate is its alkali-silica reaction. This reaction in concrete causes closure of expansion joints, displacement of structural members relative to each other and other adverse effects. One of the ways to reduce the effects of the alkali-silica reaction is to add additional cement materials such as silica foam, which is a powder with very fine silica particles that is obtained from the processing and grinding of nano silica or silica foam.

The addition of silica foam in concrete significantly improves concrete, reduces shrinkage in the drying process, which leads to the reduction of surface cracks and fractures in concrete, and increases the adhesion between cement and minerals. In addition, the presence of silica foam in concrete increases the compressive and tensile strength. Therefore, it is necessary and important to investigate the percentage of replacement and the necessary amount of silica foam to reduce the alkali-silica effect and increase the strength of concrete.

2. Laboratory program

2.1. Specifications of materials used in concrete

2.1.1. Aggregate

The aggregate used in the research concrete is from the sand of the Tonkabon spring river. The rough outer surface of the aggregate provides more surface area for materials such as water and cement to bond. The maximum size of the aggregate is another important factor, which was done by conducting a granulation test and using standard sieves, a mechanical shaking device for sieves and a scale with an accuracy of 0.1, and finally by comparing with the permitted range of ASTM. The used aggregates were completely dried in an oven at a temperature of 110°C before testing, and then they were tested vertically and horizontally in a shaking machine at a speed of 150 rpm for ten minutes.

2.1.2. Cement

The cement used in this research is type 1 Portland cement, this gray cement is called ordinary Portland cement. Type 1 Portland cement is divided into three resistance categories 325, 425 and 525 based on 28 days resistance. This used cement is the first category of type 1 cement and is for general use in making mortar and concrete.

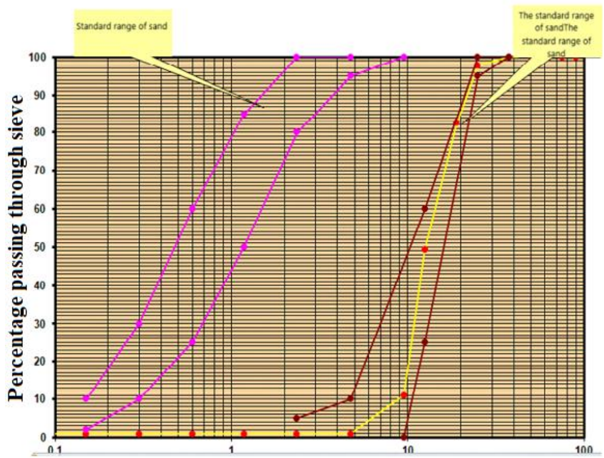

Figure 1: Gravel grading chart compared to ASTM limits

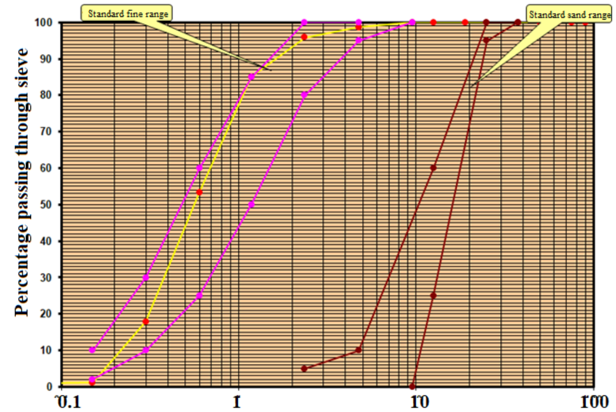

Figure 2: Graph of sand grading compared to ASTM limits

Table 1
Physical properties of cement used in concrete

Physical properties of cement	amount
Initial capture time	100-160minutes
Secondary capture time	180-240minutes
Autoclave volume expansion	0.15-0.05%
Special level	2900cm2/gr

Table 2
Comparison of chemical and physical properties of cement compounds

Feature	Portland cement	Silica fly ash	Lime fly ash	cement slag	Silica foam
SiO2	21.9	52	35	35	85-97
Al2O3	6.9	23	18	12	-
CaO	6.3	5	21	40	<1
SO3	1.7	-	-	-	-
(m2/kg) specific surface	370	420	420	400	30000-15000
Specific density	3.15	2.38	2.65	2.94	2.22
General use in concrete	Primary binder	Cement substitute	Cement substitute	Cement substitute	Amplifier

Figure 3: Appearance of silica foam.

Figure 4: Appearance of used glass shards.

2.1.3. Silica foam

Silica foam is a polymorph of the amorphous (non-crystalline) solid form of silicon dioxide. This ultra-fine powder can be produced as a by-product of silicon and ferrosilicon alloy and consists of spherical particles with an average diameter of 150 nm. The first experiment of silica fume in Portland cement concrete was done in 1952.In early research, an expensive additive called silica foam, an amorphous form of silica, was made and used by burning silicon tetrachloride in a hydrogen-oxygen flame. The specific gravity of silica foam is generally in the range of 2.2 to 2.3. The specific surface area of silica foam can be measured by the BET method or the nitrogen absorption method. It typically ranges from 15,000 to 30,000 square meters/kg.

2.1.4. Glass shards

Aggregates make up almost 70% of concrete composition, for this reason, using glass aggregates in concrete can lead to reduction of glass waste. In this research, it was done by using recycled glass and crushing them manually, and the size of the glass shards was based on the sand grading chart and coordinated with the size of the sand grains. The size of glass shards after final crushing is between 0.5 and 2.5 cm.

2.1.5. Lubricant

The additive used in this research is radon concrete lubricant, which is very suitable for the production of high-strength concrete. The consumption amount of super lubricant in this research is 2% of the cement weight in the mixing plan. Each time the super lubricant was added to the last part of the water sample and then added to the mixture.

2.1.6. Water

The water used in the construction of mixing plans and sample processing was from the drinking water of Tonkabon city.

Table 3

Characteristics of super lubricant

Increase in air percentage	less than 2%
Alkali content	Less than 5 grams of Na2O
Chemical base	Polycarboxylate ether
Chlorine ion	does not have
color	Colorless and transparent
Freezing temperature	minus three degrees Celsius
PH value	3 to 7
physical state	liquid
specific weight	1.18±0.05grams per cubic
brand	RAMKA

2.1.7. mixing designs

In this research, in order to achieve a suitable mixing plan for concrete with a strength of 30 MPa in a period of 28 days, the percentage of water to cement is 0.52 and during four mixing plans with percentages of 5, 7, 10 and 12 percent, silica foam and glass shards with A constant of 5% was considered in four mixing plans, which was done by making cubic and cylindrical samples and performing compressive and tensile strength tests by concrete breaker jack machine at the age of 7 days. The mixing plan of control concrete samples (Table 4) was made to achieve concrete with a strength of 30 MPa. 4 cubic samples 15*15*15 and 4 cylindrical samples 15*30 without lubricant were made. The best compressive strength obtained in the 7-day sample was 262 kg/m^2.

Table 4

Control sample mixing plan

cement	water	sand	sand	Water to cement ratio
380	198	1136	659	0/52

The main mixing plan of the research in Table 5, which includes concrete containing silica foam and glass shards containing lubricant. In this plan, the mixing of silica foam is considered as a percentage of the cement volume. The glass shards used in this mixing design are fixed at 5% and

Figure 5: Cubic and cylindrical samples of control concrete

Table 5
Mixing scheme of concrete containing silica foam and glass shards

Mixing design number	sand	sand	cement	Silica foam	water	shards of glass	lubricant
silica foam 5%	1136	659	361	19	198	56/8	7/6
silica foam 7%	1136	659	353/4	26/6	198	56/8	7/6
silica foam 10%	1136	659	342	38	198	56/8	7/6
silica foam 12%	1136	659	334/4	45/6	198	56/8	7/6

Figure 6: The process of making and processing samples.

have been replaced as a part of coarse sand, and the lubricant used is 2% of the cement volume.

2.1.8. Making samples

After preparing the materials, cement, silica foam, shards of glass, gravel, sand and water are first weighed. After collecting the sand materials, pour it into the mixer and add 80% of the weighed water to it, after a minute, add silica foam to the coarse sand and mix them properly. The mixing process continued for 2-3 minutes. After sand and glass shards are added to the materials in the mixer at the same time and after 2-3 minutes cement is added to it and after 2 minutes the lubricant is added to 20% of the remaining water and allowed to mix. We let the mixer continue to work for another 3-5 minutes and after 3-5 minutes, turn off the mixer and the desired concrete is ready to be placed in the mold. After cleaning the inside of the mold and greasing it with special oil, the made concrete was poured into the molds in three layers and 25 strokes in each layer by the rod and compacted. After 24 hours, the samples were removed from the mold and kept in the water pool with Ph close to 7 for processing (Figure 6).

3. Tests

3.1. Concrete slump test

In this research, to perform the slump test, first, the inside of the cone mold was completely cleaned and moistened, and concrete was poured into the funnel in three layers and with equal volume. The layers were compacted by a rod with 25 strokes. After compaction of the last layer, the slump mold was pulled up vertically without moving the base plate, and then the amount of concrete drop from the height of the rod on the metal plate to the highest point of the concrete was measured and recorded.

Figure 7: Concrete slump test

Figure 8: Cube samples after being taken out of the pond and tested for compressive strength

Figure 9: Cylindrical samples after being taken out of the pond and tested for tensile strength.

Table 6

Conversion coefficients of non-standard samples to standard samples.

150mm cubic compressive strength (MPa)	≤25	30	35	40	45	50	55
Compressive strength of standard cylinder (MPa)	1.25	1.20	1.17	1.14	1.13	1.11	1.1

3.2. Compressive strength test of concrete

In order to control the quality of hardened concrete, a compressive strength test was performed to determine the capacity of concrete made against direct compressive forces on cubic samples by a concrete breaker jack and the possibility of software analysis. Compressive strength depends on several factors, including the quality of consumables, mixing plan and quality control during concrete production. To perform the compressive strength test, after 7 and 28 days of treatment in the pond, the samples were removed from the water one day before the test and placed in the open air to dry (Figure 8). Then put the sample in the place where the sample is placed inside the device and turn on the device. After the device applied force to the sample and the number shown on the device remained constant, the device was turned off and the amount of stress and force was recorded.

3.3. Concrete tensile strength test

In this research, the samples were removed from the pond after 7 and 28 days of treatment and placed in the open space for one day to dry completely. The tensile test of concrete was performed by cutting a cylindrical sample in half based on the ASTM C496 standard. The samples were fixed and tested in the appropriate place with the help of steel rod and bottom plate in the machine. in such a way that the load is applied against the direction of concreting. After performing the test steps, it was recorded with the maximum load and the tensile strength was calculated by halving the Eq. (1).

$$T = \frac{2P}{\pi l d} \quad (1)$$

In Eq. (1):
T = halving tensile strength (kg/cm^3)
P = maximum applied load (kg)
L = length of cylindrical specimen
d = diameter of cylindrical sample (cm)

3.4. Concrete elasticity modulus test

The modulus of elasticity test of concrete is one of the important tests in evaluating the mechanical properties of concrete. The modulus of elasticity indicates the hardness and resistance of concrete against deformation under applied loads. The modulus of elasticity of concrete is defined as the ratio of applied stress to the corresponding strain in concrete. The larger the aggregates used in concrete, the higher the modulus of elasticity of concrete. With higher loading speed, the compressive strength of concrete increases, and in this direction, the modulus of elasticity of concrete also increases. The modulus of elasticity makes it possible to predict the behavior of structures under different loadings and indicates how much concrete can withstand the load without undergoing changes. To check the samples in this research, the compressive strength test results of 28-day cubic samples were used. The coefficients in table (6) were used to convert the resistance of a cubic sample to a cylindrical sample. The modulus of elasticity of concrete under tension or compression is obtained by the slope of the stress-strain curve under uniaxial loading from Eq. (2).

$$E = \left(3300\sqrt{F_c} + 6900\right)\left[\frac{\gamma_c}{23}\right]^{1.5} \quad (2)$$

In Eq. (2):
E = modulus of elasticity of concrete GPa
F_c = compressive strength of concrete MPa
γ_c = specific mass of concrete kN/m^3

4. Results and discussion

4.1. Concrete slump test

The results of the fresh concrete slump test are presented in Table 7. The result of concrete slump in concrete without silica foam has little separation and no water loss, and the amount of fresh concrete slump is 80 mm. Silica foam in concrete caused an increase in concrete slump due to its very high adhesion property. In concrete containing silica foam, concrete slump increased and the slump in concrete containing 5% silica foam was 74 mm. Also, the concrete slump containing 12% silica foam has increased and has shown a number of 50 mm, and this is a reason for the amount of water absorption of silica foam compared to the use of ordinary cement alone. The presence of silica foam in concrete has increased the water consumption.

Table 7
Concrete slump results

The name of the mix	Slump (mm)
Witness concrete	80
Silica foam 5%	74
Silica foam 7%	67
Silica foam 10%	58
Silica foam 12%	53

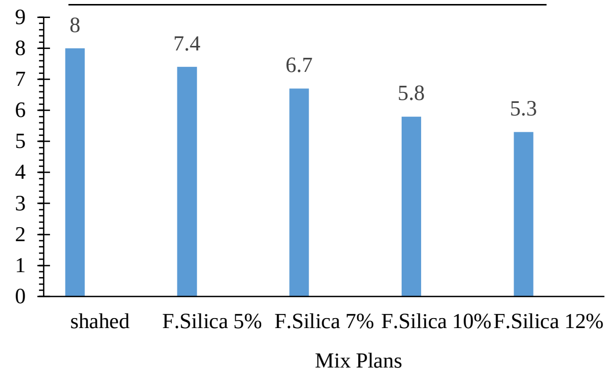

Figure 10: Concrete slump diagram (cm).

According to Figure (10), the concrete sample containing 5% silica foam decreased by 7.5% compared to the control concrete sample, and the fluidity was close to the control concrete. Also, for the concrete sample containing 7% silica foam, 16.25% slump reduction occurred. 10% and 12% silica foam samples have 27.5% and 33.75% slump reduction, respectively. The adhesion of these two samples is much higher due to the presence of more silica foam in its mixing plan.

4.2. Compressive strength test

The results of the compressive strength test show that the strength of the samples has increased due to the increasing age of processing. The strength of the 28-day concrete cube sample has increased by 24.3% compared to the 7-day sample. In the sample containing 5% silica foam, the 28-day compressive strength has increased by 22.39% compared to the 7-day sample, and in the samples with 7, 10, and 12% silica foam, it has increased by 20.93, 17.58, and 22.70%, respectively. These plans have shown a lower initial resistance than the control concrete.

7-day concrete samples containing silica foam and glass shards showed a decrease in compressive strength compared to the 7-day control sample. In the 7-day concrete samples containing 5% silica foam, there was a

34.61% decrease compared to the 7-day control sample. In 7-day concrete samples containing 7% silica foam compared to the 7-day control sample, there was a 35.18% decrease, and in the 7-day concrete samples containing 10 and 12% silica foam compared to the 7-day control sample, there was a 36.21 and 42.24% decrease, respectively. has had

Table 8
Compressive strength test results (Mpa)

No mixing	Compressive strength at 7 days	Compressive strength of 28 days
Concrete sample as witness	25.7	33.9
A sample of 5% silica foam	16.8	21.6
A sample of 7% silica foam	16.6	21
A sample of 10% silica foam	16.4	19.9
A sample of 12% silica foam	14.8	19.2

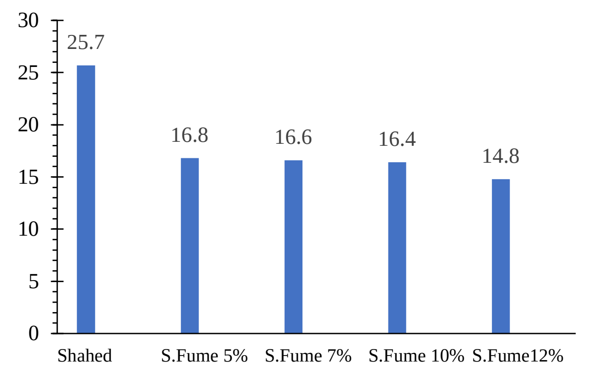

Figure 11: Graph of the 7-day compressive strength results of the samples (MPa).

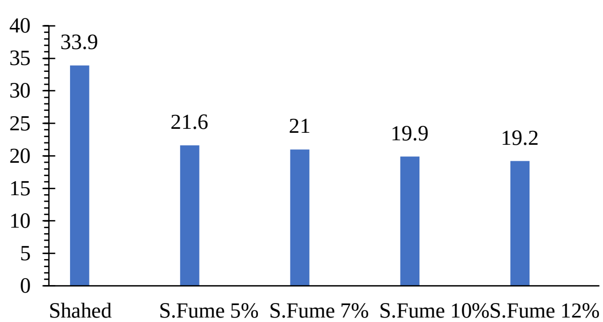

Figure 12: 28-day compressive strength results graph of the samples (MPa).

In the 28-day concrete samples containing silica foam and glass shards, it showed a decrease in compressive strength compared to the 28-day control samples. In the samples of 28 days, 5% silica foam has decreased by 36.21% compared to the control sample of 28 days. In the 7 and 10% silica foam samples, compared to the 28-day control sample, there was a decrease of 37.95 and 41.41%, respectively, and in the 28-day sample containing 12% silica foam, there was a 43.43% decrease compared to the 28-day control sample. The ratio of glass shards in all samples was 5% compared to coarse sand.

4.3. Tensile strength test

The tensile strength of concrete decreased with the decrease of compressive strength compared to control concrete. At the age of 28 days, the tensile strength of concrete in the design containing 5% silica foam and 5% glass shards has decreased by 32.05% compared to the control design, and at the age of 7 days, the 5% sample has shown a 42.8% decrease. Tensile strength of concrete in 7 days 7% and 10% silica foam samples compared to the control sample showed 51.42% and 71.42% decrease in tensile strength, respectively.

Among the samples, the largest reduction in strength was the 12% silica foam sample, which had a 74.85% reduction in strength compared to the control concrete. The highest resistance observed among the samples was the 5% sample with a resistance of 2.01 MPa. The tensile strength of concrete in the 28-day sample containing 5% silica foam has decreased by 32% compared to the control concrete. In the samples containing 7% and 10% silica foam, compared to the control concrete, it showed a 42.3% and 64.1% decrease in tensile strength, respectively. The sample containing 12% silica foam has seen a 71.7% reduction in strength compared to concrete, which is the highest reduction in strength among the samples. The highest tensile strength obtained among the samples of 28 days was related to the sample containing 5% silica foam, which showed a tensile strength of 2.65 MPa.

4.4. Elastic modulus test

The test results of concrete modulus of elasticity at the age of 28 days are presented in the table. According to the obtained results, the modulus of elasticity decreases with the increase of silica foam in concrete. The obtained result shows that the rate of increase of concrete elasticity modulus is lower than the rate of increase of concrete compressive strength and the obtained results are relatively close to each other. In the tests conducted, the modulus of elasticity increased with the increase in compressive strength. The highest number obtained in the results of the tests was related to the witness concrete.

In the design containing 5% silica foam compared to concrete, it has shown a 15.49% decrease in modulus of elasticity. In designs containing 7% and 10% silica foam,

Table 9
Tensile strength results (MPa)

The name of the mix	Witness sample	A sample of 5% silica foam	A sample of 7% silica foam	A sample of 10% silica foam	A sample of 12% silica foam
Tensile strength 28days	3.9	2.65	2.25	1.4	1.1

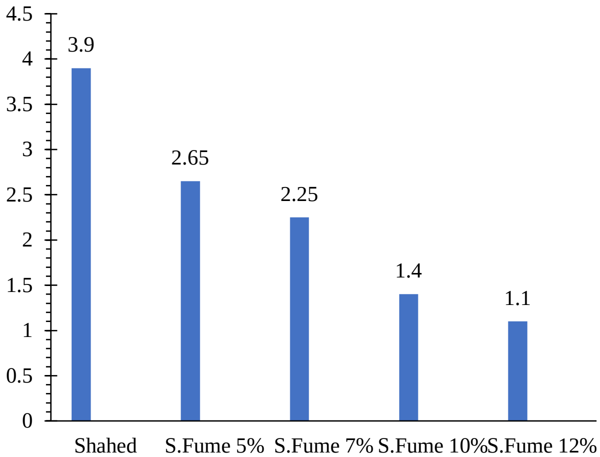

Figure 13: The graph of tensile strength test results at the age of 28 days (MPa)

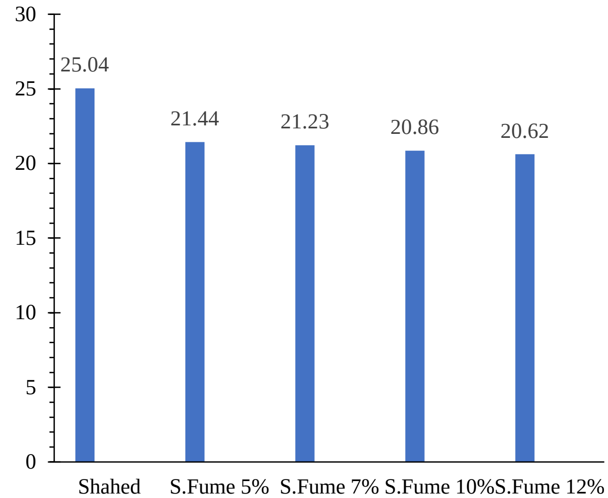

Figure 14: Diagram of modulus of elasticity of concrete at the age of 28 days (MPa)

Table 10: Modulus of elasticity of 28-day concrete (MPa)

The name of the mix	Witness sample	A sample of 5% silica foam	A sample of 7% silica foam	A sample of 10% silica foam	A sample of 12% silica foam
Modulus of elasticity	25.04	21.44	21.23	20.86	20.62

compared to the control concrete, there was a decrease of 16.47 and 18.21%, respectively, and compared to the sample containing 5% silica foam, it showed a decrease of 0.98 and 2.74%, respectively. In the design containing 12% silica foam, compared to the control sample, it has decreased by 19.36% and compared to the sample containing 5%, it has shown a decrease of 3.9%. The sample containing 12% silica foam has the lowest modulus of elasticity of concrete among the samples and the sample containing 5% silica foam has the highest modulus of elasticity of concrete.

5. Conclusions

As a result, the following conclusions were obtained:

1. The presence of silica foam in concrete due to its high adhesion has a negative effect on the mental properties of concrete and reduces the efficiency of concrete, which in concrete samples containing 5% silica foam is 7.5%, 7% silica foam is 16.25, 10% silica foam is 27.5 and the sample of 12% silica foam has decreased by 33.75% compared to the control sample.
2. The best result of compressive strength in concrete samples is related to the strength of the sample containing 5% silica foam with a resistance of 21.6 MPa and the lowest compressive strength obtained among the samples is related to the sample containing 12% silica foam with a resistance It was 19.2 MPa.
3. The highest tensile strength obtained among the samples was related to the sample containing 5% silica foam with a resistance of 2.65 MPa, and the lowest tensile strength was related to the sample containing 12% silica foam with a resistance of 1.1 MPa.
4. The highest modulus of elasticity obtained among the samples was related to the sample containing 5% silica foam with a resistance of

21.44 GPa, and the lowest amount of resistance among the samples was the sample containing 12% silica foam with a resistance of 20.66 GPa.

5. Adding shards of glass to concrete has caused the concrete to break apart and crack, and as a result, it has caused a drop in concrete strength.

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