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# Engineering properties of amorphous silica as a new natural pozzolan for use in concrete

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**Abstract**

Nowadays, in order to produce the high strength concrete in the civil engineering applications, the use of different types of admixtures is well-known. In general, these materials are either chemical or mineral products. In this paper, the formations of amorphous silica of Isparta Region are defined in a technical manner and their use in the concrete manufacturing as a natural pozzolan is evaluated. The effectiveness of amorphous silica in making high strength concrete material is analysed experimentally, and the research findings are discussed.


*Keywords:* Amorphous silica; Pozzolan; Admixture; Aggregate; Concrete

## 1. Introduction

Pozzolanic materials can be natural in origin or artificial and are available widely. They have been used throughout the world to make good quality concrete in recent years. Although they have been used successfully in many countries finding new and improved ways to build a high strength concrete with new pozzolans is receiving much attention. Due to its imparting strength to concrete and durability, silica fume by-product from industrial waste materials is a well-known and very efficient pozzolan. Recent research on energy conservation in the cement and concrete industry has been focused on the use of less energy intensive materials, such as fly ash, slag and natural pozzolans. The natural pozzolanic materials most commonly met with are: volcanic ash which is the original pozzolan, pumicite, opaline shales and cherts, calcined diatomaceous earth, and burnt clays. ASTM C618-03 describes these materials as Class N [1]. Some natural pozzolans may create problems because of their physical properties; e.g., diatomaceous earth, because of its angular and porous form, requires a high water content. Certain natural pozzolans improve their activity by calcination in the range of 550–1100 °C, depending on the material [2].

Much attention has been given to the use of condensed silica fume as a possible partial replacement for cement. Silica fume, a by-product in the manufacture of ferrosilicon and also of silicon metal, is a very efficient pozzolanic material, though there are some problems associated with its use in concrete. There exist also other processed amorphous silica containing materials. One of these is metakaolin, obtained by calcinations of pure or refined kaolinitic clay at a temperature of between 650 and 850 °C, followed by grinding to achieve a fineness of 12,000 $m^2/kg$ [3]. The resulting material exhibits high pozzolanicity. The supply of natural amorphous silica is limited in the world. A few years ago, the only amorphous silica quarry evaluated to be economical was in New Zealand in the Tikitere region. This amorphous silica rock has been used in traditional concretes and high performance concretes [4].

In this paper, a new amorphous silica material in the Keciborlu region of Turkey is introduced as a natural pozzolan. There are two amorphous silica zones in the region. Therefore, the research was carried out on silica

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Fig. 1. Geographical location of amorphous silica quarry in Turkey.

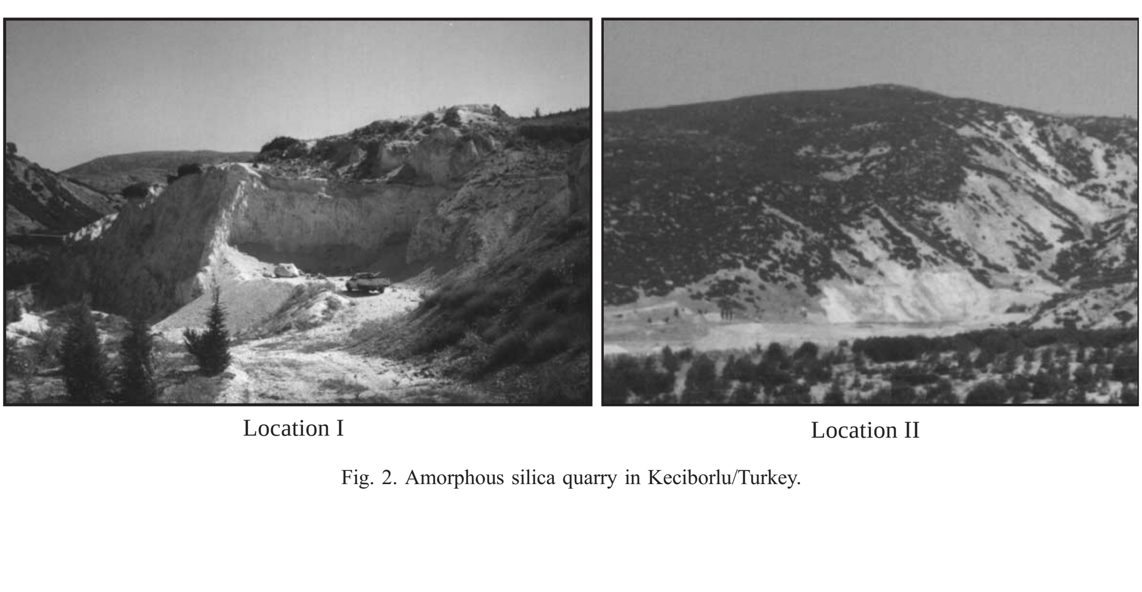
from two different locations, called Location I and Location II to determine the effectiveness of its use in concrete. The research findings are presented and the evaluation of the amorphous silica rock based on the requirements of natural pozzolanic materials is discussed.

## 2. What is amorphous silica?

Amorphous silica is a very efficient natural pozzolanic material. It is processed from natural white geosilica deposits. As aggregates or as silica powder, it is particularly suitable to the modern construction industry. It has been used for construction since 1994 in New Zealand and its use has been improved along the years [5]. Like silica fume made as a by-product in the manufacture of ferrosilicon and also of silicon metal, it can be used as a very fine powder material and falls into the microsilicon family of products. The availability of superplasticizers in concrete facilitates the use of amorphous silica to make high performance concrete mixed with Portland cement. Today, it is particularly appreciated for its mechanical strength, durability, thermal and acoustic insulation used as aggregate, all elements which in addition to savings of energy provide applications in modern buildings in harmony with the environment. The high mechanical strength of amorphous silica granulate, derived from the partial expansion of the material and of its unique chemical composition, allows for a reduction of material in concrete mixtures, thus achieving a marked cost reduction. Due to its structure, amorphous silica aggregate possesses elastic qualities which ensure optimal resistance to external mechanical effect. These characteristics, together with its durability, make amorphous silica ideal to be used in seismically active areas.

A new amorphous silica is produced in the Mediterranean region of Turkey located at about 50 km off the Isparta City centre, called Keciborlu the Sulphur Region, and shown in Fig. 1.

The deposits are all geologically recent and slightly consolidated. Amorphous silica (AS) for industrial use is produced from two locations in the quarry with different chemical composition, and an apparent density of less than 650 kg/m$^3$ under oven dried conditions. It comprised of



Location I Location II

Fig. 2. Amorphous silica quarry in Keciborlu/Turkey.

Table 1
Chemical analysis of amorphous silica from Turkey

| Major element | Location I (%) | Location II (%) |
|---|---|---|
| $SiO_2$ | 92.48 | 90.84 |
| $Al_2O_3$ | 2.60 | 2.66 |
| $TiO_2$ | 1.34 | 1.24 |
| $Fe_2O_3$ | 0.09 | 0.15 |
| MgO | 0.00 | 0.00 |
| CaO | 0.31 | 0.18 |
| $Na_2O$ | 1.08 | 1.12 |
| $K_2O$ | 0.04 | 0.09 |
| $SO_3$ | 0.09 | 0.06 |
| Loss on ignition | 1.85 | 3.51 |

silica and minor amounts of iron, calcium, sodium, potassium and magnesium.

The amorphous silica is extracted from the deposit by open pit mining without the use of explosives to maintain the integrity of the original granular shape (Fig. 2).

The ore is extracted by loaders or excavators in the deposits and transported by dump trucks to the factory for optimum crushing, screening and grinding. Then the processed amorphous silica is stored in silos and used as aggregates for lightweight masonry blocks by ISBAS A.S.

## 3. Material characteristics of the amorphous silica

Increasing utilization of high strength concrete materials in civil structuring applications, is making amorphous silica rock a very popular raw material as a natural pozzolanic material. Due to its good suitability for different concrete products based on its physical, chemical and mechanical properties, the amorphous silica is increasing its share of the market in the construction industry. In order to design an initial stage of a high strength concrete building project, the construction material properties should be well evaluated. Therefore, the need arises to analyse the materials to be used in construction experimentally in detail. This forms the backbone of any material analysis models in engineering applications.

### 3.1. Chemical composition

The Keciborlu amorphous silica rocks generally contain more than 90% silicon dioxide, 68.90% of which are amorphous. The chemical composition of the product may vary considerably even though the physical properties may be similar. Table 1 shows the chemical composition of amorphous silica rocks from two locations in the quarry.

Table 2
X-ray diffraction analysis results of amorphous silica samples

| Sample no. | pH | Quartz (%) | Anatase (%) | Total % | Difference (%) | Amorphous phase | Other phase |
|---|---|---|---|---|---|---|---|
| 1 | 7.76 | 35.8 | 1.0 | 36.9 | 63.1 | Opal | – |
| 2 | 7.28 | 38.6 | 1.3 | 39.9 | 60.1 | Opal | – |
| 3 | 7.40 | 44.8 | 1.4 | 45.8 | 54.2 | Opal | – |
| 4 | 7.53 | 46.6 | 2.0 | 48.6 | 51.4 | A. silica | – |
| 5 | 7.25 | 9.8 | 1.6 | 11.4 | 88.6 | A. silica | – |
| 6 | 7.30 | 12.2 | 4.4 | 16.7 | 93.3 | A. silica | – |
| 7 | 7.39 | 19.7 | 1.8 | 21.5 | 78.5 | A. silica | – |
| 8 | 7.42 | 49.6 | 1.1 | 50.8 | 49.2 | A. silica | – |
| 9 | 7.19 | 7.6 | 2.7 | 10.3 | 89.7 | A. silica | – |
| 10 | 7.08 | 22.0 | 1.6 | 23.6 | 76.4 | A. silica | – |
| 11 | 7.41 | 31.1 | 1.2 | 32.3 | 67.7 | A. silica | – |
| 12 | 7.53 | 27.4 | 1.7 | 29.1 | 70.9 | A. silica | – |
| 13 | 4.90 | 11.7 | 1.1 | 12.8 | 87.2 | Opal, A. silica | – |
| 14 | 3.20 | 23.2 | 0.9 | 24.1 | 75.9 | A. silica | – |
| 15 | 3.15 | 62.8 | 1.2 | 64.0 | 36.0 | A. silica | Sulphur |
| 16 | 2.02 | 34.0 | 1.1 | 35.1 | 64.9 | A. silica | – |
| 17 | 2.96 | 52.6 | 1.3 | 53.9 | 46.1 | A. silica | – |
| 18 | 3.20 | 0.5 | 0.0 | 0.5 | 99.5 | A. silica | – |
| 19 | 5.06 | 32.0 | 1.2 | 33.2 | 66.8 | A. silica | – |
| 20 | 4.51 | 9.0 | 0.8 | 9.7 | 90.3 | A. silica | Jarosit |
| 21 | 6.24 | 19.7 | 1.4 | 21.1 | 78.9 | A. silica | – |
| 22 | 7.03 | 37.1 | 2.3 | 39.4 | 60.6 | A. silica | – |
| 23 | 5.96 | 7.9 | 0.7 | 8.5 | 91.5 | A. silica | Gothite |
| 24 | 6.67 | 5.4 | 0.8 | 6.1 | 93.9 | A. silica | – |
| 25 | 7.36 | 5.1 | 0.7 | 55.8 | 44.2 | Opal, A. silica | – |
| 26 | 6.06 | 44.1 | 1.5 | 45.6 | 54.4 | A. silica | – |
| 27 | 7.21 | 82.5 | 1.8 | 84.3 | 15.7 | A. silica | – |
| 28 | 6.60 | 6.7 | 2.7 | 9.3 | 90.7 | Opal, A. silica | – |
| Average | 6.10 | 29.62 | 1.46 | 31.09 | 68.91 | – | – |

(1) X-ray Diff. Analyses was carried out by Silver–Baryte Mining—Kentpo Epeynas Kaı Analiz Lab.
(2) pH was measured in a $CaCl_2$ matrix according to Quarzwerke method.
(3) Total crystalline content equals the sum of quartz and anatase ($TiO_2$). (These are the only detectable crystalline phases present in all but 3 samples.)
(4) The difference is approximately equal to the amount of amorphous silica present either in the form of opal or glassy amorphous silica.

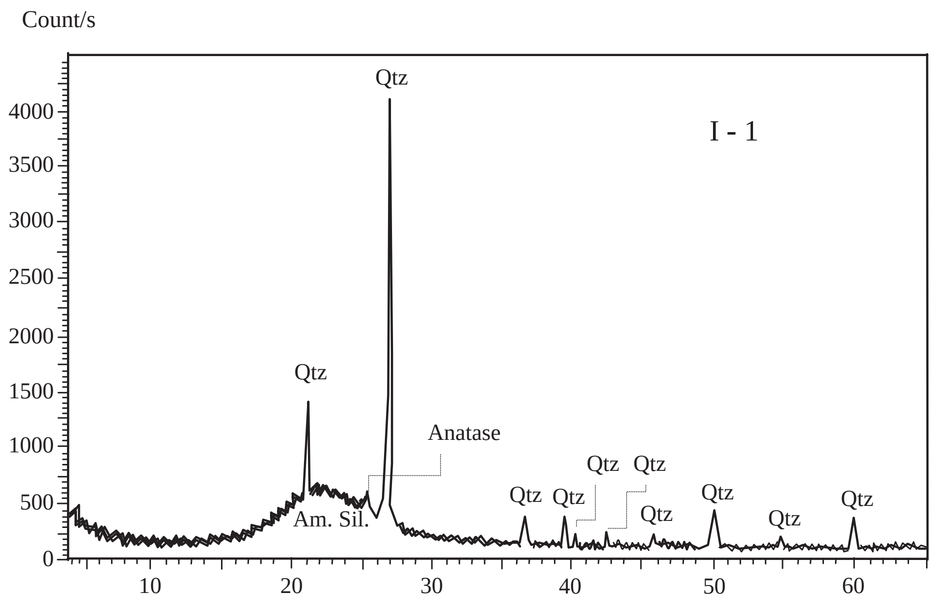



Fig. 3. X-ray analyses diagram for amorphous silica Location I.

Because of its high silica component, the material is acidic (pH = 6.10). Although amorphous silica materials are mainly formed by hard minerals such as silica and alumina, (Mohs hardness of silica is 7 and Mohs hardness of alumina is 9) the spectrogram analysis also shows notably smaller amounts of the elements sodium, chlorine, potassium, calcium, titanium and iron. XRD analyses were carried out for 28 amorphous silica samples from each location in the deposit. The results are given in Table 2 and the X-ray traces are given in Figs. 3 and 4 for the two locations, respectively.

The high silica content has considerable influence on the quality of the amorphous silica rock. In particular, it increases the hardness of the material and its resistance to chemical attack because the longer siliceous chains (–Si–O–Si–O–Si) result in the alkaline sodium and potassium ions being more firmly attached [6]. The chemical structure of amorphous silica is determined by the presence of monovalent and polyvalent ions of potassium, sodium, calcium, titanium, magnesium, aluminium etc. in the network of silica. They are arranged irregularly thus creating an amorphous structure.

The high silica content of the material and its great surface area make it react rather easily when in contact with alkalis and humidity. Because this fine-grained amorphous silica is a well-known commodity, it is used

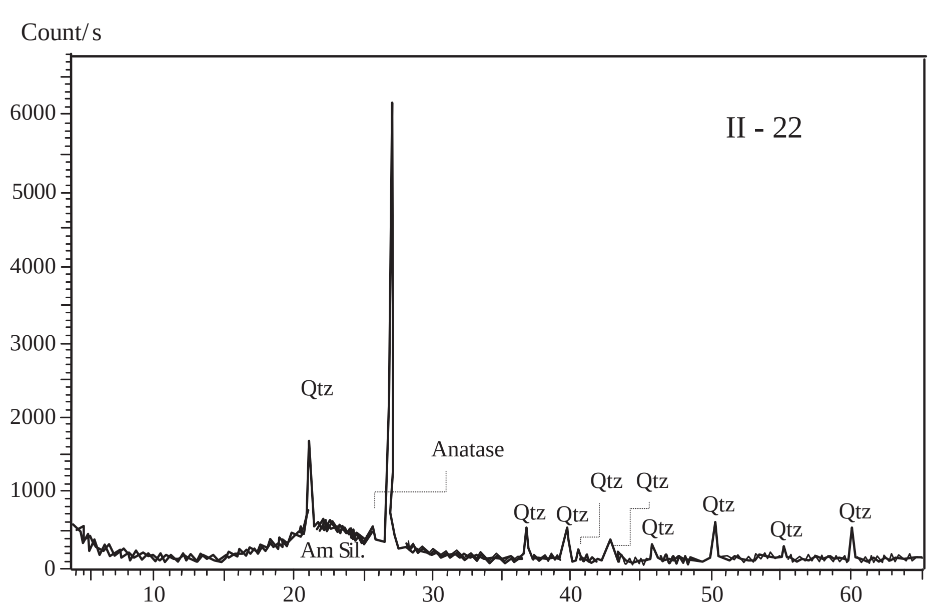



Fig. 4. X-ray analyses diagram for amorphous silica Location II.

Table 3
Comparison of the other common natural pozzolanic materials [7]

| Chemical composition | Requirement | Common natural pozzolan (%) | Location I (%) | Location II (%) |
|---|---|---|---|---|
| $SiO_2+Al_2O_3+Fe_2O_3$ | Minimum | 70 | 95.17 | 93.65 |
| MgO | Maximum | 5 | 0.00 | 0.00 |
| $SO_3$ | Maximum | 3 | 0.09 | 0.06 |
| Loss on ignition | Maximum | 10 | 1.85 | 3.51 |

as a pozzolan with hydraulic cements. Table 3 gives a comparison of other common natural pozzolans to amorphous silica based on their chemical compositions. Thus the ignition loss of the material is very low compared to the other pozzolanic materials, which reflects upon the fact that its metamorphoses are negligible and on the absence of clayey material.

### *3.2. Physical characteristics of the amorphous silica rock*

The physical properties of the amorphous silica are governed by the extremely fine cellular structure of the matrix. Keciborlu amorphous silica rocks can be described as a solid foam with a spherical or pseudo polyhedral structure whose pores are made of very thin layers of silicate substance (Fig. 5). This natural phenomenon is unique in its microscopic uniformity. Through a scanning electron microscope, the micropores of amorphous silica are irregular and each grain shows small closed forms. An electromicrograph as shown in Fig. 6 illustrates this extremely fine porosity. Actually the basic cell diameters are of sizes ranging from 1–15 μm. This fine porous structure gives the amorphous silica good elasticity which is responsible for its soft abrasive character and excellent mechanical workability.

The material colour changes from white to light cream colour according to its chemical composition. The general physical properties of the material are given in Table 4.

Particle size distribution analyses of crushed material were carried out according to the TS 1114 standard by the

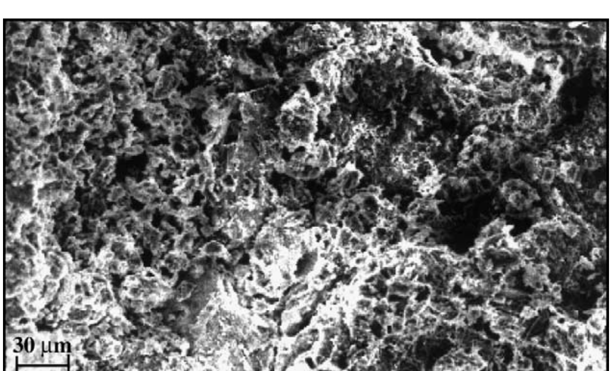



Fig. 5. The microstructure of amorphous silica rock (SEM).

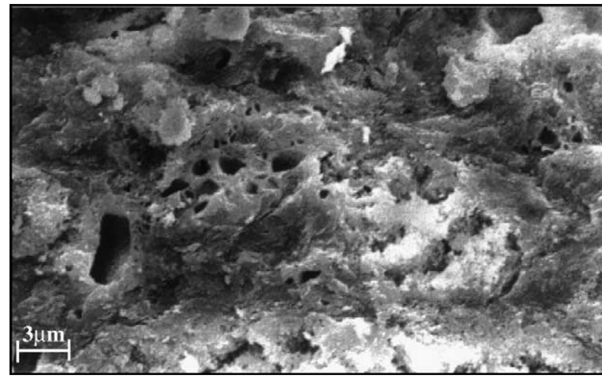



Fig. 6. The view of glassy phases in the amorphous silica rock (SEM).

use of square opening screens [8]. The analysis results are given in Fig. 7 as an average value of a number of results.

The moisture in amorphous silica aggregates changes the unit weight value as it affects the internal friction of the particles. In addition, the composite of the amorphous silica aggregates is another factor which affects the water absorption capacity and the fullness ratio of the particles in structural form. The water absorption capacities of the amorphous silica samples are given in Fig. 8 complying with TS 3526 [9].

The desired water absorption degrees for 24 h for amorphous silica particles are approximately 25% in fine aggregates and 50% in coarse aggregates by weight. But these values may change according to the source of aggregates, granulometry, particle form and the surface structure. To use amorphous silica aggregates, necessary precautions need to be taken.

Two different definitions can be made for the porosity of the amorphous silica aggregates: Apparent porosity and real porosity. The apparent porosity is a function of unit volume weight and water absorption by weight. Real porosity value is also as the function of the average volume weight and specific gravity of the amorphous silica particles. Another physical property is the parameter of the saturation degree. This value indicates that the water amount in total cavities of the amorphous silica aggregates. The parametric values of the porosity and saturation degrees of amorphous silica samples are given in Table 5.

For the materials whose saturation degree is over 80%, the water in cavities will freeze and the shatter effect will occur as a result of the expansion of water volume ratio of

Table 4
Physical properties of the amorphous silica rock

| Properties | |
|---|---|
| Hardness (Mohs) | 5, 5–6 |
| Unconfined compressive strength of rock | 10 MPa |
| Specific gravity | 2.39 g/cm$^3$ |
| Bulk density | 630 kg/m$^3$ |
| Apparent porosity | 45% |
| Water absorption by weight | 50% |
| Thermal conductivity | 0.11–0.13 W/m K |

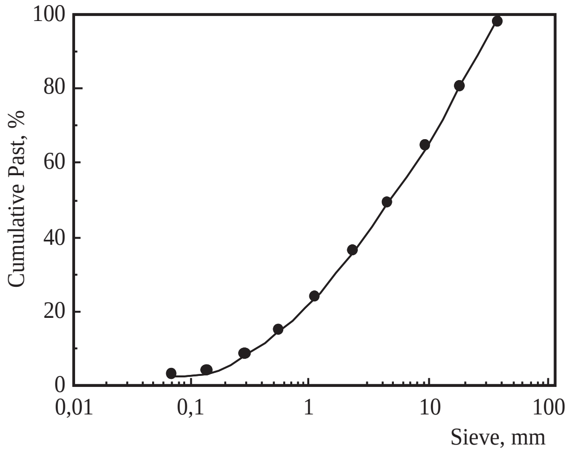



Fig. 7. Sieve analysis results of the crushed amorphous silica rock.

10%. For this reason, the desired value for saturation degree of the materials is under 80%. In this respect, when the state of the amorphous silica aggregates is examined, it can be observed that the saturation degrees of the particles except coarse ones are under 80%.

The organic materials found in the composition of aggregates which will be used for cement production, affect the structure of cement. For this reason, the present of these materials is not desirable. In order to examine the content of detrimental materials whether in aggregates or not, the chemical solution of 3% NaOH was prepared. The amorphous silica aggregates were exposed to this chemical solution for a 24 h duration time in a vessel. The colour changes on the amorphous silica particles were then observed. The colours beyond the dark red colour indicate the existence of the excessive organic material in the composition [10].

The analyses of organic material content performed on the amorphous silica aggregates indicate that any organic material content for the amorphous silica formations belongs to amorphous silica quarries. It is accepted that the clay content of the aggregate composition will reduce the strength of concrete by the proportion of approx. 50% in construction industry. In the standard experiments, it is desired that the proportion of clay/aggregate is not more than 3% by weight [11]. In addition, aggregates to be used for concrete construction should not exceed 5% amount of flame materials. According to the research findings, the parametric values of the amorphous silica are about 2.27%, which are acceptable.

In sulphur analysis, basically 1% of $SO_3$ component is the maximum value. According to the analysis, the sulphur component of the amorphous silica has a maximum value of 0.17%, which meets standard required the sulphur components as $SO_3$ are the acceptable values comparing the standards [10]. The analyses results also show that the amorphous silica aggregates could be used in construction industry based on the detrimental material analyses.

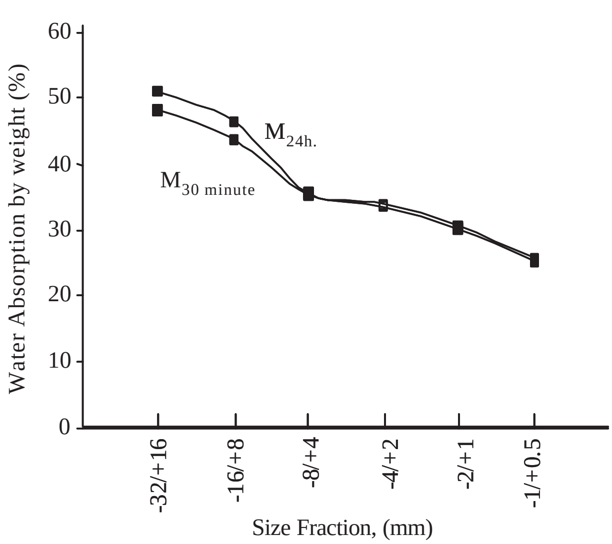



Fig. 8. Water absorption characteristics of the amorphous silica.

Table 5
The porosity values of amorphous silica aggregates

| Size fraction (mm) | Apparent porosity (%) | Apparent composity (%) | Real porosity (%) | Real composite (%) | Saturation degree (%) |
|---|---|---|---|---|---|
| 32–16 | 42.338 | 57.662 | 65.265 | 34.735 | 78.143 |
| 16–8 | 46.665 | 53.335 | 58.011 | 41.989 | 80.158 |
| 8–4 | 38.207 | 61.793 | 55.345 | 44.655 | 64.685 |
| 4–2 | 40.444 | 59.556 | 50.229 | 49.771 | 67.690 |
| 2–1 | 36.673 | 63.327 | 49.856 | 40.144 | 61.377 |
| 1–0.5 | 28.591 | 71.409 | 53.632 | 46.368 | 48.106 |

Table 6
The specific values of the temperature effects analysis [10]

| Test no. | Temperature (°C) | Aggregate weight (g) | Loss of ignition (%) |
|---|---|---|---|
| 1 | 20 | 19.5774 | 0.0000 |
| 2 | 200 | 19.5245 | 0.2702 |
| 3 | 300 | 19.522 | 0.2830 |
| 4 | 400 | 19.5123 | 0.3325 |
| 5 | 500 | 19.4934 | 0.4291 |
| 6 | 600 | 19.4674 | 0.5619 |
| 7 | 700 | 19.4527 | 0.6370 |
| 8 | 730 | 19.4439 | 0.6819 |
| 9 | 760 | 19.4362 | 0.7212 |
| 10 | 790 | 19.4343 | 0.7309 |
| 11 | 820 | 19.4311 | 0.7473 |
| 12 | 850 | 19.429 | 0.7580 |
| 13 | 880 | 19.4116 | 0.8469 |
| 14 | 910 | 19.4089 | 0.8607 |
| 15 | 940 | 19.4071 | 0.8699 |
| 16 | 970 | 19.4058 | 0.8765 |
| 17 | 1000 | 19.4045 | 0.8832 |
| 18 | 1030 | 19.4028 | 0.8918 |
| 19 | 1060 | 19.401 | 0.9010 |
| 20 | 1090 | 19.3987 | 0.9128 |
| 21 | 1120 | 19.3963 | 0.9250 |
| 22 | 1150 | 19.3897 | 0.9588 |
| 23 | 1180 | 19.3831 | 0.9925 |

Table 7
Specific surface area of different pozzolan materials [12,13]

| Material | Method | Fineness, $m^2$/kg |
|---|---|---|
| Silica fume | BET | About 20,000 |
| Fly ash | Blaine | 400–700 |
| Ordinary Portland cement | Blaine | 300–400 |
| *Amorphous silica powder (approx. particle size 5 μ) | Blaine | About 12,000 |

*The surface area was measured by using Blaine method in GOLTAS A.S. Quality Control Lab.

Due to the unique chemical composition and morphology amorphous silica has a high granular compressive strength. The high mechanical strength of amorphous silica granulate derived from the partial expansion of the material and of its unique chemical composition allows for a reduction in wall thickness thus achieving a marked decrease in costs.

The flame retardant of amorphous silica is below the accepted norms [10]. In order to determine the sintering temperature values of the amorphous silica aggregates, an experimental research was carried out and showed that the sintering and melting point of amorphous silica granules differ based on their chemical compositions. The specific values of the findings are given in Table 6.

The amorphous silica in the form of glass is highly reactive, and the fine particles accelerate the reaction with calcium hydroxide produced by the hydration of Portland cement. The very small particles of amorphous silica can enter the space between the particles of cement, and thus enhance the pore refinement. The specific surface area of the amorphous silica rock was determined based on the Blaine method. The amorphous silica rock consists of very fine vitreous particles with a specific surface area in the order of 12,000 $m^2$/kg which is 30–40 times higher than that of normal Portland cement determined by the same method (Table 7).

Most particles of ground amorphous silica powder are smaller than 15 μm (Fig. 9). The high reactivity of amorphous silica powder with Portland cement is primarily due to its very high specific surface and its high content of amorphous silicon dioxide.

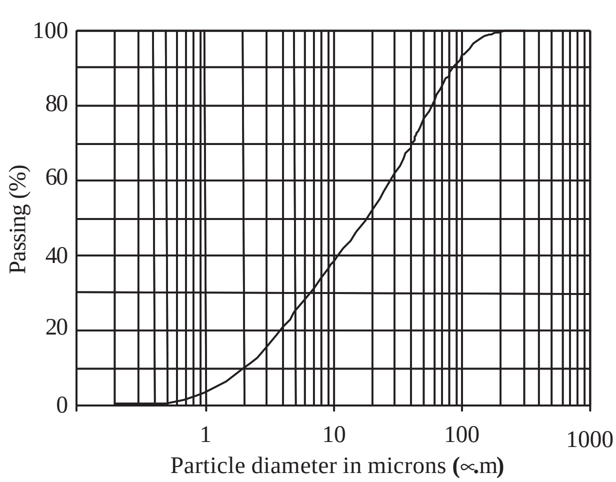



Fig. 9. Particle size distribution analyses of ground amorphous silica.

Table 8
The test results of pozzolanic activity of amorphous silica with ordinary Portland cement [7]

| Pozzolanic Activity | | |
|---|---|---|
| Blaine | | 12.124 $cm^2$/g |
| Fineness | 200 μ | 1.8 |
| | 90 μ | 8.8 |
| Specific weight | | 2.32 g/$cm^3$ |
| Dansite | | 920 g |
| Concrete results | | |
| Bending strength at 7 days | | 1.6 N/$mm^2$ |
| Compressive strength at 7 days | | 11.9 N/$mm^2$ |

For an assessment of pozzolanic activity with cement, TS 25 prescribes the measurement of a strength activity index. This is established by the determination of strength of mortar with a specific replacement of cement by pozzolan. The outcome of the test is influenced by the cement used, especially its fineness and alkali content [1]. According to the standard, the pozzolanic activity of the amorphous silica with ordinary Portland cement was measured. The bending strength value was determined as 1.6 MPa which is 1.6 times higher than the bending strength value of ordinary Portland cement and the compressive strength value was also determined as 11.9 MPa which is 2.98 times higher than that of ordinary Portland cement by the same method (Table 8).

## 4. The influence of using the amorphous silica in concrete

The amorphous silica containing silica in a reactive form is one of the natural pozzolan materials classified as cementitious. A more formal definition of ASTM 618-03 describes pozzolan as a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but will, in finely ground from and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. It is essential that pozzolan be in a finely ground state as it is only then that silica can combine with calcium hydroxide produced by the hydrating Portland cement in the presence of water to form stable calcium silicates which have cementitious properties [12]. When it is added to Portland cement, generally the following properties could be observed in a high strength concrete [5]:

• a very low chloride ionic diffusion,
• increased compressive strength,
• reduced water absorption,
• increased abrasion resistance,

Table 9
The mixture proportions used in the study according to TS 802, TS 1247, TS 3068 ISO 2736-2 and TS 2141 [14–17]

| Sample | Cement (kg) | Fine aggregate (kg) | Coarse aggregate (kg) | Water (l) | AS (%) | Superplasticizer (%) | $D_{max}$ (mm) | w/c | Slump (cm) |
|---|---|---|---|---|---|---|---|---|---|
| C20–K | 314 | 948.2 | 695.25 | 220 | – | 1.25 | 12.5 | 0.70 | 7–12 |
| C20–A5 | 314 | 948.2 | 695.25 | 231 | 5 | 1.25 | 12.5 | 0.74 | 7–12 |
| C20–A10 | 314 | 948.2 | 695.25 | 242 | 10 | 1.25 | 12.5 | 0.77 | 7–12 |
| C20–A15 | 314 | 948.2 | 695.25 | 253 | 15 | 1.25 | 12.5 | 0.81 | 7–12 |
| C20–R5 | 298.3 | 948.2 | 695.25 | 220 | 5 | 1.25 | 12.5 | 0.74 | 7–12 |
| C20–R10 | 282.6 | 948.2 | 695.25 | 220 | 10 | 1.25 | 12.5 | 0.78 | 7–12 |
| C20–R15 | 266.9 | 948.2 | 695.25 | 220 | 15 | 1.25 | 12.5 | 0.82 | 7–12 |
| C30–K | 440 | 948.2 | 695.25 | 220 | – | 1.25 | 12.5 | 0.50 | 2–6 |
| C30–A5 | 440 | 948.2 | 695.25 | 231 | 5 | 1.25 | 12.5 | 0.53 | 2–6 |
| C30–A10 | 440 | 948.2 | 695.25 | 242 | 10 | 1.25 | 12.5 | 0.55 | 2–6 |
| C30–A15 | 440 | 948.2 | 695.25 | 253 | 15 | 1.25 | 12.5 | 0.58 | 2–6 |
| C30–R5 | 418 | 948.2 | 695.25 | 220 | 5 | 1.25 | 12.5 | 0.53 | 2–6 |
| C30–R10 | 396 | 948.2 | 695.25 | 220 | 10 | 1.25 | 12.5 | 0.56 | 2–6 |
| C30–R15 | 374 | 948.2 | 695.25 | 220 | 15 | 1.25 | 12.5 | 0.59 | 2–6 |

(1) Sample: C20 or C30 based on the TS 802, TS 1247, TS 3068, TS 3068 ISO 2736-2 and TS 12141 standards.
(2) (The class of concrete) K (control concrete), A (amorphous silica when used as an admixture), R (amorphous silica when used as a partial replacement for cement).
(3) Amount of amorphous silica (AS) = cement dosage × (5%, 10% or 15%).
(4) Amount of superplasticizer (SP) = (amount of cementitious material in mixture) × 1.25%.
(5) $D_{max}$ = maximum grain size of aggregate in mixture concrete (mm).

- increased chemical resistance,
- reduced efflorescence.

Basically, designing the amorphous silica mixtures consists of selecting the correct proportions of cement, cementitious additive material, superplasticizer and water content. The properties most usually specified for the mixture design are: workability, required strength at a specific curing time, and elastic and shear characteristics by specifying the minimum cement content. Grading of the amorphous silica material for workable mixture requires more water content because of water absorption by large surface area. To make workable mixture for a good quality concrete with required strength, water content should be determined experimentally. Research was carried out to determine the optimum workable conditions for the use of amorphous silica in concrete and the water/cement ratio was determined as 0.70 for C20 and 0.50 for C30 concrete mixtures with the use of superplasticizer. Also, a comprehensive experimental research work was carried out to determine the influence of the amorphous silica on the concrete strength. The tests were performed in the Pumice Research Centre Laboratory of Suleyman Demirel University, Turkey according to TS 802, TS 1247, TS 3068 ISO 2736-2 and TS 2141 standards. Two different batches of concrete mixtures using AS as admixture and replacement for cement, respectively were investigated.

Small quantities of amorphous silica as admixture, 5–15% by weight of cement was added to concrete mixtures with 300 and 450 kg ordinary Portland cement dosages. The mixture proportions used in the research are given in Table 9. The test samples are the standard cylindrical concrete with a nominal diameter of 150 mm and 300 mm in height. The samples were tested at 7, 14 and 28 days curing time. In order to evaluate the influence of the amorphous silica in concrete mixes, a control mix was also made and all the

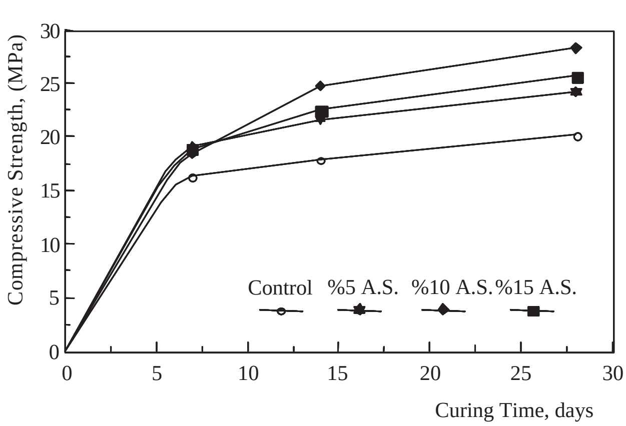



Fig. 10. Compressive strength versus age of concrete (C20).

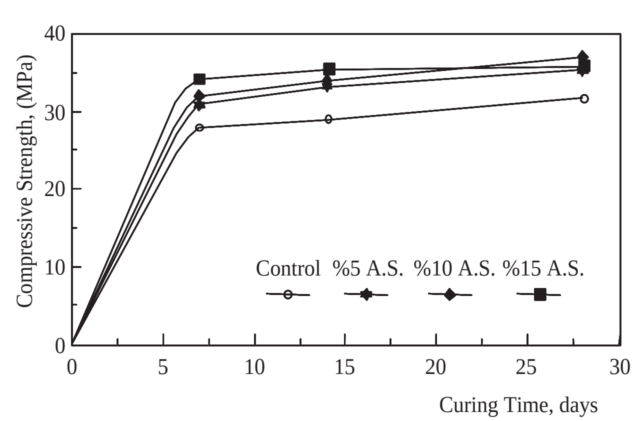



Fig. 11. Compressive strength versus age of concrete (C30).

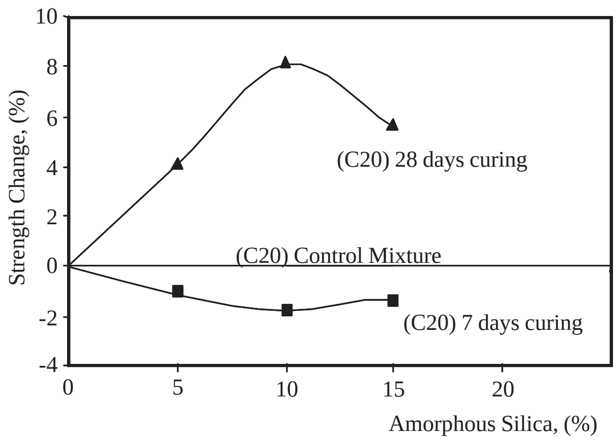



Fig. 12. Percentage of strength change (C20) versus amorphous silica addition.

mixes were cured under the same curing conditions. The resulting loss in slump of mixes with amorphous silica was compensated by addition of more water. Therefore, the water/cement ratio of the mixtures was used between 0.50 and 0.82. The results are presented in Figs. 10 and 11.

Figs. 10 and 11 show strength enhancement with the addition of AS at all curing ages and higher strengths are obtained in comparison with that of control mix.

The research showed that the strength enhancement is obtained for mixes with up to 10% AS as an admixture (Figs. 12 and 13). The highest strength was obtained with the 10% addition of amorphous silica to the concrete mixtures (C20 and C30) with 300 and 450 kg ordinary Portland cement dosages as an admixture. For a constant workability, the increase in the water demand of concrete due to amorphous silica is usually between 5% and 10% by comparison with a Portland cement only mix having the same cementitious material content. Because of the decreasing strength, more than 10% amorphous silica as an admixture in concrete mixes is not beneficial.

Another method of using the amorphous silica in concrete is its use as a partial replacement for cement.

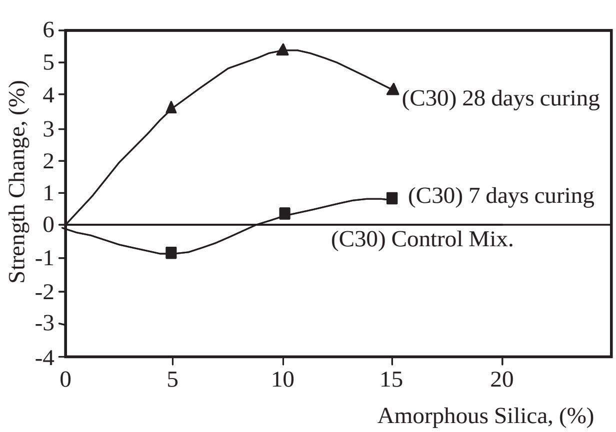



Fig. 13. Percentage of strength (C30) change versus amorphous silica addition.

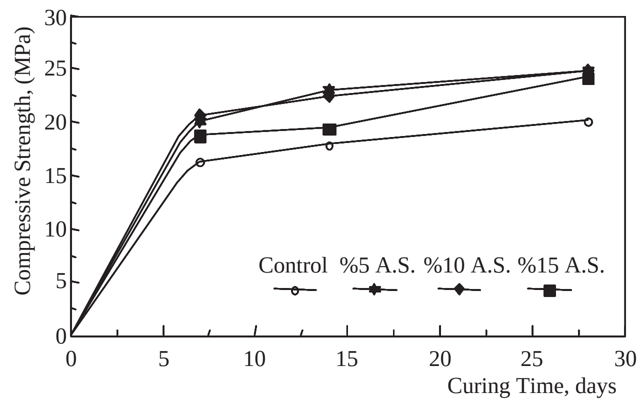



Fig. 14. Compressive strength versus age of concrete (C20).

The percentage replacement may vary from 0–15%. Though this does not change the total weight of the cementitious materials, there is an increase in the water demand because of the larger surface area replaced with amorphous silica. In order to maintain the same water–cement plus amorphous silica-ratios, superplasticisers should be used to maintain the required slump. This approach also results in a remarkable increase in compressive strength at the age of up to 28 days.

The contribution of amorphous silica to concrete strength can be quantified in terms of efficiency or an efficient factor. The efficiency of amorphous silica is defined as the ratio of the additive material dosage to the amount of cement that can be replaced to maintain strength. In order to analyse this effect for the amorphous silica mixes for both of the C20 and C30 samples, a comprehensive experimental research was carried out. A series of compressive strength tests were performed on mixtures with 5%, 10% and 15% of amorphous silica as a partial replacement for cement. Specimen were standard cylindrical concrete with 150 mm in diameter and 300 mm in height. The strength were evaluated at 7, 14 and 28 days curing time. In order to evaluate the influence of amorphous silica in concrete mixes, a control mix was also cast and all mixes were cured in water in 20 °C. The resulting loss in slump of mixes with amorphous silica was compensated by addition of more water. The research findings are given in Figs. 14 and 15 for

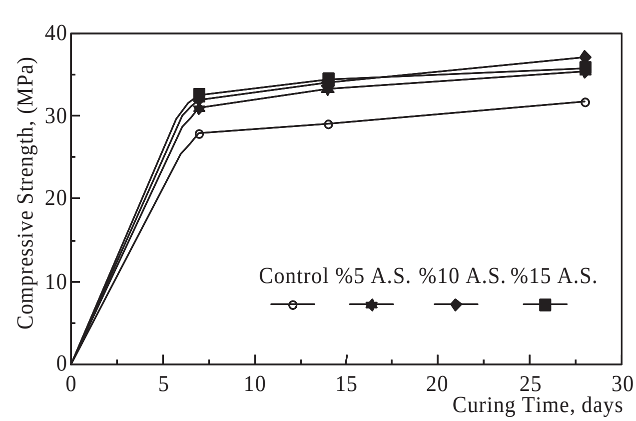



Fig. 15. Compressive strength versus age of concrete (C30).

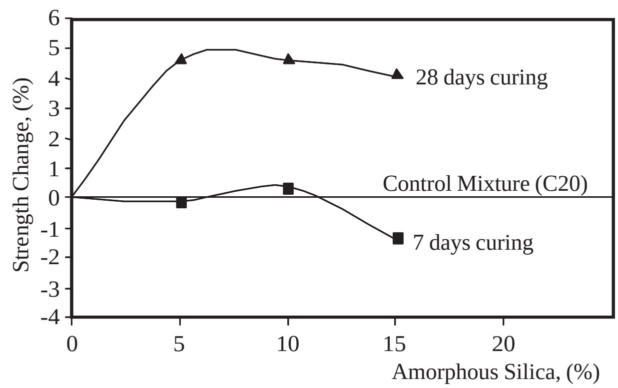



Fig. 16. Percentage of strength (C20) change versus amorphous silica addition as a replacement cementitious material.

5%, 10% and 15% amorphous silica in the C20 and C30 concrete samples, respectively.

From the Figs. 16 and 17, it can be seen that strength of the concrete increases with increase of AS replacement level up to 10%. However, 15% of AS addition in C30 concrete samples does not show the similar strength development of C20's one. The decrease of strength in concrete using more than 10% AS might not be attributed to AS, but increase of W/C ratio. Therefore, there is a certain amount of AS to use as a replacement material in the concrete with Portland cement. This effect was also analysed as the strength change scale for the test results (Figs. 16 and 17). The strength of concrete is slightly lower after an amount of amorphous silica addition. The highest strength was obtained with the 6.65% addition of amorphous silica to the C20 mixes and with the 7.20% addition of AS to the C30 mixes as a replacement material. This shows that in addition to the pozzolanic reaction between the AS and calcium hydroxide produced by the hydration of Portland cement, AS contributes to the progress of hydration of the latter material. This contribution arises from the extreme fineness of the AS particles which provide nucleation sites from calcium hydroxide. Thus, early strength development takes place. Therefore, the efficiency factor of AS usage in concrete

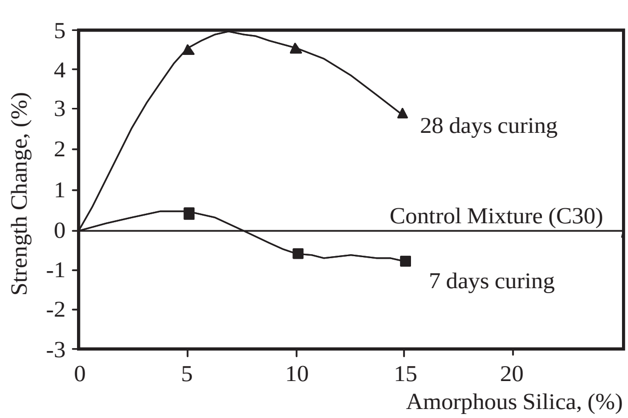



Fig. 17. Percentage of strength change (C30) versus amorphous silica addition as a replacement cementitious material.

Table 10
An analysis of ready mix concrete supplied to major projects confirm the efficiency gains of using microsilica in concrete [5]

| Project | Average strength | Efficiency factor |
|---|---|---|
| Industrial floors | 55 Mpa | 2.5 |
| Bridge construction | 53 Mpa | 2.8 |

could be determined. According to the research, the efficiency factor was determined as 2.26–2.60 for C20 concrete mixes and 1.50–1.55 for C30 concrete mixes. This value is a similar value of concrete using amorphous silica given by Branz (The Building Research Association of New Zealand) for the Tikitere amorphous silica rock from New Zealand (Table 10).

## 5. Conclusions

In this paper, the use of Keciborlu amorphous silica as an admixture and replacement for cement in the normal concrete was investigated. The followings are the main research findings.

The experimental work showed that the use of amorphous silica as a lightweight concrete aggregate is suitable for the lightweight concrete mixture based on the related standards. Specially:

- its low bulk density (as 630 kg/m$^3$),
- its high $SiO_2$ contaminant (90–92% ),
- its very high thermal insulation capability based on its homogenous micro-porosity structure ($\lambda$=0.11–0.13 W/m K.),
- its strength ($\sigma_c$=10 MPa),
- its very high adhesion because of its high pozzolanic activity.

These technical properties show AS could be used as potential lightweight concrete aggregate.

Furthermore, the use of amorphous silica as a mineral admixture in normal concrete mixes was also experimentally evaluated and the research findings were presented in this paper. For this research work, the material was crushed and ground to powder with 15 μm maximum size, and the pozzolanic activity and the blain properties were also examined. The ground material was added to the C20 and C30 concrete mixtures with the superplasticizer, respectively. The mixtures water/cement ratio were in the range of 0.50–0.82. The amorphous silica was added as 5%, 10% and 15% admixture and blended with cement as a partial replacement at 5%, 10% and 15% levels, respectively. The following basic results are obtained from the research:

- The strength of all AS concrete mixtures is higher than control mixture.
- The efficiency factor ($k$) of AS concrete samples is determined for each mixture. The best $k$ factor is

obtained from the mixture of C20 concrete with 10% AS as an admixture.

The strength characteristics of AS concrete were evaluated in this paper, but the more analyses such as durability will be evaluated in the future.

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