Effect of partial replacement of cement by silica fume on strength of high-strength concrete

Mohammad Noor Jan Ahmadi
eng.ahmadi786@gmail.com
Naqib Ahmad Naeemi
naeemi.naqib@gmail.com
Saifullah Amin
eng.saifamin@gmail.com
Shaikh Zayed University, Afghanistan

Abstract: Silica fume is a component of high-strength concrete, which is one of the most important factors in concrete strength. Silica fume is a by-product resulting from the reduction of high-purity quartz with coal, coke, and wood chips in an arc furnace during the production of silicon metal or silicon alloys. The effects of silica fume on the strength of concrete have been shown in the results of the research. Many studies have been done on concrete technology, which has led to various advances in this field. The strength of the concrete is greatly influenced by its ingredients, including silica fume. The materials used in this research can be found in Kabul, and these materials have been selected for laboratory work that can be tested by standard laboratories. In this research, the effects of silica fume on the compressive and tensile strengths of concrete have been studied. In the laboratory work, in addition to the basic ingredients such as cement, sand, gravel, and water, additional admixtures such as silica fume and superplasticizer have been used. The concrete specimen tests have been conducted according to ASTM standards. In this research, the cement is partially replaced with Silica Fume. The same concrete mixtures with different amounts of silica fume (0%, 10% and 15%). The objective of this research is to comprehensively determine the effect of silica fume on high-strength concrete. The result shows that as the amount of silica fume increases up to 10%, the compressive and tensile strengths of concrete also increase, but when the amount of silica fume increases to 15%, the compressive strength of concrete decreases but the tensile strength increases.

Keywords: High Strength Concrete (HSC), Silica Fume, Compressive Strength, Tensile Strength

I. Introduction

Concrete is one of the most widely used materials in structures and buildings. To produce high-strength concrete (compressive strength higher than 40 MPa) water/cement ratio has to be reduced to 0.4 or more. Mineral admixtures (supplementary cementitious materials) are used as an alternative to increasing cement content. They are either partially replaced with cement or added additionally. The studies show that silica fume is superior to other admixtures. During the last three decades, great steps have been taken to improve the performance of concrete as a construction material. Particularly, Silica Fume (SF) and fly ash, individually or in combination, are essential in the production of high-strength concrete for practical applications. The use of silica fume as a pozzolana has increased worldwide attention over recent years because, when properly used in a certain percentage, it can enhance various properties of concrete both in the fresh and hardened states, like cohesiveness, strength, permeability and durability. When the compressive strength of concrete is greater than 40 MPa, it is defined as high-strength concrete (HSC).

High-strength concrete, according to the American Concrete Institute Committee ACI 363 R, is the type of concrete that has a specific compressive strength of 41 MPa or more at 28 days. Silica fume is made up of small particles with an average specific surface area when measured by nitrogen absorption. The particles are approximately 100 times smaller than cement particles. The first standard for the use of silica fume was established in 1990 (AAS HTO). Its behavior is related to the high content of amorphous silica (> 90%). According to the ACI code, silica fume is a small particle of non-crystalline material produced in arc power plants from silicon and silicon alloys [5].

Silica fume is a by-product resulting from the reduction of high-purity quartz with coal, coke, and wood chips in an arc furnace during the production of silicon metal or silicon alloys. Silica fume is known to improve the mechanical characteristics of concrete. The principal physical effect of silica fume in concrete is that of filler, which, because of its fineness, can fit into the space between cement grains in the same way that sand fills the space between particles of coarse aggregates and cement grains fill the space between sand grains. The silica fume content in concrete generally ranges from 5 to 20 percent of the total cementitious material content (as a partial replacement by weight of cement). [6] In the production of high-strength concrete, great care is taken with the choice of materials in order to ensure its durability. The materials used in this research for concrete can be found in Kabul, have high quality, and have been selected after standardized testing. Also, in the selection of these materials, the characteristics of the manufacturing factories have been carefully studied. It is important to note that the materials used in the research are common and have no superiority over other materials. Several studies are going on around the world to study the impact of the use of these pozzolanic materials as cement replacements, and the results are encouraging. One advantage of high-strength concrete is that its modulus of elasticity and tensile strength are higher than those of normal concrete. Increased stiffness is advantageous when deflections or stability govern the design, while increased tensile strength is advantageous for service load design in pre-stressed concrete. [7]

For the reasons mentioned above, in order to produce high-strength concrete at a suitable cost, we selected this topic for our research. In all the studies reviewed here, silica fume is recognized as an appropriate mineral admixture to enhance the performance of high-strength concrete without increasing cement content. However, no attempt was made to investigate the overall mechanical performance of concrete mixtures with silica fume in terms of compression and tension in the same study. Therefore, the objective of this research is to comprehensively determine the effect of silica fume on high-strength concrete performance in terms of compressive and tensile strength. The mechanical properties were assessed by compressive, splitting tensile, and flexural strengths.

II. Experimental Investigation

In this part, the materials and their properties that were used in mix design are explained, followed by the procedure of mix design and the procedure of conducting tests.

Materials: In the laboratory work, the effects of silica fume on the compressive and tensile strengths of concrete have been studied. For conducting tests on specimens, the different ingredients of the materials for the research are shown below:

i- Cement: The first type of cement has been used in this laboratory work; its commercial name is Maple Leaf. The related tests of cement have been conducted in the Geotechnical and Construction Materials Testing Laboratory (GCMTL), and the 28-day compressive strength has been shown to exceed 10,000 psi.

ii) Sand: The sand has been brought from the Bagram River and is also tested in GCMTL. Its unit weight in loose condition is 1.61 gr/cm^3, the specific gravity is 2.71, water absorption is 1.55%, and the fineness modulus is 3.27.

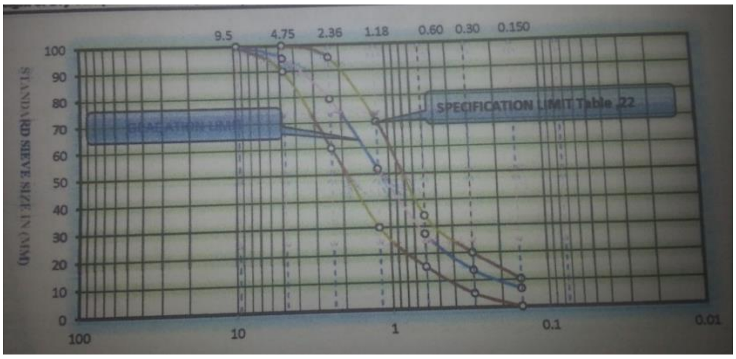

Fig. 1 Gradation Curves for Sand and Gravel (This graph has been taken from laboratory report)

iii. Gravel: The gravel used in this laboratory work has been brought from Mutmaeen Crush Plant, and related tests have been carried out in GCMTL. In the gravel, 56% of the grains consist of 19.5 mm-40 mm gravel grains and 44% of 12.5 mm-19.5 mm grains. In loose condition, the unit weight of 19.5 mm and 40 mm gravel grains was 1.403 and 1.387 gr/cc, respectively. The specific gravity of 19.5 mm and 40 mm gravel was 2.701 and 2.703, respectively. Water absorption of 19.5 mm and 40 mm gravel was 0.43% and 0.72%, respectively. Gravel abrasion content was 23.7%, the flakiness index was 20.54, the elongation index was 19.31, and the soundness of Fine and Coarse Aggregate was 1.7% and 0.69%, respectively.

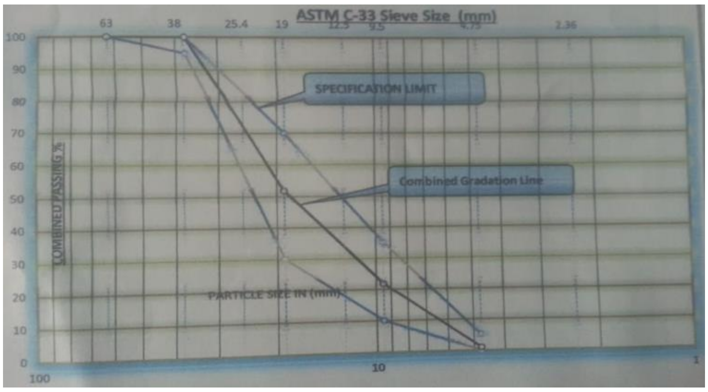

Fig. 2 Gradation Curves for Gravel (This graph has been taken from laboratory report)

iv. Silica fume: SF particles are very small, and more than 95% of them are softer than l µm. It is either premium white or gray in color. SF is composed primarily of fresh silica in non-crystalline form. X-ray diffraction analysis of different silica fumes revealed that the material is basically vitreous silica, mainly of cristobal form. It has a very high content of amorphous silicon dioxide and is composed of very fine spherical particles. Silica fume generally contains more than 90% SiO. Small amounts of iron, magnesium, and alkali oxides are also found in SF (Bentur and Goldman, 1989).

The silica fume used in this laboratory work was purchased from the Izomat Company.

v- Superplasticizer: The super-flowing materials used in laboratory work have been bought from the Isomat Company. Its commercial name was BEVETOL-SPL according to ASTM C-494, A, D, and G, and ELOT EN 934-2: T11.1 and T11.2.

vi- Water: The water used in the laboratory work is free from any harmful substances such as oil, acid, dust, and others. The water was potable and was used by the people in their daily activities.

2. Mix Design

To achieve the desired compressive strength and other properties of RGPC, a proper mix design is required. The absence of a suitable mix design technique for GPC in general and RGPC in particular is the cause of its limited utilization in structural applications. [8] The boundary between the strengths of ordinary and high-strength concrete is set at 40 MPa.

3. Method of Manufacturing Concrete

The process of preparing concrete that has been conducted in the laboratory is explained below:

1. Weighing clean sand and gravel and mixing it by hand in a pan.
2. Weighing cement and silica fume, adding it to sand and gravel, and mixing well.
3. Weighing the water and the super-flowing materials and slowly adding them to the mixture.
4. Mixing the ingredients well after adding water.
5. Conducting the slump test after ensuring that the mixture is well mixed.
6. Lubricating the cubic and cylindrical molds and making sure that there is no problem.

Fig. 3 Weighing and Mixing of Gravel and Sand and Adding Superplasticizer to the Concrete Mixture

Fig. 4 Performing the slump test after ensuring that the mixture is well mixed.

Fig. 5 Checking and lubricating molds for cubic and cylindrical specimens

7. After pouring concrete in three layers into the molds and tamping it twenty-five times with a rod and hitting it with a plastic hammer from the outside, when the mold is filled, the surface should be leveled.

8. Placing an information sheet on the sample to know when the sample was made and when it should be tested. Also, the characteristics of the materials that were used in making the sample should be written on this sheet.

Fig. 6 Pouring concrete into the mold and freshly made samples with an information sheet

9. The molds are removed from the samples at least 16 hours and maximum 3 days later and the hardened samples are placed in the water tank until the time of testing [23].

Fig. 7 Removing the molds from the samples and placing them in the water tank

4. Tests on Concrete Specimens

In the present research, two types of tests were conducted on the concrete containing different amounts of silica fume to determine the mechanical properties of the HSC. One was the compressive strength test, and another was the tensile strength test. The tests were conducted after 7 and 28 days, and the strength of concrete was determined for all samples containing different amounts of silica fume. A total of 36 specimens were made in this laboratory work; 18 specimens were used for determining the compressive strength of concrete and 18 specimens for the tensile strength of concrete. In each of the 18 specimens, the 6 specimens of concrete contained 0% silica fume, 6 specimens of concrete contained 10% silica fume, and 6 specimens of concrete contained 15% silica fume.

I. Compressive Strength Test

According to testing standard requirements, different geometries of samples are used to determine the compressive strength of concrete. The most commonly used geometries are cylinders and cubes. The shape effect on compression strength has been extensively studied, and there are different relationships between the compressive strengths obtained for these geometries.

The cubes were cured in the laboratory at an average temperature of 28 ^{o}C (82.4 ^{o}F). In the results, the average compressive strength values are shown for 7 and 28 days. The compressive strength test was conducted according to ASTM C 109-94a.

Fig. 8 Determining the Compressive Strength of Cubic Specimens of Concrete

II. Tensile Strength Test

The tensile strength of concrete can be experimentally determined in three different ways: (1) a uniaxial tensile test; (2) a split cylinder test; and (3) a beam test in flexure. The first method of obtaining the tensile strength may be referred to as "direct", and the second and third methods may be referred to as "indirect". In the direct test for tensile strength, the specimen is gripped at its ends and pulled apart in tension; tensile strength is the failure load divided by the area experiencing tension. In the splitting tension test, a cylinder is loaded in compression on two diametrically opposite sides, and the specimen fails in tension on the plane between the loaded sides. In the beam flexure test (modulus of rupture test), a rectangular beam is loaded at the center or third point and fails in flexure; the computed tensile stress at the failure load is called the modulus of rupture. [10]

Fig. 9 Splitting Tension Test of a Concrete Cylindrical Specimen

III. Results and Discussion

After mixing the concrete, tests were conducted on the fresh concrete to determine slump flow. From each concrete mixture, cubic and cylinder samples were cast to determine compressive strength and split tensile strength, respectively. The compressive strength of concrete was determined in accordance with ASTM C 109-94a. A splitting tensile strength test was carried out as per ASTM C496.

1. Compressive Strength

As can be seen, the use of silica fume increases the compressive strength of concrete with the passage of time. While comparing concretes with 0% and 10% silica fume contents, a marginal difference in compressive strengths can be observed. However, a significant difference can be perceived when comparing 10% and 15%

silica fume content concrete's. It can be concluded that an increase in the contents of silica fume increases the compressive strength development of concrete.

In this part, first the compressive strength of concrete is compared between the concrete specimens.

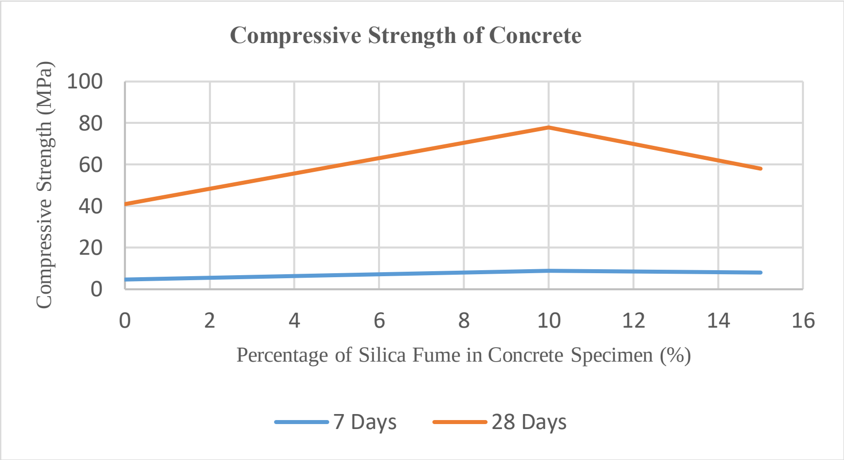

Fig. 10 Compressive Strength of Concrete after 7 and 28 Days

From Fig. 10 above, it is observed that the 7-day compressive strength of concrete containing 10% silica fume is increased by 89.36% as compared to the concrete containing 0% silica fume, and the compressive strength of concrete containing 15% silica fume is increased by 72.34% compared to the concrete containing 0% silica fume.

Fig. 10 exhibits that the 28-day compressive strength of concrete containing 10% silica fume is increased by 90% compared to the concrete containing 0% silica fume, and the compressive strength of concrete containing 15% silica fume is increased by 41.71% compared to the concrete containing 0% silica fume.

The silica fume reacts with this calcium hydroxide to form an additional binder material called calcium silicate hydrate, which is very similar to the calcium silicate hydrate formed from Portland cement. It is an additional binder that gives silica-fume concrete its enhanced properties.

By adding excessive silica fume, the compressive and flexural strength of HPC decreases because the increase in silica fume content also increases the water demand.

2. Tensile Strength

The tensile strength is also worked out for three specimens of each type of concrete containing different silica fumes, and then the average strength for each type of concrete is compared as below:

From Fig. 11 below, it is clear that the 7-day tensile strength of concrete containing 10% silica fume is increased by 75.51% as compared to the concrete containing 0% silica fume, and the tensile strength of concrete containing 15% silica fume is increased by 124.50% as compared to the concrete containing 0% silica fume.

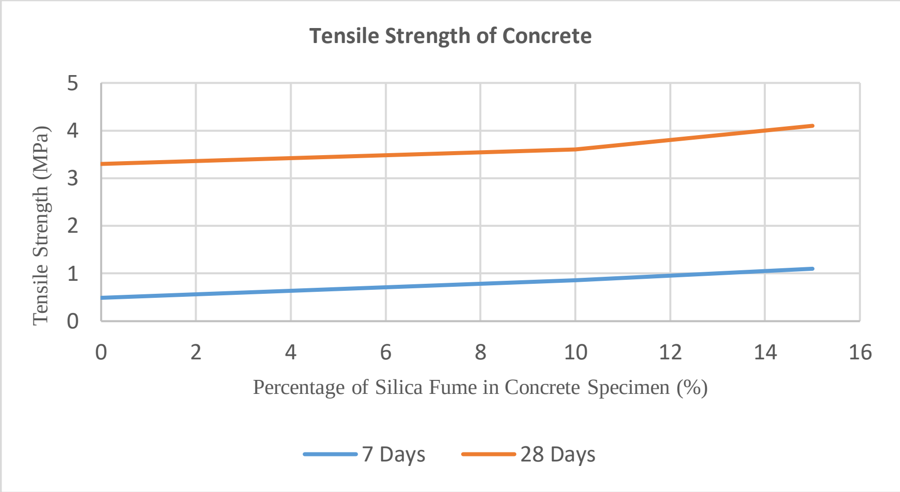

Fig. 11 Tensile Strength of Concrete after 7 and 28

In Fig. 11, it is observed that the 28-day tensile strength of concrete containing 10% silica fume is increased by 9.1% as compared to the concrete containing 0% silica fume, and the tensile strength of concrete containing 15% silica fume is increased by 24.24% as compared to the concrete containing 0% silica fume.

Using an extra amount of silica fume (more than 10%) may reduce the strength of polymer-modified concrete and its modulus of elasticity. This can be attributed to the brittleness that results from the addition of silica fume.

SF has a chemical composition and physical properties that make it a suitable material to enhance the strength and durability of cement concrete, especially UHPC and high-strength concrete (HSC). However, workability and shrinkage of concrete are usually affected due to the high specific surface area and fine particle size of SF, making a higher demand for extra water at mixing time in addition to using superplasticizer.

IV. CONCLUSION

In this research, the effects of silica fume on the compressive and tensile strengths of concrete have been studied, and the properties of high-strength concrete have been considered. This paper summarizes the use of silica fume (SF) as a supplementary material in cement-based composites. The following concluding remarks can be drawn from the results obtained from this study:.

1. Chemical and mineral additives are added to the concrete along with ordinary components such as sand, gravel, and cement to improve the properties of the concrete.

2. The results show that as the amount of silica fume increases up to 10%, the compressive and tensile strengths of concrete also increase, but when the amount of silica fume increases up to 15%, the compressive strength of concrete decreases but the tensile strength increases.

3. The 28-day compressive strength of concrete containing 10% silica fume is increased by 90% as compared with concrete containing 0% silica fume, and the

compressive strength of concrete containing 15% silica fume is increased by 71% compared with concrete containing 0% silica fume.

4. It can be concluded that the appropriate amount of silica fume used in concrete is 7-10%.

References

1. Sulimani Suliman, High Strength Concrete and the Effects of the Largest Aggregate on It, Master's Thesis, Mazandaran University of Science and Technology, 1997.

2. Jain Anurag, Pawade P. Y., Characteristics of Silica Fume Concrete, International Journal of Computer Applications, 2015.

3. ACI Journal, State of the All Report on High-strength Concrete, Reported by ACI Committee 363, 2011.

4. Gražulytė Judita, Vaitkus Audrius, Šernas Ovidijus, Čygas Donatas, Effect of Silica Fume on High-strength Concrete Performance, 5th World Congress on Civil, Structural, and Environmental Engineering (CSEE'20), October 2020.

5. U.S. Department of Transportation, Silica Fume User's Manual, Federal Highway Administration, 400 7th Street, SW Washington, DC, 20590, 2005.

6. Srivastava Vikas, Kumar Rakesh, Agarwal V. C., and Mehta P. K., Effect of Silica Fume on Workability and Compressive Strength of OPC Concrete, Journal of Environmental Nanotechnology, 2014.

7. Shah S. P., Ahmad Shuaib H., Structural Properties of High Strength Concrete and its Implications for Precast Pre-stressed Concrete, PCI Journal, 1985.

8. Cai Jiweia, Liu Zixiana, Xu Gelonga,*, Tian Qinga,*, Shen Weiguoc, Li Bowangb, Chen Tiaoc,d, Mix design methods for pervious concrete based on the mesostructure: Progress, existing problems, and recommendations for future improvement, elsevier.com/locate/cscm, 2022.

9. Lutfawi Reza and Sajidi Seyed Fathullah, Feasibility of Making High Strength Concrete in Laboratory Conditions in Khuzestan Province, Islamic Azad University, Dezful, Iran, 2008.

10. Mawlood Shelan Shareef, Ministry of Constructiona and Housing, Sulaimaniyah, Iraq.

11. Bhanja S., Sengupta B., Influence of silica fume on the tensile strength of concrete, Cement and Concrete Research, Volume 35, Issue 4, April 2005, Pages 743-747.

12. Mccormak Jack C., & Brown Russell H., Design Of Reinforced Concrete. United States of America, 2014.

13. Srivastava Vikas, Kumar Rakesh, Agarwal V. C., and Mehta P. K., Effect of Silica Fume on Workability and Compressive Strength of OPC Concrete, Journal of Environmental Nanotechnology, 2014.

14. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-12) and Commentary (318R-02)", 2011.

15. ACI, 234R-96, Guide for the Use of Silica Fume in Concrete", Reported by ACI, Committee, 234, 1-1996.

16. ASTM, Standard C109, Standard Test Method for Compressive Strength of Concrete Cube Specimens, Annual Book of ASTM Standards, ASTM International, West Conshohoen, PA, 2002.

17. Azghari Nima (2016), Compressive Strength of Concrete and Cubic Samples, Iran.

18. Delmi Ardeshir Engineer, High Strength Concrete (HSC) in Urban Structures, www.irpdf.com.

19. Engineering Group, 2016, daryan.com

20. Hamidi Mohammad Gul, Concrete Mix Design and Technology, Musteqbil Publishing Association, Kabul, Afghanistan, 2014.

21. Khademi Al-Sadat Faezeh, Akbari Mahmoud, and Khademi Seyyed Soroush, Investigating the Effects of the Amount of Microsilica Pozzolanic Materials on the Compressive Strength of Concrete, 8th National Congress of Civil Engineering, Faculty of Civil Engineering, Babol, Iran, 2014.

22. ASTM, Standard C496, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, Annual Book of ASTM Standards, ASTM International, West Conshohoen, PA, 2002.

23. Pachideh Vahid, High-strength Concretes, Riazi Bakhshaish St., Saadat Abad, Tehran, 2015.

24. Rosa Ana Carolinaa, c, Hammad W. A.b, Haddad Asseda, *, Use of operational research techniques for concrete mix design: A systematic review, Heliyon, cell.com/heliyon, Published by Elsevier Ltd., Contents lists are available at Science Direct, 2023.