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A study of micro-silica as a substitution of cement for sustainable concrete

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Abstract
Microsilica, also referred to as silica fume, is a by-product of silicon metal or ferrosilicon alloy industrial production. It is a highly reactive, structureless type of silica made up primarily of very small particles. Cement is one of the most important and most used engineering materials, but its production is costly and emits CO_2 and other harmful gases. It can be substituted by many unwanted substances like micro-silica, rice husk, fly ash, etc. As the use of concrete for high-rise construction grows, the demand for concrete with higher compressive strength rises. Researchers are relentlessly working towards enhancing the concrete's performance by using waste materials such as micro-silica, which is pretty unfamiliar in Bangladesh. So, the introduction of this high-strength waste material can be beneficial in construction. Microsilica can therefore be added to concrete as a substitution of cement, which is 100 times finer than cement or fly ash, to achieve the environmental and improved mechanical benefits. This paper descriptively represents the limited utilization of micro-silica-induced concrete and the advantages that can arise from incorporating micro-silica in concrete. such as higher strength in compression, improved strength in tension and flexure, enhanced durability, reduction in permeability, thermal cracking, corrosion and abrasion resistance, improved high-temperature performance, etc. In the future, using micro silica as an additional cementitious element will allow concrete to have a smaller carbon footprint, promoting more environmentally friendly building techniques and sustainable construction practices.
Keywords: *Microsilica; High Strength Concrete; Sustainable Concrete; Compressive Strength; Water Absorption; Tensile Strength; Permeability; Silica Fume*

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I. INTRODUCTION:

Concrete is the most essential engineering material. Cement, coarse aggregate, fine aggregate, and water are the primary components of concrete, which is a composite material. Since the time of the Greeks and Romans, it has been used by mankind and is still the most used building material (Malinowski & Garfinkel, 1991). Even though it is the most used building material, manufacturing concrete's most important component, cement, emits large quantities of CO_2. For each metric ton of cement produced, around 600 kilos of CO_2 are created. (Nature, 2021). On the other hand, industrial waste accumulation contributes to environmental concerns. Hence, the construction industry emphasizes the need for greater utilization by partly substituting it with alternative cementing materials in concrete. It uses additional elements which include micro-silica, metakaolin, fly ash, and powdered pulverized blast-furnace slag as a means to help promote sustainability (Radonjanin et al., 2013). Multiple studies have taken place to find out the strength, as well as durability of concrete which is formed by the mixing of mineral components (Casanova et al., 1997; Jianyong & Pei, 1997; Ramezanianpour & Malhotra, 1995; Sousa Coutinho, 2003; Türkmen et al., 2003).

Micro-silica (MF) was primarily used as a pozzolan or non-reactive material in concrete in Scandinavia in the initial stage of the 1950s, whereas the US was introduced with the usage of micro-silica in 1984 (Das et al., 2015). To enhance the performance of concrete, recent studies have explored the use of MS as a sustainable substitute for cement. The combined effects of the pozzolanic effect and the micro filler effect are the main factors behind enhancing the strength parameter (Jain et al., 2014a). The utilization of silica fume serves to reduce permeability and thus enhances the concrete's corrosion resistance capability (Anqi et al., 1991),(Naderi et al., 2021; Song et al., 2010) (Detwiler & Mehta, 1989; Khatri et al., 1995; Mazloom et al., 2004; Mostofinejad et al., 2023; Neville & Aïtcin, 1998; Xie & Elwi, 1995).

What is Micro-silica?

Microsilica, which is also referred to as silica-fume, is a residual product that emerges from the silicon and ferrosilicon industry's smelting process. It consists of ultrafine particles, almost 100 times smaller than an average cement particle, and exhibits a surface area that falls within the range of 13,000 to 30,000 m^2/kg (Khan & Siddique, 2011). The high surface area combined with fine particle size and abundant silica content makes it an effective pozzolanic material, meaning if exposed to water, it efficiently interacts with $Ca(OH)_2$ to generate supplementary cementitious material. It leads to improved strength and durability of concrete. It also enhances strength in compression, bond, refines immunity from abrasion, and decreases permeability, increases sulfate and corrosion resistance (Khan & Siddique, 2011).

Micro-silica in Concrete:
Concrete is incorporated with supplementary byproducts like MS. metakaolin, and powdered pulverized blast-furnace slag, fly ash to promote sustainability. It also enhances the mechanical properties of concrete. The incorporation of MS favors concrete in two ways:

Pozzolanic Effect
MS acts as a highly efficient pozzolan. It generates calcium-silicate-hydrate gel (C-S-H), which is responsible for enhanced concrete bond strength ultimately resulting in higher compressive strength (Soomro et al., 2023). In reaction, it can be described as (Bullard et al., 2011; Cheng-yi & Feldman, 1985) :
Cement + $H_2O \rightarrow$ C-S-H + $Ca(OH)_2$
$Ca(OH)_2$+ $SiO_2 \rightarrow H_2O$ + C-S-H

Micro filler Effect
The MS tiny particles reduce the void space within the concrete which makes it a micro filler (Soomro et al., 2023) and makes the concrete more durable as it is a hundred times smaller than fly ash or cement (Kim et al., 2015). The Scanning Electron Microscope (SEM) image illustrates the minuscule-sized particles of MS.

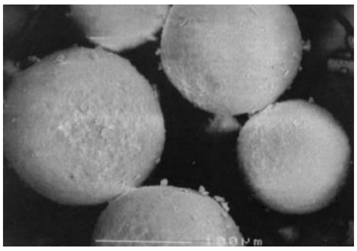

Figure: SEM image of condensed MS (Jaturapitakkul et al., 2004)

Properties of Microsilica
Physical Properties
MS particles are extremely fine with sizes spanning from a minimum of 0.1 µm to a maximum of 0.2 µm. Particles that are finer than the size of 1 µm, take up to 95%. Additionally, MS has a specific gravity less than Portland cement, approximately 2.22 (Soomro et al., 2023). The composition consists of 85%-95% SiO_2 or silica and is of spherical shape which is showcased in the following SEM image:

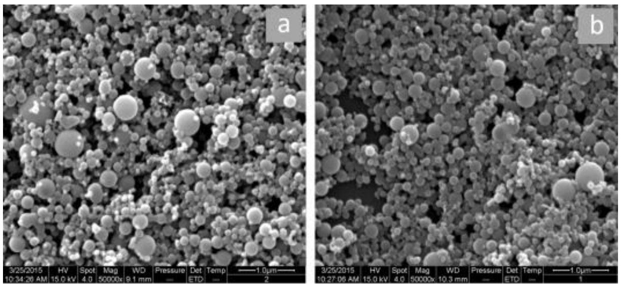

Figure: MS particles micrograph in un-compacted condition (a), compacted condition (b) (Soomro et al., 2023)
MS is primarily grey, but it can range from nearly white to nearly black. Its surface area is between 15000-25000 m^2/kg. MS particle tends to form agglomerations that are bonded loosely together (Fidjestol & Lewis, 1998).
Chemical Properties
The raw materials utilized in the furnace dictate the chemical composition of the MS. It typically contains over 85% of silica, and has relatively low oxides like ferric oxide. alumina, calcium oxide, and alkali content. The MgO content is insignificant and the carbon content ranges between 0.5%-1.5% which typically remains below 2% (Soomro et al., 2023).

Experimental Study Using Micro-silica & Other Cementitious Material:

Many studies have been conducted by researchers to identify an alternate sustainable additional material with cementitious qualities. The effect on compressive strength, water absorption and permeability, flexural strength, tensile strength, and slump and air content on concrete bound with cementitious materials like fly ash, superplasticizers, nano silica, micro-silica, etc. have been researched throughout the past years. Out of all the cementitious materials, micro silica or silica fume was found to be more acceptable as a cementitious material when judged as a replacement for cement in terms of delivering better performances in parameters discussed above in comparison with other cementitious materials.

Compressive Strength:

(Ajay & Rajeev, 2012) explored the result of using cement as a portion of OPC (Ordinary Portland Cement) by using various micro-silica levels which are 0%-15% and found that the capacity on compression of the concrete where micro-silica is used is 25% more than concrete with 0% micro-silica. Again, in the study of the micro-silica pozzolanic activity index (Al Ghabban et al., 2018a), results indicate that a significant increase in pozzolanic activity is observed which results in the overall rise in strength of concrete. (Giner et al., 2011) the research explored the effects of using micro-silica in varying quantities as a replacement of cement, upon the static mechanical and dynamic terrain of concrete and found that compressive strength is significantly higher in micro-silica concrete. (Yang & Jiang, 2003) determined that the application of smaller-sized aggregates, superplasticizers, and MS in concrete significantly increases the compressive capacity of concrete. (Arihant et al., n.d.-a) has found that there is a rise in capacity on compression as the dosage of MS increases before twelve percent of cement is replaced. However, beyond a certain point, a slight reduction in strength is observed. The rise in compressive capacity is due to C-S-H gel which is formed during the hydration process by MS and occupies the void space, resulting in dense and durable concrete. Additionally, MS(micro-silica) enhances the cohesion between the paste of cement and the aggregate used in making concrete, resulting in an augmented bond strength. This heightened bond strength contributes positively to the overall compressive capacity of the concrete. (Dhagat & Mittal, 2013) incorporated fly ash in MS-bound concrete.

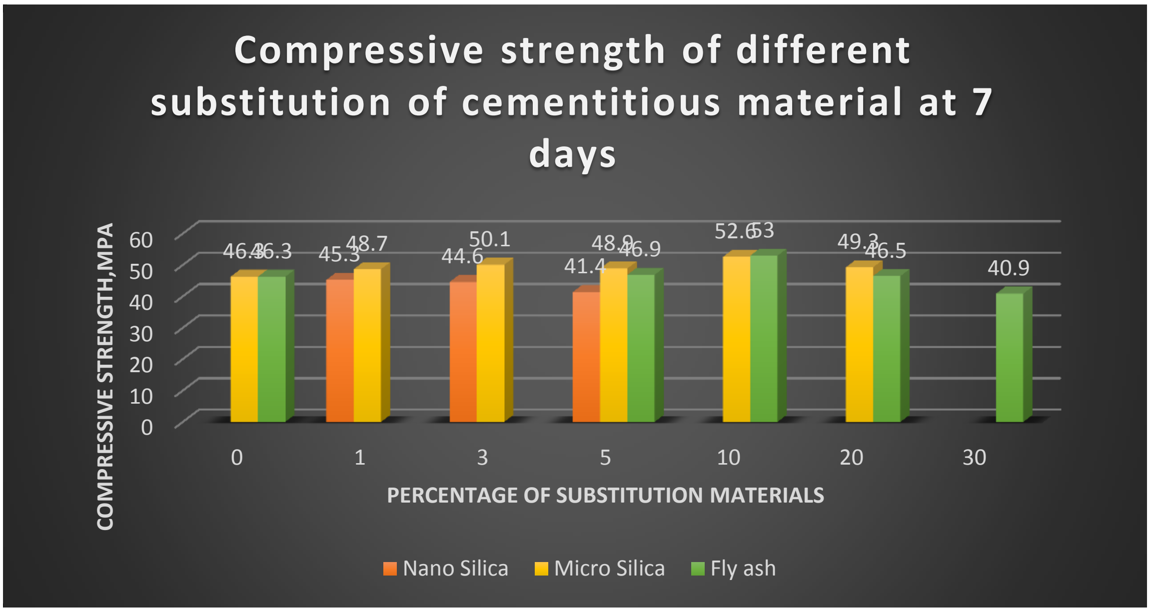

Fig: compressive strength of different substitutions of cementitious material at 7 days

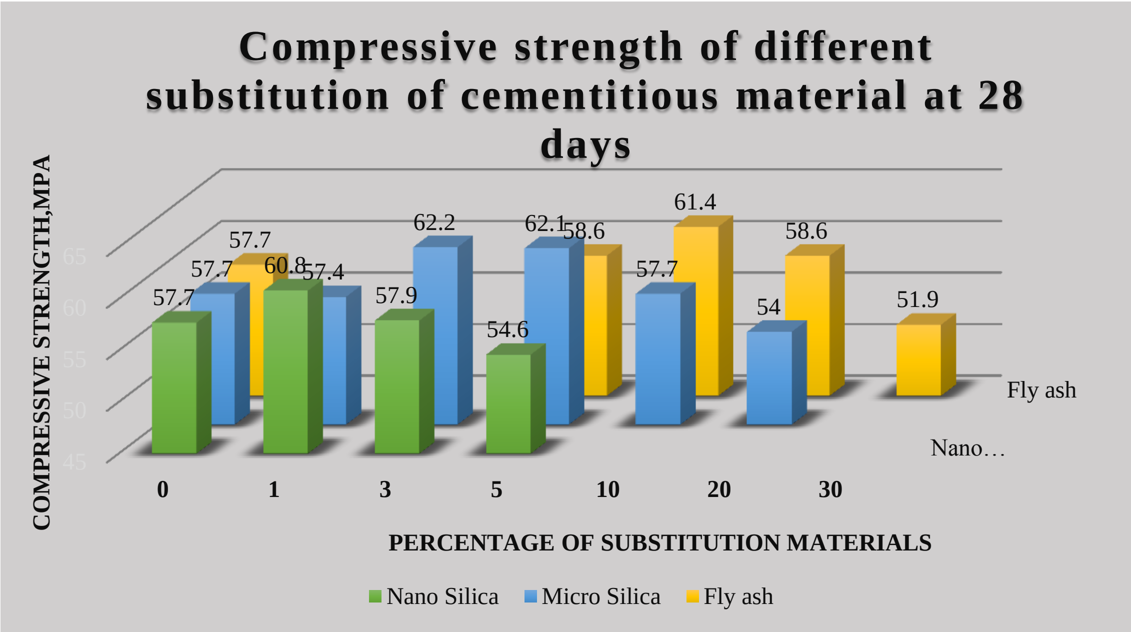

Figure: compressive strength of different substitutions of cementitious material at 28 days

In this research, there was a significant reduction in cement content by 48%, which was replaced by fly ash (43%) and micro-silica (5%) as substitutes. These materials not only reduced the cement content substantially but also contributed to a rise in compressive strength in comparison to the previous condition. The standard strength on compression, under normal circumstances, was measured at 41.3 N/mm². However, after incorporating 43% fly ash, the compressive strength increased to 44.87 N/mm². Furthermore, when 5% micro-silica was added, the compressive strength rose to 51.2 N/mm². (Hirapara et al., 2016) discovered that with the increase of micro-silica from 0% to 15%, the mixture's normal consistency noticeably increases by about 40%. It is discovered that 11% is the ideal ratio for adding micro-silica to get the best possible compressive capacity. When micro-silica is bound to concrete, compressive strength increases significantly, by 25% to 30% compared to regular M25 grade concrete. Additionally, it increases the workability. (Sharma, n.d.) determined MS increases concrete strength by more than 25%. (Bentur & Goldman, n.d.) saw even after just one day, MS concrete outperformed reference concretes in terms of strength, all without producing an excessive amount of heat. MS concrete showed less shrinkage, mostly as a result of less weight loss during drying. It's important to note that improper curing techniques had a similar negative effect on the compressive capacity and surface qualities of silica fume and reference concretes.

Water Absorption and Permeability:

(Al Ghabban et al., 2018a) found that the absorption of water is reduced by incorporating MF in concrete thus resulting in higher durability of concrete. The test was conducted according to ASTM C642. (Arihant et al.), and other researcher's work support this result. (Nayana & Rakesh, 2018),(Nili et al., n.d.), (L. G. Li et al., 2017) indicate that the merged effect of micro-silica and nano-silica results in higher durability due to the reduction of water absorption. (Chia & Zhang, 2002; Hearn et al., 1994) proposed that permeability plays part in a pivotal role in deciding the durability of concrete, SF can be a sustainable solution. As micro silica is extremely fine and has pozzolanic properties, it is known for producing low-permeability concrete. (Ji, 2005) learned with the help of a test of permeability of water, for 28-day strength concrete, that the resistance of penetration of water in concrete can be improved with the addition of nano-SiO_2. (Sobolev et al., 2009) research results suggest that mortars containing nanoparticles have greater compressive and flexural strength. The dissipation of nano-SiO2 molecules in the cement patch is crucial and determines how well concrete works in construction.(Sanchez & Sobolev, 2010) ascertain the need for nanotechnology in concrete and found that nano-silica works as a stuffer that fills the tiny voids in concrete turning in a rise in strength parameters. (G. Li, 2004) demonstrated resources of fly ash with high volume, high-strength concrete bound with nano-silica and found that even after only three days of watering, it showed a significant rise in capacity when compared to fly ash of high volume, and its pore size distribution also showed improvement. (Shoeib et al., 2018) used nanoparticles mainly nano-silica and MS to discover it increases flexural, compressive capacity, and as well as workability.

(Jalal et al., 2012) looked into the durability, rheological, mechanical, and microstructural resources of self-compacting micro-silica bound concrete with high performance which showed higher strength and consistency and decreased permeability, probability of bleeding, and segregation. (Song et al., 2010b) proposed that the possibility of water in concrete can be decreased by summing micro-silica with concrete which fills the pore spaces and densifies the concrete. (Almusallam et al., 2004) evaluated that micro-silica improves the tensile, compressive capacity, and elasticity modulus of coarse aggregate concrete of dwarfish quality. (Toutanji & El-Korchi, 1995) showed that using various water-cement ratios, the compression capacity of mortar with additional micro-silica strengthens the union between cement paste and aggregate. (Sharma, n.d.) discovered MS minimizes capillarity, absorption, and porosity because the lime in the cement reacts with its small particles. (Berke, n.d.) saw that the concrete with air-entrained MS passed freeze-thaw tests satisfactorily and showed lower levels of chloride permeability, which lowered the pace of corrosion. The performance of properly air-entrained micro-silica concrete mixes was on par with or even superior to that of the control mixes. A lower risk of corrosion was shown by a considerable drop in chloride permeability and a rise in concrete resistivity caused by the summing of silica fumes to concrete. While some control concrete mixes encountered corrosion problems, silica-fume concrete with specific water-to-cement ratios showed essentially no symptoms of corrosion. It was intended to conduct more chloride investigations to pinpoint the precise mechanisms causing the observed increase in corrosion resistance. (Safwan Khedr & Nagib Abou-Zeid, n.d.) proposed after adding MS, there was initially a loss of strength within a span of seven days, but significant gains in strength were seen within a span of 56 days later. Elastic modulus, toughness, and the connection between steel and concrete all increased as a result of the optimum amount of MS being added to the mixture. With a modest improvement in resistance to sulfate compounds, silica-fume mortar demonstrated considerable improvements in longevity against synthetic charges from sodium chloride and acids. Additionally, it showed a modest increase in mechanical erosion resistance.

Flexural Strength:

(Joshi et al.,2018) determined that MS concrete showed much-elevated compression and flexural capacity and found that the suitable percentage of replaceable cement is 10%. With the application of British Standards, the determination of compressive capacity was conducted using a 15 cm concrete specimen of cube shape. (Arihant et al., 2013) proposed that the insertion of MS as an alternative to cement made a marginal rise in flexural capacity initially. A noticeable increase in the flexure capacity of the concrete at the 28-day mark is observed, as the proportion of MS increases. This improvement is observed up to 15% substitution of cement with silica, where the maximum flexural strength is observed. About a 27% relative increase at this dosage of MS.

Tensile Strength:

(Almusallam et al., 2004) The microstructure of 16-year-old concrete with the additives of micro-silica was found to be more uniform, and dense than the microstructure of the concrete without micro-silica, according to a scanning electron microscope investigation. (Jain et al., 2014b) reviewed MS was found to be responsible for higher tensile and flexural capacity, elasticity modulus, durability improvement, increased bond strength, and toughness. Based on the result, (Arihant et al., 2013) concluded that MS concrete contributed to a slight increase in split tensile strength and this increase is not consistent. The highest split tensile strength was observed at 9% of MS replacement of cement.

Slump and Air content:

According to (Radwan et al., 2021), incorporating nano or micro silica particles into freshly mixed concrete mixtures reduces both slump and air content. The lowest slump, measuring 170mm, is seen in the concrete mixtures containing the nano-micro silica combination (CMNS81 and CMNS82). However, the mixture of concrete having the lowest air content, 0.60 percent, contains 2% NS and 8% MS.

Results Found in Literature of MS Concrete

The results of experimental research with varying percentages of silica fume and compressive strength, flexural strength, capillary absorption, and strength of split tensile tests are presented in this section. The cylinders have been cast, the following tests have been performed and observed values are found from various research. A comparison with micro silica to other possible replacements such as silica gel, nano silica, and crushed silica gel shows the reason to select MS over others.

Compressive Strength:

At the early age of concrete, silica Fume has been shown to improve the compressive strength of concrete. A denser, stronger matrix results formed by filling gaps with microscopic micro silica particles and increasing cementitious material packing. This improvement in strength may be more noticeable in high-performance and high-strength concrete mixes. The effects of micro silica on compressive strength may differ depending on characteristics such as mix design, micro-silica dose, cement type, and curing conditions. To optimize the benefits of microsilica proper mix design and testing are necessary while considering project restrictions.

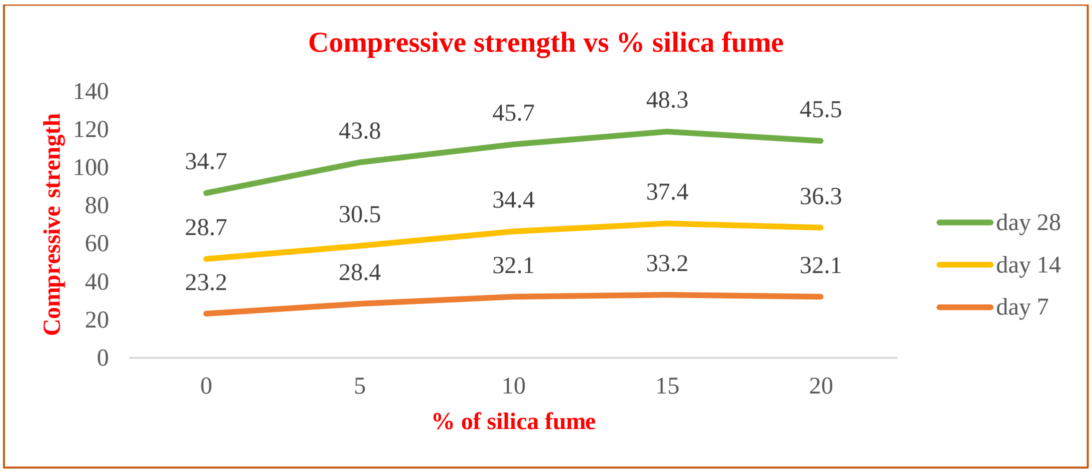

Figure: the compressive strength of silica fume at various percentages (Jain et al., 2014b)

(Jain et al., 2014b) found out that the strength of compression at different percentages of silica fume had increased up to 48.3% at 28 days which was a very significant increase. In terms of strength, 15% of silica fume gives the more optimum result.

Strength of Split Tensile:

Split tensile strength can be improved by the addition of silica fume. The reason behind this, fine-silica particles occupy spaces between cement particles, and the matrix develops denser and more cohesive. More resistance to rupture under tensile forces is caused due to increased cohesiveness, hence split tensile strength develops. Under tensile stresses, while silica fume can increase split tensile strength other factors such as curing conditions, the presence of reinforcing components, and aggregate properties can all influence the concrete's performance.

The strength of split tensile at 28 days:

% Silica Flume	Strength of split tensile (MPa)
0	3.39
3	3.18
6	3.81
9	4.1
12	3.89
15	4.1

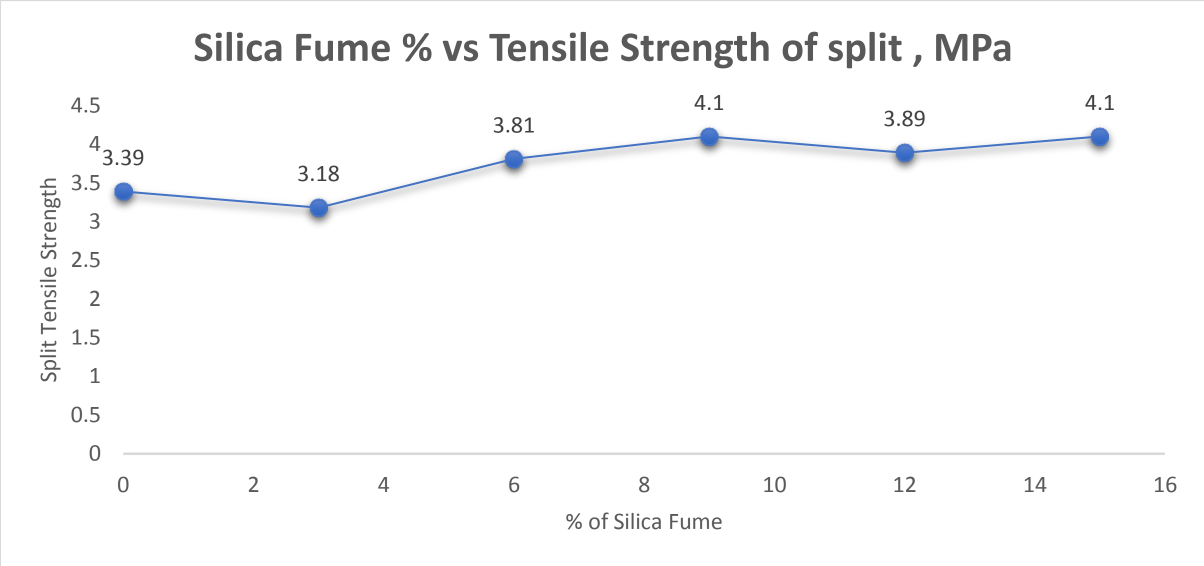

Figure: Split tensile strength at different percentages of silica fume

(Arihant et al., n.d.) determined that micro-silica instead of cement has slightly increased Split Tensile Strength but not in a definitive attitude. However, no loss is observed in strength with the increase of Silica Fume as a discretionary replacement of Cement. The maximum split tensile strength of concrete is seen with the increase of Silica content up to 9% replacement of cement.

Capillary Absorption Test:
Considerably decreased water absorbed through capillaries in concrete is shown when silica fume is introduced. The packing of cementitious materials can be improved by filling the voids between cement particles. Eventually, it results in a more impermeable matrix, which limits water's entry by capillary action.

% Silica Flume	Capillary Absorption
0	1.03
3	0.937
6	0.843
9	0.749
12	0.562
15	0.562

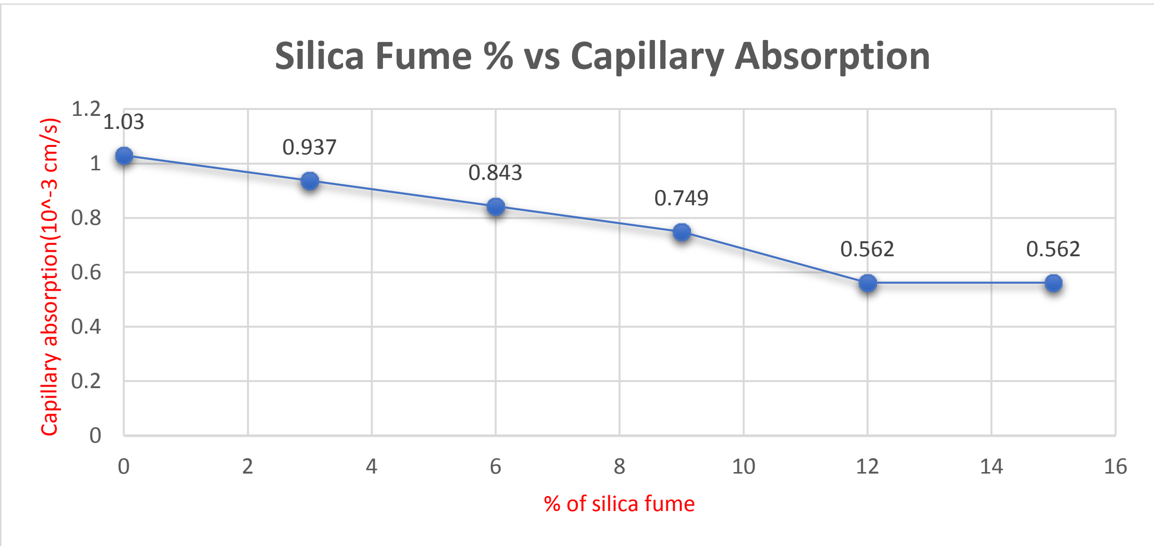

Figure: Capillary absorption at different % of silica flume

(Arihant et al., n.d.) proposed that increasing the silica fume percentage reduces capillary absorption in concrete. This is because silica fume densifies the concrete matrix, enhancing its resistance to water ingress, a major cause of concrete deterioration. Micro-silica fills micro-voids, improving concrete impermeability, which in turn boosts crack resistance and corrosion resistance while reducing susceptibility to chemical attack. The capillary retention coefficient diminishes with an expanding % of silica fume up to 15% substitution. Subsequently, silica-bound concrete is less vulnerable to disintegration and consequently more soli

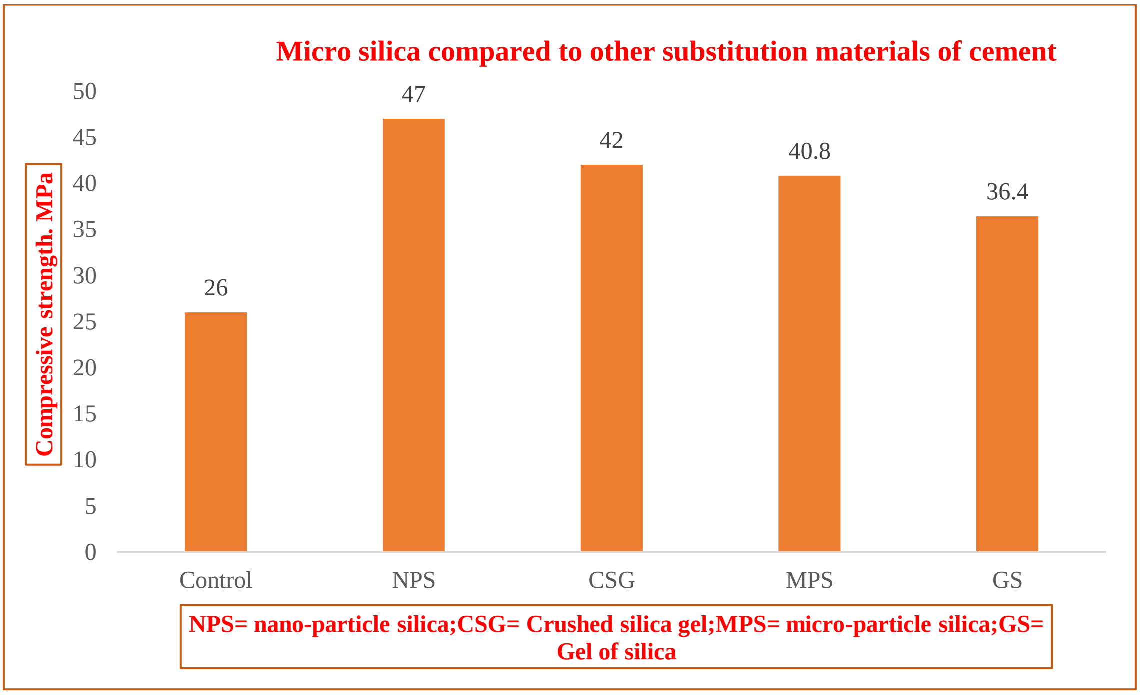

Figure: Compressive strength for cement mortar with different mixtures

From the Chart, it is obvious that Nano silica gives the greatest compressive strength result whereas micro silica gives 36.4 MPa compressive strength.

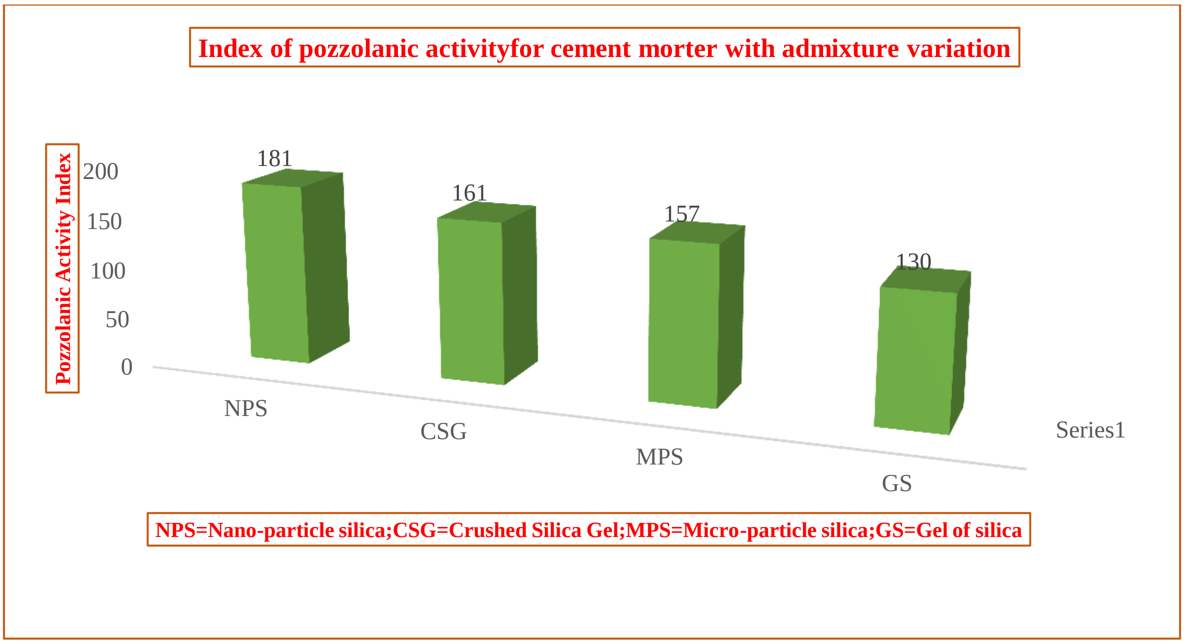

Figure: Index of pozzolanic activity for Cement Mortar with admixtures variation

(Al Ghabban et al., 2018)determined both nano silica and micro silica show solid pozzolanic action and upgrade the strength of concrete by lessening penetrability, expanding strength, and ensuring against different shapes of chemical corruption. Silica gel, on the other hand, isn't commonly utilized as a pozzolanic fabric in concrete and does not contribute to concrete toughness in the same way as nano silica and micro silica. From the Chart, it is observed that Nano silica gives the highest pozzolanic activity index result whereas micro silica gives a 157% pozzolanic activity index.

Flexural Strength Test:
Increasing flexural strength in several cases can be done by adding micro-silica to the concrete mix. Small particles of micro-silica fill the crevices between cement particles, resulting in a denser and more cohesive matrix. This densification can improve bending and tensile resistance.

% Silica Flume	Flexural Strength(MPa)
0	4.75
3	5
6	5
9	5.25
12	6
15	6.5

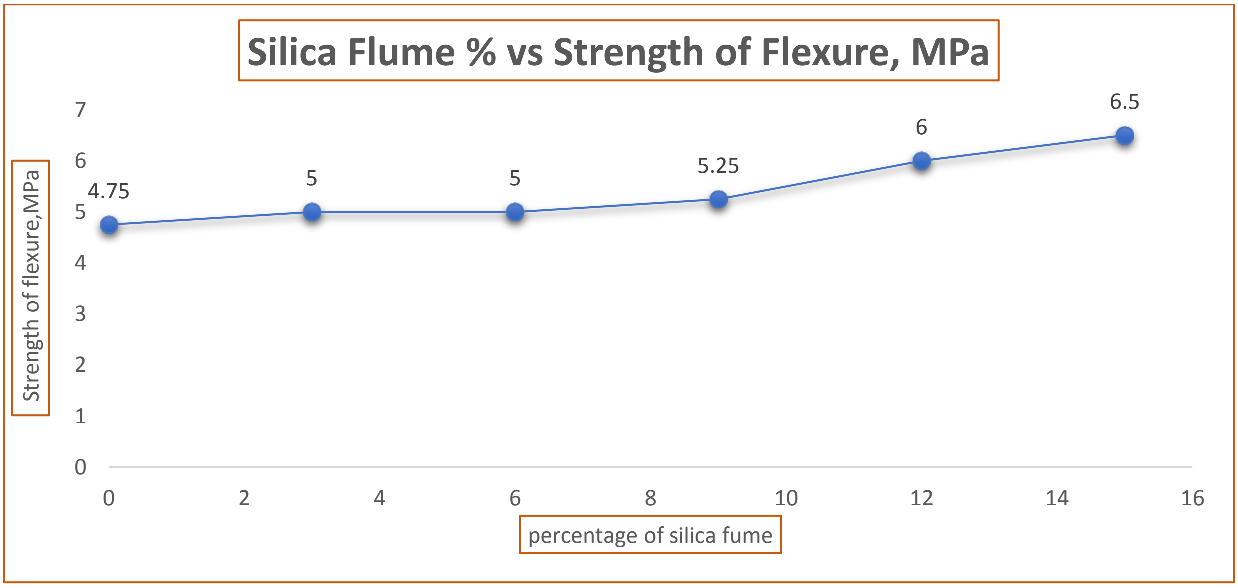

Figure: Strength of Flexure at different percentages of silica flume at 28 days

(Arihant et al., n.d.) determined the addition of micro-silica as a substitution for cement appears slight increment within the flexural strength. From the 28-day strength increments within cement in the rate of substitution of cement by silica, according to the observation the flexural strength of concrete increments with increments in silica substance up to 15% substitution of cement. The most extreme increment in characteristic strength is watched for 15%. For this dosage, the relative increment in flexural strength is found to be about 27%.

II. Conclusion:

Concrete is an excellent and widely used construction material. It has a wide range of applications, including large-scale commercial complexes, residential buildings, and infrastructure development. Many countries are still investing in concrete dams, highways, bridges, and tunnels. These initiatives are critical for economic growth and connectedness. The effect of concrete production on the environment is becoming more well-recognized. Ecologically friendly construction methods are promoted, CO_2 emissions are decreased, and environmentally friendly items are promoted. An attempt was made in this study to introduce micro-silica as a cement alternative.

In this following research, using silica fume as a cement alternative in concrete mixes can provide stronger, more durable, and ecologically friendly construction material, making it a beneficial choice for a variety of construction applications.

The following findings may be obtained after testing and inspecting data on the strength and durability of incorporating micro silica as a substitution for cement. The following sections summarize the significant findings and suggest recommendations for further studies:

1. Due to the capacity of micro-silica to decrease porousness, it can upgrade the durability of concrete. It is significantly used as filler material to improve the bond between cement particles.
2. The addition of MS enhances concrete's ability to resist abrasion, corrosion, sulfate, and other chemical reactions
3. MS exhibits improved compressive, tensile, and flexural strength along with a high modulus of elasticity and strong bond strength. An optimal proportion of micro silica incorporation of 15% shows higher tensile, compressive, and flexure strength found from analyzing data.
4. MS concrete also improves mechanical performances like durability, toughness, and consistency of concrete.
5. The inclusion of MS in concrete reduces water absorption as a result it reduces permeability. It is also beneficial for waterproofing.
6. MS can quicken or retard the setting time of concrete depending on various numerous elements like dosage, ratio of water-cement, and temperature. Accelerating the setting times can be disadvantageous where longer setting times are required. Similarly, retarding setting times can be also detrimental if faster strength development is required.

Recommendation for Further Studies:

Due to some limitations, future investigations need to be taken because of the inability to do durability and shrinkage tests in the experiment. These studies should be prioritized since they can demonstrate how porosity reduces the integration of micro-silica which will eventually increase the material's long-term performance. Significant implementation in construction projects can be done by expanding on these topics.

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