# INVESTIGATION OF THE IDEAL MIXING RATIO AND STEEL FIBER ADDITIVE IN ULTRA HIGH PERFORMANCE CONCRETE (UHPC)

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***Ultra high performance concrete (UHPC) generally has low workability due to the fact that it is a material with low water/cement (w/c) ratio and contains fiber in it. Therefore, adding a superplasticizer (SP) in its production may be a solution, so that it can self-compress, but there may be an overdosing problem. This research, conducted in two stages to determine ideal UPHC mixture, consisted of the first stage involving the determination of the sand/binder (s/b) ratio and the two stages, which included the determination of the ideal steel fiber ratio. To achieve ultra-high performance, the w/c ratio was reduced to 0.2 and the steel fiber was increased to a maximum of 2%. The fresh and hardened properties of UPHC were examined, for better workability their flow diameters and also compressive strengths, flexural strengths, densities, water absorption rates, total voids were determined in UPHC mixtures. It has been determined that the maximum strength can reach about 110 MPa without steel fiber reinforcement, but 130- 140 MPa strengths can be achieved if up to 2% steel fiber is added to the mixtures. It has been found that the strength of the UHPC is related to the s/b ratio and the fiber volume used and that the UHPCs can be obtained when the ideal ratios are taken into account.***

***Keywords:*** *Ultra high performance concrete (UHPC); cement; steel fiber; polycarboxylate ether-based superplasticizers (PCEs)*

## 1. Introduction

Concrete is a building material that plays an important role with the strength and durability of our modern world infrastructure. In other words; concrete is the most man-made building material with the necessary mechanical and durability properties together with the low cost of the desired shape and size [1-11]. Some advanced civil engineering design facilities, including high-rise buildings and nuclear power plants was constructed using ultra high performance concrete (UHPC) keeping in view the high probability of events causing extreme loading like a missile attack or an aircraft impact mainly because if their structures fail [12].

Ultra High Performance Concrete (UHPC) is considered as a desirable material for this kind of structures. UHPC has been one of the most active research fields of concrete in the recent times because it can contribute to the longer life and economic efficiency of structures. Deterioration of civil infrastructure has drawn worldwide concerns due to the large amount of annual outlay for repair and rehabilitation as well as their profound detrimental impact on the society and the environment [12,13]. Thus, sustainable construction materials have attracted intensive research interests, such as concrete with reduced embodied energy, carbon footprint and enhanced durability [14,15]. Ecological goals such as reduction in non-renewable resource extraction, renewable energy regeneration, and residue and waste reduction require the use of improved building materials.

Appropriate raw material usage is essential for building material production and waste recycling for meeting the future requirements [7-10,15]. Moreover, the innovative material and methodology development is likely to extend the infrastructural life-time. For more infrastructural durability, experts are interested in UHPC to increase the service life of the buildings [16,17].

Ultra High Performance Concrete (UHPC) implies a novel category of cementing materials, which was first introduced in France during 1990s [18]. UHPC possesses higher strength than conventional and high-strength concretes. Replacing the conventional concretes with the UHPC will result in developing smaller structural components/members. Construction of smaller members is associated with reduction in transportation, formwork, labor and maintenance costs. The high strength of UHPC assures its sustainability through the construction of slim and durable designs. UHPC's high durability mainly initiates from its resistance against all kinds of corrosion, which increases the design life of a project and reduces the maintenance cost [12, 19]. For instance, UHPC has extremely low permeability against chloride penetration, which can be counted as one of the effective factors improving durability. Other properties of UHPC, which result in its high durability, include lower total porosity, micro-porosity, water absorption and chloride ion diffusion [17, 19].

When ACI-239 produced the UHPC, it defined it as: UHPC is a concrete material with high (150MPa) compressive strength. It is very durable,

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and it exhibits toughness, and ductility for meeting the specific needs, which include and toughness [20-22]. Scientists developed UHPC as a substance, which has lowest number of weaknesses including the pore spaces and micro-cracks but they can result in superior load carrying capacity, and its component materials [17,23,24]. The UHPC development has four fundamental principles, which are given below:

1. For ultra-dense matrix and high level of homogeneity, optimized granular packing is used.
2. It has very small water-cement ratio that decreases capillaries, concrete cancer, and pore size issues that results in greater strength and durability.
3. Very strong micro-fibers are added that improves the overall ductility and tensile strength. It increases abrasive and impact resistances in addition to bridging micro-cracks.
4. Long-duration steam application (steam curing) increases the drying and initial shrinking, which enhances the material properties such as minimum creep, volumetric stability, and negligible/minimum shrinking

Since UHPC has exceptional characteristics, members, which are constructed using UHPC, have some cutting-edge properties/features, which are given below:

### *1.1. Workability*:

Despite the lowest possible water-cement ratio (w/c<0.20), it reduces the UHPC matrix porosity, which increases impermeability that increases strength and durability but for adequate flow, ultra-high PCE-based super-plasticizers are needed. In the nutshell, UHPC acts as a self-compacting concrete (SCC), which makes it possible to cast even the most slender items [18, 21, 24-26].

### *1.2. Strength*

Greater strength helps reducing the use of material, its structural load, and the overall weight in the structural design. When the strength is more than 120-150MPa, the strength of the UHPC will be almost similar to steel; however, its tensile capacity will be lower [15,18,21,27].

### *1.3. Durability*

Today's bridge designs allow construction life of a century to maximum one and a half century; so, durability of materials should be enhanced to make them long-lasting and easier-to-maintain. It doesn't facilitate the projects, which aren't maintained but still, UHPCs require time for trials so as to make experts understand its long-term performance, because now, only laboratory tests are available. The structural performance can be only assured if an entire structure is built using a UHPC, and it is observed for at least 5-10 years [12, 24].

And also UHPC is very different materials which are usually encountered in civil engineering. Apart from being far stronger than conventional concrete, it has outstanding qualities in terms of durability. The durability of concrete is determined to a great extent by its porosity and the related pore radius distribution. These two characteristics have very small values in UHPC compared to concrete with conventional strength classes. The transport of water and solutions, transporting harmful materials as chlorides, is occurred by capillary pores. As the value of capillary pores decreases the resistance to transport of harmful materials improves [28,29].

The typical compositions of concrete materials at different levels of performance and compares the properties of normal strength concrete to UHPC. UHPC has significantly superior strength, chloride resistance, and stiffness when compared to traditional concrete materials [30-32]. The durability of UHPC is related to decreased porosity and improved material homogeneity. It results in a highly improved resistance to the penetration of chlorides, frost and freezing attack, etc. UHPC's excellent resistance to freeze-thaw cycles also develop from the dense matrix, making it ideal for virtually any climate condition. Due to the dense cement matrix and small and disconnected pore structure, UHPC maintains a very low permeability: roughly 1/10 that of granite [28].

### *1.4. Aesthetic*

Aesthetic appearance of the UHPC structures is mainly because of its conspicuous aggregates, granular UHPC matrix packing distribution, higher levels of homogeneity and extra-finishing in comparison with the currently available forms of concrete. In fair-face concrete, painting/coating is not required, and its finish maintains over long-run [27].

### *1.5. Ductility*

For improving the UHPC tensile fracture characteristics, ultra-high-strength micro steel fiber can be used to reduce cracks, their propagation, and displacement-hardening, which have been observed in the UHPC + steel specimens. Other than that, many small cracks allow greater ductility to the UHPC specimens in comparison with the traditional reinforced concrete [18, 23].

### *1.6. Sustainability*

The UHPC technology is highly sustainable green technology that promotes sustainable development of the infrastructure. It implies that if UHPC is used, it will require less cement proportion in the overall concrete content; so, less concrete will be used to manufacture the members. Some scientific reports published around the globe show that global warming is a devastating process that the world is trying to handle. When UHPC is used, it leads to cost savings, low carbon dioxide emissions, and lesser embodied energy in comparison with the traditional approach. Moreover, it is sustainable as compared to other concrete forms as it has a better life-cycle [26], [33].

In this study, firstly, it is aimed to determine that the highest properties of the ratios specified in the references in the production of ultra high strength concrete. In addition, some effects of steel fiber additive on UPHC were investigated in this group.

## 2. Material and method

### *2.1. Materials*

In the UHPC production process, washed stream sand (Figure 1) at 0–2 mm sieve size obtained from the city of Kastamonu was used. Also, Portland cement (PC) used the form of type 1 (CEM II / A-M (P-L) 42,5R) (OPC) according to TS EN 197-1 standard [34], cement specific weight used is 2.94 gr/cm³ and Blaine surface area is 4191 cm²/gr. And also silica fume (SF) used according to ASTM C 1240 standard [35], SF specific weight used is 0.55-0.65 gr/cm³ and Blaine surface area is 23.36 m²/gr. the In this research PC conforming the TS EN 197-1 standard requirements from the Bolu Cement Industry Inc., Turkey was taked. Detailed physical and chemical properties of the cement used in this experiment are shown in Table 1.

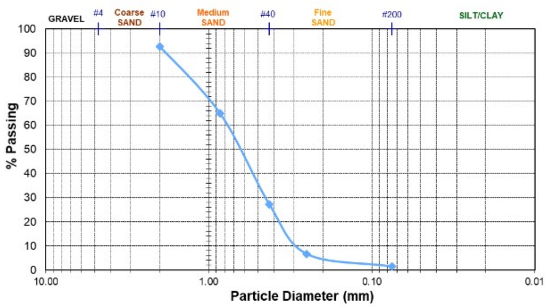


Fig. 1 - Sieve analysis of sand used.

Steel fiber (SF) with diameter 0.15 mm and length 13 mm, specific gravity 7.8, tensile strength 3000 MPa and modulus of elasticity 200 GPa were used. Polycarboxylate ether-based superplasticizers (PCEs) are adsorbed electrostatically to the cement surface with negatively charged carboxylic acids on the polymer surface. Thanks to this absorption, polyethyleneglycol side chains [36] were used as superplasticizers in this study because they were stretched towards the water phase to provide a good cement dispersing effect.

**Table 1**
The chemical composition, physical and mechanical properties of the cement and silica fume

| | PC |
|---|---|
| *Chemical composition (%)* | |
| CaO | 63.59 |
| $SiO_2$ | 20.90 |
| $Al_2O_3$ | 5,.53 |
| $Fe_2O_3$ | 3.70 |
| MgO | 1.76 |
| $Na_2O$ | 0.18 |
| $K_2O$ | 0.41 |
| $SO_3$ | 0.73 |
| Cl | 0.0027 |
| Free CaO | 2.56 |
| *Physical and mechanical properties of cement* | |
| Comp. str. 2 days (MPa) | 17.9 |
| Comp. str. 7 days (MPa) | 31.7 |
| Comp. str. 28 days (MPa) | 45.9 |
| Specific gravity | 2.94 |
| Initial setting time (min.) | 177 |
| Final setting time (min.) | 233 |
| Volume stability (mm) | 1 |
| Blaine value ($cm^2$/gr) | 4191 |
| 90 µm passing (%) | 98.8 |
| 32 µm passing (%) | 88.5 |

### *2.2. Mix proportions and test procedures*

In this study, 4 different aggregate weights (M1, M2, M3 and M4 groups) with a standard cement weight were used to determine the ideal aggregate / cement (a/c) ratio in high performance concrete production and the group providing the highest strength was determined (Table 2, Table 3). In the second stage of the study, steel fiber (SF) were added to this best group (Table 4) by adding 1%, 1.5% and 2% (SF1, SF2 and SF3) of the total volume of binder [16, 37]. Also tested to study the effect of different proportions of the UHPC materials on the compressive strength and some physical properties of UHPC. All the concrete mixtures were made using Portland cement with content 800 kg/$m^3$ [37-39]. Mixture proportions of UHPC are shown in Table 2. Crushed quartz sand replacement of fine sand by weight was used. And also, steel fibers were used with ratio of 0%, 1.5% and 2% by the concrete volume. In determining these rates, previous studies were taken into consideration (Table 5).

The experimental programme was planned to determine the effects of UHPC processes according to Table 6 and water curing applications upon the physical and mechanical properties of samples produced at different groups. W/B (water/binder) ratio of the mortar mix was set at 0.20 while their a/c (aggregate/cement) ratio [16] was set at 3. Concrete were produced in prismatic samples of 4 x 4 x 16 cm in size. Mortars were removed from the mold after 24 h and preserved in water saturated with lime at 20 ± 2 °C until the experiment day.

**Table 2**

Amounts of materials used in the concrete mix (kg/m$^3$)

| Mix No. | Cement | w/c | w/b | Silica füme | Sand. | Water | SF | PCE |
|---|---|---|---|---|---|---|---|---|
| M1 | 800 | 0.25 | 0.20 | 200 | 800 | 200 | 0 | 40 |
| M2 | 800 | 0.25 | 0.20 | 200 | 900 | 200 | 0 | 40 |
| M3 | 800 | 0.25 | 0.20 | 200 | 1000 | 200 | 0 | 40 |
| M4 | 800 | 0.25 | 0.20 | 200 | 1100 | 200 | 0 | 40 |
| SF1 | 800 | 0.25 | 0.20 | 200 | 1000 | 200 | 78 | 40 |
| SF2 | 800 | 0.25 | 0.20 | 200 | 1000 | 200 | 117 | 40 |
| SF3 | 800 | 0.25 | 0.20 | 200 | 1000 | 200 | 160 | 40 |

**Table 3**

The tests result to determine sand to binder ratio

| Mix code | | Mix 1 | Mix 2 | Mix 3 | Mix 4 |
|---|---|---|---|---|---|
| Sand: binder | | 1:1 | 1.125:1 | 1.25:1 | 1.375:1 |
| Flow table (mm) | | 250 | 240 | 230 | 230 |
| Compressive strength (MPa) | 3 days | 67.70 | 68.55 | 78.14 | 73.71 |
| | 7 days | 79.09 | 98.12 | 94.78 | 81.75 |
| | 28 days | 96.57 | 98.81 | 106.27 | 96.53 |
| Flexural strength (MPa) | 3 days | 8.40 | 8.34 | 11.62 | 10.31 |
| | 7 days | 12.52 | 11.06 | 14.94 | 12.76 |
| | 28 days | 17.03 | 16.20 | 19.05 | 15.97 |
| Density (Kg/m$^3$) | | 2315 | 2298 | 2300 | 2300 |
| Absorption (%) | | 1.38 | 1.85 | 1.85 | 1.79 |
| Voids (%) | | 1.96 | 2.83 | 2.94 | 2.84 |

**Table 4**

The tests result to determine optimum ratio of SF

| Mix code | | Control | SF1 | SF2 | SF3 |
|---|---|---|---|---|---|
| Steel fiber ratio by volume (%) | | 0.0 | 1.0 | 1.5 | 2.0 |
| PCE/b ratio (%) | | 4.0 | 4.0 | 4.0 | 4.0 |
| Flow table (mm) | | 230 | 230 | 220 | 210 |
| Compressive strength (MPa) | 3 days | 78.14 | 99.19 | 98.23 | 97.45 |
| | 7 days | 94.78 | 116.15 | 122.34 | 115.72 |
| | 28 days | 106.27 | 132.70 | 140.18 | 141.69 |
| Flexural strength (MPa) | 3 days | 11.62 | 12.08 | 14.98 | 25.81 |
| | 7 days | 14.94 | 14.13 | 21.42 | 23.53 |
| | 28 days | 19.05 | 17.39 | 25.15 | 30.91 |
| Density (Kg/m$^3$) | | 2300 | 2349 | 2392 | 2441 |
| Absorption (%) | | 1.85 | 2.57 | 1.94 | 1.61 |
| Voids (%) | | 2.94 | 3.31 | 3.12 | 2.06 |

**Table 5**

Use of studies to determine ideal ratios

| Selected ratio (%) | Reference |
|---|---|
| Binder weight = 1000 kg/m$^3$ | Buitelaar, 2004; Fehling et al., 2008; Torregrosa, 2013; D. [40-42] |
| Water to binder ratio (W/B) = 0.20 | ACI, 2018; P. P. Li, Yu, & Brouwers, 2017; Resplendino & Toulemonde, 2013. [6,20,43] |
| PCE to binder ratio = 3.5% | Torregrosa, 2013; Wang, 2012. [26,44] |
| SF to binder ratio = 20% | Fehling et al., 2008; Mo & Shi, 2008; Resplendino & Toulemonde, 2013.[42,45,46]. |
| Steel fiber to volüme = (0, 0.5, 1.0, 2.0) % | Chu and Kwan, 2019 [25] |

**Table 6**

Mixing process of the study

| Min | Process | Aspect | |
|---|---|---|---|
| 0-1 | Sand and binder mixing | Dry |  |
| 1-3 | Adding water and 50% PCE | Dry-Plastic | |
| 3-4 | Stop the mixer | Plastic | |
| 4-6 | Mixing after adding the left over PCE | Plastic-Fluid |  |
| 6-7 | High speed mixing | Fluid | |
| 7-10 | Mixing after adding steel fiber | Fluid |  |


Fig. 2 - Fiber added samples.

The samples (Figure 2) were centrally placed in a compression testing machine and load was applied at a rate of 150 kN/min. Specimens were tested using an automatic compression testing machine with a maximum capacity of 3000 kN, density and water absorption were conducted at 28 days.

Uniaxial compression tests and 3-point flexural tests were conducted on the samples at 3th, 7th and 28th day [47]. And these tests are determined in terms of the average compressive strength of three samples from each specimen using the testing procedure recommended in Turkish codes at 28th days (TS EN 12390-3) [48]. At the same time, the standard methods recommended in Turkish codes (TS EN 12390-7) [49] are used to density, water absorption and voids rate were determined at 28th days.

## 3.Results and discussion

When the test results given in Table 3 and Table 4 were examined, it was found that the flow diameter of the non-fiber groups showed a decreasing spreading due to the increasing aggregate ratio. Similarly, this reduction in fiber use continues. However, there has been an increase in aggregate utilization, which can be explained by an increase in the amount of aggregate / binder ratio of more than 1.0 with an increase in void ratio due to increased fine material (Figure 3).

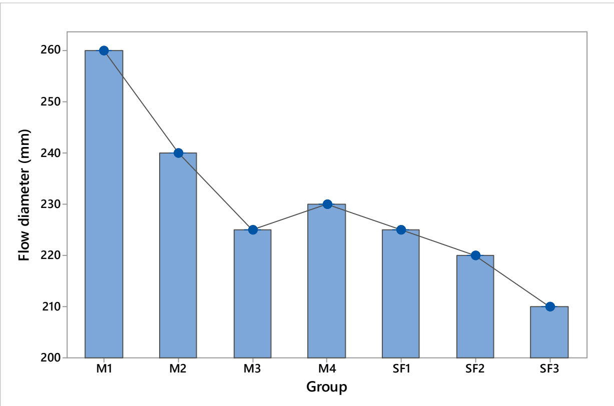


Fig. 3 - Change in flow diameter in groups.

When the Table 3, Table 4 and Figure 4 are examined for the compressive strengths that are the main subject of this study and desired to be in the standards, it is seen that 3-day compressive strengths are 75 MPa and 7-day compressive strengths are approximately 92 MPa. In addition, in

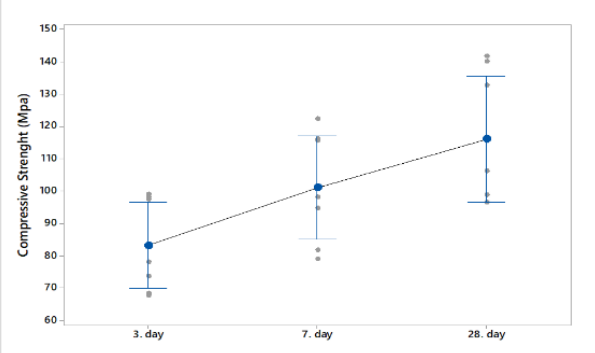


Fig. 4 - Compressive strength of UHPC concrete mixes at various ages.

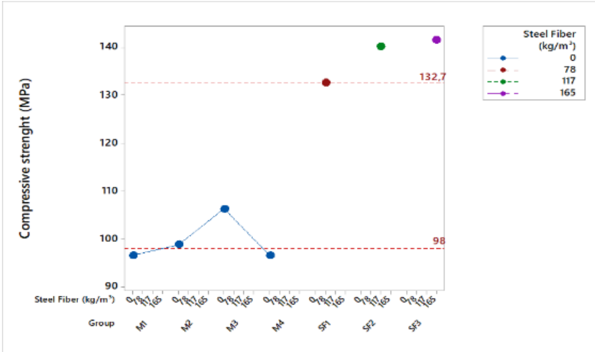


Fig.5 - The compressive strength of UHPC samples with added steel fiber.

the groups produced by using steel fiber (SF), 3-day values approached to 100 MPa compressive strengths and 7-day compressive strengths reached 110 MPa and above. In the UHPC samples, the ideal aggregate /binder ratio without SF was 1.0 and the aggregate / binder ratio, where the compressive strengths of the group reached 106.27 MPa, was about 10MPa compressive strengths losses. However, a nonlinear increase in strength of 1.0%, 1.5% and 2.0% of steel fiber use was found to be 24.87%, 31.91% and 33.33%, respectively.

The effect of steel fiber addition in UPHC is given in Figure 5. When the Figure 5 is examined, it is seen that the highest compressive strength is obtained from the M3 group in M series concrete without steel fiber and it has reached 106.27 MPa strength.

However, in the other three groups, there was an increase in strength due to increased sand and after a certain point, the increase in strength began to change and decrease. In this case, it is accepted that the occupancy rate increases due to the concrete compaction and the aggregate used increases and differs from this rate in the other groups. On the other hand, there was a nonlinear increase in fiber additive ratio with the effect of increasing ratio. This is due to a good structure with the steel fiber used. These results showed similar results with Chen et al. (2019) [50], with approximately 150 MP compressive strength and 11.8 MPa flexural strength values in 2% steel use. In these studies, they stated that the increasing fiber rate also increased the strength, but after the ideal ratio, the strengths started to decrease with the increasing gap structure between the fibers.

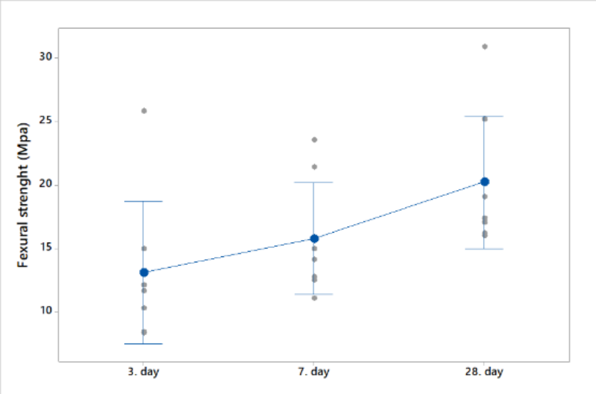


Fig. 6 - The flexural strength of UHPC concrete mixes at various ages.

When UPHC flexural strength were examined (Figure 6, Figure 7), 8.7% of the flexural strength steel fiber contributes 1% decrease was reduced to 17.39 MPa. However, if the steel fiber ratio was used more than 1%, there was a significant increase in flexural strength, a 32% increase in this 1.5% steel fiber additive (25.15 MPa) and a 62% increase in 2% steel fiber utilization (30.91 MPa) was obtained flexural strength. When using steel fibers at a rate of 1% due to lack of sufficient cross section of the fiber is decreased with concrete available on first use.

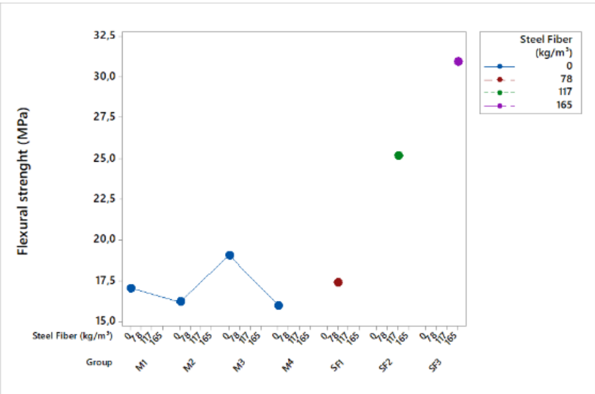


Fig. 7 - The flexural strength of samples with added steel fiber

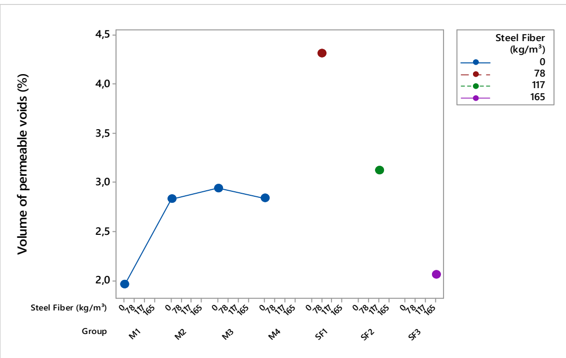


Fig. 8 - The volume of permeable voids of UHPC samples.

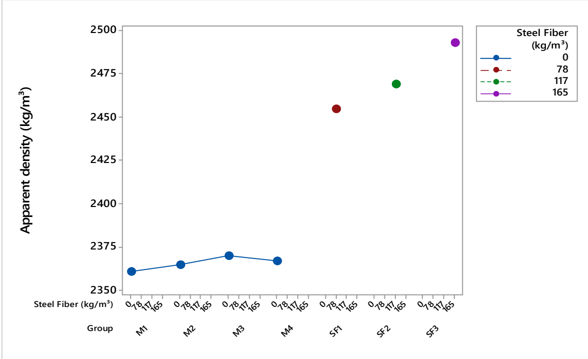


Fig. 9 - The apparent density of UHPC samples.

When Figure 8 and Figure 9 are examined, which shows that the sand content in the M1 group without fiber is lower than the other groups in terms of weight and gap, the cement paste is sufficient as the binder is homogeneously distributed between the sand grains. In addition, a change in sand / binder ratio of 0.125 was found to cause a void volume of 0.8%. However, these increase were not parallel in the following rates and the rate of increase tended to decrease. In the steel fiber additive, the added fiber caused more gaps between the grains than normal and created an extra gap ratio of approximately 1.5% in total. However, it was determined that the void ratio did not increase if steel fiber increased, but it caused a decrease of 2.5% void rate in 1% fiber increase in proportion to the increasing fiber.

The recreational relationship between compressive strength and density is shown in Figure 10. This relationship was found as important to have a statistically high correlation with $R^2$ value at the rate of 97.5%. This was similar in terms of changes in strength and fiber content.

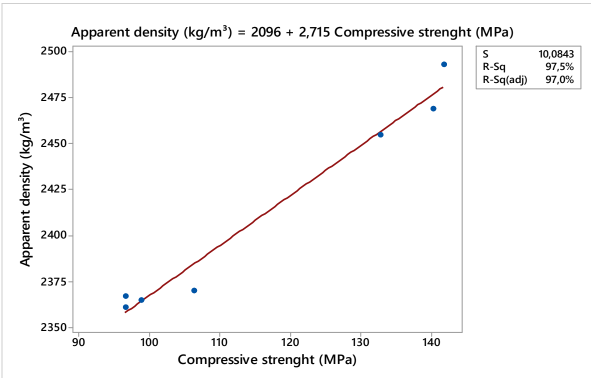


Fig. 10 - Relation between apparent density and compressive strength.

When water absorption rates were examined (Figure 11), the lowest water absorption rate in non-fiber groups was found to be 1.38% in the M1 group, which had the lowest cavity. The other M2, M3 and M4 groups showed (Figure 11) similarity with the water absorption rate, there were not very large changes and their values ranged between 1.79-1.85%.

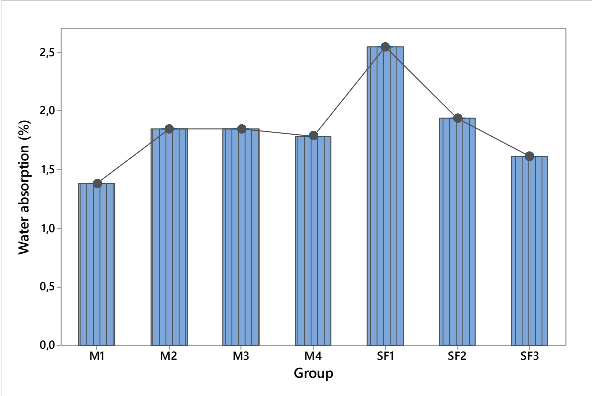


Fig. 11-Water absorption of UHPC concrete mixes.

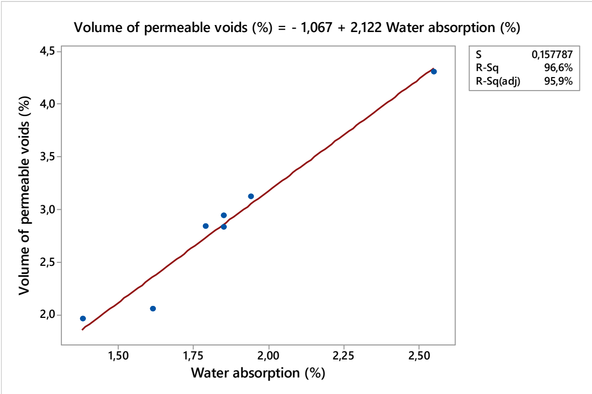


Fig. 12 - Relation between volume of permeable voids and water absorption.

However, a water absorption rate of 2.57% was achieved when using steel fiber at a rate of 1%. This change in the ratio of increasing fiber decreased and the water absorption rates of 1.94% in fiber utilization (SF2) and 1.61% in fiber utilization were obtained. When this situation is examined in the regression analysis showing (Figure 12) the relationship between the gap rates $R^2$ = 96.6% was found to be a statistically significant relationship.

## 4.Conclusions

In this study, physical and mechanical properties of high performance concrete produced using silica fume and cement binders were determined. Based on the results of this study, which includes the topic of producing high performance concrete, the following conclusions have been drawn.

-It is determined that the compressive strength values of the produced ultra high strength concrete samples vary between 96.53 MPa and 106.27 MPa when 28 days, depending on the sand / binder ratio. However, in the case of fiber use, it has been determined that the compressive strength of high strength concrete to ultra has an increasing tendency between 132.70 MPa and 141.69 MPa, according to increasing fiber ratio. Adding fiber to all three series has led to an increase in strength and it has been seen that ultra high strength concrete cannot be produced without using fiber, it is possible to use fiber up to 2% economically.

- The density of ultra high performance concretes (UHPC) for 28-day-old samples without fiber have been changed between 2300 kg/m$^3$. However, depending on the usage of the fiber, it caused a 6% increase in 2% fiber usage per weight.

- The water absorption rates, on the other hand, have changed due to the sand / binder ratio, which increased between 1.38% and 1.85% for 28-day samples. In the addition of steel fiber, water absorption rates increased up to 1%, but this rate decreased over 1% depending on the increasing use.

This clearly demonstrates that experimental research, the mechanical behavior of ultra-high performance materials is greatly influenced by the above mentioned steel fiber admixture and the ideal sand / binder effect. The results obtained are related to the importance of additives in UHPC structures in durability study.

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