

# Mechanical Properties of Ultra High Performance Fiber Reinforced Concrete Made with Foundry Sand

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**Abstract:** The ferrous and non-ferrous foundry industry produces approximately 6 million tons of foundry sand (FS) waste annually in the United States and estimates have shown that only 15% of the waste is being recycled. This study utilized FS waste in the production of Ultra High Strength Concrete (UHSC) as a partial replacement for natural sand. Natural sand was replaced with FS at the replacement levels of 0%, 10%, 20%, and 30% by volume. UHSC mixtures produced were tested to determine the compressive strength, splitting tensile strength, flexural strength, elastic modulus, and Poisson's ratio at 7, 14, and 28 days. The results showed an increase in mechanical performance up to 10% FS replacement. The results also indicate an insignificant decrease in mechanical performance at 20% replacement levels. FS had no significant impact on the Poisson's ratio of UHSC. **Keywords:** Ultra high strength concrete; Foundry sand; Mechanical properties; Workability; Superplasticizers.

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## 1. Introduction

Sustainable construction practices have been of high priority in the recent era, especially sustainable concrete materials, since concrete is the most widely used building material across the globe. Sustainable concrete has been increasingly more popular due to its capability to contain recycled materials, reduce embodied energy, ease of use and placing, and its superior durability over conventional concrete. Studies have shown that foundry sand (FS) can be used in the production of sustainable concrete, and in certain instances has a positive impact on its performance, specifically its hardened mechanical properties [1-2]. Foundry waste constitutes approximately 6-10 million tons of waste produced each year in the United States, of which only 15% is being recycled [1-4]. Foundry waste can include spent FS, slag, ash, refractory, coagulant, baghouse dust, pattern shop waste, and general debris [3-4]. The most prominent waste being slag and spent FS, which are the most promising foundry waste products to improve concrete's performance [3-4]. The source of each waste resulting from different industrial practices and certain industries produce more of each type. The automotive industry is the major generator of spent FS from its molding and casting operations and is typically reused several times before it becomes spent and unusable [1]. Generally, there are two types of FS based on the binder system used to create the mold for the metal casting process: clay bonded systems (also known as green sand) and chemically bonded molds. Both types of FSs have been shown to be suitable for recycling in concrete [1-4]. In concrete production, FS waste has typically been used as partial replacement of the fine aggregate in concrete mixtures, as opposed to a supplementary cementitious material (SCM). However, spent FS has been shown to provide both additional cementing and strength developing properties as a fine aggregate [1-4]. Many past studies have shown the positive impact that FS has on conventional concrete, which can potential be transitioned to higher strength concretes [1-4].

Ultra High Strength Concrete (UHSC) is a new generation of concrete having compressive strengths in excess of 120 MPa (17,000 psi) that cannot always be achieved routinely through conventional constituents and normal mixing, placing, and curing practice [5-6]. UHSC is typically produced with high cement content, silica fume, other SCMs, very fine sand (specifically, particles finer than an ASTM No. 30 sieve (0.60 mm [0.0236 in]), water, steel fibers, and a polycarboxylate high-range water reducing admixture [6-7]. Coarse aggregate is completely eliminated to enhance the homogeneity of the mixtures and a very low water-to-cementitious materials ratio (lower than 0.2) are used in these mixtures. These types of mixtures are considered sustainable due to their high strength to weight ratio, which is significantly higher than that of a conventional concrete as the specific weight is roughly the same, but the strength is drastically increased. Due to the primary use of fine aggregate and no coarse aggregates in these types of concrete mixtures, FS can easily translate into the design with the potential of performance improvement. Using FS in UHSC has the potential to make an already sustainable material even more sustainable, while simultaneously improving its performance. Landfilling with spent FS is not an environmentally

responsible way of disposal, therefore reusing this waste material would help in the pursuit of a more sustainable waste disposal methods while creating a more sustainable concrete. Therefore, this study demonstrates the impact of FS on UHSC mixtures' mechanical properties by producing and testing mixtures with 0%, 10%, 20%, and 30% fine aggregate replacement with FS.

## 2. Research significance

There is extensive research investigating the use of FS in conventional concrete available, however, research related to use of FS as fine aggregate in UHSC is severely lacking. UHSC is produced using high amounts of fine aggregates such as river sand or manufactured sand, which can easily be replaced with FS due to its similar size and gradation. Therefore there is the potential to combine existing efforts with UHSC mixtures to demonstrate the impact that FS has on UHSC.

## 3. Background information

Several researchers [1-4, 8-11] have reported on the use of FS in concrete primarily as partial replacement of fine aggregate in conventional concrete, with positive results. Siddique et al. [1] reported an increase in compressive strength, splitting-tensile strength, flexural strength and modulus of elasticity with increase in FS content. Three different FS percentages were used: 10, 20, and 30 percent replacement by volume. The authors have reported an increase in compressive strength from 8% and 19% depending upon the spent FS replacement percent and the age of the specimens at testing. The percent increase in the splitting-tensile strength varied from 6.5% to 14.5% and the overall increase in flexural strength was reported as 7%. Additionally, the authors have reported a 5% to 12% increase in modulus of elasticity.

Prabhu et al. [8] experimented on the use of FS as partial replacement of fine aggregates in the production of concrete. Density, workability (slump), splitting tensile strength, flexural strength, ultrasonic pulse velocity (UPV) and compressive strength tests were performed to evaluate the effect of FS on fresh and hardened properties of concrete. The test samples were produced from the mixtures developed using FS replacing 10%, 20%, 30%, 40% and 50% of natural sand. The authors [8] have reported that the increase in FS content decreased the slump of the concrete up to 10%. The slump then remained constant for higher dosages of FS after 10%. Prabhu et al. [8] reported a decrease in mechanical performance up to 10% replacement; however, an increase at the 20% replacement level was also recorded. Prabhu et al. [8] concluded that there were many impurities in the FS used in their study, which could have negatively impacted their results.

Naik et al. [9] produced bricks, blocks, paving stones and pre-cast molded concrete products with the partial replacement or inclusions of Class F fly ash, coal combustion bottom ash, and spent FS. The fine aggregate and portland cement was replaced in two percentages (25% and 35%), with spent FS and fly ash, respectively. The results reported showed an improvement in strength and durability. In the molded concrete the average compressive strength was 32% higher than the control mixture. Prabhu et al. [8] also reported a considerable reduction in freeze-thaw durability and abrasion resistance in specimens made with spent FS.

Nwofor et al. [10] conducted an experimental investigation to study the effect of FS as partial replacement of fine aggregate on mechanical properties of concrete. Specifically the compressive strength, splitting tensile strength, and flexural strengths were determined at replacement levels of 5%, 10%, 15%, 20% and 25%. The results showed that the addition of FS helped in improving the mechanical properties of concrete produced up to 15% replacement level for all mechanical properties tested.

Sohail et al. [11] were able to show the effect of FS on the mechanical and durability properties of concrete. The mechanical properties studied were compressive strength, splitting tensile strength and flexural strength. The tested samples were categorized according to natural sand replacement level by its mass (0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100%) with FS. Sohail et al. [11] carried out an all-encompassing analysis that ranged from partial to total percentage replacement. The authors established the postulation of FS impacting concrete properties up to a particular percentage replacement value (20%). Sohail et al. [11] postulated that this could be because of the increased water absorption ratio of the concrete mixture with increase in percentage weight of FS. The results showed that an increase in FS negatively impacted the workability of all tested concrete mixtures. The results also showed a consistent increase in the compressive strength of concrete mixtures up to 90% FS replacement level. However, concrete samples with 100% FS replacement showed a decrease in compressive strength. The samples also exhibited an increase in splitting tensile strength up to 70% FS replacement level. The flexural strength samples showed an increase in strength up to a 50% replacement level.

Torres et al. [12] completed a study on the mechanical properties of using general foundry waste in concrete. This study used "as received" unprocessed foundry waste that included a mixture of large pieces of slag and FS. Since the as received material contained both coarse (slag) and fine constituents (foundry sand), the authors replaced virgin coarse and fine aggregates in a conventional concrete control mixture at 10%, 20%, and 30% levels

by mass. Torres et al. [12] produced two sets of test mixtures; one set that replaced the coarse and fine aggregates individually with the corresponding coarse and fine foundry waste, and another set that replaced both coarse and fine foundry waste simultaneously. The compressive strength, splitting-tensile strength, flexural strength, and modulus of elasticity were measured for both sets of mixtures at an age of 7, 14, and 28 days. The results indicated that general foundry waste as either coarse, fine, or combined by mass replacement of natural aggregate has no impact on the mechanical performance of PCC up to 30% for individual replacement or 20% combined. This result not only demonstrates a possible avenue to increase the amount of foundry waste recycled annually, but it also reduces the demand for virgin aggregates for concrete production.

Overall, all of these studies demonstrated that FS could ultimately benefit the mechanical performance of concrete with FS replacement percentages up to approximately 30% and higher in some cases depending on the mechanical property. Therefore, FS should have similar impacts on the production of UHSC and is the basis of this study.

## 4. Experimental program

### 4.1 Cementing materials

Type I/II portland cement was used, which satisfies ASTM C150 [13]. Type I/II was selected as it is a commonly used and locally available. Silica fume was also used, which satisfies ASTM C1240 [14]. The chemical compositions of cement and silica fume are presented in Table 1.

**Table 1. Chemical composition of cement and silica fume.**

Compound	Type I/II Cement	Silica Fume
SiO <sub>2</sub>	21.4%	95.7%
Al <sub>2</sub> O <sub>3</sub>	4.53%	0.17%
Fe <sub>2</sub> O <sub>3</sub>	3.16%	0.20%
CaO	64.12%	0.29%
K <sub>2</sub> O	NA	0.28%
Na <sub>2</sub> O	0.51% (Equiv.)	0.21%
MgO	1.91%	0.21%
SO <sub>3</sub>	2.90%	0.11%

### 4.2 Foundry sand and natural aggregates

FS was obtained from a local metal casting company. The sand was spent sand from molds used in their facility and is classified as a green sand (clay bonded system). Since the FS is unique and has prior processing, the physical and chemical composition of the obtained FS was determined through ASTM C128 [15] and X-Ray Fluorescence (XRF) and the results are shown in Table 2 and Table 3 along with the results of the natural sand.

**Table 2. Physical properties of FS and river sand.**

Property	Fine Foundry Waste	River Sand
Specific gravity	2.45	2.43
Unit weight (kg/m <sup>3</sup> ) [lb/ft <sup>3</sup> ]	1536 [95.88]	1431 [89.33]
Absorption (%)	1.4	0.89
Fineness modulus	1.64	1.62

According to Siddique et al. [1], the high number of fines present in FS contributes to a denser concrete, which results in increased mechanical performance, especially in UHSC. In addition, the chemical analysis reveals a high percentage content of SiO<sub>2</sub> present in the FS which is advantageous in terms of mechanical strength. Prabhu et al. [8] reports that the high SiO<sub>2</sub> present in FS contributes to increased cement hydration, which also results in an increased mechanical performance. It was reported in the literature [1, 8] that no undesired longer-term effects from using fine FS in concrete.

Locally obtained river sand was used as the natural aggregate in the UHSC mixtures, which meets the requirements of ASTM C33 [16]. However, for the purpose of this study, both the river sand and FSs were sieved to obtain the material finer than the No. 30 sieve (0.60 mm [0.0236 in]) for using as very fine sand in UHSC mixtures. As previously indicated, UHSC is a special type of concrete with superior strength and commonly

produced with use of finer aggregate particles. A sieve analysis was also completed on the river sand for comparison with the FS and was completed in accordance to ASTM C136 [17] and can be found in Fig. 1.

The sieve analysis show a very similar grain size distribution between the river sand and the FS, which makes FS a compatible replacement for river sand in regards to size. The two sands also have a similar fineness modulus with the river sand being 1.64 and the FS being 1.62.

**Table 3. Chemical composition of FS and River sand.**

Compound	Foundry Sand (%)	River Sand
MgO	0.0	0.0
Al <sub>2</sub> O <sub>3</sub>	1.7	.77
SiO <sub>2</sub>	94.1	99.0
K <sub>2</sub> O	0.0	0.0
P <sub>2</sub> O <sub>5</sub>	0.0	0.0
CaO	0.2	0.1
TiO <sub>2</sub>	0.0	0.8
MnO	0.0	0.0
Fe <sub>2</sub> O <sub>3</sub>	5.8	0.2

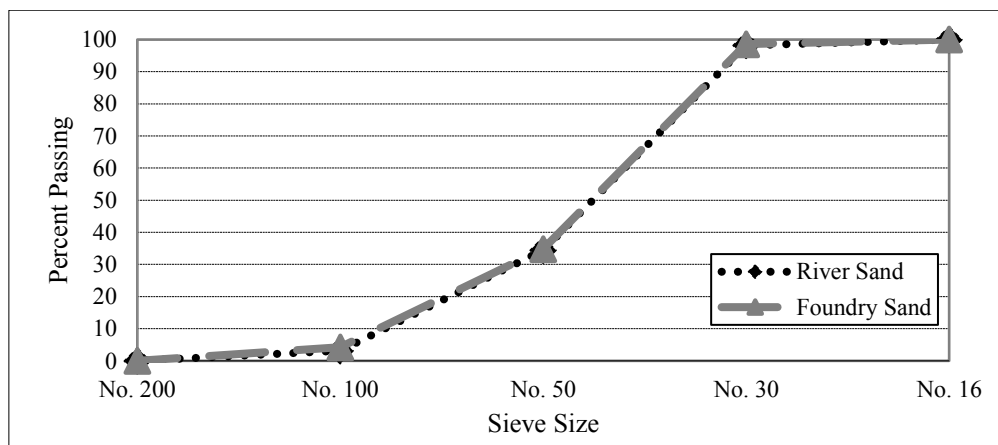


Fig.1. Sieve analysis of river sand and FS.

### 4.3 Mixture proportions

The concrete mixtures were developed based on a literature review [1-3, 6-7, 17-22]. In these studies, high volumes of cement and silica fume, as well as finely graded natural sand, was used to produce UHSC. This study follows suit, the final UHSC mix designs consisted of fine aggregate sieved and passed through ASTM No. 30 sieve (< 0.595-mm [0.0234-in]), Type I cement, silica fume, and steel fibers. The steel fibers used were from Nycon Corporation and are their type 1 steel needle fiber 0.2-mm (0.007-in.) diameter and 13mm (.5-in.) long. The steel fibers were used to improve the ductility and fracture toughness of UHSC. UHSC mixtures were prepared at a constant water-cementitious materials ratio (w/cm) of 0.20 in order to monitor the impact of spent FS on the mechanical performance on UHSC. The FS used was also sieved and passed through ASTM No. 30 sieve to achieve a size of < 0.595-mm (0.0234-in.) to match the size of the virgin fine aggregates. Based on of the literature, the most successful natural sand replacement with FS percentages were at or below 30%, therefore this study used natural sand replacement with FS by mass at 0%, 10%, 20%, and 30% replacement increments, where the 0% FS represented the control mixture. A polycarboxylate-based HRWRA was used to achieve a sufficient workability. The mixture proportions of the all mixtures are shown in Table 4.

### 4.4 Preparation and casting of concrete specimens

Following sieving the aggregates as described previously, the aggregates were then thoroughly washed over a No. 200 sieve to remove any fine dust and particles. This helped to ensure there was no water lost due to fine dust

particles as recommended by the literature [5, 7, 19–22]. After washing, the aggregates were oven dried at 110°C (230°F) for a minimum of 24 hours to achieve a 0% moisture content.

The constituents of each mixture were then mixed for approximately 20 minutes using a laboratory pan mixer. The dry constituents (aggregate, cement, silica fume) were mixed for the first 2 minutes and then 75% of the water was added. After thorough mixing, the HRWRA was added with the remaining 25% of the water. This mixing sequence was used based on of the literature and experience [20–25].

Following mixing, each mixture's workability in terms of flow was determined using a flow table in accordance to ASTM C1856 [6]. This was done in order to help assess the impact of FS on rheology, which impacts mechanical performance. The average flow values are reported in Table 5 along with fresh concrete density, which was obtained in accordance to ASTM C138-17 [26].

**Table 4. UHSC Mixture Proportions.**

Mixture Name	Cement kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	Silica Fume kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	River Sand kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	Foundry Sand kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	Steel Fibers kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	HRWRA l/m <sup>3</sup> (gal/yd <sup>3</sup> )	Water kg/m <sup>3</sup> (lb/yd <sup>3</sup> )
0FS	890 (1500)	222 (375)	821 (1384)	-	119 (200)	29.7 (6)	222 (375)
10FS	890 (1500)	222 (375)	739 (1246)	90 (152)	119 (200)	29.7 (6)	222 (375)
20FS	890 (1500)	222 (375)	657 (1108)	180 (303)	119 (200)	29.7 (6)	222 (375)
30FS	890 (1500)	222 (375)	575 (455)	270 (455)	119 (200)	29.7 (6)	222 (375)

**Table 5. Flow Test and Fresh Density Properties**

Mixture Name	Flow Diameter mm (in)	Fresh Density kg/m <sup>3</sup> (lb/ft <sup>3</sup> )
0FS	193.5 (7.6)	2522 (157.4)
10FS	181.6 (7.2)	2512 (156.8)
20FS	167.4 (6.6)	2510 (156.6)
30FS	157.2 (6.2)	2503 (156.3)

As seen in Table 5, the fresh density and flow diameter decrease with an increase in addition of foundry sand. This is likely due to the higher degree of angularity of the FS versus the smooth nature of the river sand used as the primary aggregate [1-3].

In order to minimize as many variables as possible, one curing regime was tested for the compression testing samples, which was selected based on the literature review developed by Allena and Newtonson [23]. This curing regime consists of curing the samples at room temperature 23°C (73°F) for the first 24 hours. After demolding all specimens, the specimens were then heat cured in a water bath at 50°C (122°F) until 2 days prior to testing. At two days prior to testing, the specimens were removed from the water bath and dry cured at 200°C (392°F). Curing at elevated temperatures accelerates the hydration of silica fume thus forming the secondary calcium silicate hydrates, thereby enhancing the microstructure of UHSC.

## 5. Results and discussion

### 5.1 Compressive strength

Compressive strengths of UHSC mixtures produced with and without FS were determined at 7, 14, and 28 days. Compressive strength specimens were molded using 50-mm (2-in.) cube molds. Cubes specimens were used to avoid problems with end preparation of cylindrical specimens. After the specimens were properly cured they were individually tested according to BS 120-3-2009 [27]. The British Standard was used as it provides greater detail to testing hardened concrete cubes in compression than ASTM C 39-15a [28]. An average of three samples were tested per data point, which can be seen in Fig. 2.

The compressive strengths obtained from all mixtures are greater than the compressive strength demonstrated by a typical UHPC mixture of 120 MPa (17,000 psi) [6]. The control (0 – FS) mixture obtained a strength of 148 MPa (21,579 psi) at 28-day. In fact the, 7-day age control mixture also achieved ultra-high strength of 134 MPa (19,461psi). The results also showed that once FS was incorporated into the mixtures, an increase in compressive strength was observed at a 10% replacement level. The 28-day 10 – FS sample exhibited a compressive strength of 160 MPa (23,206 psi), which was an increase of 7.9% from the 28-day 0 – FS sample. All 10 – FS mixtures exhibited greater compressive strengths than the 0 – FS specimens with an average increase of 7.8%. When investigating the impact of UHSC specimens produced with 20% FS replacement, the results showed a marginal decrease in compressive strength when compared to the control mixture. Comparing 28-day strengths revealed a

loss in compressive strength of approximately 1.4%. The average strength loss from control to 20% FS replacement was only 1.4%. Looking at the last data set in this series (30 – FS), the results also reveal a decrease in compressive strength with the addition of FS up to 30% replacement. The 28-day strength results show a decrease of 9.4% in compressive strength. The average decrease from the control mixture to the 30% replacement samples, shows a decrease of approximately 9.2%.

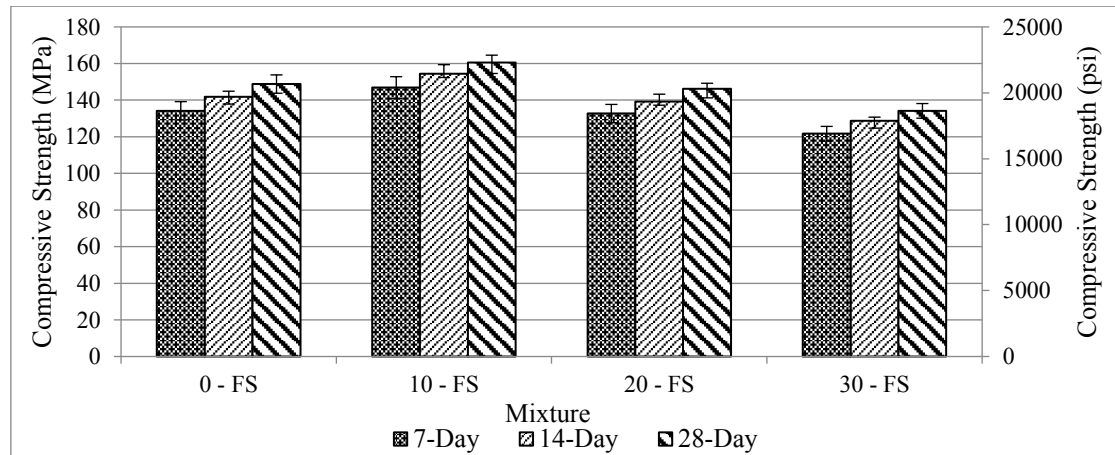


Fig. 2. Compressive strength results.

A t-test with a confidence level of 95% was applied to compare the control specimens with the three FS replacement levels and the results show a significant difference between the 0 – FS and 10 – FS, no significant difference between 0 – FS and 20 – FS, and a significant difference between 0 – FS and 30 – FS. The statistical analysis reveals that FS increases the compressive strength of UHSC up to 10% and has no impact at 20% replacement. At 30% FS replacement, a negative impact on the compressive strength of UHSC was observed. The compressive strength results achieved are similar to those currently published on FS on conventional concrete [1-5]. The decrease in compressive strength with increase in FS content beyond 20% can be attributed to the effect of FS on concrete rheology and density as the FS increases. As can be seen from Table 5, workability decreased with increase in FS content as well as the fresh density and this decrease could lead to lower compressive strengths. With the increase in FS content, its workability is impacted and there by compaction is affected thus decreasing the concrete's density and consequently its strength. Additionally, Siddique et al. [1, 2] and other authors from other studies [3, 4, 12, 21] describe the SCM abilities of FS due to its high siliceous content, and have also used FS as an SCM (replacing cement content) as opposed to an aggregate replacement. However, these authors demonstrate that FS is better suited as an aggregate than an SCM due to its size being larger than traditional SCMs (silica fume, fly ash, etc.). Aggarwal et al. [29] completed a microstructural analysis on conventional concrete produced with FS and revealed that C-S-H gel becomes more widespread on samples with 20% or less FS replacement and conclude that the SCM impact from FS is limited. Therefore the results obtained in this study for the compressive strength are consistent with previous authors findings on concrete incorporating FS. Combining this finding and the reported loss in workability and fresh density resulted in an increase in performance at 10% FS replacement, virtually no change at 20% FS replacement, and a minor decrease in compressive performance at 30% FS replacement.

## 5.2 Splitting tensile strength

The splitting tensile strength of concrete mixtures made with and without FS were measured at 7, 14, and 28 days in accordance to ASTM Standard C496 [30] and the results are depicted in Fig. 3.

The variation in the splitting tensile strength with any combination of FS was very similar to that observed in the case of the compressive strength. The general trend was an increase in splitting tensile performance with an increase of FS up to 10% replacement and a decrease thereafter. It was found that the control mixture had splitting tensile strength values 6.2 MPa (910 psi), 6.9 MPa (1,000 psi) and 7.2 MPa (1,050 psi) at 7, 14 and 28 days, respectively. Similar to compressive strength, there was a marginal increase by approximately 5.8% in the values for the 10% FS mixture at all the three ages. This was followed by a reduction in the splitting tensile strength for the 20% FS and 30% FS mixtures. Specifically, there was an average decrease of approximately 7.9% for the UHSC mixtures from 0 – FS to 20 – FS. Following this, there was a decrease of 28.3% from 0 – FS to 30 – FS. As with the compressive strength data, a t-test was performed to determine statistical significance. The t-test revealed a statistical significance between 0 – FS and 10 – FS, as well as between 0 – FS and 30 – FS. However, there was no statistical significance between 0 – FS and 20 – FS, which is a favorable result as it shows that FS

has no impact at a 20% replacement level, which can increase the sustainability of the material without sacrificing splitting tensile strength. As with the compressive strength results the effect of the FS reducing density and workability, along with the literature [29] demonstrating a reduction of SCM ability from the FS, had the same effect on the splitting-tensile strength, which is expected based on the literature [1-5, 20-29].

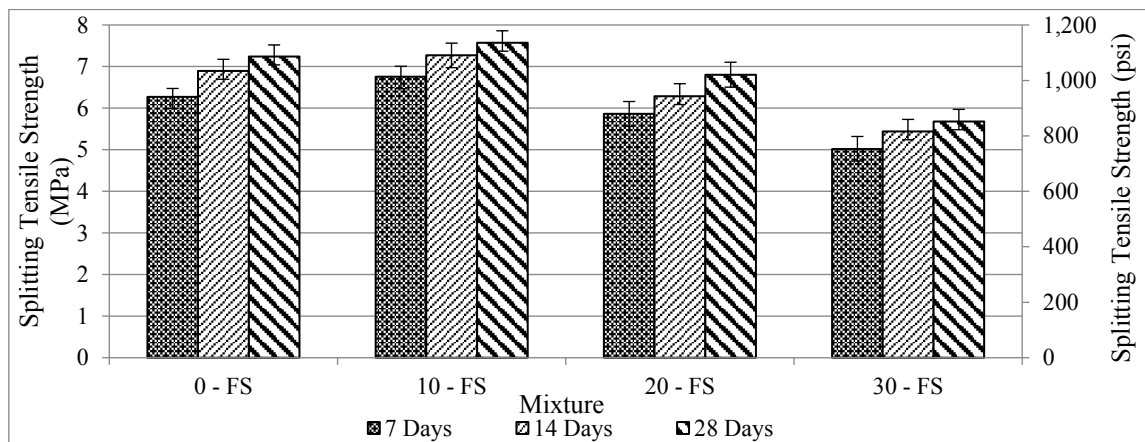


Fig. 3. Splitting tensile strength results.

### 5.3 Flexural strength

Flexural strength of concrete mixtures made with and without FS was determined at 7, 14, and 28 days in accordance to ASTM Standard C293 [31] and the results are shown in Fig. 4.

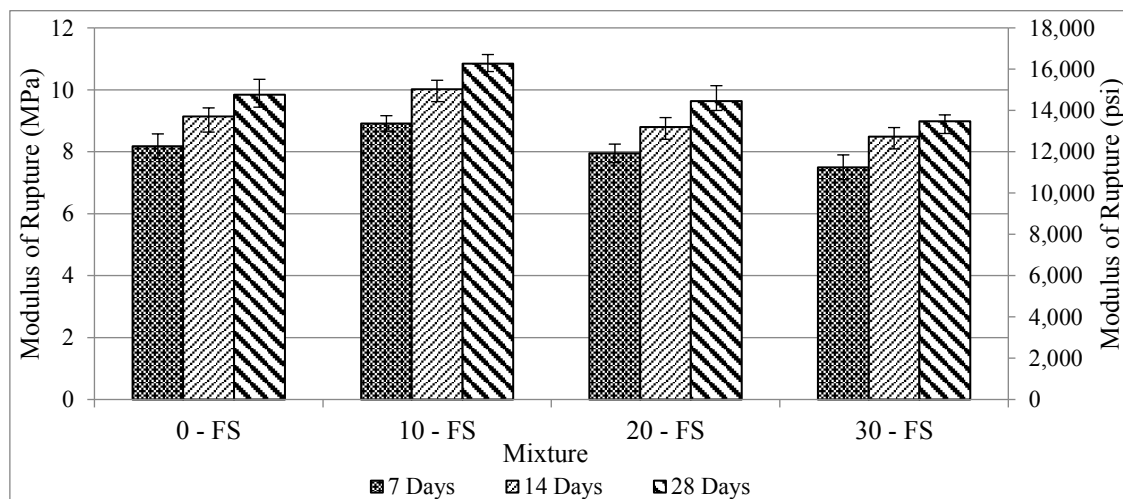


Fig. 4. Flexural strength results.

The results shown in Fig. 4, demonstrate an increase in flexural strength with age, as expected. It was found that there was a steady increase of approximately 8.5% with age in case of specimens produced from control mixture. The control mixture exhibited a flexural strength of approximately 8.1 MPa (1,186 psi), 9.1 MPa (1,325 psi) and 9.8 MPa (1,427 psi) at 7, 14 and 28 days respectively. When it comes to the 10% FS, the flexural strength values of approximately 8.9 MPa (1,293 psi), 10 MPa (1,453 psi) and 10.8 MPa (1,572 psi) were observed at 7, 14 and 28 days, respectively. It is observed that the 10% FS replacement level improved the flexural strength by approximately 9.5% depending upon age. This slight increase in flexural strength for the 20% FS replacement was not observed. In particular, the 20% FS mixture had flexural strength values of approximately 7.9 MPa (1,153 psi), 8.8 MPa (1,277 psi) and 9.6 MPa (1,397 psi) at 7, 14 and 28 days respectively. The average flexural strength for the 20% FS mixtures was approximately 8.8 MPa (1,276 psi), which was a slight reduction in flexural strength from the average control mixture strength of 9 MPa (1,313 psi). This is a 2.2% decrease in flexural strength when compared to control mixture. This is lower than the 10% FS flexural strength values. Lastly, the 30% FS mixture had average flexural strength values of approximately 8.3 MPa (1,203 psi). This represented a decrease in the flexural strength of approximately 8.3% from the control mixture. The decrease in the flexural strength for the different FS substitution mixtures shows that greater the FS content, the weaker the concrete. The results from the

flexural testing demonstrated a slight increase in strength with the addition of FS up to 10%, then a reduction in strength with the addition of 20% and 30% FS. Although there was a reduction in strength with the 20% and 30% FS replacement, the testing demonstrated a less than 10% reduction in flexural strength with a FS addition up to 30%. A t-test with a confidence level of 95% was completed to compare the control specimens with the three FS replacement levels and the results show significant results between the control and the 10% FS replacement and non-significant results between the 20% and 30% FS replacement. This ultimately demonstrates an impact due to FS replacement on HSC up to 20%, but no impact up to 30%. Again, these results can be explained by similar results obtained by other authors [1-5, 20-30], in which FS has an impact on density, workability, and has SCM like abilities up to 20% replacement, which results in the flexural strength improvement up to the same amount.

#### 5.4 Modulus of elasticity

The modulus of elasticity was determined for this study as it is an important parameter in structural design. The modulus of elasticity of this study was calculated at 40% of the maximum stress. The modulus of elasticity for this study was determined at 7, 14, and 28-days in accordance to ASTM C469-14 [32] and the results are shown in Fig. 5.

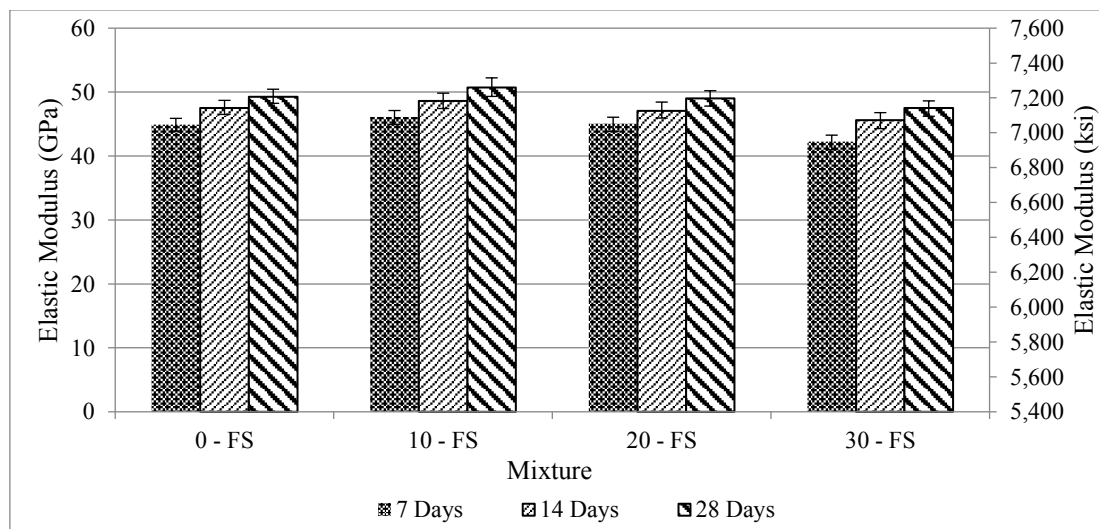


Fig. 5. Elastic modulus results.

According to the results of the elastic modulus, there was increase was observed at 10% FS replacement, similar results at 20% FS replacement, and a small decrease at 30% FS replacement. In particular, the average elastic modulus values for the control (0% FS) were approximately 44.9 GPa (6,511 ksi), 47.5 GPa (6,890 ksi) and 49.2 GPa (7,143 ksi) for the 7, 14 and 28 days ages respectively. Whereas the 10% replacement displayed the highest average modulus of elasticity values of 46.1 GPa (6,689 ksi), 48.6 GPa (7,054 ksi), 50.7 GPa (7,357 ksi) at each age tested. The 20% FS replacement specimens showed average results of 45.0 GPa (6,537 ksi), 47.0 GPa (6,823 ksi), 49.0 GPa (7,10p ksi), for 7, 14, and 28 days ages respectively, which is virtually identical to the control (0% FS) samples. Lastly, the 30% FS replacement exhibited average elastic modulus results of 42.3 GPa (6,131 ksi), 45.6 GPa (6,612 ksi), and 47.5 GPa (6,892 ksi) at 7, 14, and 28 days ages respectively. These results are also consisted with the literature [1-5], in that FS replacement tended to have a slightly large impact on the elastic modulus than other mechanical properties. Nwofor et al. [10] and Sohail et al. [11] showed an increase in flexural strength performance up to 20% and 70% respectively. The results determined in this study are more consistent with the results obtained by Nwofor et al. [10]. As described by Nwofor et al. [10], Sohail et al. [11], and previously described in this study, the same effect of FS replacement is affecting the modulus of elasticity results. That is that the FS has effected the workability of the mixtures and at the same time FS is exhibiting SCM like abilities up to a point of approximately 20% replacement, at which point the lack of workability and lower density dominates and a loss of performance is measured. A t-test was also performed on the elastic modulus testing, which revealed a significance between the 0 – FS and the 10 – FS, no significance between 0 – FS and 20 – FS, and a significance between 0 – FS and 30 – FS. These results shows an impact of FS replacement up to 20% replacement, but a marginal decrease in elastic modulus performance up to 30% FS replacement. This is consistent with all others investigated in the literature review [1-5, 10, 11, 20-23].



## 5.5 Poisson's ratio

The last mechanical performance testing completed was the Poisson's ratio tested in accordance to ASTM C469-14 [32] and the results can be seen in Fig. 6.

It can be seen that all the mixtures had approximately the same Poisson's ratio. For instance, the control mixture and the 10% FS mixture had a Poisson's ratio of approximately 0.207 for all ages. This showed that the aging of the concrete does not influence the Poisson's ratio. On the other hand, it could be noted that there was a slight decrease in the Poisson's ratio for the 20% FS. In particular 20% FS had the ratios at approximately 0.198, 0.203 and 0.202 at 7, 14 and 28 days, respectively. Again, the 30% FS had the ratios at approximately 0.208, 0.209 and 0.21 at 7, 14 and 28 days, respectively. These fluctuations in the Poisson's ratio values at three different ages indicated that there was a slight change with time. The marginal difference shows that the Poisson's ratio is not mainly affected by aging of concrete or even the level of FS substitution. A t-test was performed on the FS mixtures and compared to the control mixtures to confirm significance. The student t-test revealed no significance between the mixtures. Therefore, the addition of FS had no impact on the Poisson's Ratio.

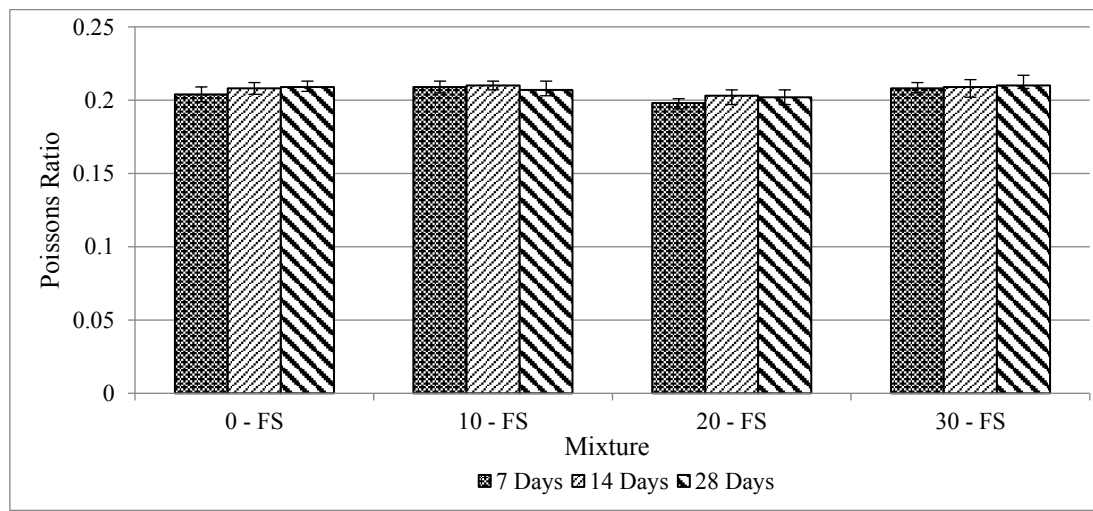


Fig. 6. Poisson's Ratio results.

## 6. Conclusions

This study has demonstrated the feasibility of using FS in UHSC as a substitute of river sand by evaluating the mechanical strength properties of concrete. The following conclusions have been made based on the compressive strength, splitting tensile strength, flexural strength, elastic modulus, and Poisson's ratio conducted on UHSC made with 0%, 10%, 20%, and 30% FS replacement:

- 1) With increase in FS content, workability decreased; consequently the decreased workability affected the consolidation and the fresh density of the samples thereby mechanical strength.
- 2) The compressive, splitting tensile, and flexural strength of UHSC mixtures increased with 10% FS replacement.
- 3) The compressive, splitting tensile, and flexural strength of UHSC mixtures showed no statistically significant change with 20% FS replacement.
- 4) A decrease in compressive, splitting tensile, and flexural strengths were observed in the specimens produced with 30% FS.
- 5) The Poisson's Ratio had no statistically significant effect due to any FS replacement level.
- 6) FS was shown to be a suitable replacement of river sand up to at least 10% in all mechanical properties tested.

From these conclusions, it is shown that FS has an applicability in the use of UHPC up to 20%. Therefore, FS can be used to produce a more sustainable UHPC concrete with cost reductions to the producer and consumer. This type of concrete has applications in bridge decks, girders, military bunkers, and high-rise structures. The challenge of producing this type of concrete is with the mixing. Due to the low w/cm, high shear mixing is almost always necessary. Future research into this area is to focus on developing mixtures that produce the same performance, but do not require high shear mixing to produce.

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