THE DEVELOPMENT OF ULTRA HIGH STRENGTH CONCRETE MIXTURES USING WASTE FOUNDRY SAND

by

Chizitelu Modebelu, B.S

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Committee Members:

Anthony Torres, Chair

Srinivas Allena

Fred Aguayo

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DEDICATION

I would like to dedicate this to my parents, Samuel Modebelu and Ezinwa Modebelu. Your affection made the nuances of life a lot more colorful and beautiful.

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ABSTRACT

This study presents the development of Ultra High Strength Concrete (UHSC) mixtures using waste foundry sand (WFS). This was done through an iterative laboratory trial batching process and experimental evaluation of the compressive strength and splitting tensile of UHSC, produced at different replacement levels of WFS. Multiple concrete specimens were produced which included, control specimens and specimens with WFS replacement percentages of 10%, 20%, and 30%. Initial trial batching consisted of manufactured sand that passes through #30 sieve, silica fume, Type I Ordibary Portland Cement, high range water reducing admixture (HRWRA), water, and steel fibers. After initial testing, the manufactured sand was replaced with river sand, and batch proportioning was adjusted until a suitable UHSC control was developed. Once the control mixture was developed, the river sand was replaced with WFS by volume in 10%, 20%, and 30% increments, and the impact of WFS on two very important mechanical properties was investigated. Compressive strength and splitting tensile strength are the mechanical properties investigated in this research. All concrete mixtures surpassed 18000 psi; which was the compressive strength benchmark used in this study. The final compression strength ranged from 17,471psi - 19614 psi. The splitting tensile strength results ranged from 2124 psi - 2355 psi. A statistical analysis of the 10% WFS mixtures showed a 10% drop in compressive strength(7days) and 5% drop in compressive strength (28 days), compared to the 7 and 28 days strength of the control mixtures. There was no signigicant change in

compressive strength from the control at 20% and 30% WFS replacement. A statistical analysis shows a 16% drop in splitting tensile (28 days) at 10% WFS replacement level, compared to the control mixture at equivalent age. There was no siginificant change in splitting tensile strength from the control at 20% and 30% WFS replacement.

1. INTRODUCTION

Background

The need for durable and long-lasting infrastructure influenced the production of concrete with enhanced mechanical properties. Several experiments and researches have shown that, the deliberate optimization of the concrete composites can yield Ultra High Strength Concrete (UHSC) with enormous compressive, flexural, and splitting tensile strength.. UHSC is used and has several applications where there is need for heavy duty construction, like a nuclear waste containment structure, where high durability, impermeability, resistance to corrosion and abrasion is of utmost importance. The growing sensitization to sustainability and the impact of carbon footprints on the ecosystem, has also influenced the need for supplementary cementitious materials (SCM) and/or partial replacement of fine aggregate, and alternative/recyclable materials to be considered and tested for the production of UHSC. The foundry and metal casting industry deposits 9 million metric tons of waste foundry sand from casting molds, in landfills annually (Rafat , Geert, & Noumowe, 2009). The high silica content of foundry sand posits it, as an ideal fine aggregate, because it's SCM like properties would not negate expected mechanical properties. Several researches have also shown that manipulating the water-to-cement/cementitious material ratio, the curing type/duration and gradation of fine aggregates also influences the mechanical properties of concrete (Srinivas & Newston, 2010). This study focuses on the development and testing of UHSC produced with foundry waste sand. It provides an opportunity for the enhancement of sustainability in concrete industry. UHSC produced in the present research is composed of fine sand and waste foundry sand of 0.00295-0.0236 inches (75-600μm) gradation, type 1 Ordinary Portland Cement, high range water reducing admixtures (HRWRA), silica fume, and steel fibers.

2. LITERATURE REVIEW

Ultra High Performance Concrete Definition and Application

Ultra-High Performance Concrete (UHPC) is a concrete that is invaluable in the construction industry, due to its exceedingly high performance ability. Since its inception, many authors have investigated the design, development, and nature of UHPC. (Graybeal, 2011) conducted an extensive research that provided insight and an in-depth analysis of UHPC. Graybeal enumerated substantive findings, on the applications of UHPC, constituent materials, production of UHPC, curing procedures, testing procedures and mechanical properties of UHPC. The aforementioned research also includes the applicability of UHPC in structural design and modelling. UHPC is defined concrete with compressive strength greater than 21700 psi at 7 days (Graybeal, 2011). UHPC also consists of optimized gradation of granular particulates, with w/cm ratio less than 0.25 and a substantial amount of internal fiber reinforcement (Graybeal, 2011). Enhanced durability of UHPC can be attributed to the discontinuity in pore structure that reduces liquid absorption. The excellent mechanical property of UHPC makes it ideal for use as thin overlays, claddings or shells. The author also pointed out examples where, the high tensile strength property of UHPC is advantageous in the elimination of mild steel reinforcement shear stirrups. The durability of UHPC is vital in the construction of resilient lightweight deck and facilitation of accelerated construction (Graybeal, 2011). UHPC is also used as field-cast closure pour or grout. UHPC affords engineers the flexibility to redesign and simplify construction systems, without impacting long term durability. A difference in the mode of production between UHPC and conventional concrete is the amount of energy output required (Graybeal, 2011). UHPC typically requires higher energy output and increased mixing time. Energy requirement for production can be drastically reduced by replacing mix water with ice, and an addition of chemical accelerators and the use of high-energy mixer (Graybeal, 2011). The author also postulated that limited external form of vibration can facilitate the release of entrapped air.

ASTM Testing of UHPC Systems and Curing Methods

Different curing methods has been shown to enormously impact the mechanical properties of UHPC. Previous researches have shown that appropriate curing methods, would inhibit loss of water prior to hydration (Graybeal, 2011). Additionally, the application of supplemental heat and steam treatment has been shown to accelerate setting behavior and the enhancement of mechanical properties of UHPC. Appropriate calibration of supplemental heat is vital in preventing material dehydration (Graybeal, 2011). Graybeal also showed that testing procedures of UHPC involves, different specimen shapes, higher test machine capacity and different specimen preparations (Graybeal, 2011). ASTM C1437 standard is typically employed in measuring the flow test. Slightly modified ASTM C39 standards is applicable in compressive strength evaluation of UHPC. Slightly modified ASTM C469 standards have been shown to be applicable in the analysis of the modulus of elasticity and tensile cracking strength of UHPC. According to (Graybeal, 2011), there is ongoing research on how to evaluate the post-cracking tensile behavior of UHPC in the United States. AASHTO T259 and ASTM C1202 standards are applicable in the chloride penetration test of UHPC. Freeze-thaw cycle analysis of UHPC can be accomplished via testing methods as stipulated by ASTM

C512 standards. Graybeal concluded that an in-depth understanding of flexural and shear properties of UHPC is very critical in the development of UHPC designs (Graybeal, 2011).

Ultra High Strength Concrete Comparison to UHPC

In a broad sense, UHPC possesses a lot of similarity as Ultra High Strength Concrete (UHSC). The only difference is centered on the fact that UHPC assumes it's definition based off of its durability with regards to performance. The durability performance evaluation of UHPC in this sense is categorized on the impact of steel fibers or basalt on resistance capacity of UHPC to abrasion, without the compromising of expected mechanical properties(Graybeal, 2011). Whereas the mechanical property of utmost importance in an UHSC is it's compressive strength. Hence the reason why steel fibers are not typically considered a primary component of a UHSC mix design. There are several scholarly papesr with substantive findings on UHSC otherwise known as Reactive Powder Concrete (RPC). The information garnered showed that producing RPC with high compressive strength and ductility is very feasible. Researches have shown that the production of RPC, with compressive strength as much as 800 MPa and fracture energies ranging from 1200 to 40000 J/m is also attainable (Richard & Cheyrezy, 1994). The mechanical properties of RPC are dependent on the level of homogeneity that can be attained during production. The replacement of coarse and fine aggregates with ground quartz (<300microns), enormously improves the homogeneity of RPC mixtures (Richard & Cheyrezy, 1994). An even particle distribution in RPC mixtures also improves the modulus value (from 55 GPa to 75 GPa) and also nature of the modulus between cement paste and quartz powder (Richard & Cheyrezy, 1994). The authors also postulated that an increase in dry-compacted density, improves the mechanical properties of concrete. Improvement in compaction can be enhanced with the use of superplasticizer and silica fume (Richard & Cheyrezy, 1994). Alternatively, maintaining a certain amount of pressure on RPC mixtures at molding and setting stage, can enormously improve its dry-compacted density up to 6% (Richard & Cheyrezy, 1994) . This is largely due to resultant effects such as, removal of air bubbles, expulsion of excess water and partial reduction of chemical shrinkage during setting (Richard & Cheyrezy, 1994). The author also discussed the influence of temperature (during curing) on the improvement of the microstructure of RPC concrete mixtures. Results from porosimetry test show a reduction in the porosity of RPC's, when subjected under hot curing (90ºC) for 2 days (Richard & Cheyrezy, 1994). The authors postulated that the resultant 30% increase in resistance has a direct correlation, with the improvement of the pozzolanic reactions in the microstructure of silica fume. Previous researches shows that chemical processes such as; transformation of amorphous cement hydration, formation of xonotlite, entrapment of water vapor in mixtures, are contributory factors in the improvement of microstructure of RPC's during hot curing (Richard & Cheyrezy, 1994). The authors also pointed out that the addition of steel micro-fibers enhances the ductility of RPC mixtures. Increase in fracture energy of RPC's is indicative of high ductility (Richard & Cheyrezy, 1994) . Depending on the type of hot curing employed, fracture energy which ranges between 10000 J/m to 40000 J/m is attainable. RPC 200 and RPC 800 are material identification of the reactive powder concrete analyzed in this referenced paper (Richard & Cheyrezy, 1994). The authors noted that both concrete mixtures have a lot of similarity in material composition. The mixture was made with a Type V OPC, fine quartz (150-300 microns), densified silica fume and partly synthesized/precipitated silica fume. The only exception in material composition stems from the fact that, RPC 200 contains steel fibers (12.5 mm long, 180 microns in diameter) and RPC 800 contains stainless steel microfibers (3 mm long). The result shows that RPC 200 exhibited higher compressive strength value (230 MPa) at hot curing, as opposed to curing at ambient temperatures (170 MPa) (Richard & Cheyrezy, 1994) . The authors also postulated that variation in flexural strength and fracture energy is dependent on the percentage of fibers added. RPC 200 exhibited higher flexural strength and ductility. Pre-stressed RPC's with enhanced mechanical properties does not require passive reinforcement (Richard & Cheyrezy, 1994). The authors also postulated that compressive strength as much as 800 MPa can be attained, when steel powders are used in lieu of fine sand. SEM images captured by the author also illustrated the high strength of the bond that exists in the interface of the particulate constituents of an RPC mixture.

River Sand and Foundry Sand in UHSC Production

Subsequently, some researchers have shown the economic viability of use of local materials, in the improvement of mechanical and durability properties of UHSC. (Srinivas & Newston, 2010) produced UHSC with local materials. Mechanical properties such as compressive strength, flexural strength and ductility were investigated. The authors also probed the impact of curing regimens, aging, steel fibers and silica fume on the mechanical properties of UHSC. The premise of their research paper was centered on the sustainability and economic viability, associated with producing UHSC with locally sourced materials. Previous researches referenced by said authors, have shown that modifications in content and production methods, can lead to the maximization of the compressive strength potential of UHSC. Manipulating silica fume content and HRWA, has been shown to enhance the density of UHSC (Srinivas & Newston, 2010). Whereas adjustments in production methods such as; applying pre-setting pressure, using post-setting heat treatment, low water-to-cementitious materials ratio and numerical packing model, can further densify the microstructure of UHSC. Aforementioned adjustment has been used in producing UHSC with compressive strength of 29,000 psi. Compositionally, UHSC typically constitutes of fine sand, quartz powder, micro silica, steel fibers and HRWRA. The authors enunciated that addition of micro silica enhances the mechanical properties of concrete paste by producing secondary hydrates. Subsequently there is concurrent enhancement of rheology properties of UHSC. The lower w/c ratio of concrete mixture with HRWRA inadvertently reduces the porosity of the cement paste and improves durability. Previous researchers also recommended the use of silica fume for increased pozzolanic reaction and removal of coarse aggregates in order to improve homogeneity (Srinivas & Newston, 2010). The materials the authors used in their experiment were, Type I/II OPC, silica fume, fine local sand (0.00295- 0.0236 in.), steel fibers (0.511 inches) and polycarboxylate-based HRWRA(Srinivas & Newston, 2010). The concrete specimens were classified into five different categories (A, B, C, D, and E). Specimen categorization was based off of steel fiber content, w/c ratio, and silica fume content (Srinivas & Newston, 2010). All concrete samples contained HRWRA. All specimens were consolidated with the use of a high frequency vibrating table. The authors also investigated 3 curing regimens. The first curing regimen involved initial curing at 65^0F (first 24 hours) and moist curing at 73.4^0F (after demolding with humidity at 100%). The second curing regimen involved initial curing at 65^0F (first 24 hours) and heat curing in water bath at 122^0F (after demolding). The third curing is similar to the second curing regimen except for the fact that it is eventually removed from the water bath and dry cured at 392^0F. The compression test was conducted in accordance with ASTM C 39 specifications and modulus of rapture was conducted in accordance with ASTM C 78 specifications. The authors also investigated repeatability of compressive strength test results. The compressive strength of all specimens was measured at 7, 14, and 28 days. The results showed a wide range of disparity. Concrete mixture AL00 (w/c ratio of 0.28, no silica fume) yielded a compressive strength of 6,940 psi. The authors postulated that, low compressive strength could be attributed to the absence of silica fume. Sample BLOO (1.6% less sand, 36.84% less HRWRA than AL00, 1.5% steel fiber and 24.5% silica fume) exhibited a compressive strength of 6,880 psi. The compressive strength of sample BL20 (20% increase of all components of sample BL00) tested at 7, 14, 28 days, yielded compressive strength values of 7,080psi, 8,090psi and 9,210 psi respectively. Sample CL00 (w/c ratio of 0.22, no steel fibers) tested at 7, 14, 28 days, yielded compressive strength values of 14,080 psi, 14,250 psi and 16,250 psi respectively. Sample CL20 (similar to CLOO with 20% volume increase), exhibited compressive strength of 13,560psi, 14,360psi and 15,200psi, at 7, 14 and 28 days respectively. The second type of curing was used on all aforementioned samples. The results also showed that specimens produced from the third type of curing exhibited greater compressive strength, than specimens produced from the second type of curing. The authors postulated that this could be as a result of a direct correlation of acceleration in pozzolanic reaction to increase in temperature. Previous researches have shown that accelerated pozzolanic reaction leads to formation of dense calcium silicate hydrate compounds(Srinivas & Newston, 2010). The results also showed that reduction of w/c ratio has an inversely proportional relationship with compressive strength. HRWRA also improved the workability of all concrete samples. Sample EL00 exhibited the largest compressive strength values of 21,180psi, 23,420psi and 24,010psi, at 7, 14 and 28 days respectively. The results also showed that post-setting and curing regimens exerts enormous influence on the compressive strength of UHSC. The authors made various recommendations that can improve the economic viability of the production of UHSC. This includes the incorporation of fly ash as SCM, use of polypropylene fibers in lieu of steel fibers and the investigation of formation of ettringite, and alkali silicate residue.

Foundry Sand in Concrete production

For decades there has been extensive researches conducted to study the effect of foundry sand in concrete production. Researchers have categorized the various ways and means of reusing foundry waste (Silvia & Maria, 2007). The categorization is based off of elemental components classification achieved through chemical analyses and particle size. The research conducted by the authors (from a cast iron plant) showed that the main source of foundry waste is molding sand (360 t/d) (Silvia & Maria, 2007). The rest are from molds from dust abatement/molding lines (150 t/d), furnace and ladle slags (100 t/d), powdered sands from shakeout and slotting (90 t/d), broken cores (50 t/d), powders from core thermal regeneration plants (6 t/d) and exhaust lime from desulphurization processes (6t/d) (Silvia & Maria, 2007). This categorization is critical to the current study because it gives a better understanding of unique chemistry of different foundry waste. In terms of particle size classification, foundry waste residue above 0.6mm can be reused in core production, because of their metallic content (Silvia & Maria, 2007). The authors also postulated that the fraction of the foundry waste with particle sizes that ranges between 0.1mm and 0.6mm can be reused after undergoing regeneration treatment, and the fraction between 0.1mm and 0.0025mm can be used as supplementary cementitious material in the concrete industry (Silvia & Maria, 2007). The authors used an Andreasen apparatus in analyzing the particle size, Atterberg's Limits test in analyzing the clay content, and various chemical test were used in elemental quantification. Their results showed that sample MS1 with a particle size distribution that ranged between 0.1mm and 0.6mm can be reused in core production after undergoing regeneration treatment. Sample MS3 was found to possess particle sizes above 0.6mm and Sample MS2, FD, CR and FP had a higher fine fraction (below 0.1mm) (Silvia & Maria, 2007) . Samples FD, SH1 and SH2 could be used as furnace charge and samples MS2, FPM, MDI, FP and NIF was found to be quite suitable for reuse in mold production (Silvia & Maria, 2007). OPC concrete manufacturers generally require that percentage CaO, SiO_2, Al_2O_3 and Fe_2O_3 to be about, 65%, 25%, 4-10% and 1-3% respectively (Silvia & Maria, 2007). The results of the chemical test conducted by the authors showed that, due to the high silica content of sample CR and its inert and fine particulate nature, sample CR is suitable for white concrete production (Silvia & Maria, 2007). After the addition of new raw materials, samples FPM and MDI can be used in concrete production. This is largely due to their high silica content. The authors also postulated that sample MD21, possesses the requisite chemical contents that makes it ideal for Portland cement production (Silvia & Maria, 2007). However, it must be refined via cyclone treatment to get the appropriate particle size gradation (Silvia & Maria, 2007). The results by the authors also showed that sample CF had high silica content. Samples SH1, SH2 and FD can only be recycled to be used as charge at the furnace. This is because high amount of Fe_20_3 makes it economically unviable for concrete production. The heavy metallic contents of Samples TH1 and TH2 render them unviable for any recyclable use (Silvia & Maria, 2007). The authors of this research were able to show the economic viability, and the blueprint for recycling foundry waste from metal casting plants.

Density, slump cone, split tensile strength, flexural strength; ultrasonic pulse velocity (UPV) and compressive strength tests, were used in ascertaining the effect of foundry sand (FS) in concrete (Prabhu, Jung, & Yun, 2014). The samples used by the authors were categorized into; 10%, 20%, 30%, 40% and 50%, FS replacement level (Prabhu et al., 2014). By definition, foundry sands are by-products from metal casting plants, with high silica content and sand bonded with clay and other metals (Prabhu et al., 2014). Previous researchers have shown that at 10%, 20%, and 30% FS replacement in concrete, there is a marginal but nonetheless remarkable increase in the compressive strength. Researches has also showed that 10% FS replacement level is also ideal for asphalt concrete production (Prabhu et al., 2014). Five different concrete mixtures and concrete mixtures without foundry sand (control sample) were prepared. Those five sample mixtures were at 10%, 20%, 30%, 40% and 50% FS replacement levels. The authors also used blue-gray sandstone as coarse aggregate, and fine sand sourced from the bank of rivers as fine aggregates (Prabhu et al., 2014). OPC was used as binding material. OPC used had a specific gravity value of 3.14, and fine and coarse aggregates; 2.48 and 2.67 respectively. These values were determined from testing as stipulated by IS 2720 standards. The foundry sand had a specific gravity value of 2.24 and density of 1576 kg/m^3. Test results also showed that FS had water absorption value (1.13%), which is considered to be higher than normal (Prabhu et al., 2014). This can be attributed to the ash and wood contents of the foundry sand. Grain size distribution analysis conducted via sieve analysis showed that, 8% of the FS is less than 75lm (Prabhu et al., 2014). According to stipulated standards (IS 2720), this is a satisfactory equivalency value for fine aggregates size (Prabhu et al., 2014). The authors prepared the concrete mixtures at a proportionality value of 1:1.53:2.86. A consistent water/cement ratio of 0.44 was maintained for all the test samples mixtures and the control mixtures. In preparing the foundry sand, the authors washed the quantity to be used with fresh water. This aids the removal of ash and clay particles in FS. The compressive strength test was carried out with a CTM with a capacity of 2000kN and at curing ages of 7, 28, 90 and 180 days. The authors also evaluated splitting tensile and flexural strength at 28, 90 and 180 days. A slump cone test was used in analyzing the workability of the concrete mixtures. This was conducted at initial time of 0 minutes and duration/interval of 30 and 60 minutes. The results show that an increase in the replacement level of FS, negatively impacts the workability of concrete. This is because water absorption increases with an incremental change in FS proportion(Prabhu et al., 2014). Increase in water absorption also has a direct correlation with the fineness of foundry sand (Rafat , Geert, & Noumowe, 2009). Alternatively, the authors also postulated that the high absorption properties could possibly be attributed to the ash and clay content of FS (Prabhu et al., 2014). However, the results also show negative impact on the workability of the concrete mixture is insignificant at 10% replacement level. The authors postulated that a modification of water quantity could potentially counteract the slump loss attributed to either the fineness of FS and its ash and clayey content. The authors were able to experimentally show that in all ages of curing, there was a consistent decrease in compressive strength. However, the compressive test result also showed that the sample mix with 20% FS has compressive strength value that is similar to that of the control mix. The authors postulated that the reduction of the specific gravity of the concrete due to its ash and clay content might explain the resultant reduction in compressive strength. The flexural strength and splitting tensile strengths results were also similar to the compressive strength results. This shows a marginally incremental change in flexural strength, with progression in the age of curing (Prabhu et al., 2014). However, there isn't a remarkable enhancement in flexural strength for all tested samples. Once again the only exception is with the concrete mixture of 20% FS replacement level, which showed a distinct similarity in flexural strength as the control mix. The splitting tensile strength result shows that high replacement proportion (40%, 50%), will enormously decrease the tensile strength of concrete (Prabhu et al., 2014) . The authors concluded that the fineness and impurity of FS are underlying factors that impacts the compressive, flexural and tensile strength of a concrete mix with FS as replacement for fine aggregates (Prabhu et al., 2014) However, appropriately determining the right proportion (20%) will inevitably, counteract any negative impact on the mechanical properties of a concrete mix.

Rafat et al. (2009) have shown the potential of using waste foundry sand (WFS) in the production of concrete. Their experimental investigation showed how different replacement levels of WFS as fine aggregate, affects the mechanical properties of concrete. The mechanical properties investigated are; compressive strength, splitting-tensile strength, flexural strength and modulus of elasticity. The values of the investigated properties were determined at different ages of concrete samples (28 days, 56 days, 91 days and 365 days). The authors categorized their experiment at 3 replacement level percentages (10%, 20% and 30%). Based off of binder system content, UFS can be classified into; clay bonded UFS otherwise known as green sand, and chemically bonded UFS. This classification is centered on physical and environmental factors. Previous researches has also shown that, the naturally occurring components such as high quality silica sand (85-95%), bentonite clay (4-10%) and carbonaceous additive (4-10%), makes clay bonded UFS ideal for use as replacement material. This is largely because of high silica content and also the adhesive properties and fine particulate nature of its clayey content. In designing the experiment, the authors used type 1 OPC as specified by ASTM C150 standards. The locally sourced UFS was also chemically tested as per standards specified by IS 383-1970-23 and ASTM C33 Rafat et al., 2009). Chemically analysis shows that UFS used has lower unit weight and fine modulus, in comparison to OPC (Sohail, Wahab, & Khan Md, 2008). Rafat et al. (2009) also used locally sourced coarse aggregates of 10mm and 20mm gradation as per IS: 383-1970 23 standards. Melamine-based superplasticizers were used in the mixing and preparation of all tested samples (Rafat et al., 2009). The authors prepared four different concrete mixtures. Three of the mixtures were of 10%, 20% and 30% UFS percentage weight. The control sample was without UFS. All concrete samples were stored at 23^0C temperature to minimize loss of moisture, demolded after 24 hours and then put in a water-curing tank. The authors investigated properties such as slump, unit weight, temperature and air content as stipulated by Indian Standard Specifications IS: 1199-1959 [25. The results showed that all specimens attained a marginally significant increase in compressive strength at 28 days of curing. Control mixture M-1 showed compressive strength value of 28.5 MPa.

The other test samples (M-2 and M-3) had compressive strength values of 30.0 MPa and 31.3 MPa respectively. Quantitatively, test samples M-2 and M-3 showed compressive strength increases of 5.2% and 9.8% respectively. All tested concrete mixtures showed increases in compressive strength that is directly proportional to curing age. The consistency in the results of all tested concrete mixtures showed that UFS can positively impact the compressive strength of concrete. The authors postulated that this could be attributed to the fineness of UFS. This particular quality can enormously influence the density of concrete matrix. Splitting tensile strength, flexural strength and elasticity modulus test result showed a lot similarity to the compressive strength result. At 28 days of curing, concrete mixtures M-1, M-2, M-3 and M-4 showed splitting tensile strength values of 2.75 MPa, 2.85 MPa, 2.9 MPa and 3.0 MPa respectively. Concrete Mixtures M-1, M-2, M-3 and M-4 achieved flexural strength of 3.41 MPa, 4.0 MPa, 4.1 MPa and 4.18 MPa respectively. Concrete Mixtures M-1, M-2, M-3 and M-4 also showed elasticity of modulus values of 25.1 GPa, 26.75 GPa, 27.60 GPa and 28.4 GPa. This marginally significant increase in tensile strength and flexural strength was directly proportional to increase in curing age (Rafat et al., 2009).

Impact of Foundry Sand on the Mechanical Properties of Concrete

Sohail et al., (2008) were able to show the impact of foundry sand on the mechanical and durability properties of concrete. The authors studied the intrinsic physical effects of foundry sand when used as partial replacement material. The mechanical properties studied were compressive strength, split tensile strength and flexural strength. The tested samples were categorized according percentage weight (0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100%) of foundry sand used as replacement material. The authors carried out an all-encompassing analysis that ranged from partial to total percentage replacement. Previous researches enunciated by the authors, shows a definitive pattern, of the impact of FS on concrete. This postulatio centered on several experiment buffers the notion that, FS positively impacts the mechanical properties of concrete (Sohail et al., 2008). However, some results have also shown that, above or below a particular percentage replacement value (20%), there is a reduction in strength performance and density of concrete mixtures tested. The authors postulated that this could be because of the increased water absorption ratio of the concrete mixture with percentage weight of FS(Sohail et al., 2008). Sohail et al. (2008) also investigated the absorptivity, initial surface absorption and water absorption properties of all concrete samples tested. The authors used OPC (grade 53) as specified by IS: 12269-1987 standards. The chemical and physical properties of aggregates used were also investigated. The authors postulated that flat and elongated particles caused blocking problems in confined zones. This factor influenced their decision to choose well graded and angular shaped coarse aggregate. Well graded coarse aggregates help prevent particulate segregation in concrete mixtures (Sohail et al., 2008). Locally sourced fine aggregates used was devoid of clayey matter, salt and organic impurities. The authors also investigated the specific gravity and bulk density of the fine aggregates used, in accordance with IS 2386-1963 standards. The results showed that increase in FS negatively impacted the workability of all tested concrete mixes. The results also showed a consistent increase in the compressive strength of concrete mixture samples up to 90% FS replacement level. However, concrete samples with 100% FS replacement showed a decrease in compressive strength. The concrete samples also showed increase in splitting tensile strength up to 70% FS replacement level. However other samples showed reduced split tensile strength. Optimum split tensile strength was achieved at 40% FS replacement. The results also showed that increased age of curing positively impacts split tensile strength of all tested samples (Sohail et al., 2008). All tested samples exhibited an increase in flexural strength with the exception of concrete mixture samples with FS replacement value more than 50%. The duration of curing also enhanced the flexural strength of all tested concrete samples.

Extensive research has been conducted on the assessment of the impact of foundry sand (FS), as replacement material in concrete production (Nwofor & Ukpaka, 2016). The authors investigated the influence of FS on the mechanical properties of concrete production. Least square sum statistical model was employed in determining the impact of FS on the compressive strength, split tensile strength and flexural strength. The experiment also showed that, duration of curing is a determinant factorn (Nwofor & Ukpaka, 2016). The authors made concrete mixture with water/cement ratio of 0.5. Proportionally the design mix was 1:24. Coarse aggregates samples used were of 20mm gradation. Samples M-1, M-2, M-3, M-4 had FS replacement value of 5%, 10%, 15%, 20% and 25% respectively. The authors also investigated physical properties of the concrete mixture such as, bulk density and specific gravity. The results showed that FS improves the compressive strength of concreten (Nwofor & Ukpaka, 2016).

As described above, researchers demonstrate the impact of foundry sand on concrete production, whereas some researchers have shown the specific use of foundry waste materials in the improvement of HSC and UHPC (Yucel, Yasin , Muhsin, Ahmet, & Senayi, 2010). Yucel et al. (2010) have shown the potential of re-using waste foundry sand in high strength concrete. The authors replaced the natural fine sand of a control high strength mixture with waste foundry sand at 5%, 10%, and 15% by mass. The authors primarily focused on investigating the impact of foundry sand on mechanical properties such as the compressive strength, splitting tensile strength, and the modulus of elasticity, however, the slump and water absorption were determined. Additionally, the impact of freezing–thawing resistance and dynamic elasticity modulus was also reported on the compressive strength. The authors point out that waste foundry sand typically meets the 5% maximum allowable fine aggregate particles that pass through sieve No. 200 standard as set by ASTM C33 (Yucel et al., 2010). Yucel et al. (2010) used the Turkish Standard TS706 (1980) to distribute the waste foundry sand, such that the curves were between the standard's A16 and B16 reference curves (Yucel et al., 2010). This distribution curve translates to particles between 16-mm and 0.25mm (0.23-in. and (0.0098-in.). The fineness modulus of the waste foundry sand was 2.53. The designated crushed stone-1 has a grain size distribution between 8-mm and 16-mm (0.31-in and 0.23-in.) and crushed stone-2 has a grain size distribution of 4-mm – 8-mm (0.15-in – 0.31-in.) (Yucel et al., 2010). The natural fine aggregate that was used and partially replaced in the experimental mixtures had a particle distribution of less than 4-mm (0.15-in.) (Yucel et al., 2010). The waste foundry sand was obtained from Toprak Casting Industry in Eskisehir, Turkey. The sand was used as a molding sand to cast metal parts at temperatures of approximately 1,500ºC (2,732ºF). The authors completed a Scanning Electron Microscope (SEM) test on the waste and found that the particles to be sub-angular to round in shape and the grain size was uniform with 100% of the particles under 1-mm (0.039-in.) (Yucel et al., 2010). The results showed a reduction in compressive, tensile and elastic modulus with the inclusion of waste foundry sand. However, the 10% replacement mixture exhibited almost similar results to the control mixture, although the 5% and 15% did not. The same results were recorded for the samples that were subjected to freezing-thawing conditions (80 cycles) (Yucel et al., 2010). Additionally, the slump and the workability of the fresh concrete decreased with an increase in waste foundry sand (Piotr & Danuta, 2016). The water absorption results show an increase in absorption at 5% replacement level at an age of 56 days(Yucel et al., 2010). It is also shown that the water absorption ratio decreased for the specimens with 10% and 15% replacement. The major results from this study is that the fine aggregate used in these mixtures generally constitute clay and silt (≤200 μm) that weaken the cement/aggregate adherence, increase the amount of water needed, retard cement hydration and may cause voids. The increase in waste foundry sand reduced the mechanical strength of the control high strength concrete aside from the 10% replacement level, which was quite similar to the control mixture. The only positive result from the study by Yucel et al. (2010) is that the concrete is still within the acceptable limits set by ACI.

Impact of Coal Cinder on the Mechanical Properties of Concrete

Researches has been conducted on the mechanical and durability properties of High Performance Concrete (HPC), incorporating coal cinder (CC) and waste foundry sand (WFS) (Piotr & Danuta, 2016). The mechanical and physical properties investigated were; compressive strength, absorptivity, density, open porosity, contact angle, surface free energy, splitting tensile strength, flexural tensile strength, freezing-thawing resistance and salt resistance. The authors also showed the effect of surface energy on adhesion properties of HPC, and the effects of the microstructure of CC and WFS on the porosity and distribution of cracks in HPC. Coal cinders are known to have high silica content, with a sparse distribution of heavy metals (Piotr & Danuta, 2016). Its physical properties are also characterized by an inhomogeneous particulate nature (Piotr & Danuta, 2016). Waste foundry sand also has high silica content (90%). The other contents of WFS are iron and aluminum oxide. The authors point out that variation in the mineralogy, shape and particulate nature of waste foundry sand can be attributed to the variability in physical parameters such as density. WFS had density, specific gravity and absorption of values of, 1052– 1554 kg/m^3, 2.38–2.72g/cm^3 and 0.38–4.15% respectively. Previous studies enunciated by the authors shows that, there is a decrease in compressive strength of HPC produced with WFS as replacement material (Piotr & Danuta, 2016). The particle size distribution of the granite, gravel and quartz sand aggregates used were determined, according to EN_933-1997 standards. The granite aggregates showed an apparent density, open porosity and water absorption, of 2625kg/m3, 0.9% and 0.33% respectively (Piotr & Danuta, 2016). It also showed a compressive strength, flexural strength and abrasion resistance of, 190 MPa, 11.5 MPa and 6050mm^3 respectively(Piotr & Danuta, 2016). The polycarboxylate content and the weight of cement and silica fume were determinants in quantifying the amount of superplasticizer needed (Piotr & Danuta, 2016). The authors analyzed the Portland cement used in this experiment according to Polish standards PN-EN 197-1:2012 and PN-B-19707:2013. An X-ray diffraction test showed the dominant component of the CC to be SiO_2 in the form of crystallized quartz in the amount of about 79%, carbon in the form of graphite in the amount of 11%, and iron oxide: Fe_3O_4 – magnetite and Fe_2O_3 in amounts respectively of 3% and 7%. A radioactive isotope concentration test carried out on the CCs showed that it is within standards deemed to be scientifically permissible for use as raw material in construction of building (Piotr & Danuta, 2016). The analysis of WFS showed a chemical composition of SiO_2 (95.3%), Al_2O_3 (1.9%), Fe_2O_3 (0.7%), and CaO (0.35%) (Piotr & Danuta, 2016). Porosity and bulk density were determined in accordance with EN 12390-7-2001 standards, the absorptivity test in accordance with BS 1881-122 and the compressive strength test in accordance with to EN 12390-3:2002. The splitting tensile strength test was conducted according to EN 12390-6:2001 standards, freezing-thawing resistance test the EN 12012:2007 standards, resistance to salt crystallization according to EN 12370:2001 standards, and flexural strength test in accordance with EN 12390-6:2001 (Piotr & Danuta, 2016). The authors of this research paper conducted the entirety of the test on the mechanical properties of the HPC mixtures after 28 days of curing. SEM was used in investigating microstructures and the nature of the interfacial transition zone between the paste and aggregates. The authors categorized the samples into, CO (control sample with neither CC nor WFS), CC10 (10% CC), CC30 (30% CC), CC25W5 (25% CC, 5% WFS) and CC15W15 (15% CC, 15%WFS). Results from the study of the physical properties showed that, an increase in the quantity of CC affects the increase in concrete absorptivity (Piotr & Danuta, 2016). The authors point out that the addition of 30% coal cinder in concrete mixtures (CC30), increases the concrete absorptivity by 12%. This phenomenon has a direct correlation with the observation that, concrete samples with 30% CC, exhibited an increase in porosity by 12%. However, sample CC15W15 showed an increase in absorptivity by 9%, in comparison with the control sample (CO). Sample CC30 also shows absorptivity value that ranges from 6.05

to 6.87%. In comparison with the control sample, the result shows an increase in CC inadvertently leads to an increase in the density of the concrete. The analysis of the physical properties of the sample mixtures shows that, an increase in CC increases the compressive strength of the HPC mixtures. However, the results from the physical properties did not show any distinguishable impact on the compressive strength of HPC with granitic coarse aggregates, with 15% CC and 15 % WFS (Piotr & Danuta, 2016). The results also show that at the same CC replacement level (30%), HPC mixtures with gravel aggregate had a higher increase in compressive strength when compared to HPC mixtures with granite. The flexural and splitting tensile strength test, showed similarity results to the compressive strength test. The authors point out that, all HPC samples with CC, WFS or a combination of both waste as replacement material, exhibited an increase in SFE, in comparison to the control mix. The authors postulate that the high SFE value shows that surface energy is potentially a measure of the wettability and open porosity of concrete with waste materials (Piotr & Danuta, 2016). The samples were all immersed in a salt solution. The results showed samples with the highest amount of coal cinder were the most affected. The authors point out that sample CC30 showed an enormous reduction in density. This is in light of the fact the penetration of sodium sulphate caused a remarkable damage to the matrix of the of the HPC mixture with the most coal cinder (Piotr & Danuta, 2016). However, the authors also point out that the CC15W15 also showed an enormous reduction in density. The authors used SEM images to show the good adhesive properties between the coal cinders and mortar. All tested samples with the exception of the control sample exhibited a poor frost resistance. The authors concluded that CC and WFS, has negative and positive impact on the mechanical properties of high performance concrete mixes. The level of impact on the compressive strength, is dependent on the nature of the coarse aggregate (gravel, granite) used. The authors also pointed out that the difference in compressive strength could be due to gravel having better adhesion properties than granite. Generally, coal cinder increases the porosity of HPC concrete mixtures (Piotr & Danuta, 2016). The resultant effect is the increase in absorptivity. The authors also point out that, a combination of coal cinder and waste foundry sand resulted in an increase in resistance to salt crystallization.

Ultra-Fine Ground Granulated Blast Furnace Slag in Concrete

The importance of ultra-fine ground granulated blast furnace slag (UFGGBS), in the concrete industry cannot be overemphasized. Susanto et al. (2013) were able to show the benefits associated with the incorporation of ultra-fine ground granulated blast furnace slag (UFGGBS) in concrete production. The mechanical properties investigated were compressive strength, flexural strength and modulus of elasticity. The durability test included chloride penetration/corrosion, ionic permeability and electrical permeability. The authors conducted this experiment with four mixtures of varying proportions of water/cement ratio and UFGGBS. Prior to experimentation the authors studied the particle characteristics of UFGGBS and ordinary Portland cement (OPC) (which was used as control). These particle analysis studies were completed via BET, XRD test, chemical analysis, and particle size analyzer. Through an XRD test, the authors were able to show that UFGGBS has a much lower number of peaks when compared to OPC (Susanto et al., 2013). The interpretation of those results from those test showed an absence of a crystalline phase in UFGGBS. This is one of the main defining properties that distinguish UFGGBS form a ground granulated blast slag (Susanto et al., 2013). The authors postulate that this is due to the presence of a crystalline phase in a UFGGBS, that makes it a very slow reactant. The slow reactant nature of GGBS ultimately affects the early and ultimate compressive strength of concrete (Susanto et al., 2013). The particle analysis tests also showed that UFGGBS has a mean particle size of 4.09 lm and OPC is 15.96 lm. UFGGBS shows an absence of a crystalline phase and a substantially small mean particle size (Susanto et al., 2013). This particulate characteristic makes it very susceptible to chemical reactions. The authors conducted a concrete experimentation with four different concrete mixtures labeled, A, B, C and D. Mix A had a w/c of 0.35 and 450 kg/m^3 of cementitious material, Mix B had the same w/c ratio as Mix A, but with 30% UFGGBS incorporated in the mix. Mix C had a w/c ratio of 0.28 and 520kg/m^3 and Mix D is proportionally the same with the only exception being the incorporation of 30% UFGGBS in the concrete mix. The compressive strength test showed that specimen B and D achieved compressive strength of 82.5 MPa and 110 MPa respectively at 28 days of curing. Samples from Mixtures A and C achieved compressive strength of 76.5MPa and 91.5 MPa, within the same curing duration as mixtures B and D. The result shows that the compressive strength was remarkably improved by the addition of ultra-fine ground granulated blast slag. Consequently, it also shows that there is a direct correlation between the degree of effectiveness of UFGGBS and water/cement ratio in concrete. The effectiveness of UFGGBS is greater when the water/cement ratio is lower (Susanto et al., 2013). Flexural strength test and modulus of elasticity yielded a similarity in results with the compressive strength test. After 28 days, the flexural strength of mixtures A, B, C and D were 6.7, 7.2, 8.5 and 11.8 MPa respectively (Susanto et al., 2013). The results from the elasticity of modulus test for mixtures A, B, C, D are 30.6GPa, 34.1GPa, 33.8GPa, and 40.2GPa respectively. The results also showed that the effectiveness of UFGGBS with regards to flexural strength is a lot greater in concrete with lower water/cement ratio. Rapid chloride migration test results show that the coefficient of the chloride migration is inversely proportion of age of concrete. Electrical resistivity measured at 100 Coulombs and 4000 Coulombs, also showed a reduction in permeability (Susanto et al., 2013). The authors point out that data from the test of the four different mixtures showed that a reduction in chloride permeability has a lot more to do with the UFGGBS percentage, than it has to with water/ cement ratio. Particle size analysis shows that the physical densification of the microstructure produced with the addition of UFGGBS aided by pozzolanic reactions, inadvertently leads to the formation of C-S-H. Chemical analysis conducted by the authors shows that the formation of C-SH increases electric resistivity of concrete. This increase in resistivity directly correlates with resistance to corrosion. In summary the authors of this research were able to ascertain that; mechanical properties of concrete with UFGGBS reduced after 28 days of curing, as with conventional concrete. However, there is a continual enhancement of its durability properties with aging. The authors points out that, this is due to increase in hydration, which causes a reduction in chloride penetration.

Halit et al., 2010) completed experimentation to determine the mechanical properties of steel microfiber reinforced reactive powder concrete (RPC) with GGBFS as SCM, when subjected under different curing conditions. The curing conditions employed in this experiment were; autoclave and steam curing. Standard curing was used on RPC control mixtures. The authors investigated RPC mixtures that are proportionally categorized based on its different aggregates content (sintered bauxite, granite and quartz) and

GGBFS replacement level (20%, 40% and 60%). The mechanical properties investigated by the authors were specifically the compressive strength and flexural strength. The authors also conducted a microstructural analysis of the reactive powder mixtures. Their intention is to decipher the role that the microstructures of the different components of the RPC mixtures, play in the chemistry that ultimately leads to enhanced mechanical properties in an RPC. The authors pointed out that previous researches has shown that; by deliberately manipulating the micro-structure of a reactive powder concrete, the compressive strength value of RPC can be optimized up to 800MPa (Halit et al., 2010). The authors used Sintered bauxite (0–1mm and 1–3 mm), granite (1–3 mm) and quartz (0–0.4 and 0.5–1.0 mm), as aggregates in the mix. The superplasticizer used (polycarboxylate) was in accordance with the guidelines as stipulated in ASTM C-494. The RPC mixtures were classified into mixtures with bauxite as aggregate and GGBFS as an SCM, and mixtures with granite as aggregate and GGBFS as SCM. The control RPC mix had OPC and silica fume as SCM. The sample with 20% GGBFS exhibited slightly increased compressive strength, when compared with control mixtures without GGBFS. However, at 40% GGBFS the compressive strength is slightly similar and consequently further reduced at 60% GGBFS. The authors noted that; these results were obtained when RPC mixtures were subjected under all curing methods. The only exception was when samples were subjected under 7- day standard water curing. The results showed that RPC sample mixtures exhibited a reduction in compressive strength at 40% and 60% GGBFS replacement. The authors were also able to show that under all types of curing, RPC mixtures with granites possessed lower compressive strength, when compared with RPC mixes with bauxite as aggregate. The investigation of the microstructure of RPC mixture showed that an RPC mixture has a very dense microstructure. This easily explains the lower porosity and low presence of entrained or entrapped air. The authors also noted a remarkable homogeneity in particulate nature of RPC concrete mixes. The SEM also showed that the pores are spherical in nature. Due to the fact that RPCs are typically used as precast concrete, the authors deemed it necessary to investigate the compressive strength of RPC mixtures when external pressure is applied during curing. The results showed that the increase in compressive strength can be directly correlated to the enhanced density of the matrix phase of the spherical pores of all the RPC tested (Halit et al., 2010). Halit et al. (2010) were able to show that, at lower GGBFS content, RPC sample mixtures exhibited a greater flexural strength after 90 days of standard curing. This research was able to clearly show that GGBFS affects the mechanical properties of RPC in a general positive manner. The level of impact of GGBFS on RPC is dependent on the type of aggregate used, the duration of curing and the type of curing employed.

3. SCOPE OF RESEARCH

Research Significance

The objective of this study was to develop UHSC mixtures using WFS, and investigate the impact of WFS on the compressive strength of UHSC. A simple comparative analysis of compressive strength was conducted between 2-in. cube control specimens (without foundry sand), and specimens of the same size that contains foundry sand at 10, 20, and 30% replacement of fine aggregate. Another simple comparative analysis of the splitting tensile reults, was conducted between 4-in. x 8-in. cylinders control specimens (without foundry sand) and specimens of the same size that contains WFS at 10, 20 and 30% replacement level. For consistency, all samples were mixed, cured, and tested in the same manner. Data ascertained from this research will further compliment established researches that has shown that, at certain percentage replacement levels, UHSC produced with WFS is capable of exhibiting comparable and in some cases, equivalent compressive and splitting tensile strength.

Assumptions and Limitations

Manufactured sand, also known as “man sand” (crushed limestone), was used as fine aggregate in lieu of river sand, during the preliminary stages of this research. However a deliberate decision was made to revert to river sand, when initial control mixtures made with man sand, did not meet desirable compressive strengths based off of the literature review. A detailed explanation of the processes that informed this decision is enumerated in the discussion of initial results sub-section of this research. Therefore, this study is limited to siliceous sandstone obtained from a single source, as the fine aggregate used throughout the rest of the research. River sand possesses obvious advantages such as quality gradation in required proportion and the absence of organic and soluble compounds, which might affect the setting time and properties of the cement. Additionally, river sand is a rounded aggregate that can result in better particle compaction and a more workable mixture. This property has the potential of positively impacting the strength properties of the concrete mixtures. According to the literature, aggregate passing #30 sieve, produces a higher packing density and ultimately a higher strength than conventional concrete, therefore, this understanding has been assumed to be true (Srinivas & Newston, 2010). Due to the high compressive strength of UHSC, there were issues with compressive testing and exposed laboratory sample surface. Traditional compressive testing either requires sulfur capping or bearing pads, both techniques will produce inaccurate results with UHSC specimens due to a weaker material or uneven stress distribution, respectively. Therefore, 2" cube specimens are used and the specimens are tested on the mold finished surface.

Delimitations

The delimitations of this study includes the control mix design, the constituents of the mix design, and the replacement level of WFS. The literature has many options of UHSC mix designs in which each has slightly varying means of achieving a UHSC mixture. The control mix design selected was produced initially by (Srinivas & Newston, 2010), and was selected as it used no specialty aggregates, no specialty SCMs, or unique admixtures. Delimitations have been set on the constituents as well such as the <#30 sieved river sand, the HRWRA, the type of cement, and the silica fume. Lastly, the percent replacement of WFS is considered a delimitation of this research and the replacement percentages are based off the literature.

Hypothesis Statement

The hypothesis and null hypothesis of this study is as follows:

H_1: The replacement of fine aggregate with WFS in a control UHSC mixture up to 30% will increase the strength of the UHSC control mixture.

H_0: The replacement of fine aggregate with WFS in a control UHSC mixture will have any affect and/or reduce the strength of the UHSC control mixture.

4. MATERIALS AND METHODS

Cement

Type 1 ordinary Portland cement (OPC) was used in the preparation of all concrete mixtures developed in this research in accordance with ASTM C150 standard (ASTM, 2007) . Table 4-1 contains the chemical composition of the Type 1 OPC used in all concrete mixtures.

Table 4-1**:** Physical properties of Cement.

Physical test	Results	ASTM C150 Requirement
Fineness (retained on 90 µm sieve) %	3.6	-
Fineness: specific surface (air permeability test)(m^2/kg)	348	260 min
Vicat time of setting; Initial (min)	68	45 min
Vicat time of setting; Final (min)	293	375 max
Compression strength (MPa); 3 days	24.4	12 min
Compression strength (MPa); 7 days	39.2	19 min
Compression strength (MPa); 28 days	48.4	-
Specific gravity	3.15	-

Aggregates

The literature review suggests only fine aggregate sieved below #30 (0.0234-in.) be used, in order to increase the compaction density of the concrete (Srinivas & Newston, 2010). Therefore man sand, river sand and waste foundry sand was collected past the #30 sieve.

Once the sieved fine aggregates were obtained, the aggregates were washed over a #200 sieve to remove any remaining fine particles from the aggregate (Srinivas & Newston, 2010). Once the aggregates were washed, they were subsequently dried in the oven at 392ºC (200ºF) and stored in an airtight container prior to mixing. Material preparation and characterization involved the characterization of the initial fine aggregate used (man sand), the fine aggregate eventually used (river sand) and WFS used. All this was determined through ASTM C-136 (ASTM, 2014). This characterization determined the specific gravity, absorption, gradation, and fineness modulus of the aggregate. Table 4-2, Table 4-3 and Table 4-4 shows the properties determined for the <#30 sieved man sand, the <#30 sieved foundry sand and <#30 sieved river sand respectively.

Table 4-2: Man Sand Properties.

ASTM C128 Man Sand <#30 Washed	
Specific Gravity (OD)	**2.58**
Specific Gravity (SSD)	**2.63**
Absorption, %	**1.85%**

Table 4-3: Reclaimed WFS Properties.

ASTM C128 Reclaimed Sand <#30 Washed	
Specific Gravity (OD)	2.61
Specific Gravity (SSD)	2.62
Absorption, %	0.1%

Table 4-4: River Sand Properties.

ASTM C128 Reclaimed Sand <#30 Washed	
Specific Gravity (OD)	2.59
Specific Gravity (SSD)	2.61
Absorption, %	0.76%

The fineness modulus gradation of as received man sand, WFS and as received river sand, was also obtained and are shown in Figure 4-1.

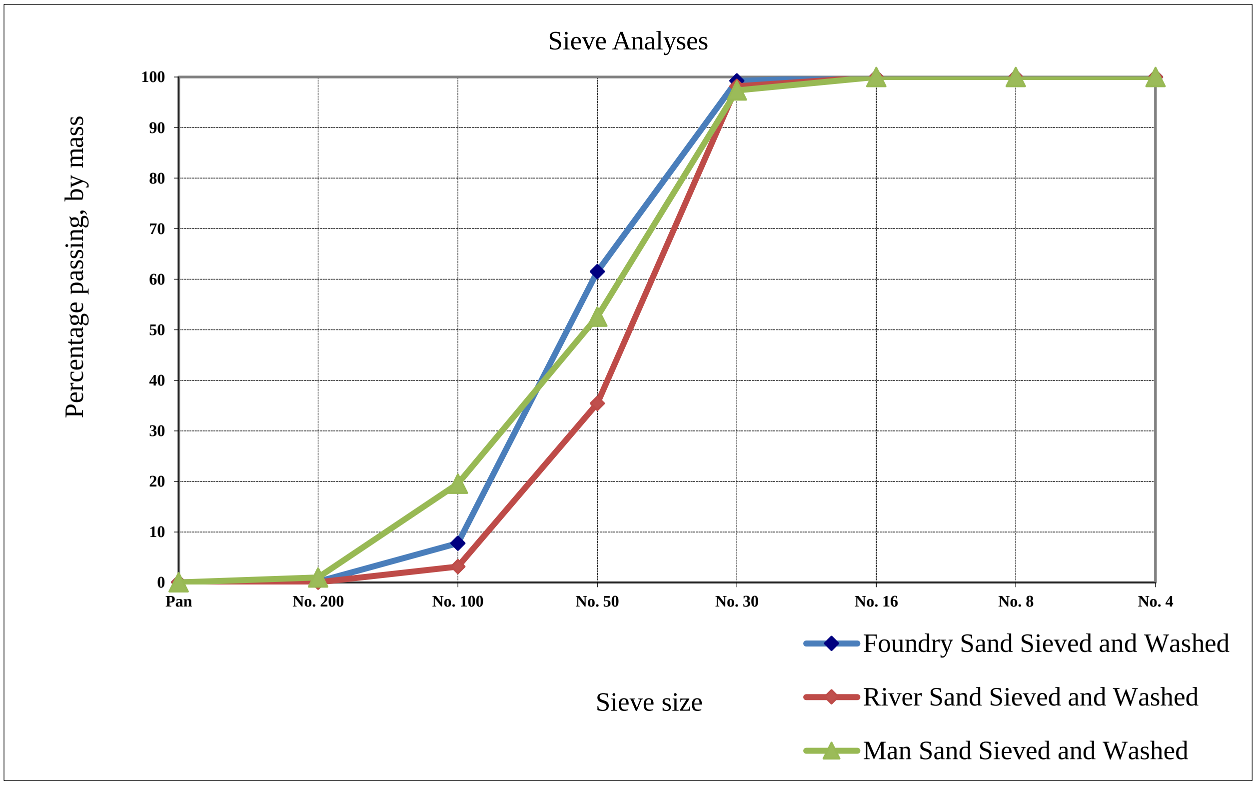


Figure 4-1**:** Gradation curve for manufactured sand, WFS and River Sand

It can be seen in Figure 1 that the majority of particles in the as received manufactured and foundry sand, are already less than the #30 sieve. WFS possess uncanny physical and chemical similarities to siliceous sand (River sand). Both aggregates possess similar impervious micro-structure and angular macro-structure. A very distinctive chemical property, which is also considered a shared similarity, is the very high silica content of the WFS and River sand.

High Range Water Reducing Admixture

The HRWRA used in this research is polycarboxylate-based MasterGlenium 3030 from BASF. This particular type of superplasticizer possesses a chemical structure that enhances excellent particulate distribution/or dispersion. This very chemical characteristic is vital, considering the very low w/c ratio that was employed in the mixture design. Previous researches have shown that the judicious introduction of polycarboxylate-based HRWRA in a concrete mixture with low w/c ratio also improves the workability of said concrete, without negatively impacting the performance (Srinivas & Newston, 2010).

Steel Fibers

Steel fibers of 2-in dimension, was used to improve the durability and long-term performance of concrete. Previous researches showed how enhanced impact resistance structure of steel fibers, improves the long term performance of concrete (Srinivas & Newston, 2010).. Also the enhanced ductility of steel fiber reinforced concrete is primarily due to the extensibility of steel fibers that negates cracking tendencies of an otherwise very brittle concrete mixture.

Initial Mixture Design

The initial UHSC was designed based off published results that demonstrated the desired performance characteristics. The design produced by Srinivas et al. (2010) was used during the preliminary and later stage of this research, as their study produced UHSC with locally available materials and is easily produced. Table 4-5 shows the mixture proportions for the initial UHSC control mixture.

Table 4-5: Initial mixture proportions of UHSC control mixture.

Constituents	Unit	Amount / yd^3	Amount / ft^3
Type I/II Portland Cement	lb	1500	55.56
Silica Fume	lb	375	13.89
Fine Sand	lb	1396	51.71
Steel Fibers	lb	200	7.41
HRWRA	gal	6	0.22
Water	lb	402	14.89

Mixing Procedures

After aggregate separation and washing, the constituents were batched, mixed, casted, and cured. The mixing procedure was developed based off the literature (Srinivas & Newston, 2010). The procedure is as follows:

1. Add Sand
2. Add Cement
3. Add Silica Fume
4. Mix until a uniform dry mixture appears
5. Add 75% of water and mix thoroughly
6. Add HRWRA
7. Add remaining 25% water
8. Mix thoroughly for approximately 20 – 30 mins
9. Once a consistent mixture is created, very slowly add the fibers until the fibers are consistently mixed in.
10. Stop mixing

The 2" cubes were placed and compacted in two lifts in accordance to ASTM C157 standard. Figure 2 shows the compaction sequence as stipulated by ASTM C157, which was done as recommend by the literature (Srinivas & Newston, 2010). The compacting sequence can be seen in Figure 4-2.

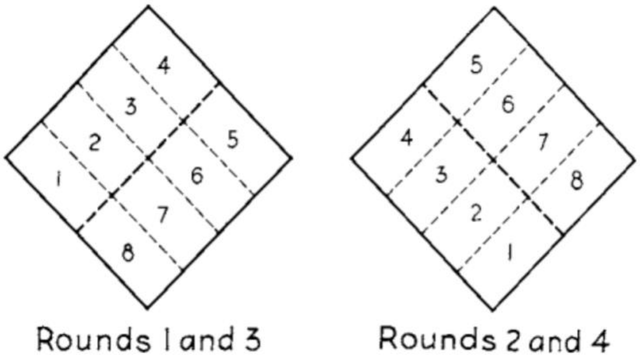


Figure 4-2: Compacting sequence of 2" cubes

Curing Regimen

Following the casting of the specimens, the specimens were cured as follows:

1. After casting, leave in lab air for first 24hrs
2. Demold specimens and place in 50^0C (122^0F) water bath (submerged).
3. Two days prior to testing, place samples in oven at 200ºC.

Flow of Hydraulic Cement Mortar Test

This test was conducted in accordance with ASTM C1437 standards (ASTM, 2015). It was used to determine the flowability and workability of all concrete mixtures. The result ascertained from the test is shown in figure 4-3 below.

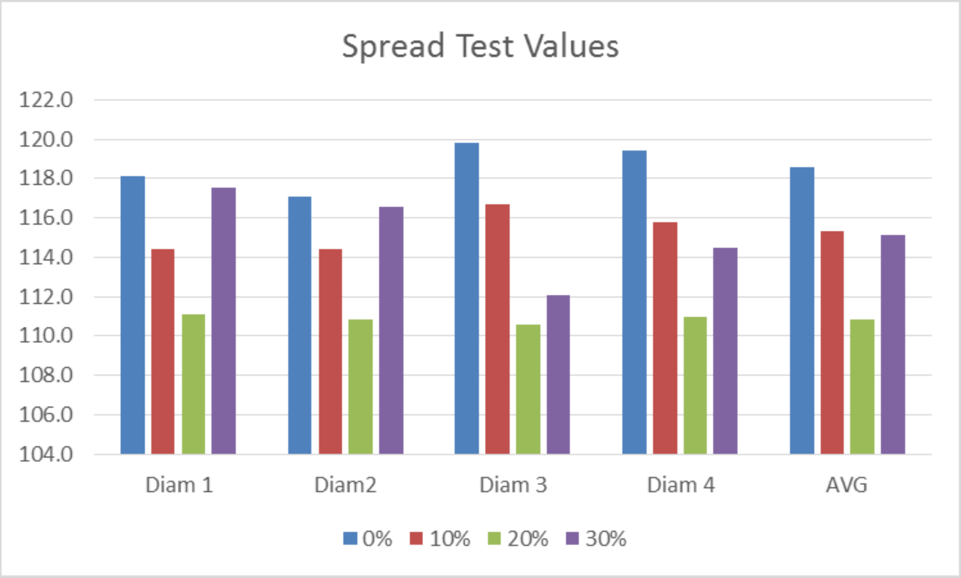


Figure 4-3: Spread test results

The average of all the results ranged from 118mm to 110.5mm. All concrete mixtures exhibited low workability. A t-test was conducted to determine the disparity between the workability of all concrete mixtures. The test was performed with a 95% confidence level and the statistical significance (p value) evaluated at 0.05 level of confidence significance. All comparisons had p-values lower than 0.05. This translates as a very significant disparity amongst the workability of all the concrete mixtures compared. The singular exception was the comparison between concrete mixtures with 10% WFS and 30% WFS. Both concrete mixtures (10% and 30%) exhibited identical spread test values.

Compressive Strength

All concrete samples were tested using BS EN 12390-3-2009 standards (ESI, 2009). This involves an even placement of lubricants on the steel plates on which the concrete samples will be placed. This ensures that failure is solely due to exerted compression. After sample placement, compression due to loading should be conducted at a very nominal pace, within range of $0.2N/mm^2s$ to $0.4N/mm^2s$, as per BS EN 12390-3-2009 standards. After complete failure, compressive strength values are determined by dividing the maximum load applied to the 2-in. cube samples, by the cross-sectional area of the sample.

Splitting Tensile Strength

Splitting tensile strength of all tested concrete samples was determined as per ASTM C496 (ASTM, 2004). After diametrical lines are drawn, an average of three diameters taken on three different axial planes is determined. Samples are then positioned in such a manner that there is a clear intersection between the center of the upper bearing plate and the thrust of the spherical bearing block. Loads are applied continuously at constant rate between 100 to 200psi/min. as per ASTM C496 standards. The splitting testing value is ascertained at maximum failure.

5. RESULTS AND DISCUSSIONS

Compressive Strength

As previously stated, a UHSC mixture design was selected based off of a thorough literature review. All UHSC concrete mixtures were produced in the concrete laboratory at Texas State University. Mixing procedures was kept as consistent as possible. In order to determine if an UHSC mixture can be produced, a compressive strength benchmark needs to be established. There is currently is no established compressive strength threshold for the categorization of UHSC. The American Concrete Institute (ACI) committee 363 who reports on High Strength Concrete (HSC) reports a range of compressive strengths that would be considered HSC of 8,000 – 10,000psi at 28 days (ACI 363, 2005). There is currently no ACI committee or documentation that covers UHSC. However committee 239 covers UHPC. According to ACI committee 239, the threshold for compressive strength of UHPC is 20,000psi at 28 days (ACI 239, 2015) . Therefore, one can conclude that anything above 10,000psi at 28-days can be considered. Due to lack of clear guidelines for the compressive strength expectations of UHSC, a decision was made to use the threshold of at least 18,000psi at 7-days. The initial UHSC design prepared and developed as described in Table 4-5 was produced and tested. The results for the initial test can be seen in Table 5-1.

Table 5-1: Average Compressive Strength of Initial Concrete Mixtures (Man sand)

Age	Average Compressive Strength
7-days	14,182
14-days	16,129
28-days	14,299

The compressive strengths from the initial batch yielded 14,182, 16,129, and 14,299psi for 7, 14, and 28 days respectively. As previously stipulated, the threshold for UHSC was a minimum of 18,000psi at 7-days, therefore the initial batch came up short. The large disparity in compressive strength could be attributed to unevenness or lack of uniformity in the consolidation of samples, poor mixing, material issues, or mix design issues. To gain a better understanding of what could be the issue with the initial design, a petrographic analysis of a polished cut-section of one of the untested cubes at an age of 7 days was completed and shown in Figure 5-1

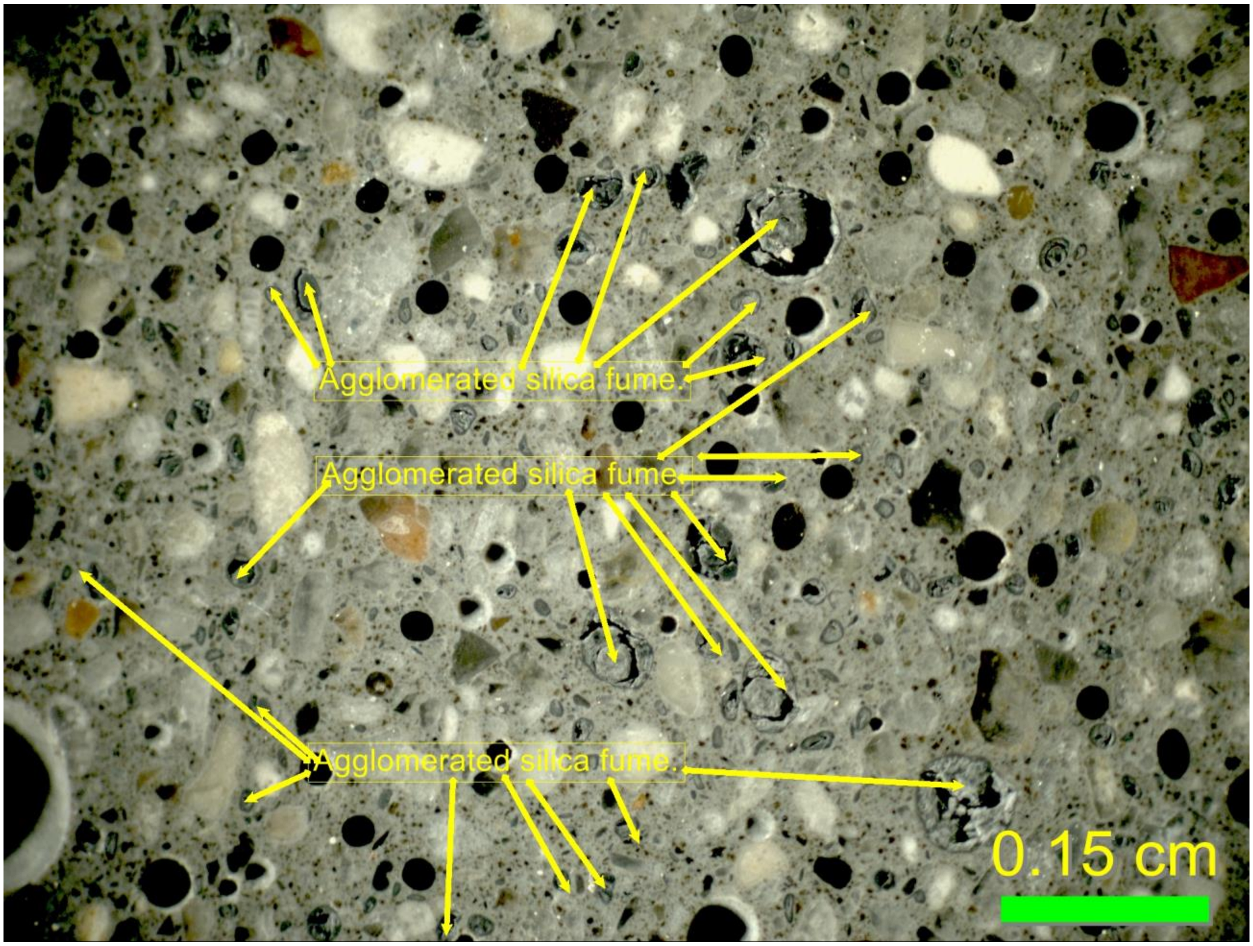


Figure 5-1: Petrographic analysis

The petrographic analysis showed silica fume agglomeration distributed throughout the sample. The silica fume agglomeration could largely be attributed to the fact that the fine nature of the manufactured sand did not exert enough resistance to break down the densified silica fume. Additionally, the pan mixer used was not a "high shear" mixer that is often used in UHSC/UHPC research; therefore the lack of high shear mixing could also be a factor, as to why a lack of thoroughness/or unevenness in the concrete mixture led to silica fume agglomeration. Silica fume agglomeration certainly contributed to the lower than expected compressive strength of tested UHSC, as there was un-hydrated silica fume in the mixture that hindered compressive strength gain. Additionally the lack of siliceous content in manufactured sand, could be a contributory factor. Other sands, like river sand, have higher siliceous content that can help contribute to strength gain. Due to this insight, alterations to the design and/or procedure, needed to be made to reach the minimum threshold of 20,000psi. Alterations were kept to a minimum in order to fully understand the affect each change would have. A review of the literature suggested that river sand is more often used in UHSC/UHPC research over manufactured sand due to its round particle shape and higher siliceous content. Therefore, the first step was to simply change the mixture design to include river sand also sieved below the #30 sieve. River sand used was washed and dried in the same manner as the manufactured sand. The batch quantities of the river sand mixture is shown in Table 5-2.

Table 5-2: Mixture proportions of river sand mixture.

Constituents	Unit	Amount / yd^3	Amount / ft^3
Type I/II Portland Cement	lb	1500	55.56
Silica Fume	lb	375	13.89
River Sand	lb	1423	52.72
Steel Fibers	lb	200	7.41
HRWRA	gal	6	0.22
Water	lb	386	14.29

As shown in Table 5-2, the mixture proportions of the river sand mixture are very similar to the initial mixture that contained manufactured sand. The major difference stems from the amount of sand used, due to a slight difference in the specific gravity of river sand. The river sand mixture was then produced and 2-in. cubes were tested for compressive strength. The 7-day compressive strength of the river sand samples can be seen in Table 5-3.

Table 5-3: Compressive Strength Result of river sand mixture (w/cm:0.16)

Age	Strength (PSI)
7	16,694
14	16,097
28	15,825

Compressive strength test of initial 2-in. cubes produced with river sand showed significant elevation in compressive strength. This could be attributed to a reduction in silica fume agglomeration, and also an increase in compacted density. However, this was not verified through petrographic analysis. Due to the average of all samples tested at 7days, 14 days and 28 days were well below expected compressive strength values, a decision was made to lower the w/cm ratio to 0.16 instead of the w/cm of 0.20 which was originally used. The lower w/cm ratio should help increase the strength beyond 18,000psi at curing age of 7-days. The adjusted mixture design of the river sand control samples are shown in Table 5-4 below.

Table 5-4**:** Mixture proportions of river sand mixture (w/c: 0.16).

Constituents	Unit	Amount / yd^3	Amount / ft^3
Type I/II Portland Cement	lb	1500	55.56
Silica Fume	lb	375	13.89
Fine Sand	lb	1584	58.67
Steel Fibers	lb	200	7.41
HRWRA	gal	8	0.28
Water	lb	312	11.56

Compressive strength results of three 2-in. cubes tested at 7- days showed remarkable improvement in compressive strength. Table 5-5 shows the compressive strength results at an age of 7 days.

Table 5-5: Compressive strength (7- days, w/cm: 0.16) results of river sand mixture

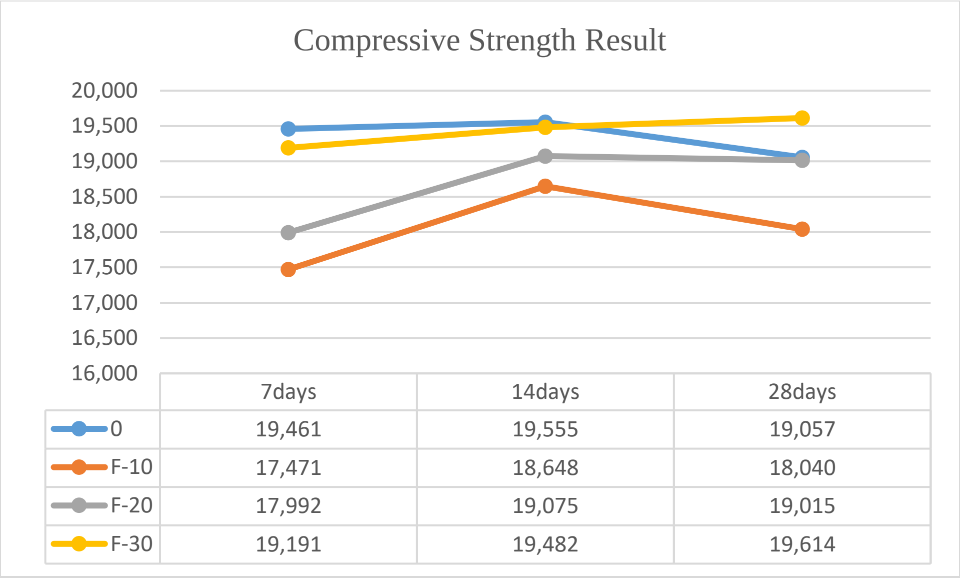
Age	Strength (PSI)
7	19,514
7	18,764
7	20,104
AVG	19,461

As shown above, the results of the 7-day compressive strength tests of river sand mixture (w/cm = 0.16) produced results higher than 18,000psi. Therefore the minimum strength threshold was eventually met and the new design was used as the control mixture for this study. Table 5-6 shows the final mixture proportion (Control and WFS mixtures) at w/cm ratio of 0.16.

Table 5-6**:** Final Mixture Proportions

	FW %:	0% (Control)	10%	20%	30%
Constituents	Unit	Amount / yd^3	Amount / yd^3	Amount / yd^3	Amount / yd^3
Type I/II Portland Cement	lb	1500	1500	1500	1500
Silica Fume	lb	375	375	375	375
Fine Sand	lb	1584	1426	1267	1109
Foundry Sand	lb	0	169	319	506
Steel Fibers	lb	200	200	200	200
HRWRA	gal	7.5	7.5	7.5	7.5
Water	lb	312	311	310	309

After test samples were produced with stipulated final mixture proportions specification, each concrete mixture was tested as described previously. The compressive strength result of all samples can be seen in Figure 5.



	7days	14days	28days
0	19,461	19,555	19,057
F-10	17,471	18,648	18,040
F-20	17,992	19,075	19,015
F-30	19,191	19,482	19,614

Figure 5-2: Compressive Strength Result

The control concrete mixture yielded average compressive strengths of 19,461psi, 19,555psi and 19,057psi, at 7, 14 and 28 days respectively. The result showed a 2% decrease in compressive strength between the early strength (7-days) and late strength (28 days) of the control mixture. All other concrete mixtures exhibited fluctuations in compressive strength. The control, 10% WFS, 20% WFS, 30% WFS were labelled group one, group two, group three and group four respectively. Group two (10% WFS) yielded average compressive strength of 17,471psi, 18648psi, 18,040psi at 7, 14 and 28 days respectively. Concrete mixture samples with 10% WFS exhibited 3% increase in compressive strength between the early strength (7-days) and late strength (28-days). Lower than expected compressive strength value of concrete at 10% WFS replacement, could be attributed to silica fume agglomeration. Group three (20% WFS) exhibited compressive strength of 17,992psi (7-days),19,075psi (14-days) and 19,015psi (28-days) Group four yielded compressive strength of 19,191psi(7days), 19,482psi(14 days), and 19,614psi(28 days) The aforementioned result shows that group three exhibited a 5% increase in compressive strength between early strength (7-days) and late strength (28-

days). Group four also showed a 2% compressive strength increase between early strength and late strength. All concrete samples exhibited a marginal increase and decrease in strength gain. A t-test was conducted in order to determine if there is a statistical difference between all four groups. This statistical evaluation was performed at 95% confidence interval and a statistical significance of 0.05. A comparative analysis between the control and group one (10% WFS), yielded p-values less than 0.05 (0.02) at 7 days. This result shows that there is considerable decrease in the compressive strength of concrete at 10% WFS replacement level compared to UHSC without WFS. Further evaluations showed that compared to the control samples, group one showed a 10% decrease at early strength (7days) and a 5% decrease at late strength (28days). A 7 day comparative analysis between control and group three (20% WFS), control and group four (30% WFS) yielded p-values 0.12 and 0.36 respectively. A comparative analysis at 7 days between group two (10% WFS) and group three (20% WFS), and group three (20% WFS) and group 4 (30% WFS), yielded p-values 0.04 and 0.17 respectively. All other comparative analysis conducted at 14 and 28 days, structured in aforementioned pattern yieled p-values greater than 0.05. Further evaluations showed that compared to group two (10% WFS) concrete mixtures, group four (30% WFS) concrete mixtures showed 8% increase in early strength (7days) and late strength (28days). In summary there is a significant but marginal decrease in compressive strength when UHSC concrete is produced with 10% WFS and when the WFS content of a UHSC is increased from 10% to 30%. With the exception of the 10% early strength decrease between UHSC at 0% WFS and UHSC at 10% WFS replacement level, the rest of the results clearly shows that the impact on the compressive strength of UHSC produced at 20% and 30% WFS, is not significant. All concrete mixtures, showed fluctuation in compressive strength, between 7 and 28 days, with the exception of group 4 mixtures (30% WFS). There was a very consistent but marginal loss of strength in all concerete mixtures, between age of 14 and day 28. Once again the only exception was mixtures from group 4 (30% WFS), which showed marginal but consistent strength gain, between day 7 and day 28 days.

Splitting Tensile Strength

Splitting tensile strength was included in this study, in order to characterize as many mechanical properties as possible. Splitting tensile strength of all concrete mixtures were tested at 7 and 28 days, based on stipulated standards. The results can be seen in Figure 5-3.

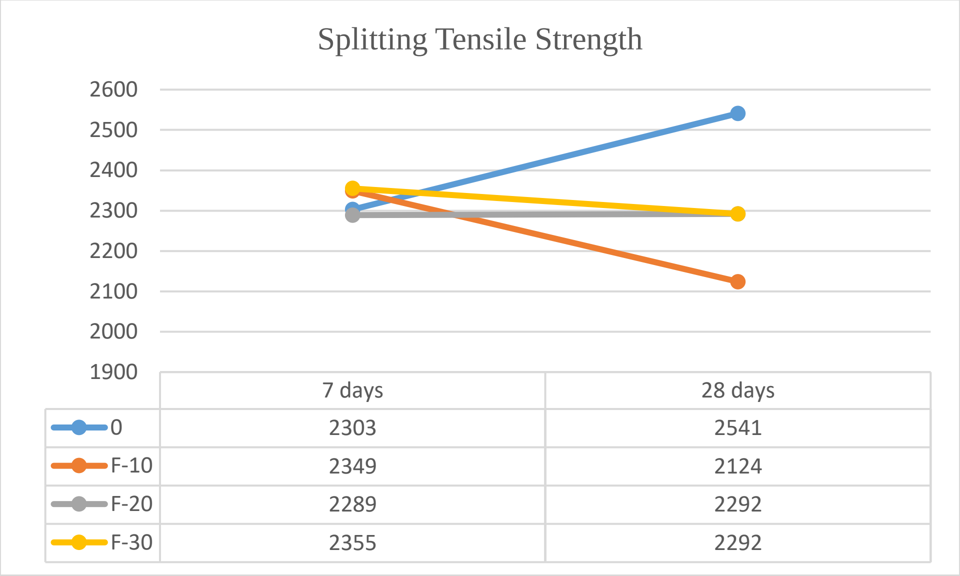


Figure 5-3: Splitting Tensile Strength Results

These values were ascertained at 7 and 28 days, in accordance to ASTM Standard C496. All tested concrete samples exhibited splitting tensile strength above 2100psi. The results from the splitting tensile testing showed a similar trend to that of the compressive strength results, especially with the 28-day strengths. All groups of concrete (with the exception of group 3), showed a reduction in splitting tensile strength at 28 days. However the 10% group exhibited the most significant reduction in splitting tensile strength. Concrete mixtures at 30% WFS replacement level exhibited the highest splitting tensile strength other than the control, amongst all tested samples with WFS. Interestingly, group three samples demonstrated very similar splitting tensile results at both 7-days and 28-days. A t-test was conducted in order to confirm any statistical difference in all tested concrete samples. The comparative analysis showed p-values greater than 0.05 for the 7-day strengths and 28 days, which is expected. The results showed that there is no statistical significance between WFS replacement samples at 20% and 30% replacement level and the control However UHSC mixtures at 10% WFS replacement level, exhibited a 16% differential in splitting tensile strength compared to control mixtures at 28 days. This goes to show that splitting tensile strength equivalent to the established benchmark (2100psi) can be achieved at 20% and 30% replacement level. It is important to note that the strengths are still significantly higher than a conventional concrete mixture.

6. SUMMARY AND CONCLUSION

The impact of WFS on the compressive strength and splitting tensile strength properties of a UHSC were investigated. The WFS replacement level used were 10%, 20% and 30% by volume of fine aggregate. Due to the absence of established ASTM or ACI standards for the expected compressive strength of UHSC 18,000psi and 2100psi was assumed as the benchmark UHSC compressive strength and splitting tensile strength respectively. This assumption is peculiar to this particular research project. The modification of the mixture design involved the substitution of manufactured sand (crushed limestone) for river sand. The compressive strength for all samples were tested at 7, 14 and 28 days. Whereas the splitting tensile strength of all concrete mixtures were tested at 7 and 28 days. From the test results the following conclusions were drawn.

1. Based off the mixture design chosen, river sand produced the higher compressive strengths compared to manufactured sand (crushed limestone).
2. Petrographic analysis reveals high levels of silica fume agglomeration, which contributed to lower than expected compressive strengths.
3. The concrete mixtures of w/cm ratio of 0.16, produced the highest compressive strengths,
4. Unusually low w/cm ratio (0.16) also impacted the workability of all concrete mixtures.
5. WFS had no impact on the compressive strength of designed UHSC mixtures. However mixtures at 10% WFS replacement level, exhibited

10% and 5% differential in compressive strength compared to the control, at 7 and 28 days respectively.

6. WFS had no impact on the splitting tensile strength of designed UHSC. However UHSC mixtures at 10% WFS replacement level, exhibited a 16% differential in splitting tensile strength compared to control mixtures at 28 days.

REFERENCES

ACI Committee 239. (2015). Ultra High performance Concrete (ACI 239-63): Report of ACI Committee 239, Standard building code. Detroit: American Concrete Institute.

ACI Committee 363. (2005). High Strength Concrete (ACI 363-34): Report of ACI Committee 363, Standard building code. Denver: American Concrete Institute.

ASTM International. (2014). ASTM C136/C136M-14 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. Retrieved from https://doi-org.libproxy.txstate.edu/10.1520/C0136_C0136M-14.

ASTM International. (2007). ASTM C150-07 Standard Specification for Portland Cement. Retrieved from https://doi-org.libproxy.txstate.edu/10.1520/C0150-07.

ASTM International. (2004). ASTM C496/C496M-11 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. Retrieved from https://doi-org.libproxy.txstate.edu/ 10.1520/C0496_C0496M-11.

ASTM International. (2015). ASTM C1437-15 Standard Test Method for Flow of Hydraulic Cement Mortar. Retrieved from https://doi-org.libproxy.txstate.edu/10.1520/C1437-15.

European Standards. (2009). BS EN 12390-3 Testing Hardened Concrete: Compressive Strength of Test Specimens, Report on European Committee for Standardization, pp. 1-19.

Graybeal, B., (2011) Ultra-High Performance Concrete, TechNote. FHWA-HRT-11-038, Federal Highway Administration, McLean, pp. 1-13.

Halit, Y., Mert, Y. Y., Huseyin, Y., Serdar, A., & Selcuk, T. (2010). Mechanical properties of reactive powder concrete containing high volumes of ground granulated blast furnace slag. Elsevier, pp. 639-648.

Nwofor, T., & Ukpaka, C. (2016). Assessment of Concrete Produced with Foundry Waste as Partial Replacement for River Sand. Journal of Civil Engineering Research, pp. 1-6.

Piotr, S., & Danuta, B.-H. (2016). Mechanical and durability related properties of high performance concrete made with coal cinder and waste foundry sand. Elsevier, pp. 9-17.

Prabhu, G., Jung, H. H., & Yun, K. (2014). Effects of foundry sand as a fine aggregate in concrete production. Elsevier, pp. 514-521.

Rafat , S., Geert, D., & Noumowe, A. (2009). Effect of used-foundry sand on the mechanical properties of concrete. Construction and Building Materials, pp. 976-980.

Richard, P., & Cheyrezy, M. (1994). Reactive Powder Concretes with High Ductility and 200-800 MPa Compressive Strength. Special Publication 144-24, pp. 507-518.

Silvia, F., & Maria, C. Z. (2007). Foundry Wastes Reuse and Recycling in Concrete Production . American Journal of Environmental Sciences, Vol 3, Iss 3, pp. 135-142.

Sohail, M., Wahab, A., & Khan Md, A. (2008). A Study on the Mechanical Properties of Concrete by Replacing Sand with Waste Foundry Sand. International Journal of Emerging Technology and Advanced Engineering, pp. 83-87.

Srinivas, A., & Newston, C. M. (2010). Ultra-High Strength Concrete Mixtures Using Local Materials. Concrete Sustainability Conference (pp. 1-9). New Mexico: National Ready Mixed Concrete Association.

Susanto, T., Tze Yang, D. L., & Bahador, S. D. (2013). Durability and mechanical properties of high strength concrete incorporating ultra fine Ground Granulated Blast-Furnace Slag. Elsevie*r*, pp. 875-881.

Yucel, G., Yasin , S. D., Muhsin, Y., Ahmet, T., & Senayi, D. (2010). Re-usage of waste foundry sand in high-strength concrete. Elsevier, pp. 1705-1713.