Experimental Study on the Effects of Addition of Polypropylene Fibers on Mechanical Properties of High Strength and Normal Strength Concrete

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ABSTRACT

The use of thermoplastic polymers to improve characteristics of concrete has gained attraction over the last couple of decades. Polypropylene fiber is a type of thermoplastic that is considered to have added desirable properties to concrete. In this thesis, the effects of Polypropylene fiber on fresh and hardened properties of normal strength concrete, and high strength concrete were investigated. Different percentages of Polypropylene fiber were added by volume (0, 0.25, 0.50, 0.75, and 1.00 %) to normal strength and high strength concrete, water to cement ratio of 0.5 for normal strength concrete and 0.4 for high strength concrete.

Slump and VeBe time tests were performed to analyze the physical properties of fresh concrete, while the effect of polypropylene fibers on the mechanical properties of hardened concrete was executed by performing compressive strength test, flexural and toughness test, splitting tensile strength test, drying shrinkage test, heat degradation test (100 °C, 200 °C), Schmidt hammer test, Ultrasonic Pulse Velocity test (Pundit), water absorption test, and water permeability test.

The results show changes in mechanical properties of normal strength concrete and high strength concrete as the percentages of PPF increases. However, improvement in mechanical properties were identified after the analysis. Compressive strength of normal strength concrete decreased at 28 days while that of HSC increased as Splitting tensile strength for both concretes increased as percentage of polypropylene fiber increased at 28 days. There was increase in flexural strength and toughness in both normal and high strength concrete as polypropylene fiber percentage increases, except for 1.00 % which showed decrease. Less penetration depth was observed with the addition of fibers. Pundit test showed results of a good concrete quality with Polypropylene fiber before and after heat exposure. Decrease in compressive strength, splitting tensile strength, and ultrasonic pulse velocity was observed after 100 °C and 200 °C heat exposure.

Keywords: Polypropylene Fibers (PPF), Normal Strength Concrete, High Strength Concrete, Mechanical Properties, Shrinkage, Water absorption, Permeability, Heat exposure.

ÖZ

Betonun özelliklerinde iyileştire yapmak amacı ile termoplastik polimerlerin kullanımı son yıllarda cazibe kazanmıştır. Polipropilen elyaf (PPE), betondaki belirgin özellikleri iyileştireceği düşünülen bir tür termoplastiktir. Bu tez çalışmasında polipropilen elyafın (PPE) kullanılması ile normal dayanımlı betonun (NDB) ve yüksek dayanımlı betonun (YDB) taze ve sertleştirilmiş özellikleri üzerindeki etkileri araştırılmıştır. Farklı miktarlarda elyaf kullanılarak (%0, %0.25, %0.50, %0.75 ve %1.00) elde edilen betonlar iki farklı su/çimento oranı (0,4 ve 0,5) kullanılarak üretilmiştir.

Taze betonun fiziksel özelliklerini analiz etmek için çökme ve VeBe zaman deneyleri yapılmıştır. Sertleşmiş betonun mekanik özelliklerini analiz etmek için ise basınç dayanımı deneyi, eğilme ve tokluk deneyi, basmada yarma dayanımı deneyi, kuruma büzülme deneyi, ısı bozunma deneyi (100°C, 200°C), Schmidt çekci deneyi, ultrasonik darbe hızı (UPV) deneyi (Pundit), su emme deneyi ve su geçirgenlik deneyi yapılmıştır.

Sonuçlara bakıldığı zaman ise PPE'nin karışım miktarı arttıkça, NDB ve YDB'nin mekanik özelliklerinde değişiklikler görüldüğü faredilmektedir Deney sonuçlarının analizinden sonra mekanik özelliklerde iyileşme tespit edilmiştir. NDB'nun basınç dayanımı 28 günde azalırken, YDB'de artış görülmüştür. Diğer taraftan ise 28 gün sonra PPE'nin karışım miktarı arttıkça, hem NDB hem de YDB’nin basmada yarma dayanımının artmış olduğu gözlemlenmiştir. PPE miktarı arttıkça hem NDB hem de YDB'da eğilme dayanımı ve tokluk (%1.00 elyaf miktarı hariç) artmıştır. Elyafın betona katılması ile daha az su geçirgenliği de gözlemlenmiştir. Beton sıcaklığının 100°C ve 200°C'de olduğu durumda basınç dayanımı, basmda yarma dayanımı, tokluk ve UPV'de düşüş gözlemlenmiştir.

Anahtar Kelimeler: Polipropilen Elyaf (PPE), Normal Dayanımlı Beton, Yüksek Dayanımlı Beton, Mekanik Özellikler, Büzülme, Su Emme, Geçirgenlik, Yüksek Sıcaklık

DEDICATION

I am blessed, honored, humbled and passionate. I dedicate this study to my spiritual support my beloved Mother, and the long living backbone in my life my Father. For every one in my life that believed in me and has become a moral support, I dedicate this to you and I’ll continue to strive for more success.

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Muhieddine Kaj

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HPC	High performance concrete
HSC	High Strength Concrete
NSC	Normal Strength Concrete
PPF	Polypropylene Fiber
PPF-HSC (0.00)	0% PPF in HSC
PPF-HSC (0.25)	0.25% PPF in HSC
PPF-HSC (0.50)	0.50% PPF in HSC
PPF-HSC (0.75)	0.75% PPF in HSC
PPF-HSC (1.00)	1.00% PPF in HSC
PPF-NSC (0.00)	0% PPF in NSC
PPF-NSC (0.25)	0.25% PPF in NSC
PPF-NSC (0.50)	0.50% PPF in NSC
PPF-NSC (0.75)	0.75% PPF in NSC
PPF-NSC (1.00)	1.00% PPF in NSC
SF	Silica Fume
SP	Superplasticizer
UPV	Ultrasonic Pulse Velocity
w/b	Water to binder ratio
w/c	Water to Cement Ratio

Chapter 1

INTRODUCTION

1.1 Study Overview

In the past two decades, high strength concrete (HSC) has become an increasingly popular choice of concrete. Its growing popularity is due to the benefits it offers. The growing use of HSC also comes with the risk of exposure to elevated temperatures. Understanding the behavior of HSC under various conditions increases the confidence in the use of HSC. It is essential to predict the reaction of structures that use HSC. To achieve that, the mechanical properties of HSC must be studied before and after exposure to elevated temperatures.

The workability, strength, and durability of HSC is known to be greater than conventional concrete, or normal strength concrete (NSC) at ambient temperatures (Xiao & Falkner, 2006). However, they can have a dramatic, or rapid failure when exposed to fire, which is categorized as explosive spalling (Khoury, 2000).

Explosive spalling is a critical and dangerous type of failure that degrades the structural integrity of concrete. It has been a controversial subject on the susceptibility of HSC to explosive spalling compared to NSC. Some investigations such as (Kalifa, Menneteau, & Quenard, 2000; Sullivan, 2000), state that HSC have a propensity to explosive failure by heating more NSC.

To resist explosive spalling, and other deteriorations might be found in HSC as an effect of heating, using different fibers including steel, cellulose fibers or polymer have been investigated in the study of (Czoboly et al., 2017).

Explosive spalling deteriorates the load resistance of structures. The lifetime reduces drastically, and may sometimes lead to structural collapse (Won, Kang, Lee, Lee, & Kang, 2011). Addition of PPF to concrete is known to be one of the most economical (Radik, M. J., Erdogmus, E., & Schafer, T. 2010) and technological methods of preventing explosive spalling. It is also worth noting that the use of PPF is recommended by the Eurocode 2 in construction. Over the past two decades, the application of fiber-reinforced concrete is mostly observed in tunnel linings. It is commonly applied to precast tunnel segmented linings that are underground.

It has been documented that the use of PPF in concrete may significantly reduce the amount of explosive spalling for HSC at elevated temperature. Theoretical, and experimental studies show that at high temperatures, PPF melt and form channels where the water vapor pressure that is created is released. The release of the water vapor reduces the explosive tendency considerably for HSC when under fire. (Shihada, S. 2011).

The micro-channels created from the thermal decomposition of PPF simultaneously connects to form a netlike micro-crack formation which reliefs internal stresses (mechanical effect), and permeable formation of transport system for the water vapor (permeation effect).

1.2 Problem Statement

The scientific fact that concrete material being brittle is true. It is indicated through its weakness in tension, as well as having a high density and its ability to absorb water which causes it to be affected by tensile loads, high temperatures and annual changes in condition that may affect the mechanical properties of concrete such as shrinking (due to loss of water), swelling (due to gaining moisture) and weakness of its tensile strength which would cause cracking, spalling and deterioration. In spite of its relatively high compressive strength but it may cause explosive failure over high heat exposure. Therefore, PPF is a high tensile material compared to concrete and its aptitude being heat resisting where it has a high burning point (590 ºC) which makes it remarkable to study the impact of PPF on the behavior of concrete where adding such fibers may enhance the mechanical properties of concrete and reduce the risk of heating. Studies are continuously carried out to find the appropriate combination of polypropylene within the concrete.

1.3 Objectives of the Study

Finding the appropriate proportion of PPF in concrete is imperative for structural stability where the use PPF contribute to the construction industry in multiple ways. The prevention of structural collapse as a result of exposure to extreme temperature is an obvious advantage. Also, durability of the structures is enhanced significantly. The effects of PPF on concretes has been studied at some levels in the literature.

In this thesis, the effects of PPF on concrete were investigated. The mechanical properties of PPF are tested on both HSC, and NSC. This is achieved by adding PPF with different volumes. The percentages of PPF tested are: 0, 0.25, 0.50, 0.75, and 1.00 %. At elevated temperatures. The following tests were conducted, and discussed:

- Slump and VeBe (Workability) tests
- Compressive strength for 7 and 28 days
- Flexural strength for 7 and 28 days
- Splitting tensile strength for 7 and 28 days
- Flexural toughness test
- Water absorption
- Water penetration
- Drying Shrinkage test
- Non-destructive test (Schmidt hammer and pundit)
- Heat resistance test (Degradation) at 100 °C and 200 °C

Results of the experiments will be analyzed, and regression analysis will be performed to establish new relation between HSC, and NSC that contain PPF. The new relationship will explain the efficiency of PPF addition by volume, and its effect on concrete behavior at fresh and hardened stages, for NSC and HSC.

1.4 Thesis Outline

To achieve the objectives of the thesis, the remainder of the thesis is organized as follows. Chapter 2, presents a literature review of studies that has used PPF in concrete. The experimental works, and methodology of the thesis is discussed in details in chapter 3. Chapter 4 presents the results, and discussion of the performed experiments. And chapter 5 concludes the thesis.

Chapter 2

LITERARTURE REVIEW

2.1 Introduction

Most recently, several studies have been conducted on the characteristics of concrete when fibers are added. Such concrete is used for repairing the covering of tunnels, retrofitting structures, and stabilizing structures, etc. Advantages of fibers on concrete include increase in bending strength, and formability (Kakooei, Akil, Jamshidi, & Rouhi, 2012).

Concrete is a brittle material. The tensile strength of concrete is low when compared with its compressive strength. Utilizing short fibers is an effective method of stabilizing the cracks, and improving the tensile strength and ductility of concrete (Bei-Xing, Ming-xiang, Fang, & Lu-ping, 2004).

The two main types of fibers that are added in concrete are steel fibers, and PPF (Bažant & Kazemi, 1990; Shah, Swartz, & Ouyang, 1995). Compared to steel fibers, PPF has low modulus, light density, and small monofilament diameter (Bei-Xing et al., 2004; Kakooei et al., 2012).

Utilizing PPF in concrete may add the following characteristics:

- Improved performance characteristics
- Reasonable cost

- Improved shrinkage and cracking characteristics
- Improved toughness
- Reduced salt water amount
- Improved impact resistance.
- Increased formability
- Improved strength against impulse.

2.2 Components of Concrete

Concrete is a composite substance made up of mixing fine, and coarse aggregates such as: gravel, crushed stones, rock, and sand held together with cement paste (water-cement). The concrete properties depend on the materials, or components used, and their proportions. In concrete formation, the cement and water are mixed together, and hydration occurs. The strength of the concrete increases as hydration continuous.

2.3 Normal Strength Concrete (NSC)

Same concrete components are used in both NSC and HSC, but the distinguish between all concretes are in the percentages, and quantities of main components used, and using admixtures to produce required mix. NSC is a concrete with a compressive strength below 41 MPa, which is used for ordinary building in normal environmental conditions. With time, many experiments were done on NSC to have the ability to resist harsh conditions which came up with HPC by using some chemical admixture for better mechanical enhancement.

2.4 High Strength Concrete (HSC)

The uses, and applications of HSC has increased remarkably in the past two decades. High rise building are the most common applications of HSC. A great development of HSC manufacture has obtained nowadays to easily meet prominent concrete compressive strength reach up to 100 MPa.

The distinctive factor between HSC, and NSC is the compressive strength which represents the maximum resistance of concrete to applied load. However, no exclusive point of separation is stated between HSC and NSC. According to American Concrete Institute, a concrete with compressive strength greater than 41 MPa can be considered as HSC(ACI, 2018). (Portland cement association, PCA. 2018)

The structural application problem of normal concrete is its weakness when tension is exerted, and its brittle nature which comes from the low tensile strength. (Uygunoğlu, 2008).

To manufacture HSC, the basic ingredients of NSC are optimized. The factors that affect compressive strength are manipulated to achieve the required strength. In addition to using high quality Portland cement, optimized aggregates, optimized materials percentage by using different cement proportions, aggregates, water, and admixtures.

In selecting HSC aggregates, the following are considered: strength, elasticity, and size of aggregates, as well as the texture of the aggregates surface. ASTM C33/C33m-18 must be considered. These are important factors that could limit the strength of the concrete.

HSC technology has become a developed major in the industry of concrete construction. Furthermore, the behavior of concrete is improved by the collaboration of the microstructure behavior of cementitious materials at nano levels, such as: nano-silica and SF. Considering that using Pozzolans as supplementary cementitious materials in concrete have contributed to the fast development of HSC and HPC.

Moreover, replacing the pozzolanic materials such as SF with cement content in the mix can decrease the porosity of concrete.(Fallah & Nematzadeh, 2017).

SF with some additives can work as a lubricator, enhancing the workability of concrete. In addition, slow improvement of strength was observed due the natural pozzolanic reaction. However, considerable high strength gain can be detected at long-term. (Khedr, S. A., & Abou-Zeid, M. N.1994).

The nano-silica, and silica pozzolan, when used in the composite as a percentage of cement weight; Calcium silicate hydrate (C-S-H) gel is produced from the cement replacing pozzolan in concrete during the reaction between calcium hydroxide by cement hydration. This produces high strength, and low porosity in the concrete (Rashiddadash, Ramezanianpour, & Mahdikhani, 2014).

At ambient temperature, the workability, strength, and durability of high strength concrete are superior to normal strength concrete (König, Dehn, & Faust, 2002).

Self-compacting concrete (SCC) is a kind of high-performance concrete with excellent segregation resistance, and deformability properties. It was developed in 1986 in Japan. During the placing process, no vibration is needed to fill the gap of reinforcements, and mold corners (Hajime Okamura, 1997; H Okamura, Ozawa, & Ouchi, 2000).

The use of PPF in self-compacting concrete, may improve the flexural strength, toughness, impact strength of concrete. Hence reduce slump and flowability of concrete. In addition it may not affect the compressive strength of concrete. (Mazaheripour, Ghanbarpour, Mirmoradi, & Hosseinpour, 2011).

2.5 Properties of Polypropylene fiber (PPF)

Polypropylene is a by-product of petroleum, and it is a 100 % synthetic textile fiber. It is made up of 85 % propylene, and considered to be harmful to the environment because it is non-degradable by soil, and causes harm to the soil. In addition, it cannot be decomposed by water. Below are some of the properties of PPF (Fibres, 2018): Table 1 illustrates the properties of PPF.

Table 1: Properties of PPF. (Zhang, P., & Li, Q. F. 2013).

Density (g/cm^3)	Linear density (dtex)	Fiber length (mm)	Tensile strength (MPa)	Elastic modulus (MPa)	Melting point (°C)
0.91	10–20	10–20	⩾450	⩾4100	160–170

dtex: unit of textile measurement stands for (decitex). Refers to mass in gram per 10,000 meters

PPF has a specific gravity of 0.90 - 0.91 gm/cm^3. Due to the low specific gravity, polypropylene provides the highest volume of fiber for a specific weight. Technically, it means that PPF give a good bulk, and cover while having light weight. Polypropylene is the lightest of all fibers, even lighter than water. It has a 20 % lighter weight than nylon.

Polypropylene has the lowest thermal conductivity compared to any natural, or synthetic fiber. It retains more heat for a considerably longer period, and has great insulation characteristics. Polypropylene has a maximum processing temperature of about 140 °C, with a melting temperature of 165 °C. When exposed to heat for long period, it degrades. At extremely cold temperature of about -55 °C it is flexible.

Polypropylene is described as being combustible, but not flammable. It has a trouble of ignition. However, with additives it becomes flammable. The water absorption of polypropylene is about 0.3 % when immersed in water for 24hrs. The dimensions of polypropylene are considered stable because it hardly absorbs moisture. It is characterized as an excellent resistant to majority of the acids with the exception of concentrated sulfuric acid. It has an excellent resistance to Alkalis except some oxidizing agents.

2.6 Effects of Polypropylene fibers (PPF) on Concrete

In general, the application of fibers can improve the mechanical properties of concrete significantly (Afroughsabet, Biolzi, & Ozbakkaloglu, 2016; Mohammadi, Singh, & Kaushik, 2008). The tensile stress within the micro structure of concrete enhance the widening of microcracks. As a result, fibers are used in concrete to compensate for the tensile weakness of the concrete(Ganesan & Shivananda, 2000).

The role of fibers generally depends on many factors such as: properties, volume, and type of fibers. PPF are commonly used due to its low cost, spectacular toughness, and improved resistance of shrinkage cracks. (Fallah, S., & Nematzadeh, M. 2017).

(Yew, Mahmud, Ang, & Yew, 2015) studied the effect of PPF in the mechanical properties of HSC, different proportions of monofilament PPF were used by volume of 0.25, 0.35, and 0.50 %, tensile strength was greatly improved by 8 – 27 % using PPF, and compressive strength results enhanced at days 1, 3, 7, and 28, where 0.25, and 0.50 % mixes had increased results by 6.4 and 10.9 % of compressive strength at day 28. Slump reduced by 95.8 % with 0.5 % of PPF. In addition, (Bošnjak, J., Ožbolt, J., & Hahn, R. 2013) clarified that using PPF in concrete demands higher quantity of SP in order to attain better workability.

(Afroughsabet & Ozbakkaloglu, 2015) investigated the mechanical, and durability properties of concrete containing PPF. A 12 mm length PPF at 0.15, 0.3, and 0.45 % were tested. They replaced 10 % of the cement content with SF. The results indicated improvement in mechanical properties of normal, and high strength concrete. Concluding that addition of SF improved mechanical properties of concrete, and addition of polypropylene gave positive results.

The effects of PPF on normal concrete and lightweight self-compacting concrete was analyzed by (Mazaheripour et al., 2011). The properties of the PPF used were: 12 mm length, 900 Kg/m^3 density, tensile strength of 450 MPa, and melting point of 160 °C. The percentages added were 0.1, 0.2 and 0.3 %. They compared the mechanical properties of lightweight self-compacting concrete with normal concrete. Flexural strength was increased by 4.9, 8.6, 10.7 %, respectively. Splitting tensile strength was increased by 14.0 % at 0.3 % of PPF.

The study of (Fallah & Nematzadeh, 2017) examined the mechanical properties of HSC containing PPF at different percentages: 0.1, 0.2, 0.3, 0.4, and 0.5 %, and then analyzed the effects of SF and nano-silica in HSC. They have found that using SF and PPF were reduced the workability. Splitting tensile strength was increased by 9.06, 12.81 and 10.77 % for PPF volume of 0.1, 0.2 and 0.3 %, respectively, but decreased at 0.4 and 0.5 %.

The effects of PPF concrete were studied by (Kakooei et al., 2012). Different fiber amount ranging from 0 to 2 Kg/m^3 were used. They concluded that specimen with 1.5 Kg/m^3 PPF showed improved results. Where the permeability was reduced, shrinkage and expansion as well. Concluding further that using coral aggregates in making concrete is not suitable for concrete structures in onshore atmosphere due to its low compressive strength and high electrical resistivity.

(Fallah, S., & Nematzadeh, M. 2017) studied the effect of PPF on the mechanical properties of HSC at different percentages: 0.15, 0.30, 0.45 %, and concluded that the addition of PPF into the mixture reduces the water absorption of concrete which enhances shrinkage crack resistance in concrete where the length of PPF utilized is 12 mm, and SF replaced 10 % of the cement content.

2.6.1 Compressive Strength

As one of the primary parameters in structural design, compressive strength is a fundamental mechanical property of quality concrete.

Compressive strength is identified by researchers to be the most imperative mechanical property of concrete. It is the maximum stress (load) that a concrete can endure. It presents the resistance of concrete to axial loading. Compressive strength is measured in pound per inch square (psi), or newton per millimeter square (MPa).

(Afroughsabet & Ozbakkaloglu, 2015) investigated the addition of fibers on concrete. The test results show that the increase in volume of PPF increased the compressive strength. They attributed the increase in compressive strength to the fibers ability to restrain from crack extension by reducing stress concentration to tip, and delay growth of cracks. A 5 % increase in compressive strength is observed with 0.15 % increase in PPF.

The experimental result of (Shihada, S. 2011) showed that compressive strength of the fibrous specimens was reduced compared to the control specimens at room temperature. Where PPF was used as percentages of 0.5 and 1.0 %. Also, the same trend of compressive strength results in research of (Bei-Xing et al., 2004), where monofilament and mesh types of PPF were used at volume of 0.91 Kg/m^3.

The result of (Fallah & Nematzadeh, 2017) shows that specimen with 0.1 % of PPF exhibited the maximum improvement in compressive strength with 11.5 % increase. While the other proportions of 0.2, 0.3, 0.4, 0.5 % had a gradual decrease till the lowest at 0.5 % of PPF. SP was used within the mixture. They stated that improvement in compressive strength stems from the fibers ability to delay, and restrain the propagation of cracks.

2.6.2 Flexural Strength

The flexural strength test can be applied on specimens after 28 days, according to the standard ASTM C293 (Concrete & Aggregates, 2014).

The study of (Afroughsabet & Ozbakkaloglu, 2015) shows slight increase in the flexural strength of concrete containing PPF compared to control concrete mixture. The observed increase range is between 5 % and 14 %. Also, flexural strength results in the study of (Mazaheripour et al., 2011) showed increase as PPF content increases. Where the flexural strength increased by 3.7, 7.6, and 8.7 % for PPF content of 0.1, 0.2, 0.3 %, respectively.

(Nili, M., & Afroughsabet, V. 2010) Studied the effect of PPF as an addition by volume on concrete of 0.2, 0.3, and 0.5 %.They concluded that the flexural strength of fibrous mixes increased compared by the control mix, and was greatly incremented with the replacement of SF. A 7.83 MPa as a maximum flexural strength value was recorded for the concrete which contained SF, and 0.5 % of PPF.

The study of (Mirmahaleh, M. M., Shoushtari, A. M., & Haghi, A. K. 2014) showed an improved results of flexural strength in the mixtures contains 2.25 % of PPF by 13 % higher than non fibrous mixtures.

2.6.3 Splitting Tensile Strength

Tensile strength can be considered as one of the basic mechanical properties of concrete. It is the highest amount of tensile stress (load) that a concrete can withstand before failure. Under tension, concrete is weak compared to compression. This is a result of the brittle nature of concrete. Figure 1 shows the relationship between tensile strength, and compressive strength.

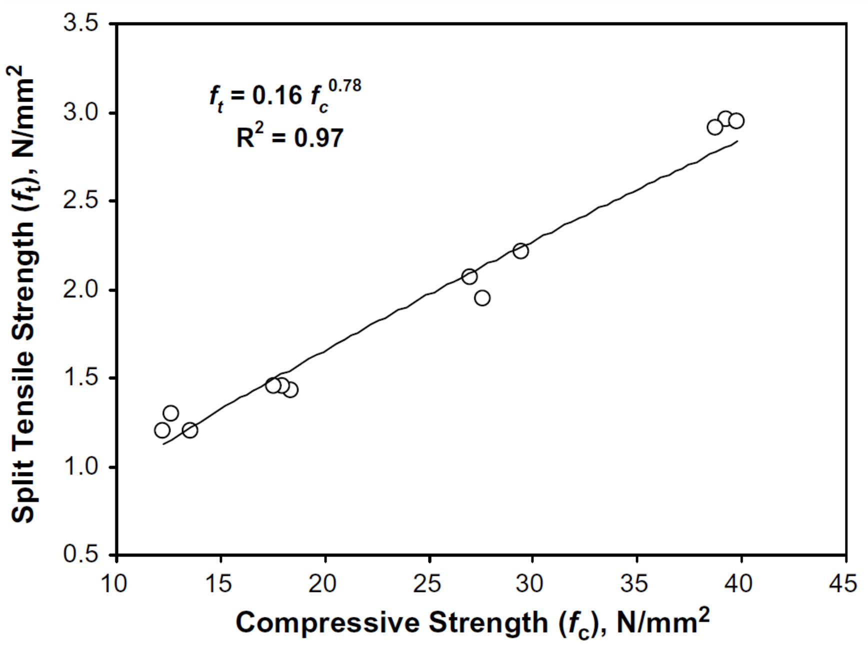

Figure 1: Relationship between tensile strength and compressive strength (Tang et al. 2008)

For splitting tensile strength test, according to the standard ASTM C496/C496M-11, cylindrical specimens are tested at 28 days.

The testing process of concrete is a delicate process. The following factors affect the tensile strength test of concrete:

- Dimension (length and diameter) of specimen: diameter of the specimen is known to affect the test result compared to the length of the specimen (Lamond & Pielert, 2006). Therefore designing the test specimens must be done carefully. The length standards of the specimen from ASTM must be abided.

- Loading rate: the load applied during the test must be relatively high in order to have an accurate result (Zhang, Lu, Chen, Teng, & Yu, 2016).

- Material component: components used in concrete affects the quality of concrete which affects the test result.

- Bearing strips: according to the ASTM C496/C496M–11, two plywood strips of 3.0 mm thick and 25 mm wide are used to confirm to the sample of the concrete and distribute the applied load accurately (Lamond & Pielert, 2006).

(Afroughsabet & Ozbakkaloglu, 2015) used straight PPF with volume fractions of 0.15, 0.30, 0.45 %, SP and SF were used for each mixture. The results of splitting tensile strength at 28 days showed a significant increase, by 13, 16, 20 %, respectively.

The test results of splitting tensile strength from (Mazaheripour et al., 2011) using PPF in the specimen prevent them from separation at the middle in normal concrete. When PPF is added to self-compacting concrete, the specimen became viscid. They concluded that adding PPF in self compacting concrete increases the tensile strength of concrete by about 14 %.

The splitting tensile strength results from (Fallah & Nematzadeh, 2017) mentioned that a 0.3 % increase of PPF ameliorated the splitting tensile strength by 10.77 % , moreover at 0.1 and 0.2 % the splitting tensile strength improved in plain concrete by 9.06, and 13.8 %, respectively. In addition to that, the Specimens containing 0.4, and 0.5 % PPF showed a tensile strength reduction of 2.73 and 3.96 %.

2.6.4 Water Absorption

Water absorption represents the porosity of concrete indirectly, where it is a crucial parameter reflecting the durability of concrete. Moreover, measuring water absorption capacity of concrete is an indicator of corrosion reinforcement, alkali-aggregate expansion, sulfate attack, freeze-thaw damage, chloride ingress, and most importantly concrete durability (Parrott, 1992).

It is an indicator of porosity, or pore volume of concrete after hardening. In accordance with ASTM C642−13, the water absorption of a concrete specimen can be tested after 28 days of curing.

According to (Castro, Bentz, & Weiss, 2011) the factors that can affect the water absorption capacity of concrete are as follows:

- Aggregate volume
- Water cement ratio
- Environmental conditions
- Humidity
- Primary component of concrete (cement, water, coarse and fine aggregate, and admixtures)
- Mixture percentage

According to the study of (Afroughsabet & Ozbakkaloglu, 2015) the water absorption of concrete containing PPF decreased as volume of PPF increased in the concrete. The results show that the mixture with 0.45 % PPF had the lowest water absorption. While PPF mixture of 0.15 % was the highest. While the average reduction in water absorption of PPF mixture was by 14 % compared to the control mix contained SF.

(Fallah, S., & Nematzadeh, M. 2017) Studied the effect of PPF addition on concrete. Where the water absorption test was performed and the results show that the lowest percentage of absorbing water was recorded at PPF content of 0.2 %. However, the highest was recorded at volume of 0.4 %. Where 0.1, 0.2, 0.3, 0.4, and 0.5 % PPF proportions were used. 0.1, 0.2, and 0.3 % were below the water absorption percentage of the control mixture.

2.6.5 Drying Shrinkage

Shrinkage stays a major concern in drying of concrete which is affected by many factors such as: heat of hydration, w/c ratio, size of aggregates, and moisture conditions. Drying shrinkage is basically the Evaporation of water content in concrete after setting and hardening. The cracks formulate over time as a result of plastic and autogenous shrinkage, drying shrinkage as well. (Zhang, P., & Li, Q. F. 2013). However, the use of fibers in concrete improves the post cracking behavior of concrete, hence the growing use of PPF (Agrawal & Shrivastva, 2017).

The study of (Saje, D., Bandelj, B., Šušteršič, J., Lopatič, J., & Saje, F. 2010) on using PPF in HPC stated that drying shrinkage of fibrous concrete reduced by two thirds than comparable mixes. The difference in shrinkage among the fibrous mixes itself was insignificant. 0.25, 0.50, 0.75 % of dried and moistened PPF were used.

The study of shrinkage in concrete was conducted by (Grzybowski & Shah, 1990) using steel and PPF. The test was conducted at 0.1 to 1.5 %, the concrete was preserved under special conditions for 2 to 4hrs and dried for 28 days at 40 % relative humidity and 20 °C. A minor decrease in shrinkage of concrete was observed for the test specimen.

(Zhang, P., & Li, Q. F. 2013) added PPF of amount 0.06, 0.08, 0.10, 0.12 %, SF, water reducers and fly ash on concrete. The drying shrinkage of fly ash PPF mixes had very low drying shrinkage. Where the maximum reduction in drying shrinkag observed was 24 % from maximum drying shrinkage, changing in microstrains from 579 to 441, fiber volume of 0.12 %.

2.6.6 Schmidt Hammer and Pundit (UPV)

The Schmidt hammer was first introduced for non-destructive testing of concrete by (Schmidt, 1951), and was later used for rock strength estimation. (Cargill & Shakoor, 1990).

Non-destructive testing is of great technical importance in concrete. The use has grown over the years especially in quality assessment of concrete. An advantage of non-destructive testing in concrete is that it avoids damaging structural component. Additionally, they are quick and simple. Schmidt rebound test has proven to be useful in testing the strength of concrete (Shariati, Ramli-Sulong, KH, Shafigh, & Sinaei, 2011).

The use of Schmidt hammer provides an inexpensive and quick test for the surface hardness of concrete. This test minimizes time and expenses used for collecting testing samples. For accuracy of experimental results, the test standard for Schmidt hammer is ASTM C805.

The pundit test is another non-destructive testing method. It is performed using transmission of ultrasonic pulse. The ultrasonic pulse is used to determine concrete characteristics such as quality of concrete, depth of cracks and compressive strength.

The application process of the pundit test is as follows: low frequency pulse is generated. The time taken for them to go through the specimen on transducer to the other is measured. (Moon, Sim, & Oh, 2005).

2.6.7 Heat Resistance

High strength concrete are said to have a high propensity to display spalling in concrete due to heat when it is exposed to high temperatures such as fire (Maluk, Bisby, & Terrasi, 2017). This may debilitate concrete microstructure causing deterioration of concrete.

Spalling mainly acts upon multiple factors such as, structural type, permeability of concrete, content of moisture, and the interdependence relations among these factors with the spalling phenomena.(Khoury, 2000). According to the study of (Drzymała et al., 2017), adding PPF to concrete is one of the most technological and economical method of preventing spalling.

To test the ability of concretes having PPF to resist heating and induced-spalling, (Maluk et al., 2017) used a different types, and dosages of PPF to analyze heat resistance. Monofilament PPF, multifilament PPF, and fabrillated PPF were used with diameters of 6 mm, 12 mm, and 20 mm respictively. The results showed obvious influence of the type, length, and dosage of fibers used in the mixtures, where the monofilament type with length of 6 mm, dosage of 0.68, and 1.20 Kg/m^2 showed no spalling in the specimen during the 60 min duration of the test. While the other mixture had worse results against spalling, the fabrillated PPF of 20 mm in particular with dosage of 1.20 and 2.00 Kg/m^2 which showed spalling in about 7 min of the test duration.

Theoretically, to illustrate the fire induced spalling phenomena within the concrete ; simply the reason is by the pore pressure build up and the cracking mechanism. Where dense concrete starts to spall when evaporation takes place, consiquently result from the pore pressure development while the permeability and brittility of concrete prevent the dissipation of pores, the tensile strength of concrete microstructure is lower than pore pressure. (Bazant 1997; Kodur. 2003). Illustraded by the study of (Khaliq, W., & Kodur, V. 2017) in using PPF of amount 1.0 Kg/m^3 with SF and water reducers. The structural and thermal response were studied at temperatures up to 600 °C. They founded that PPF mixes did not abrupted as non-fibrous mixtures of NSC and HSC without fibers, where NSC failed in 180 minutes of test duration, HSC failed after excessive contraction in 75 minutes. However PPF mixes last for about 221 minutes .

Denser HSC with higher impermeability preclude dispersal of pore pressure which is resultant of evaporated water drops into the heated concrete. When this pore pressure surpass the tensile strength of concrete; spalling occurs.(Kodur, V. K. R., and Dwaikat, M. B. 2008).

2.6.8 Water Penetration

The volume of pores concrete microstrucure is characterized by porosity, and the connection between pores is characterized by permeability. Permeability is said to be one of the most important parameters of concrete durability, and there is an effective relationship between the compressive strength and permeability, much more specs are common related to the permeability as well in concrete field. Denser concretes have better permeability; having better porosity, and permeability preventing aggressive minerals penetrate easily into the concrete. (Bošnjak, J., Ožbolt, J., & Hahn, R. 2013).

As long as the permeability has conducted to be a parameter for durability, (Zhang, P., & Li, Q. F. 2013), studied the effect of adding PPF on conrete with different percentages: 0.06 %, 0.08 %, 0.1%, and 0.12 %, containing SF and fly ash. Their results showed that PPF with SF and fly ash increased the impermeability significantly.

The reduction of permeability in fibrous mix observed was 37.5 % compared to the control mix.

(Zhang, Peng, and Qing-fu Li. 2013) studied the influence of adding PPF on permeability. Fiber length of 10 to 20 mm, and fiber volume fraction of 0.06, 0.08, 0.10, 0.12 %, concluding that PPF has a great effect on water penetration in concrete, where mixtures having PPF, SF and fly ash resulted in reduction of permeability by 20 %; from 8.7 mm depth of water to 7.0 mm. In addition, the presence of PPF improved the microstructure to resist cracking.

Chapter 3

RESEARCH METHODOLOGY

3.1 Introduction

Based on the thesis objectives, PPF were added at different percentages (0, 0.25, 0.50, 0.75, and 1.00 %) to form NSC and HSC mixes. A w/c ratio of 0.5 was used for NSC, and 0.4 for HSC. The objective was to investigate the effects of PPF on the mechanical properties of concrete. To achieve that, the following experiments were performed:

1. Slump and VeBe time test
2. Compressive strength test on 7 and 28 days
3. Flexural strength test on 7 and 28 days
4. Splitting tensile strength test on 7 and 28 days
5. Flexural toughness (deformation)
6. Drying Shrinkage test
7. Heat Degradation test (100 °C, 200 °C)
8. Schmidt hammer test
9. Ultrasonic Pulse Velocity (UPV) test (Pundit)
10. Water absorption test
11. Water permeability test

In this chapter, all materials used in the experiments mentioned above were described. Also, the ASTM standards or any related standards used in the experiments were explained. The procedures for the tests, machines, and tools were also explained.

3.2 Materials used

The following sections present the materials used for the experiments in this thesis.

3.2.1 Portland Cement

In this research the cement used was Blast-furnace Slag Cement CEM II/B-S 42.5 N in conformity with ASTM C595-17. This type of cement is moderately modified to resist sulfate attack and exhibit normal hydration rate. The chemical and physical properties of cement which used in this research are shown in Tables 2 and 3.

Table 2: Chemical properties of cement

Chemical Properties	Analyzed results	Method
Insoluble Residue (%)	0.09	EN 196-2
Loss Ignition (%)	1.18	
SO_3 (%)	2.72	
SiO_2 (%)	18.65	
CaO (%)	60.24	
CaO free (%)	0.98	
MgO (%)	2.32	
Al_2O_3 (%)	2.05	
Fe_2O_3 (%)	2.5	
Cl (%)	0.0	EN 196-21

Table 3: Physical properties of cement

Physical Properties		Analyzed results	Method
Specific Gravity (g/cm^3)		3.15	EN 196-6
Fineness (cm^2/gm)		3620	
90 µm Sieve Residue (%)		0.14	
45 µm Sieve Residue (%)		3.98	
w/c Ratio		29.0	EN 196-3
Initial Setting Time (minute)		175	
Strength Pressure (MPa)	2 days	20.32	EN 196-1
	7 days	33.80	
	28 days	52.77	

3.2.2 Silica Fume (SF)

SF is the result of producing ferrosilicon alloys. It is basically made up of amorphous (non-crystalline) silicon dioxide (SiO_2) in order to enhance the properties of concrete. SF particles are very small, around 1/100th of cement particle size which is due to its high silica content and extreme fineness. In addition, SF is a very effective pozzolanic material. It was added as supplementary material where 5 % of cement content for SF was used for NSC, while 10 % for HSC. The particle size distribution of SF is shown in Figure 2. And Table 4 shows the chemical and physical properties of SF.

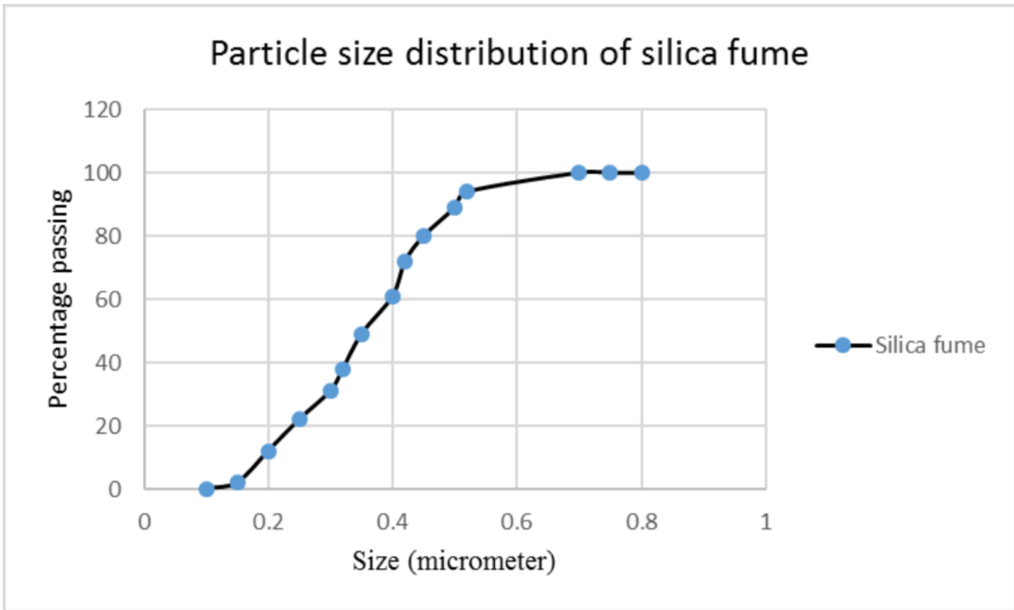

Figure 2: Particle size distribution of SF

Table 4: Chemical and physical properties of SF

Oxide	**Percent (%)**
SiO_2	82.2
Al_2O_3	0.50
Fe_2O_3	0.42
CaO	1.55
MgO	0.00
SO_3	3.03
LOI	5.66
Specific surface	29,000 (m^2/kg)
Relative density	2.20

3.2.3 Fine Aggregate

Fine aggregate that is mechanically crushed with maximum size diameter of 5 mm is called sand. Fine aggregates were used in the experiments of this research. ASTM C136M-14 sieve analysis was done to find the gradation of fine aggregates. Figure 3 illustrates the sieve analysis for fine aggregate.

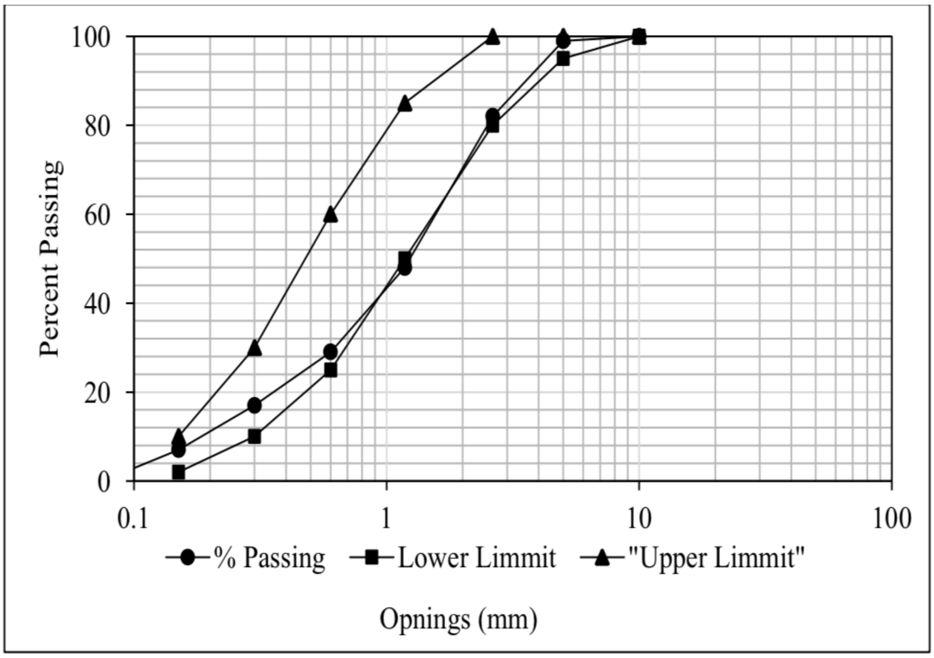

Figure 3: Sieve analysis for fine aggregates

3.2.4 Coarse Aggregate

Crushed coarse aggregate of size 10 mm, and 20 mm are used in this study. The gradation of coarse aggregate was discovered according to ASTM C136-14 sieve analysis was attained for all sizes according to ASTM C33M-16. Figure 4 shows the sieve analysis for coarse aggregate.

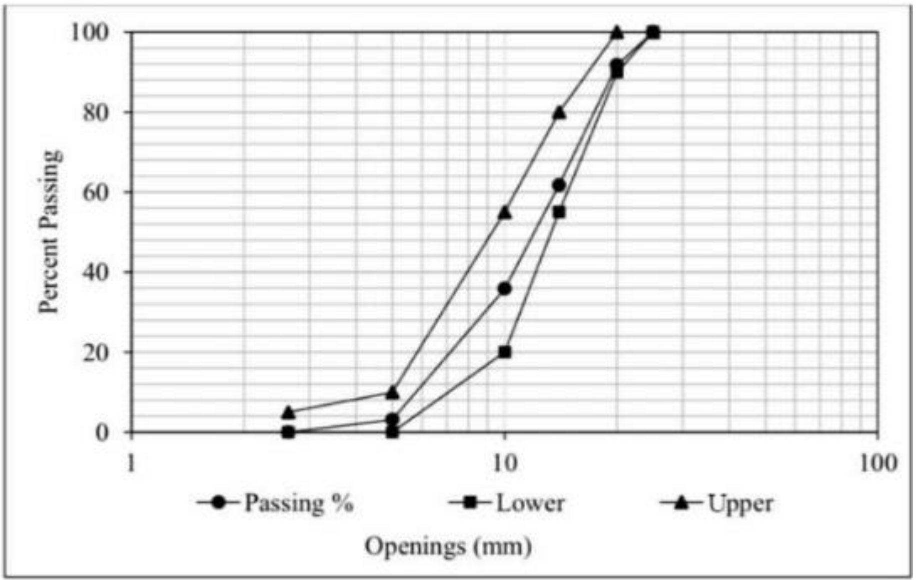

Figure 4: Sieve analysis for coarse aggregates

3.2.5 Mixing Water

Drinkable tap water was used during the concrete mixing and curing process. Where it is free from oils, alkalis, acids and other organic materials.

3.2.6 Superplasticizer (SP)

The high range water reducing agent of Type F Poly-carboxylic, referred to as (Master GLENIUM 27) was utilized in our experiment. Apart from improving the workability of the concrete, it also provides high strength and concrete durability. For the mixture, 1 % of binder for SP was added for NS and 2 % was added for HS concrete, where the w/b ratio was 0.48 for NSC, and 0.38 for HSC.

3.2.7 Polypropylene fibers (PPF)

The PPF (dry) used in the experiment had a length of about 18 mm. The water absorption was 0.019 % with a tensile strength of 32 MPa. The tensile modulus was at 115.8 MPa and a density of 900 Kg/m^3. Figure 5 shows the PPF used in this research.

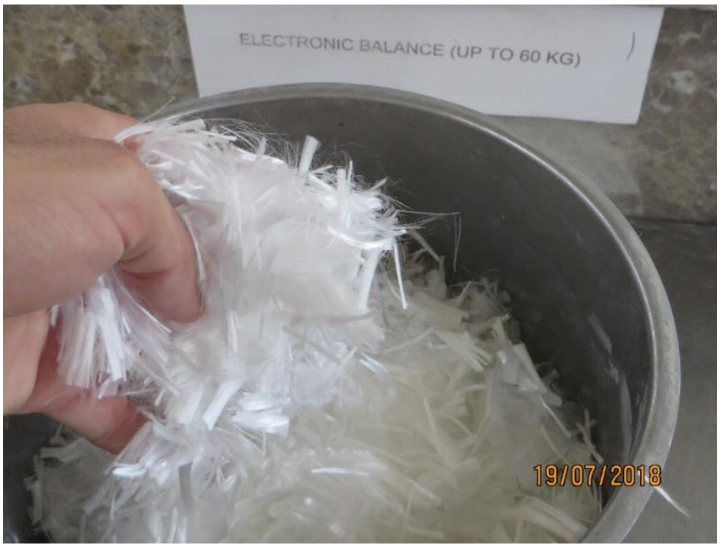

Figure 5: PPF used in the experiments

3.3 Mix Design

Mix design refers to the calculation of ratios and quantities of the main materials of concrete component required to characterize specific properties such as strength, workability, formability, durability, and permeability for the purpose of achieving a proper concrete mix. According to BRE method (Teychenné, D. C., Franklin, R. E., Erntroy, H. C., & Marsh, B. K.1975) for designing mixes, Tables 5 and 6 show the mix design for NSC and HSC.

Table 5: Proportions and Quantities of mixing materials for 0.5 w/c ratio for NSC mixes

Type	PPF %	C Kg/m^3	PPF Kg/m^3	W Kg/m^3	FA Kg/m^3	CA Kg/m^3	SF Kg/m^3	SP Kg/m^3
Control	0	450	0	225	475	1220	22.50	4.72
PPF-NSC (0.25)	0.25	450	2.27	225	475	1220	22.50	4.72
PPF-NSC (0.50)	0.50	450	4.55	225	475	1220	22.50	4.72
PPF-NSC (0.75)	0.75	450	6.82	225	475	1220	22.50	4.72
PPF-NSC (1.00)	1.00	450	9.10	225	475	1220	22.50	4.72

PPF: Polypropylene fiber; C: Cement; W: Water; FA: Fine aggregate; CA: Coarse aggregate SF: Silica fume; SP: Superplasticizer

Table 6: Proportions and Quantities of mixing materials for 0.4 w/c ratio for HSC mixes

Type	PPF %	C Kg/m^3	PPF Kg/m^3	W Kg/m^3	FA Kg/m^3	CA Kg/m^3	SF Kg/m^3	SP Kg/m^3
Control	0	565	0	225	510	1080	28.25	11.86
PPF-HSC (0.25)	0.25	565	2.27	225	510	1080	28.25	11.86
PPF-HSC (0.50)	0.50	565	4.55	225	510	1080	28.25	11.86
PPF-HSC (0.75)	0.75	565	6.82	225	510	1080	28.25	11.86
PPF-HSC (1.00)	1.00	565	9.10	225	510	1080	28.25	11.86

PPF: Polypropylene fiber; C: Cement; W: Water; FA: Fine aggregate; CA: Coarse aggregate SF: Silica fume SP: Superplasticizer

3.4 Concrete Mixing

In the concrete preparation, the batching, mixing process, and weighing was performed using the ASTM C192/C192M-16a standard. In each batch, using the mixing machine of volume 0.25 m^3, aggregates, cement, SP, and SF were mixed with water for about 3 minutes. Then, the PPF were proportionally added and mixed for about 4 minutes. In this phase, the concrete workability tests (slump, and VeBe time tests) were performed on the fresh concrete, after that the concrete was put back to remix for about 40 more sec.

3.5 Fresh Concrete Tests

3.5.1 Workability (Slump, and VeBe) Tests

Slump and VeBe tests were performed to measure the workability of concrete. They indicate the segregation resistance, filling ability, and passing capacity of fresh concrete. Slump test was performed according to ASTM C143/C143M-15a as shown in Figure 6. VeBe test was performed according to ASTM C1170/1170M-14 as shown in Figure 7.

Figure 6: Slump test

Figure 7: VeBe time test

3.6 Casting and Curing of Specimens

Four shapes and sizes of the specimen were produced for this experiment to examine the properties of concrete with PPF. Cylindrical specimens of size 100 mm diameter × 200 mm long, cubic specimens of size 150 × 150 × 150 mm, 100 × 100 × 100 mm, and beams of size 100 × 100 × 500 mm.

Before using the steel cylindrical molds, and the plastic beams, and cubes, they were cleaned, then polished with thin layer of oil to enable smooth demolding of specimens.

After completing the slump test, the concrete was mixed for about 40 – 60 seconds, and was immediately molded and compacted by steel tamping rod, then compacted by the vibration table for about 30 seconds to afford better formability, it was then moved to the casting room for 24 hrs. The specimen was then demolded and put in the water tank (see Figure 8).

After the demolding, the specimens were moved to the curing water tank of normal temperature of about 23 ± 2 °C for 28 days. After that, it was then removed for testing.

Figure 8: Curing specimens in water tank

3.7 Hardened Concrete Tests

3.7.1 Compressive Strength Test

To investigate the effect of PPF on NSC and HSC, the compressive strength test was performed on cubic specimens of size 150 × 150 × 150 mm specimen after 7 days and 28 days according to ASTM 32 C39/C39M – 17 Standard. The experiment was performed for both NSC and HSC at different percentage of PPF. Three cubes were used for each proportion of concretes. And the loading rate was (0.4 MPa/s). Figure 9 shows a specimen under failure in the compressive strength testing machine.

Figure 9: Specimen failure in compressive strength test

3.7.2 Flexural Strength Test

The flexural strength test in this study was performed at days 7, and 28 according to (ASTM C 26 1609, 2010) on beams of size 100 × 100 × 500 mm. At day 7 the load subjected on the beams without shock, and increased constantly until the first crack (failure). Figure 10 shows the flexural strength test machine used.

Figure 10: Flexural strength test

The flexural strength and toughness tests were performed for 28 day using the same specimens' dimensions where the sensors were used to measure the deformation, and the loading rate remained very low while the load is increasing uniformly, and the values were taken as the peak load subjected on specimen before failure.

3.7.3 Splitting Strength Test

Three cylindrical specimens of size 100 mm × 200 mm were used to test the effect of PPF on the tensile strength of NSC, and HSC at 7 and 28 days. The procedure used was done according to ASTM C496/C496M – 11. Figure 11 shows the splitting tensile strength specimen, and its failure under stress.

Figure 11: Specimen failure under stress (splitting tensile)

3.7.4 Drying Shrinkage Test

The aim of the drying shrinkage test is to determine the change in concrete length as a result of change in moisture content. According to the ASTM C596, the test was performed.

The apparatus used in this test is shown in Figure 12. The procedure is as follows: after removing the specimens from water, they were left out to dry their surfaces in order to stick the pins on them using Super Glue. The apparatus was adjusted on zero as a reference, after that the procedure of measuring the change in length between the pins of the specimens was done by using the apparatus as shown in Figure 13, the specimens were left in a normal conditions of room temperature, the length of the specimen was measured everyday till the distance (values) remained stable (no more shrinking was observed). At last, the final length was recorded which called "The Dry Measurement". Drying shrinkage is calculated as the difference between "Original wet length" and "Dry measurement" multiplied by 100.

Figure 12: Drying shrinkage test apparatus

Figure 13: Measuring the displacement between the pins using the apparatus

3.7.5 Heat Degradation Test (100 °C and 200 °C)

Investigating the change in compressive strength, splitting strength, ultrasonic pulse velocity (concrete quality), and crack development when the specimens are exposed to heat at (100 °C and 200 °C). The heat degradation test was performed on cubic specimens of size 100 × 100 × 100 mm.

After curing process of 28 days, the specimens were placed into the electric oven at 100 °C for 4hrs. Then, the specimens were cooled down for 2hrs. There is no standard for measuring the effects of heat on specimen. However, (Albano, Camacho, Hernandez, Matheus, & Gutierrez, 2009) specified that the specimen should be kept outside for about 2hrs, then the UPV, crack development, compressive strength, and splitting strength were measured, and compared to the values before heating.

After finishing the 100 °C tests; the specimens were also put in the electric oven of 200 °C for about 4hrs. Then, the same tests were performed after cooling the specimens down for 3hrs, in order to distinguish the effect of heat exposure on concrete at various temperatures.

3.7.5.1 Cracks Development on Specimen Surfaces after Heat Exposure

The stereo microscope was used in the experiments to investigate the effect of adding PPF in both concrete mixtures on the cracking process at room temperature and after heating up to 200 °C. Figure 14 shows the microscope which was used in this experiment.

Figure 14: Stereo Microscope

3.7.6 Schmidt Hammer Test

The Schmidt hammer test is used for testing the hardness of concrete. The standard used in this experiment for testing the compressive of the specimen is ASTM C805/C805M. After 28 days, the cubic sample of 150 × 150 × 150 mm was used for the experiment. Firstly, an average of ten results was calculated after subjecting the hammer to the cubes surface. The numbers with six units above the average amount are eliminated. Then the average of the remaining was calculated and called the rebound number. Figure 15 shows the Schmidt hammer used in the experiment.

Figure 15: Schmidt hammer

3.7.7 Pundit (UPV) Test.

The pundit test is performed to predict the uniformity and the quality of concrete without destroying the specimen. The test measures the time ultrasonic wave's passes through the sample between opposite surface of the concrete. Using the ASTM C 597-02, the test is performed at 28 days. The pulse velocity of the specimen is measured using equation (1)

$$\text{Pulse velocity}\left(\frac{\text{km}}{\text{s}}\right) = \frac{\text{Width of concrete (km)}}{\text{Time taken by pulse to pass though(s)}} \qquad (1)$$

3.7.8 Water Absorption Test

The test was performed on cubic specimens of size 150 × 150 × 150 mm to determine the amount of water absorbed when a specimen is immersed in water for 28 days.

These factors are affected by the type of fibers used, exposure length, temperature and admixtures. The results show the performance of the materials in water and humid environment. Using the ASTM D570 standard, the water absorption test was performed as follows:

The specimens are weighted before being inserted into the oven at a temperature of 100 °C for 72hrs, then immersed in water for 24hrs. After that, it was removed and patted with a dry cloth and weighed, this is called “wet weight”. Water absorption is represented as increase weight percentage.

$$Water\ absoprtion = ((wet\ weight - dry\ weight)/dry\ weight) \times 100 \quad (2)$$

3.7.9 Water Penetration Test

Water penetration test is used to evaluate the permeability of concrete as an indicator of its durability under aggressive conditions. Using the cubic specimens of size 150 × 150 × 150 mm, the test was performed at 28 days of curing by following the ASTM E331 standard. Figure 16 shows the device used for the water penetration test.

After the specimen was fixed by the screws in its position. A water pressure of 5 Kg/cm^2 (500 kPa) was applied on the specimen for 72hrs. This procedure was performed for three cubes of each mix. The pressure regulator was adjusted where there was no possibility of air leaking. The specimens’ surfaces were dried by a cloth then split in the middle, and the maximum penetration depth was recorded. This should be measured immediately after removing the specimens out of the device.

Figure 16: Water penetration test apparatus

Chapter 4

RESULTS AND DISCUSSION

4.1 Introduction

The effects of PPF on the mechanical properties of NSC and HSC were investigated using different percentages. The specimens containing PPF were compared to the control specimen. The tests were performed on both fresh and hardened concrete specimens. The fresh concrete experiment was on workability using Slump, and VeBe tests. The hardened concrete tests performed are: Compressive strength test on 7 and 28 days, Splitting tensile strength test at days 7 and 28, Flexural tensile strength at day 7, flexural toughness test at day 28, Drying Shrinkage test, Heat Degradation test (100 °C, 200 °C), Schmidt hammer test, Ultrasonic Pulse Velocity test (Pundit), Water absorption test, and Water permeability test.

To analyze the results; graphs, and figures are used to compare the results to present a meaningful, and descriptive conclusion to the experiments performed.

4.2 Effects of Polypropylene fibers (PPF) on Concrete Workability

To test the workability of concrete, the slump and VeBe tests were performed for different PPF percentages (0.00, 0.25, 0.5, 0.75 and 1.00 %) with w/c ratio of 0.5 for NSC and 0.4 for HSC. Tables 7 and 8 present the results of Slump test and VeBe test for the PPF-NSC and HSC, respectively. Figures 17 and 18 illustrate the results of Slump test for PPF-NSC and HSC, while Figures 19 and 20 show the VeBe test results for PPF-NSC and HSC, respectively.

Table 7: Slump test and VeBe test results for NSC

Mixture type	Slump test (mm)	Change in Slump (%)	VeBe test (seconds)
Control	180.00	-	4.00
PPF-NSC (0.25)	115.00	36.11	6.50
PPF-NSC (0.50)	100.00	44.44	9.00
PPF-NSC (0.75)	80.00	55.56	10.00
PPF-NSC (1.00)	50.00	72.22	15.00

Table 8: Slump test and VeBe test results for HSC

Mixture type	Slump test (mm)	Change in Slump (%)	VeBe test (seconds)
Control	185.00	-	3.00
PPF-HSC (0.25)	130.00	29.70	7.00
PPF-HSC (0.50)	115.00	37.85	9.00
PPF-HSC (0.75)	85.00	54.05	12.00
PPF-HSC (1.00)	60.00	67.57	15.00

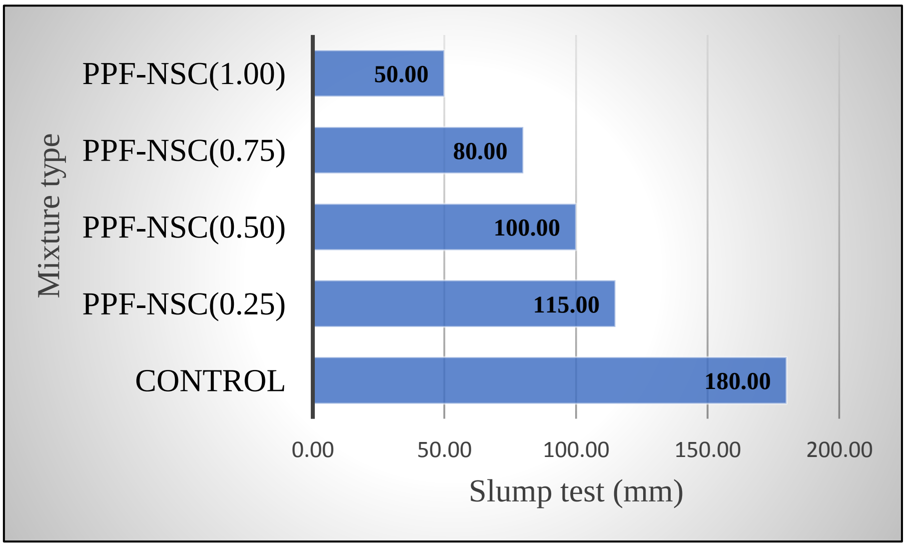

Figure 17: Slump Test Results for NSC

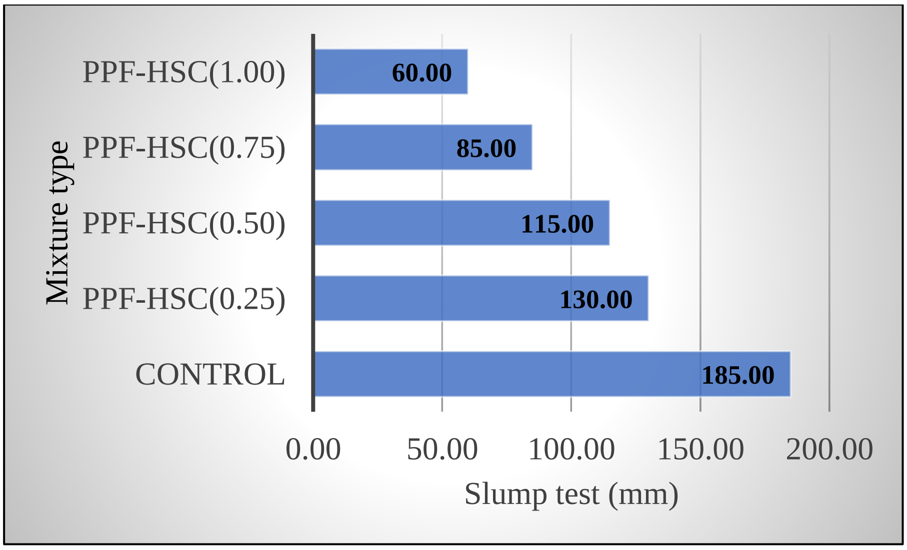

Figure 18: Slump Test Results for HSC

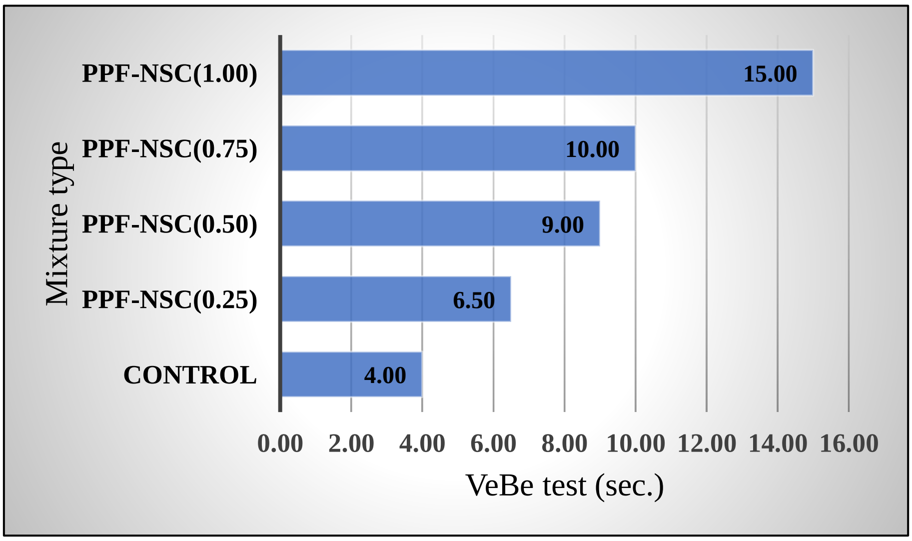

Figure 19: VeBe Test Results for NSC

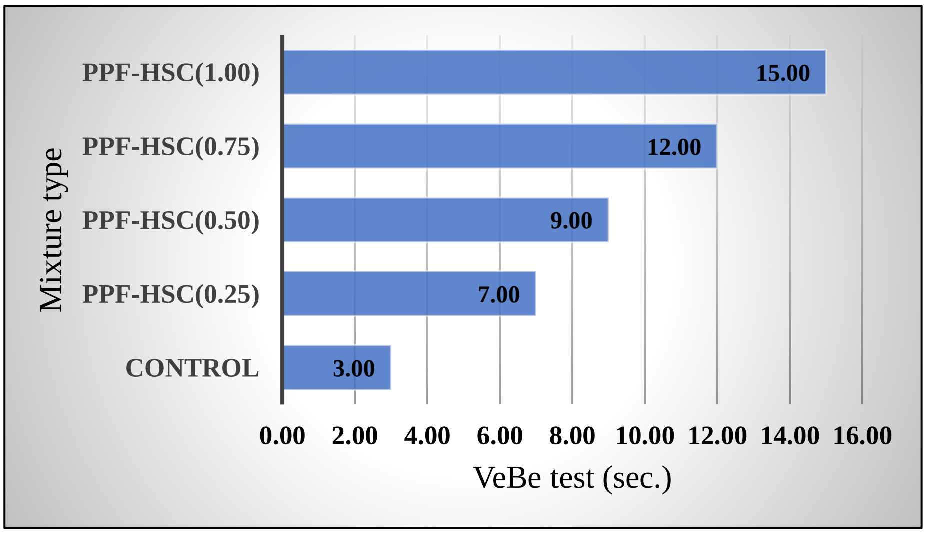

Figure 20: VeBe Test Results for HSC

As can be seen from Table 7 and Figure 17, the slump of the PPF-NSC specimen decreases as the percentage of PPF increases. Similarly, the slump of PPF-HSC decreases as the percentage of PPF increases in HSC as illustrated in Table 8 and Figure 18. However, the percentage change in slump is higher in PPF-NSC compared to PPF-HSC. The workability for PPF-HSC (1.00) is higher than the workability for PPF-NSC (1.00). This can be attributed to the higher content of SP in PPF-HSC. Furthermore, the VeBe test results illustrated in Figure 19 and 20 increase in time as the PPF percentage increase for both PPF-NSC and PPF-HSC.

In general, the reaction between PPF and concrete mixture considerably reduces the workability of concrete; the entrapped air that increased due to the presence of PPF, results in an increase of the air content. That was attributed to specific area of PPF where it needs to be coated by the mortar; high friction energy was presented resulted in reduction of concrete workability. As can be seen in the results shown above that slump was high, and then considerably plunged while PPF was added. 36 % reduction in slump in PPF-NSC with 0.25 % volume of PPF compared to control mix. And about

30 % reduction in slump in PPF-HSC (0.25) compared to control mix. PPF-HSC and PPF-NSC had a reduction in slump of about 70 % as an average when 1.00 % of PPF was added. This finding is consistent with the study of Khoury (2000). Stating that workability of concrete decreases as PPF is added to the mixture. Similarly, (Yew, Mahmud, Ang, & Yew, 2015) stated that, addition of PPF produced a 95.8 % reduction in slump. However, the use of SP is known to improve concrete workability, hence having a better workability in PPF-HSC compared to PPF-NSC.

4.2.1 Relationship between Slump and VeBe Test

Relationship between Slump and VeBe tests is further investigated using regression analysis. Table 9 and Figure 21 show the correlation between slump test and VeBe test for NSC. Table 10 and Figure 22 show the relationship between slump test and VeBe test for HSC from the experiment results.

Table 9: Slump test and VeBe test Relationship equations for NSC

	Type of Regression	Equation	R-square
NSC	Exponential	$y = 23.387e^{-0.01x}$	0.97422
	Linear	$y = -0.0803x + 17.334$	0.88916
	Logarithmic	$y = -8.658\ln(x) + 48.443$	0.97611
	Polynomial	$y = 0.0006x^2 - 0.2253x + 24.614$	0.97422
	Power	$y = 917.01x^{-1.035}$	0.96967

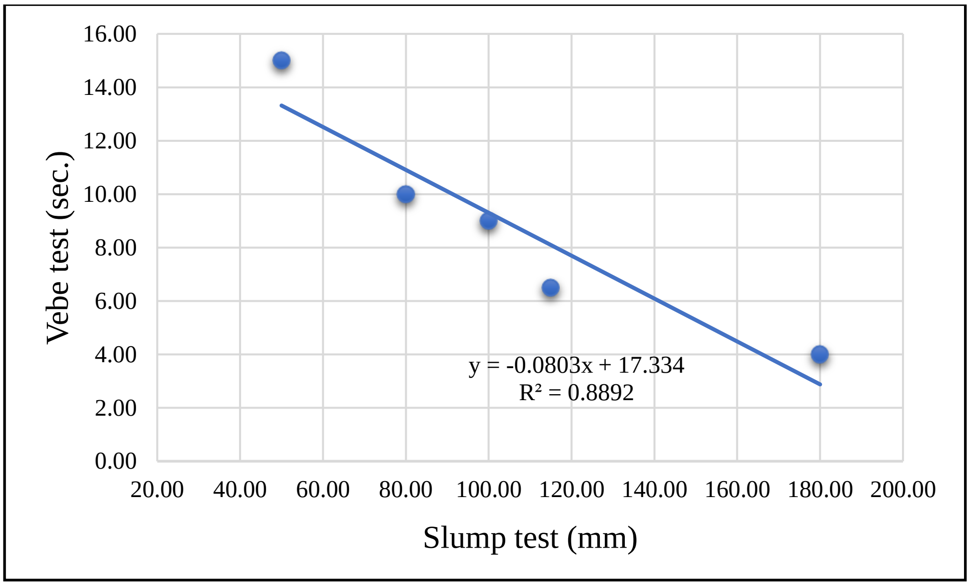

Figure 21: Slump test and VeBe test Linear Relationship for NSC

Table 10: Slump test and VeBe test Relationship for HSC

	Type of Regression	Equation	R-square
HSC	Exponential	$y = 29.364e^{-0.011x}$	0.7562
	Linear	$y = -0.0817x + 19.244$	0.83582
	Logarithmic	$y = -9.133\ln(x) + 52.421$	0.84192
	Polynomial	$y = 0.0001x^2 - 0.1156x + 21.023$	0.83851
	Power	$y = 1716.4x^{-1.133}$	0.70731

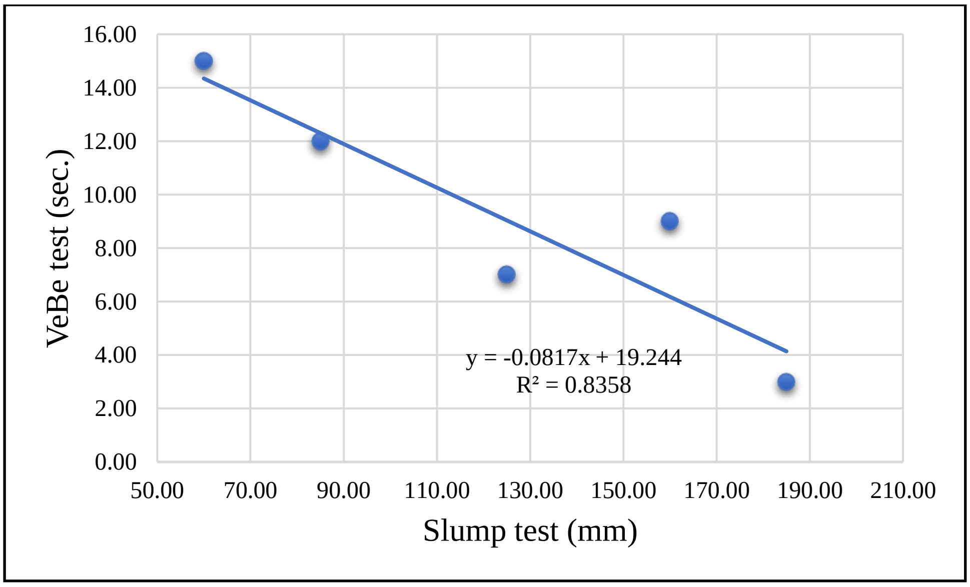

Figure 22: Slump test and VeBe test Linear Relationship for HSC

As can be seen from Table 9 and Figure 21, there is strong relationship between Slump and VeBe test results for PPF-NSC specimens. The best relationship is represented by logarithmic regression with a correlation of 97.61 %. Similarly, there is strong relationship between the results of PPF-HSC slump test and VeBe test. The highest relationship presented by logarithmic regression with score of 84.19 %. The experiments show a strong relationship for samples of NSC.

We go further by comparing the slump and VeBe test results for PPF-NSC and PPF-HSC simultaneously as illustrated in Figure 23 and 24. The slump results for PPF-HSC are higher compared to the slump results for PPF-NSC. This is a result of the larger amount of SP used in the HSC. Similarly, the VeBe time test results for PPF-HSC is higher than PPF-NSC except for the control specimen. As a conclusion the addition of PPF in concrete decreases the workability of NSC more than HSC.

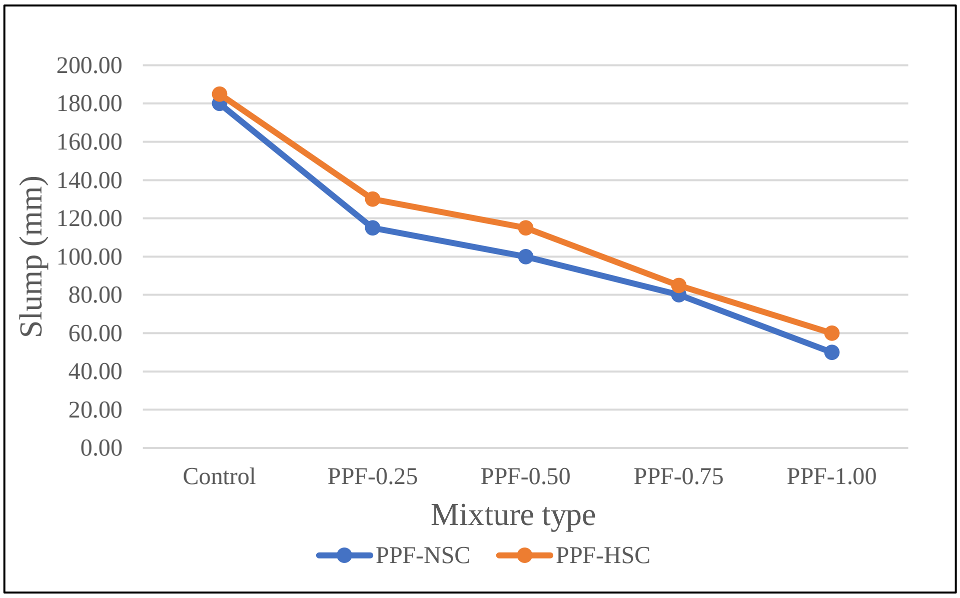

Figure 23: Slump test comparison for NSC and HSC

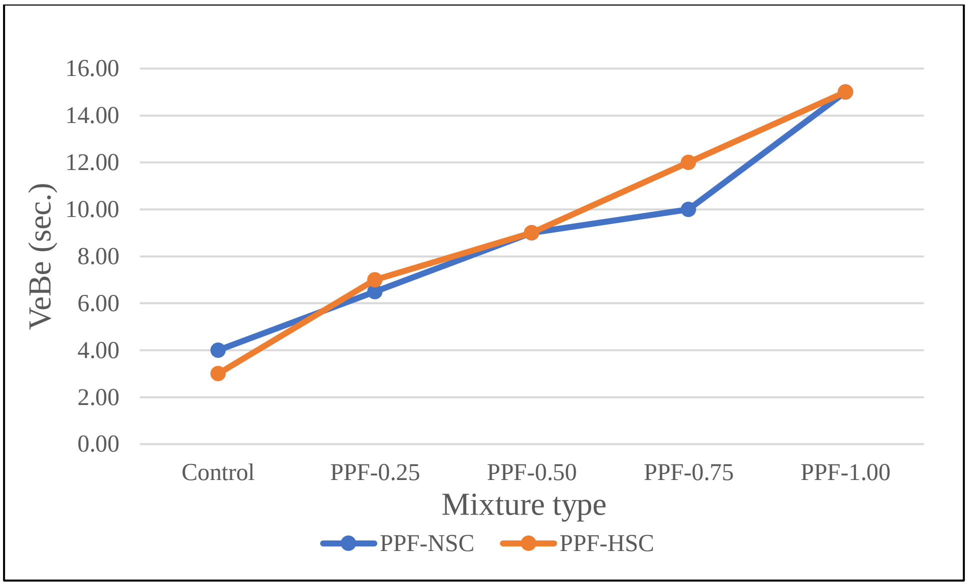

Figure 24: VeBe test comparison for NSC and HSC

4.3 Effects of Polypropylene fibers (PPF) on Compressive Strength

Using the cubic specimens of size 150 × 150 × 150 mm, three specimens for compressive strength were tested. The test was performed for both NSC and HSC specimens. Table 11 and 12 shows the results for PPF-NSC after 7 and 28 days. Figure 25 shows the comparison for both results.

Table 13 and 14 illustrates the compressive strength results of PPF HSC specimens for days 7 and 28. Similarly, Figures 25 shows the comparison of compressive strength for days 7 and 28 PPF-HSC.

Table 11: Results of Compressive strength test on NSC for 7 days

Mixture type	Maximum load (KN)	Compressive Strength (MPa)	Change of Compressive Strength (%)
Control	950.00	42.25	-
PPF-NSC (0.25)	906.00	40.30	- 4.62
PPF-NSC (0.50)	843.00	37.50	- 11.24
PPF-NSC (0.75)	742.00	33.00	- 21.89
PPF-NSC (1.00)	877.00	39.00	- 7.69

Table 12: Results Compressive strength test on NSC for 28 days

Mixture type	Maximum Load (KN)	Compressive Strength (MPa)	Change in Density (Kg/m^3)	Change of Compressive Strength (%)
Control	1236.00	54.90	2351.00	-
PPF-NSC (0.25)	1150.00	51.10	2327.00	-6.92
PPF-NSC (0.50)	1075.00	47.70	2324.00	-13.11
PPF-NSC (0.75)	876.00	41.10	2219.00	-25.14
PPF-NSC (1.00)	1026.00	45.50	2310.00	-17.12

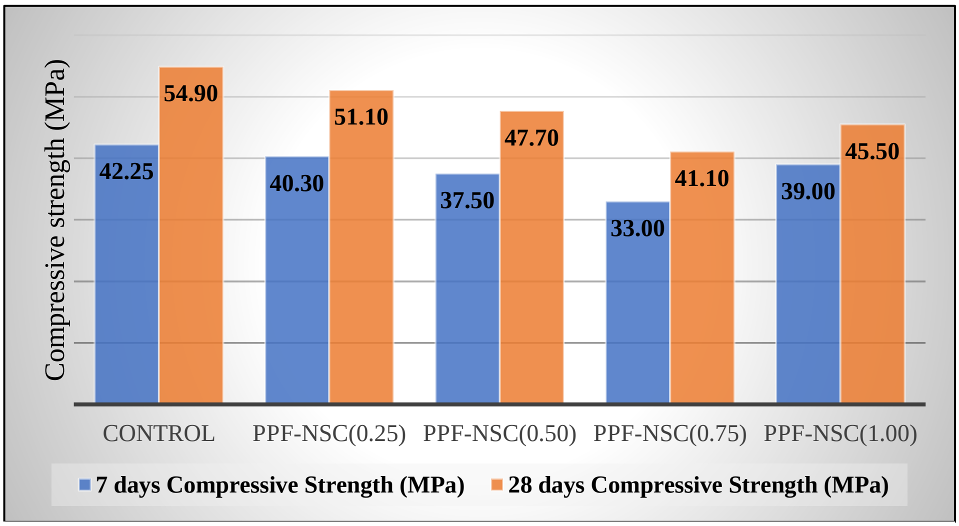

Figure 25: Comparison of Compressive strength change for 7 and 28 days NSC

According to the results shown in Figure 25 of PPF-NSC where the compressive strength of specimens at 28 days are higher than the compressive strength of specimens at day 7 as expected. In both periods, the lowest compressive strength was recorded for PPF-NSC (0.75) with 41.10 MPa at day 28 and 33.00 MPa at day 7.

The highest compressive strength was recorded for PPF-NSC (0.25) among the fibrous mixes with 51.0 MPa at day 28 and 40.3 MPa at day 7. It can also be observed that addition of PPF in NSC decreases the compressive strength of concrete. This is evident because the compressive strength for the control specimen is higher compared to the compressive strength of other specimens. The compressive strength for NSC specimen increased at day 28 compared to the day 7 results. The maximum increase was for the control specimen at 29.9 %. Followed by 27.2 % for PPF-NSC (0.50). PPF-HSC (1.00) had the lowest increase at 16.67 %.

Founding results are similar to the study results of (Abaeian, R., Behbahani, H. P., & Moslem, S. J. 2018). Since adding 1.00 % of PPF to concrete mixture, resulted in slight decrease of compressive strength, while 3.00 % of SP was used in the mixture components.

Tables 13 and 14 show results of compressive strength test for PPF-HSC after 7 and 28 days. Figure 26 illustrate the comparison of compressive strength results at 7 and 28 days. It can be observed from results shown in Figure 26 that compressive strength at day 7 decreased with increasing addition of PPF in HSC compared to the control sample. The maximum decrease observed was for PPF-HSC (0.75) at 10.87 %.

The same trend of NSC after 7 days in HSC mixture, where compressive strength was decreasing with addition of PPF as shown in Table 13. Although at day 28 compressive strength was slightly increased with addition of PPF to HSC mixtures, except for PPF-HSC (0.75) which decreased by only 1.13 % as illustrated in Table 14 and Figure 26. There was an expected increase in compressive strength at day 28 compared to day 7 and the maximum increase percentage in compressive strength was recorded at PPF-HSC (1.00) by 32.28 % from day 7 to 28.

As shown in Table 13, the specimens at day 7 gained high strength because of the SF used in the mix as an additive which increase the early strength gain. That also happened at day 7 of the PPF-NSC. The study of (Zhang, P., & Li, Q. F. 2013) verified that by the enhanced development of the interfacial structure of cement and aggregates.

Table 13: Results of Compressive strength test on PPF-HSC for 7 days

Mixture type	Maximum Load (KN)	Compressive Strength (MPa)	Change in Compressive Strength (%)
Control	1035.00	46.00	-
PPF-HSC (0.25)	956.00	42.40	-7.83
PPF-HSC (0.50)	1012.00	45.00	-2.17
PPF-HSC (0.75)	922.00	41.00	-10.87
PPF-HSC (1.00)	967.00	43.00	-6.52

Table 14: Results of Compressive strength test on PPF-HSC for 28 days

Mixture type	Maximum Load (KN)	Compressive Strength (MPa)	Change in Density (Kg/m^3)	Change in Compressive Strength (%)
Control	1387.00	61.70	2364.00	-
PPF-HSC (0.25)	1403.00	62.30	2383.00	0.97
PPF-HSC (0.50)	1434.00	63.70	2302.00	3.24
PPF-HSC (0.75)	1387.00	61.00	2333.00	-1.13
PPF-HSC (1.00)	1430.00	63.50	2334.00	2.92

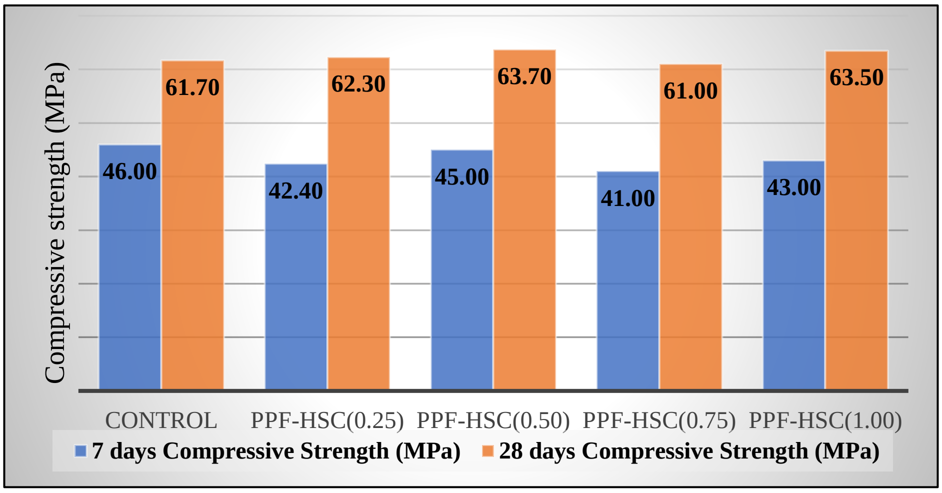

Figure 26: Comparison of Compressive strength change for 7 and 28 days PPF-HSC

It can be concluded that compressive strength decreased for PPF-NSC specimen for both test ages. With a maximum decrease of 21.89 % for day 7 and 25.14 % for day 28 testing, all from the PPF-NSC (0.75) mixture. And the control mix had higher compressive than other mixes due the incorporating particles of the Pozzolans in the concrete that resulted in improved compressive strength than expected in day 28. (Zhang, P., & Li, Q. F. 2013)

The result was a bit different for PPF-HSC where the compressive strength decreased with the increase of PPF for day 7 test, but improved with increase in PPF for 28days test with the exception of PPF-HSC (0.75) which decreased by only 1.13 %. The highest compressive strength was recorded for PPF-HSC (0.50) at 63.7 MPa.

The findings are consistent with the results of some studies in the literature. (Afroughsabet & Ozbakkaloglu, 2015) results show that the increase in the volume of PPF increased the compressive strength of HSC which verifies the result of our study. They attributed the increase in compressive strength to the fibers ability to restrain from crack extension by reducing stress concentration to tip and delay growth of cracks. 5 % increase in compressive strength is observed with 0.15 % increase in PPF in their study. While the best increase in compressive strength was recorded in Figure 26 was 3.24 % for PPF-HSC (0.50). The maximum improvement in compressive strength results recorded in the study of (Fallah & Nematzadeh, 2017) was at 0.1 % PPF volume fraction, with 11.5 % increase. Otherwise the compressive strength of PPF concrete was carried out in the study of (Mazaheripour et al., 2011), where no change was recorded in the results of compressive strength after 28 days. Whereas decrease in compressive strength was observed in NSC of this research.

The study of (Zhang, P., & Li, Q. F. 2013). Supported our results with PPF-HSC. Their study mentioned that using fibers at different volumes, and forms results in improving in compressive strength. This improvement can be illustrated by the ability of fibers to constrain the elongation of cracks, and changing their direction. Their results show that there was a clear increase in the concrete compressive strength including PPF (5 - 15 %).

In Figure 27, the changes observed in compressive strength for both PPF-NSC and PPF-HSC were compared. The trend shows an increase in compressive strength for PPF-HSC except for 0.75 %, while NSC showed a decrease in compressive strength.

PPF-HSC has a higher compressive strength results compared to PPF-NSC at days 7, and 28. This basically results from: the amount of cement content, low w/c, higher amount of SF (5 % more), and the quantity of high range water reducer (SP) which is 2 % of binder content. Moreover, as can be seen in the results, the addition of SF and the usage of SP in the control mix led to an increase in the compressive strength of about 10 % compared to the characteristic strength.

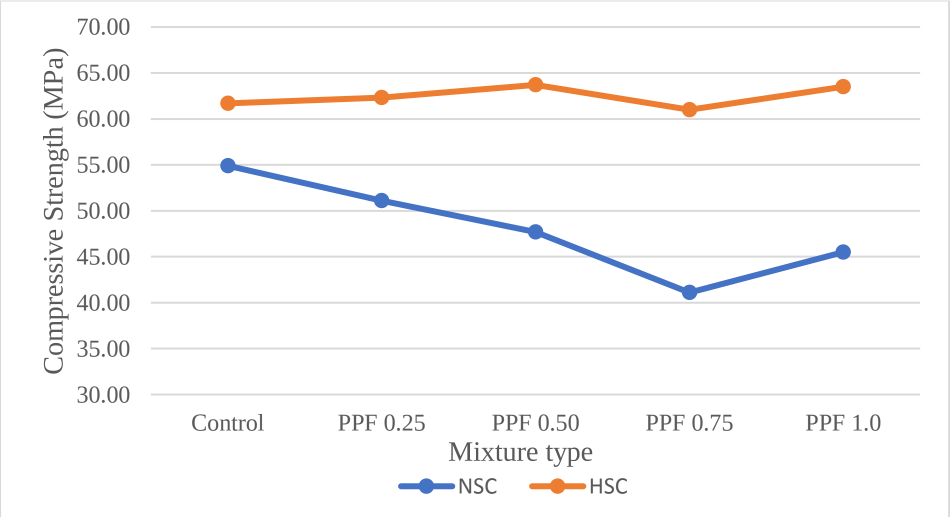

Figure 27: Comparison of compressive strength for PPF-NSC and PPF-HSC

4.4 Effects of Polypropylene fibers (PPF) on Splitting Tensile Strength

Using the 100 x 200 mm cylindrical specimens, an average of three specimens were used to record the results of each mix proportion in order to perform the splitting tensile strength test. The test was performed for both NSC, and HSC specimens. Table 15, and Figure 28 show the results for all percentages in PPF-NSC. Table 16, and Figure 29 illustrate the effects of PPF on PPF-HSC compared to the control mix. Most studies perform the splitting tensile strength test after 28 days of curing. In the research, splitting tensile strength test on both days 7 and 28 was performed.

Table 15: Results of Splitting tensile strength test on PPF-NSC

Mixture type	7 days Splitting tensile strength (MPa)	Change of Splitting tensile strength (%)	28 days Splitting tensile strength (MPa)	Change of Splitting tensile strength (%)
Control	3.22	-	3.55	-
PPF-NSC (0.25)	3.60	11.80	4.28	20.56
PPF-NSC (0.50)	3.00	-6.83	4.15	16.90
PPF-NSC (0.75)	3.30	2.48	4.00	12.68
PPF-NSC (1.00)	3.70	14.91	4.25	19.72

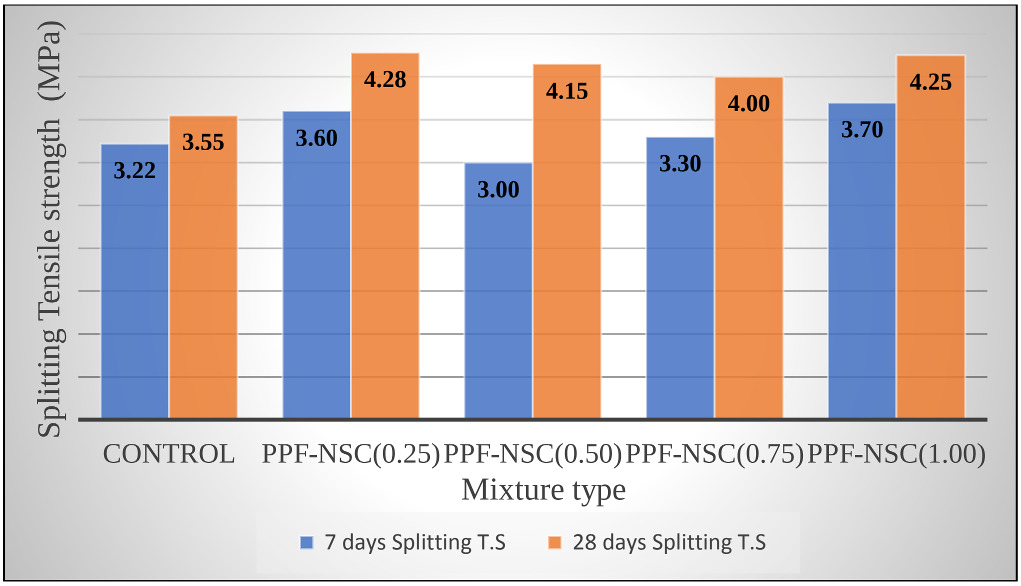

Figure 28: Splitting tensile strength for PPF-NSC

Results of the splitting tensile strength test for PPF-NSC illustrated above shows an increase in tensile strength for both days 7 and 28, except for PPF-NSC (0.50) at day 7 which shows a 6.83 % decrease, where the difference was (0.22 MPa) with the control mix, which is considered as a very slight difference. The highest splitting tensile strength was recorded at day 28 for both PPF-NSC (0.25) and PPF-NSC (1.00) with 4.28 MPa and 4.25 MPa, respectively. with a 20.56 %, and 19.72 % increase compared to the control mix. Concluding that the PPF in NSC shows an efficient role enhancing the tensile strength at all proportions of PPF used, especially after 28 days of immersed curing.

Table 16: Results of Splitting tensile strength test on PPF-HSC

Mixture type	7 days Splitting tensile strength (MPa)	Change of Splitting tensile strength (%)	28 days Splitting tensile strength (MPa)	Change of Splitting tensile strength (%)
Control	4.41	-	5.11	-
PPF-HSC (0.25)	5.11	15.87	5.37	5.10
PPF-HSC (0.50)	4.42	0.23	5.19	1.56
PPF-HSC (0.75)	4.30	-2.49	5.14	0.60
PPF-HSC (1.00)	4.70	6.58	5.24	2.54

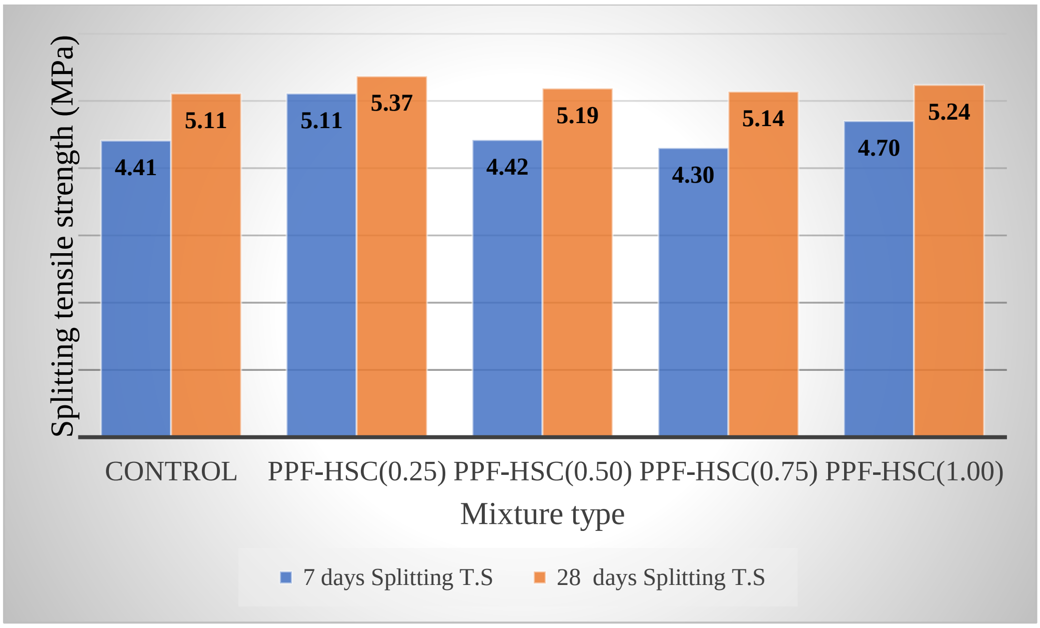

Figure 29: Splitting tensile strength for PPF-HSC

Similarly, according to Figure 29, the tensile strength of PPF-HSC showed increase with the addition of PPF after days 7 and 28 except for PPF-HSC (0.75) which shows an insignificant decrease of 2.49 % compared to the control specimen after 7 days, then it went up to attain 0.60 % increase compared to the control after the day 28. The highest splitting tensile strength was recorded after 28 days curing for PPF-HSC (0.25) with 5.37 MPa. The splitting tensile strength of PPF-HSC was greater than PPF-NSC as expected. Considering the role of SF where it improves the bond between the cement particles and the aggregates, due to the change of calcium hydroxide into calcium silicate hydrate in the presence of reactive silica placed on the surface of aggregates.

The result obtained from the splitting tensile strength is in good agreement with the results of previous studies that tested the effects of PPF on concrete. The study of (Afroughsabet & Ozbakkaloglu, 2015) also confirms that PPF addition increases the splitting tensile strength in HSC after 28 days by about 20 % when 0.45 % of PPF was used. This increase may attribute to the dispersion improved between the fibers caused by the presence of SF. In addition, (Mazaheripour et al., 2011) observed an increase in splitting tensile strength of about 14 % with PPF of 1.5 %.

The splitting tensile strength results of (Fallah & Nematzadeh, 2017) research, founded that splitting tensile strength increased only at 0.3 % volume fraction of PPF with improvement of 10.77 %. But Specimens contained 0.4, and 0.5 % PPF showed reduction of tensile strength by 2.73 and 3.97 %. Whereas results of splitting tensile strength at 28 days in this research have increase with all volume content of PPF in HSC and NSC. respectively. Some researchers defined the role of SF in fibrous concrete where (Zhang, P., & Li, Q. F. 2013) made a statement that the presence of SF led to increased splitting tensile strength up to 12 % at 28 days. PPF addition of 0.45 % PPF led to a 20 % increase in the splitting tensile strength at day 28. It was observed in this research by the higher splitting resistance of HSC than NSC, where 10 % of SF was used in HSC and 5 % in NSC.

Figure 30 shows a comparison for splitting tensile strength for PPF-NSC and PPF-HSC after 28 days curing. The splitting tensile strength at day 28 is higher than expected. It can also be observed that the trend of change in both NSC and HSC is similar, with the highest splitting tensile strength being PPF (0.25%) for both NSC and HSC.

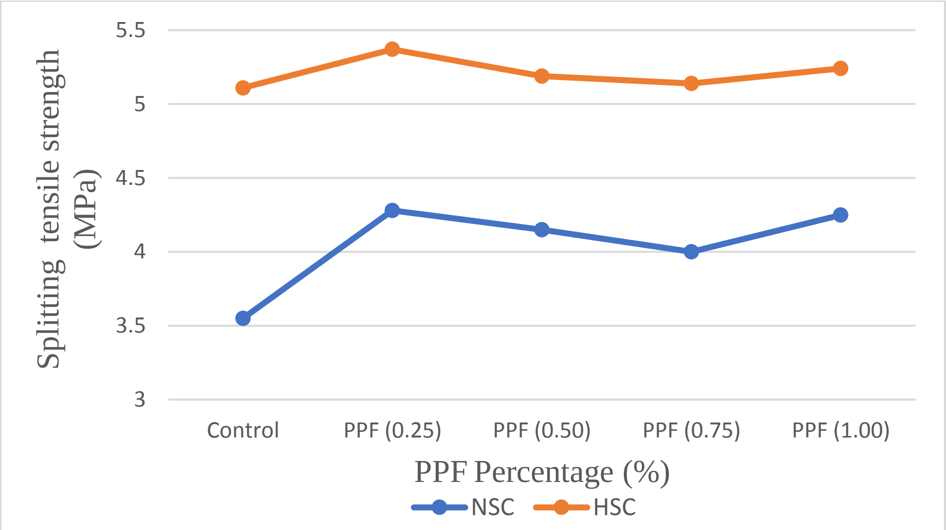

Figure 30: day 28 Splitting tensile strength results comparison for NSC and HSC

4.4.1 Compressive Strength and Splitting Tensile Strength Relationship for PPF-NSC

The previous sections present the findings of compressive strength and splitting tensile strength for both NSC and HSC. This section investigates if there is any relationship between compressive strength and splitting tensile strength of PPF-NSC. Using regression analysis, any possible relationship was explored. Table 17 shows different correlations between splitting tensile strength and compressive strength for NSC. Figure 31 shows a polynomial relationship between splitting tensile strength and compressive strength at 28 days.

The relationship between splitting tensile strength and compressive strength at day 7 was very weak, this may be attributed to the lack of stability of the specimen at day 7. However, results of day 28 presented in Table 17, and Figure 31. There is a weak relationship using exponential, linear, logarithmic and power regression analysis. Polynomial regression $y = -0.0101x^2 + 0.9409x - 17.697$ shows a strong relationship with R-Square= 0.84152 (Figure 31). The inconsistency was at PPF-NSC (0.25%), when compressive strength decreased and splitting tensile strength increased. After that, whenever compressive strength decreased, splitting tensile strength decreased and vice versa.

Table 17: 28 days Compressive and Splitting tensile strength Relationships for NSC

	Type of Regression	Equation	R^2
NSC	Exponential	$y = 5.6537e^{-0.007x}$	0.23304
	Linear	$y = -0.0263x + 5.3089$	0.21601
	Logarithmic	$y = -1.154\ln(x) + 8.5089$	0.18316
	Polynomial	$y = -0.0101x^2 + 0.9409x - 17.697$	0.84152
	Power	$y = 0.0409x^{1.17}$	0.4063

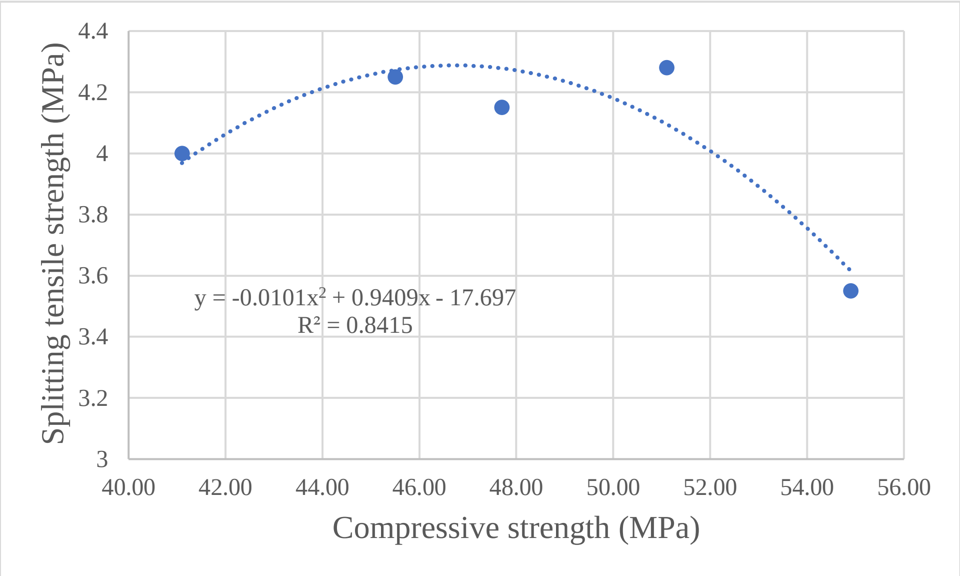

Figure 31: 28 days polynomial Relationship for Compressive and Splitting tensile strength of NSC

4.4.2 Compressive Strength and Splitting Tensile Strength Relationship for PPF-HSC

This section presents the relationship for compressive strength and splitting tensile strength results for PPF-HSC at day 28. As can be seen in Table 18 and Figure 32, the relationship at day 28 for PPF-HSC is weaker than that of PPF-NSC. However, the trend in change was consistent except for PPF-HSC (0.50). The compressive strength for PPF-HSC (0.50) increased to reach 63.70 MPa then it plunged at PPF-HSC (0.75) to 61.00 MPa below the control mix, and rose up again to 63.50 MPa at PPF-HSC (1.00) where in splitting strength results at 0.50, 0.75, and 1.00 % PPF were almost similar with increasing percentages of 1.56, 0.6, and 2.54 % compared to the control mix. The relationship between compressive and splitting tensile strength at day 7 were weaker than relation of day 28, lack of stability of specimens can be justified according to the presented results, and in the day 28, specimens are more likely to have the better strength and stability.

The results for day 28 PPF-HSC relationship improved. Polynomial regression had the strongest value because the trend in changes for both compressive and splitting tensile strength are consistent, except for PPF-HSC (0.50).

Table 18: 28days Compressive and Splitting tensile strength Relationships for HSC

	Type of Regression	Equation	R^2
HSC	Exponential	$y = 3.6357e^{0.0058x}$	0.1167
	Linear	$y = 0.0297x + 3.355$	0.113
	Logarithmic	$y = -1.8718\ln(x) – 2.5279$	0.1152
	Polynomial	$y = -0.0713x^2 + 8.9358x – 274.53$	0.4352
	Power	$y = 1.1625x^{0.03628}$	0.1189

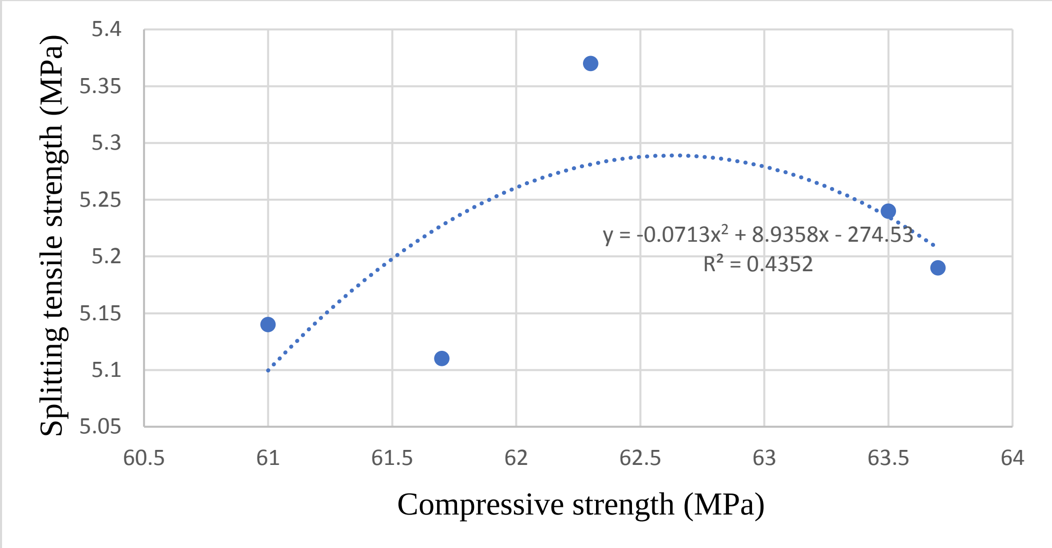

Figure 32: 28days Relationship for Compressive and Splitting tensile strength for HSC

4.5 Effect of Polypropylene fibers (PPF) on Flexural Strength and Toughness

To perform the flexural strength and toughness test, beams of 500 x 100 x 100 mm were used for all the concrete mixtures. Results of the test for 7 and 28 days are reported in Tables 19 and 20 for PPF-NSC, respectively. And Tables 21 and 22 show the results for PPF-HSC at 7 and 28 days. Figures 33(a-e) illustrates the deformation behavior of all the percentages of PPF-NSC, and Figures 34(a-e) describes that of PPF-HSC for all the percentages respectively.

As can be seen from Tables 19, 20 and Figures 33(a-e). The maximum flexural strength among specimens recorded in day 28 was for PPF-NSC (0.25 %) specimen with an increase of 23.46 % compared to the control specimen, subsequently, the flexural strength continues to decrease with increase in PPF, until it reaches its lowest at 13.64 MPa with PPF-NSC (1.00), 14.21 % lower than the flexural strength of the control specimen. While the flexural strength of PPF-NSC (0.50) and (0.75) remained higher than control mix by about 14.53 % and 0.13 %, respectively. That decrease of PPF-NSC (1.00) can be attributed to the low bonding property between PPF and mortar. In addition, the agglomeration of PPF leads it to work as a repellant of bonding among the aggregate surface and the cement particles.

Moreover, this plunged result of rupture at 1.00 % of PPF in NSC can be attributed to the poorly compacted mixture due the high amount of PPF, relatively low amount of binder, and high aggregate content. The compatibility between SP and cement particles where not effectively achieved because of the littleness amount of SP used to the high volume of 1.00 % PPF added to NSC.

The results of our experiment are similar to the study of (Nili, M., & Afroughsabet, V. 2010). Where the straight fibers used with SF, water to binder ratio was 0.46, and the volume of fibers was 0.2, 0.3, and 0.5 %, resulting in an increase of flexural strength of 5.46, 5.68, and 6.14 MPa, respectively. The addition of PPF volume less than or equal 0.75%, helped in improve the flexural strength of concrete, as SF were added to the mixtures.

Table 19: 7 days Flexural strength test results for PPF-NSC

Mixture type	Max. Load (KN)	Flexural Strength (MPa)	Change in Flexural Strength (%)
Control	5.50	4.95	-
PPF-NSC (0.25)	6.95	5.96	20.40
PPF-NSC (0.50)	5.78	5.18	4.65
PPF-NSC (0.75)	5.72	5.16	4.24
PPF-NSC (1.00)	4.73	4.26	-13.94

Table 20: 28 days Flexural strength test results for PPF-NSC

Mixture type	Maximum Load (KN)	Flexural Strength (MPa)	Change in Flexural Strength (%)
Control	17.67	15.90	-
PPF-NSC (0.25)	21.81	19.63	23.46
PPF-NSC (0.50)	20.24	18.21	14.53
PPF-NSC (0.75)	17.69	15.92	0.13
PPF-NSC (1.00)	15.16	13.64	-14.21

As can be seen in Figures 33(a-e), the deformation parameter of all proportion of PPF increased except for the PPF-NSC (0.25), whereas it has the most prominent value of rupture resistance. However, the lowest ductility among the other mixtures. The mixture components were enhanced in ductility with higher addition of fiber above 0.50 % of PPF; and the coarse aggregate content which enhances brittle behavior of concrete affected the results as shown in Figure 33 - b. Moreover, the fiber volume was low for enhancing the ductility enough like other fibrous mixes. The results show the efficiency of PPF in flexural strength and ductility, where the tensile strength of these fibers improved the ductility of mixtures contained 0.50, 0.75, and 1.00 % of PPF while the control mix was highly brittle which is non-fibrous.

On the other hand, the addition of fibers resulted in a decrease in gaining strength within the mixtures of PPF-NSC and PPF-HSC in the very first days as shown in the results, due to the low bonding property of PPF with the cement particles resulted from the presence of voids, (O. Karahan. 2011). Till the efficiency of fibers appeared after the stability of the mixtures was attained.

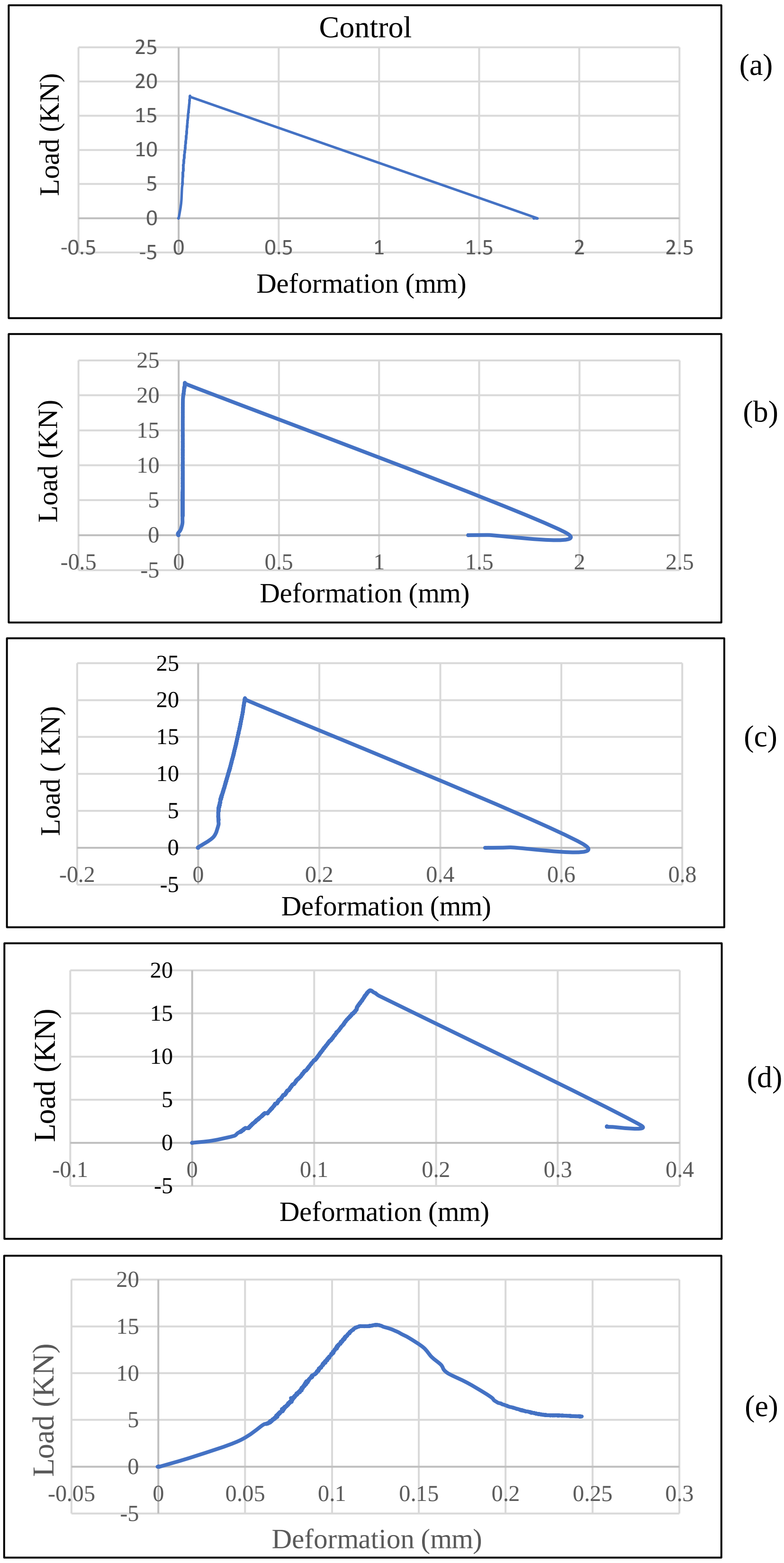

Figure 33: Flexural toughness test results of (a) Control (b) PPF-NSC (0.25), (c) PPF-NSC (0.50), (d) PPF-NSC (0.75) and (e) PPF-NSC (1.00).

Contrary to the flexural strength results of PPF-NSC, PPF-HSC showed increase in flexural strength as PPF increases. According to Tables 21 and 22, 22.95 MPa was recorded for PPF-HSC (0.75 %) after 28 days. Showing a 24.05 % increase in flexural strength compared to the control specimen. The dispersing compositions in the mixture led to an effective role of larger amount of PPF used in the mix, where the SF was 10 % in HSC and SP was 2.0 %. After the increase, the flexural strength decreased to 21.10 MPa. still higher than the control mix, and the PPF-HSC (0.75) was the proper volumetric addition to flexural resistance. From this experiment, PPF-HSC exhibited a higher flexural strength compared to the PPF-HSC. However, PPF-NSC showed higher brittleness than PPF-HSC, as was mentioned in the previous discussion that the amount of coarse aggregate was higher in NSC. Nevertheless, SF used in the mixtures made concrete to have more brittle structure as can be clearly seen in the control mixes' deformation.

Many researches carried out similar results of flexural strength property of concrete with using fibers such as research of (Afroughsabet & Ozbakkaloglu, 2015) which reported a 5 – 14 % increase in flexural strength when PPF are added. And 3.70 – 8.70 % increase in flexural strength was recorded in (Mazaheripour et al., 2011) research of using PPF. Lastly (Zhang, P., & Li, Q. F. 2013) research where the found a slight improvement of flexural strength using PPF. Clarifying that increase due to the short length of the fibers and the relative low modulus of elasticity of PPF, considering the content of the fibers, and the age of concrete at time of testing.

Table 21: 7 days Flexural strength test results for PPF-HSC

Mixture type	Max. Load (KN)	Flexural Strength (MPa)	Change in Flexural Strength (%)
Control	6.67	6.00	-
PPF-HSC (0.25)	7.00	6.30	5.33
PPF-HSC (0.50)	7.77	7.00	16.83
PPF-HSC (0.75)	8.11	7.30	21.50
PPF-HSC (1.00)	8.00	7.20	19.83

Table 22: 28 days Flexural strength test results for PPF-HSC

Mixture type	Max. Load (KN)	Flexural Strength (MPa)	Change in Flexural Strength (%)
Control	20.56	18.50	-
PPF-HSC (0.25)	22.50	20.25	9.46
PPF-HSC (0.50)	22.99	20.69	11.84
PPF-HSC (0.75)	23.35	22.95	24.05
PPF-HSC (1.00)	23.43	21.10	14.05

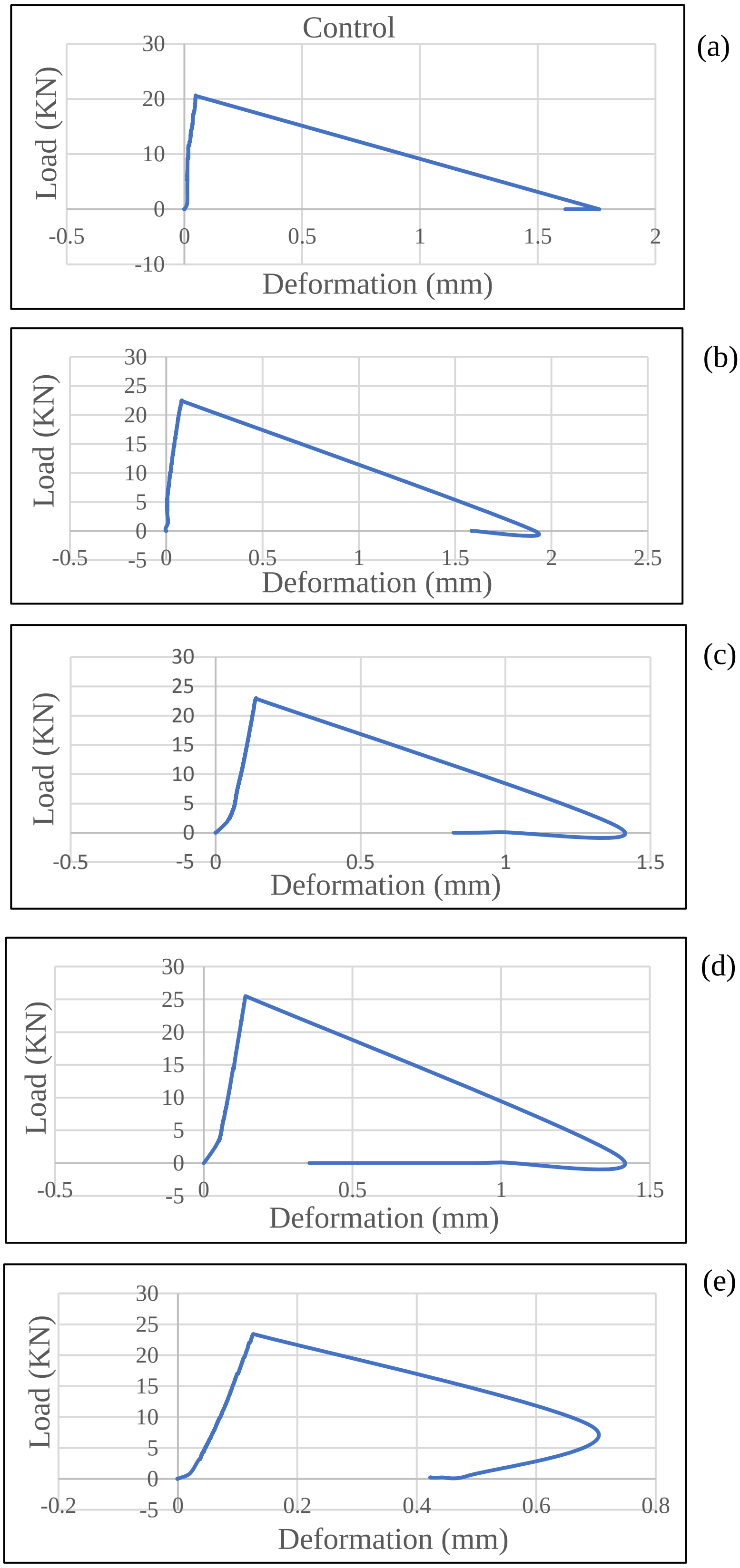

Figure 34: Flexural toughness test results of (a) Control, (b) PPF-HSC (0.25), (c) PPF-HSC (0.50), (d) PPF-HSC (0.75), and (e) PPF-HSC (1.00).

4.5.1 Compressive and Flexural Strength Relationship for PPF-NSC

In this section, many attempts were done to establish if there is some sort of relationship between flexural strength and splitting tensile strength of concrete. Table 23 depicts the achieved results. Using all forms of regression analysis, the results shows that there is no relationship between flexural strength and compressive strength of NSC.

Table 23: Relationship between Flexural and Compressive strength of NSC

	Type of Regression	Equation	R^2
NSC	Exponential	$y = 10.841e^{0.0088x}$	$R^2 = 0.1087$
	Linear	$y = 0.1453x + 9.6753$	$R^2 = 0.10935$
	Logarithmic	$y = 7.1702\ln(x) - 11.072$	$R^2 = 0.11705$
	Polynomial	$y = -0.0286x^2 + 2.8922x - 55.661$	$R^2 = 0.19285$
	Power	$y = 3.1263x^{0.4306}$	$R^2 = 0.11505$

As shown in the Table above, no relation was noticed due to the results of 0.25 % of PPF in both tests. It had the maximum flexural strength value among the mixes and started to decrease till PPF-NSC (1.00) below the control mix. While in the compressive strength test the results started to sink with 25.14 % decrease at 0.75 % of PPF compared to control mix. Then it rose up at PPF of 1.00 %.

4.5.2 Compressive and Flexural Strength Relationship for PPF-HSC

Table 24 and Figure 35 illustrate a relationship between compressive strength and flexural strength for PPF-HSC specimens. Generally, no relationship was identified for both tests on the specimen using multiple regression analysis method. However, polynomial regression analysis shows a 0.57 correlation using the function $y = 1.4559x^2 - 181.98x + 5705.4$ as shown in Figure 35.

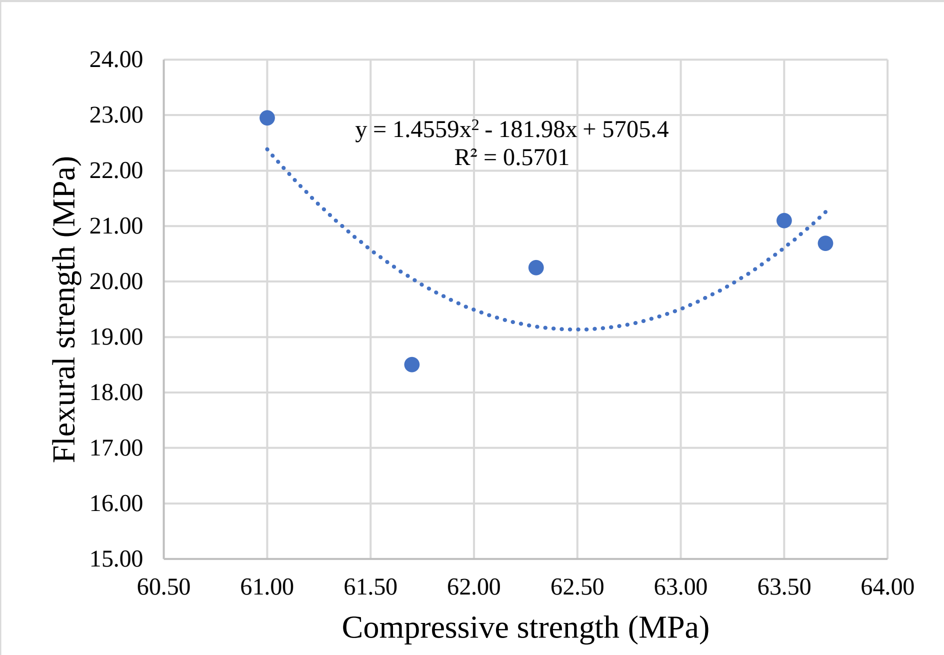

Figure 35: Polynomial Description of Flexural and Compressive strength for HSC

It is observed that, as the compressive strength increases, the flexural increases for PPF-HSC 0, 0.25, and 0.50 %. However, PPF-HSC (0.75) showed decrease in compressive strength while compressive strength increases, and PPF-HSC (1.00) shows increase in compressive strength and flexural strength decreases. So, the relationship between compressive and flexural strength of PPF-HSC is stronger than that of PPF-NSC.

Table 24: Relationship between Flexural and Compressive strength for HSC

	Type of Regression	Equation	R^2
HSC	Exponential	$y = 33.973e^{-0.008x}$	0.01413
	Linear	$y = -0.2126x + 33.97$	0.02356
	Logarithmic	$y = -13.63\ln(x) + 77.042$	0.02486
	Polynomial	$y = 1.4559x^2 - 181.98x + 5705.4$	0.57009
	Power	$y = 173.67x^{-0.515}$	0.01513

4.5.3 Flexural and Splitting Tensile Strength Relationship

As can be observed in regressions shown in Tables 25 and 26, it can be noticed that relations between splitting tensile and flexural tensile strength are weak, except the regression of polynomial was the strongest in both concretes, where R^2= 0.60135 for PPF-NSC, and R^2= 0.54883 for PPF-HSC.

Table 25: Relationship between flexural and splitting tensile strength for NSC

	Type of Regression	Equation	R-square
NSC	Exponential	$y = 3.5499e^{0.0077x}$	$R^2 = 0.05453$
	Linear	$y = 0.0303x + 3.5407$	$R^2 = 0.05557$
	Logarithmic	$y = 0.4074\ln(x) + 2.9032$	$R^2 = 0.03679$
	Polynomial	$y = 0.0508x^2 - 1.6665x + 17.487$	$R^2 = 0.60135$
	Power	$y = 3.0166x^{0.1038}$	$R^2 = 0.03625$

Table 26: Relationship between flexural and splitting tensile strength for HSC

	Type of Regression	Equation	R-square
HSC	Exponential	$y = 5.1995e^{9E-05x}$	$R^2 = 5.5E-05$
	Linear	$y = 0.0003x + 5.2046$	$R^2 = 1.7E-05$
	Logarithmic	$y = 0.0449\ln(x) + 5.0742$	$R^2 = 0.00116$
	Polynomial	$y = -0.0286x^2 + 1.1875x - 7.0454$	$R^2 = 0.54883$
	Power	$y = 5.0627x^{0.0094}$	$R^2 = 0.00141$

The other regressions show weak relationships between splitting tensile and flexural strength of PPF-NSC and PPF-HSC. That is attributed to the trend difference in the effect of PPF on concrete, since the flexural strength results rose up by 23.46 % at 0.25 % of PPF in NSC compared to control mix then it plunged to reach a value below the control mix at 1.00 % of PPF with 14.21 % decrease. But in splitting tensile strength experiment; 20.56 % increase in splitting strength was recorded then gradual decrease was observed till 0.75 % of PPF, whereas 19.72 % increase of splitting tensile strength was noticed at PPF content of 1.00 %.

4.6 Effects of Polypropylene fibers (PPF) on Schmidt Hammer Test

The Schmidt hammer is a non-destructive test that is mainly used to measure rocks' surface hardness, and compressive strength of concrete. The Schmidt hammer arbitrary scale ranges from 10-100. To make our test results accurate and to eliminate errors, multiple hits on the surface were performed and the average was calculated. The rebound value is used to measure the value of the compressive strength using the conversion chart.

Tables 27 and 28 shows the Schmidt results for NSC and HSC, respectively. The results decrease in compressive strength as the percentage of PPF increases. PPF-NSC (0.50 %) showed the best Schmidt result with only 13 % decrease compared to the control specimen. Comparison between PPF-NSC and PPF-HSC as illustrated in Figure 36 shows that compressive strength of PPF-HSC is higher than that of PPF-NSC.

Table 27: Schmidt Hammer results for PPF-NSC

Mixture type	Schmidt hammer test results (MPa)	Loss of Compressive Strength (%)
Control	42.80	-
PPF-NSC (0.25)	35.40	17.29
PPF-NSC (0.50)	37.20	13.08
PPF-NSC (0.75)	33.70	21.26
PPF-NSC (1.00)	36.00	15.89

Table 28: Schmidt Hammer results for PPF-HSC

Mixture type	Schmidt hammer test results (MPa)	Loss of Compressive Strength (%)
Control	45.00	-
PPF-HSC (0.25)	43.70	2.89
PPF-HSC (0.50)	40.50	10.00
PPF-HSC (0.75)	37.40	16.89
PPF-HSC (1.00)	42.00	6.67

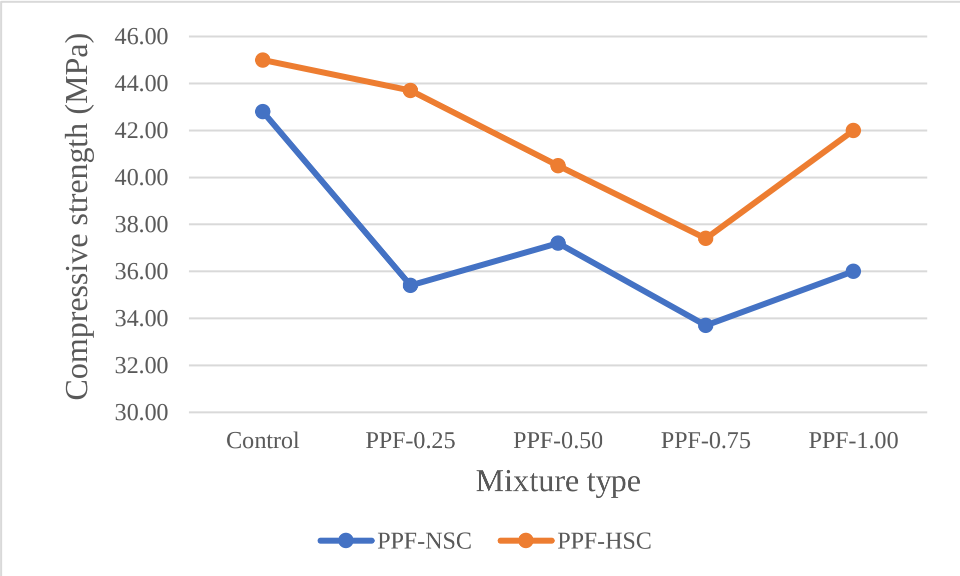

Figure 36: Polynomial Description of Flexural and Compressive strength for PPF-HSC

4.6.1 Relationship between Schmidt Hammer and Compressive Strength Results

Different correlations between Schmidt hammer, and compressive strength results are shown in Tables 29 and 30. As expected a strong relation was observed between compressive strength test by machine and Schmidt hammer test as they both indicate the same property. The polynomial regression in both concretes is the strongest, R^2= 0.70929 for NSC, and R^2= 94718 for HSC.

Table 29:Relationship between Schmidt and Compressive strength test for NSC

	Type of Regression	Equation	R-square
NSC	Exponential	$y = 18.375e^{0.0258x}$	$R^2 = 0.65746$
	Linear	$y = 1.2522x + 1.705$	$R^2 = 0.67889$
	Logarithmic	$y = 48.428\ln(x) - 126.67$	$R^2 = 0.68841$
	Polynomial	$y = -0.1049x^2 + 9.3454x - 153.19$	$R^2 = 0.70929$
	Power	$y = 1.2899x^{1.0014}$	$R^2 = 0.66935$

Table 30: Relationship between Schmidt and Compressive strength test for HSC

	Type of Regression	Equation	R-square
HSC	Exponential	$y = 59.689e^{0.0011x}$	$R^2 = 0.02945$
	Linear	$y = 0.0652x + 59.72$	$R^2 = 0.02773$
	Logarithmic	$y = 3.1164\ln(x) + 50.819$	$R^2 = 0.03762$
	Polynomial	$y = -0.1595x^2 + 13.191x - 209.22$	$R^2 = 0.94718$
	Power	$y = 51.572x^{0.0512}$	$R^2 = 0.03962$

4.7 Effect of Polypropylene fibers (PPF) on Degradation Test after and before Heating.

To test the effect of PPF on NSC and HSC when exposed to high temperatures, cube size of 100 × 100 × 100 mm was used. Compressive strength test, splitting tensile strength test, crack development and UPV tests were performed.

4.7.1 Effect of Polypropylene fibers (PPF) on UPV of PPF-NSC and PPF-HSC by Heating

The UPV method is used to draw and classify cracks to specimens such as concrete by transmitting a sonic wave through the specimen. Table 31 and Figure 37 illustrates the time it took for the sonic waves to pass through the specimens in micro seconds for PPF-NSC before and after heating. The final velocity is calculated by dividing the length of the specimen by the time the sonic waves used to pass through the specimen.

It’s illustrated in Table 32 and Figure 38 for PPF-HSC. The velocity is calculated as follows:

V (km/s) = (d (km)/t (sec)).

From the formula above, the longer it takes for the sonic wave to pass through the concrete, the lower the velocity.

Table 31: UPV results for PPF-NSC after 100 °C and 200 °C Heat Exposure

Mixture type	UPV before heating (micro sec.)	UPV after 100 °C heating (micro sec.)	UPV after 200 °C heating (micro sec.)
Control	19.05	19.80	22.10
PPF-NSC (0.25)	19.95	21.24	23.70
PPF-NSC (0.50)	20.90	21.85	23.55
PPF-NSC (0.75)	21.75	22.00	23.40
PPF-NSC (1.00)	22.24	20.89	22.85

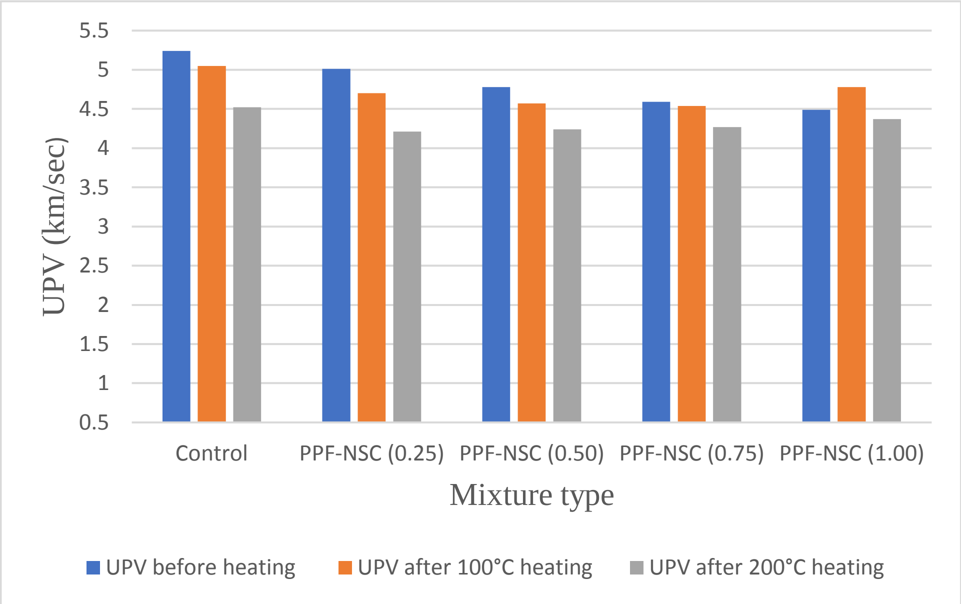

Figure 37: Description of UPV for NSC results after 100 °C and 200 °C

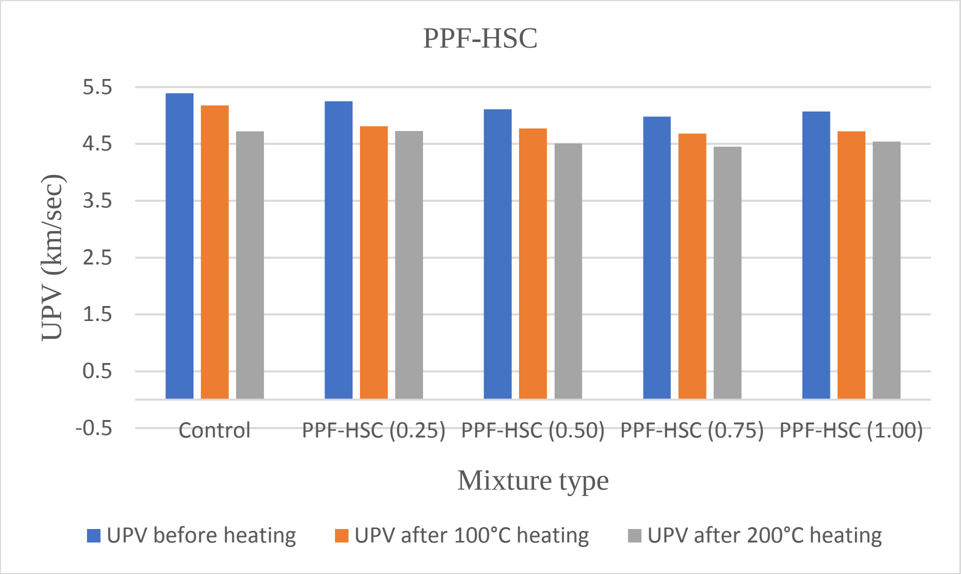

Figure 38: Description of UPV for HSC results after 100 °C and 200 °C

Table 32: UPV results for PPF-HSC after 100 °C and 200 °C Heat Exposure

Mixture type	UPV before heating (micro sec.)	UPV after 100 °C heating (micro sec.)	UPV after 200 °C heating (micro sec.)
Control	18.53	19.28	21.15
PPF-HSC (0.25)	19.02	20.75	22.10
PPF-HSC (0.50)	19.56	20.96	22.15
PPF-HSC (0.75)	20.06	21.35	22.45
PPF-HSC (1.00)	19.72	21.15	22.00

According to the results recorded in Tables 31 and 32, it can be inferred that with increase in heat exposure, the time it takes for the sonic sound to pass through the concrete increases. Thus, decreasing the pulse velocity; the concrete quality is affected by heat exposure due to the volume change of the cubic specimen where minute cracks took place, in addition, the moisture loss into the capillaries result of tiny cracks left behind. This is observed for both PPF-NSC and PPF-HSC. The decrease in UPV can be translated to decrease in compressive strength of the concrete. Contrary to the study of (Hiremath et.al, 2018) which showed increase in UPV as percentage of PPF increases, results of this study show decrease in UPV test results as percentage of PPF increases. Observing that in NSC and HSC with PPF had worse results after being exposed to 100 °C compared to the control mix that results from the evaporation process of water into the pores leaving cracks behind. Although after 200 °C heating in both mixtures the test results of PPF specimens were mostly close to the control, but with better performance for the HSC where it kept the quality higher than NSC, and was denser than NSC.

4.7.2 Effect of Polypropylene fibers (PPF) on Compressive Strength of PPF-NSC and PPF-HSC by Heating

Using the 100 × 100 × 100 mm cubic specimens, the compressive strength of concrete with heat exposure was performed. Tables 33 and 34 presents the results for PPF-NSC and PPF-HSC, and Figures 39 and 40 depicts the findings of PPF-NSC, and PPF-HSC, respectively.

Results from PPF-NSC analysis show significant decrease in compressive strength when exposed to high temperature. Considerable decrease was identified for PPF-NSC (0.25). The specimen with the highest compressive after 200 °C exposure was PPF-NSC (0.50). Similarly, the study of (Shihada et al. 2011) since 200 °C heating was the exposure of specimens contains PPF, residual compressive strength was promoted. PPF-NSC (0.50) was recorded as the highest compressive strength specimens among the fibrous mixtures after heating with 25.2 % loss in compressive strength. Since the least loss in compressive strength recorded at PPF-NSC (1.00) with 14.5 % decrease after 200 °C heating.

Table 33: Compressive strength results for PPF-NSC after 100 °C and 200 °C Heat Exposure

Mixture type	Compressive strength before heating (MPa)	Compressive strength after 100 °C (MPa)	Compressive strength after 200 °C (MPa)	Compressive strength loss after 200 °C (%)
Control	64.70	57.00	53.50	17.3
PPF-NSC (0.25)	61.10	51.80	35.90	41.2
PPF-NSC (0.50)	55.90	42.50	41.80	25.2
PPF-NSC (0.75)	49.50	37.45	38.80	21.60
PPF-NSC (1.00)	46.20	45.50	39.50	14.50

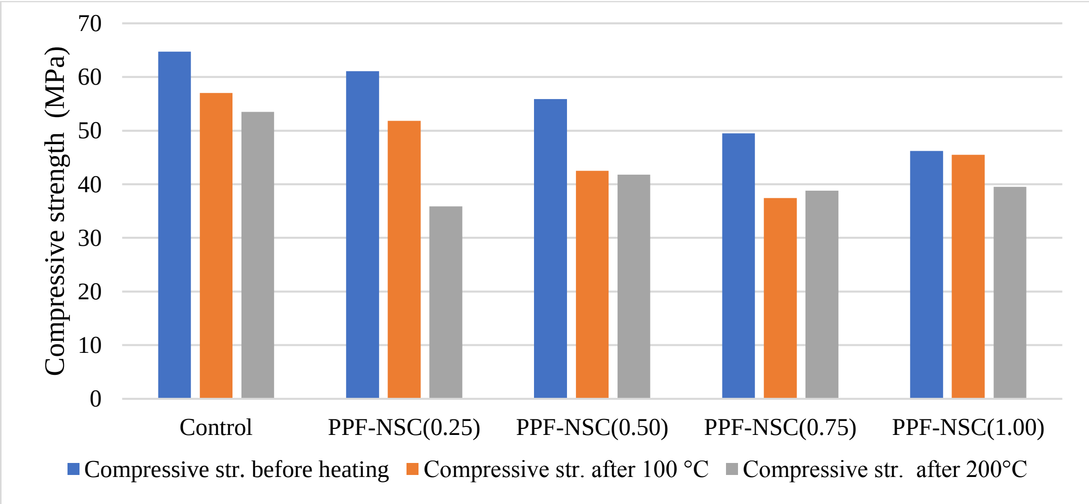

Figure 39: Description of Compressive strength results for NSC after 100 °C and 200 °C

As can be seen in Table 34 and Figure 40, exposing PPF-HSC to high temperatures decreases the compressive strength of the specimen significantly. The specimen with the highest compressive strength among the fibrous mixes after 100 °C and 200 °C exposure is PPF-HSC (0.25). 9.4 % decrease was observed after 100°C and 17.6 % decrease after 200 °C. however, the PPF-HSC (1.00) resulted in less compressive strength loss percentage, 9.0 % decrease after 200 °C, and 1.5 % after 100 °C.

The study of (Abaeian 2018) showed 1.00 % PPF addition to HSC to exhibit the best compressive strength after exposure to 200 °C, while our study showed PPF-HSC (0.50) to have the highest compressive strength after 200 °C among the fibrous mixes. (Abaeian 2018) used SP in their study of 0.3 %, w/c ratio of 0.35, and 572 Kg of cement. Their results presented a 5.2 % decrease in compressive strength for 1.00 % PPF in HSC, our study showed 8.9 % decrease, and the other PPF mixes showed almost similar decrease in compressive results by about 17.0 % after heat exposure.

Table 34: Compressive strength results for HSC after 100 °C and 200 °C Heat Exposure

Mixture type	Compressive strength before heating (MPa)	Compressive strength after 100 °C (MPa)	Compressive strength after 200 °C (MPa)	Compressive strength loss after 200 °C (%)
Control	76.30	72.90	64.40	15.50
PPF-HSC (0.25)	72.40	65.60	59.60	17.60
PPF-HSC (0.50)	69.80	62.80	57.30	17.90
PPF-HSC (0.75)	63.70	60.52	52.70	17.27
PPF-HSC (1.00)	64.50	63.50	58.70	8.90

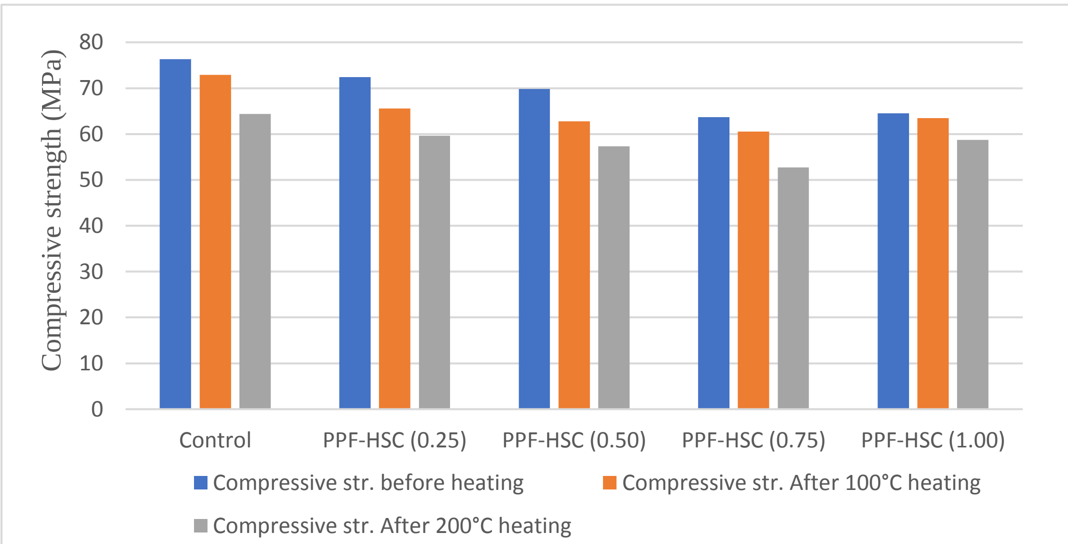

Figure 40: Description of Compressive strength results for HSC after 100 °C and 200 °C.

A research of (Abaeian, R., Behbahani, H. P., & Moslem, S. J. 2018) was carried out and supports results of this study by their results which showed reduction in strength for specimens of NSC and HSC when exposed to heat at 100, 200, 300 °C. Compressive strength of PPF-NSC were affected significantly after 100 °C exposure except for PPF-NSC (1.00); the compressive strength reduced by about 1.5 %, also after 200 °C heating this mix recorded the least loss in strength percentage among the mixes. That is due to the recompensed presence of PPF instead of water preventing the negative effect of evaporation that occurs due to high amount of water in the microstructure. The PPF melts at high temperatures up to 200 °C where the residue melted fibers replenish the capillaries, and the insulator PPF led to reduce the risk of heating exposure.

The study of (Bošnjak, J., Ožbolt, J., & Hahn, R. 2013) illustrated that the addition of PPF at elevated temperatures close to the melting temperatures of fibers will significantly influence the permeability of concrete, whereas the compressive strength has a strong relation with permeability, it was concluded that the flow of PPF in the surrounding material after melting process affected the permeability, decreased the compressive strength as well. Adding that, the mixture of PPF-HSC (1.00) was having the least reduction of 8.90 % in compressive strength after 200 °C heating. However, the control mix remained the highest value of compressive strength.

4.7.3 Effect of Polypropylene fibers (PPF) on Splitting Tensile Strength of PPF-NSC and PPF-HSC by Heating

The effects of PPF on the splitting tensile strength of NSC and HSC were tested using cubes size of 100 × 100 × 100 mm. the results of the tests are presented in Table 35 and Figure 41 for PPF-NSC. Table 36 and Figure 42 presents the results of PPF-HSC.

Similar to the results of compressive strength, the results show decrease in splitting tensile strength after heat exposure. PPF-NSC (1.00) showed the highest splitting tensile strength after 100 °C and 200 °C. However, PPF-NSC (0.25) recorded less strength loss after heating of 12.67 %. While PPF-NSC (0.75) was negatively affected by heating having the lowest splitting tensile strength of 2.99 MPa with loss percentage of 13.70 %. obviously shown in the table below that the non-fibrous mixture had the worse heating behavior with percentage of tensile strength loss of 28.40 %.

A clear evidence of the addition of PPF on normal strength concrete in enhancing the heat resistance by insulation property of this type of fibers is the percentage loss of splitting tensile strength in the control mix of 28.40 %.

Table 35: Splitting tensile strength results for NSC after 100 °C and 200 °C Heat Exposure

Mixture type	Splitting tensile strength before heating (MPa)	Splitting tensile strength after 100 °C (MPa)	Splitting tensile strength after 200 °C (MPa)	Splitting tensile strength loss after 200 °C (%)
Control	3.10	2.96	2.22	28.40
PPF-NSC (0.25)	3.55	3.36	3.10	12.67
PPF-NSC (0.50)	3.94	3.54	3.40	13.70
PPF-NSC (0.75)	3.87	3.21	2.99	22.73
PPF-NSC (1.00)	4.30	3.85	3.70	14.00

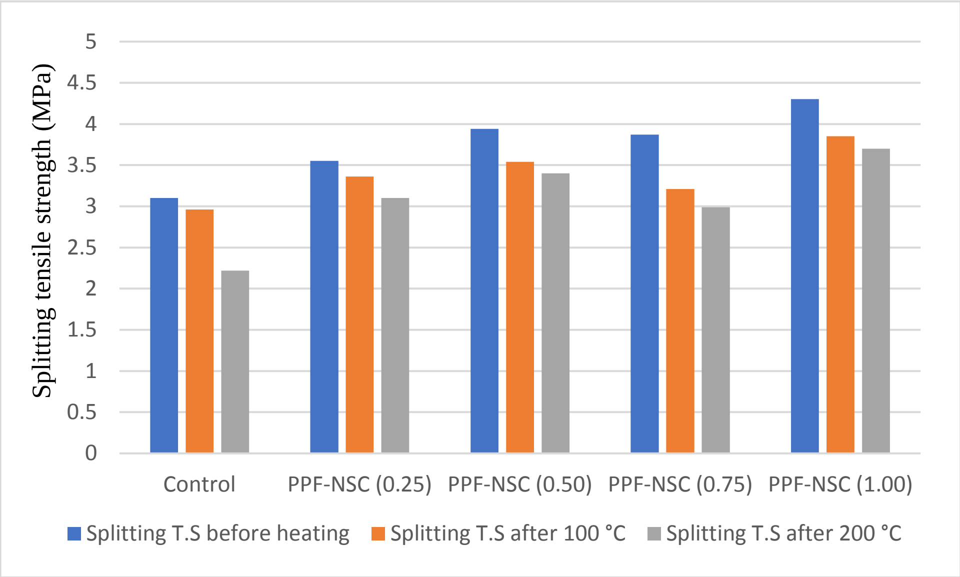

Figure 41: Description of Splitting tensile strength for NSC results after 100 °C and 200 °C.

According to Tables 35 and 36, the results of PPF-HSC showed different characteristics of PPF-NSC. PPF-HSC (0.25) showed the highest splitting tensile strength before heating, but adversely it was affected by heat exposure of 200 °C where it lost 22.12 % of splitting strength among fibrous mixtures. Also, PPF-NSC (1.00) had the best resistance against heating where its tensile strength remained high adjacent to the maximum with less strength loss of 11.44 %.

Comparing the splitting tensile strength of PPF-NSC and PPF-HSC after heat exposure, PPF-HSC (1.00) showed 13.1 % more splitting tensile strength than PPF-NSC (1.00) after 100 °C exposure. Similarly, PPF-HSC (1.00) shows a 5.12 % more splitting tensile strength than PPF-NSC (1.00) after 200 °C heat exposure, good results were recorded at 0.50 % of PPF in both mixes, where the splitting tensile strength of PPF-NSC (0.50) was reduced by 10.0 % after 100°C, and by 13.7 % after 200 °C recorded at 3.40 MPa, whereas in HSC the reduction percentage of splitting tensile strength after 100 °C was 4.23 % followed by 13.3 % after 200 °C at 3.90 MPa.

The study results of (Abaeian. 2018) showed a 1.5 % reduction in splitting tensile strength for 1.00 % PPF in HSC after 200 °C heating, while our study showed a noticeable increase in splitting tensile strength using PPF affected by heating to record slight reduction. As a conclusion the mechanical properties of concrete after exposure to extreme temperature showed reduction. Similarly, the study of (Noumowe, 2005) which showed in their results decrease in splitting tensile strength of HSC when PPF was added and exposed to 200 °C. A 38 % reduction was recorded, from 4.7 MPa to 2.9 MPa. Many studies investigated the effect of PPF on concrete under heat exposure such as: (Noumowe, 2005) which concluded that the mechanical properties of concrete appear to decrease when PPF are added to concrete.

Table 36: Splitting tensile strength results for HSC after 100 °C and 200 °C Heat Exposure

Mixture type	Splitting tensile strength before heating (MPa)	Splitting tensile strength after 100 °C (MPa)	Splitting tensile strength after 200 °C (MPa)	Splitting strength loss after 200 °C (%)
Control	4.13	3.70	3.03	26.63
PPF-HSC (0.25)	4.70	4.20	3.66	22.12
PPF-HSC (0.50)	4.50	4.31	3.90	13.34
PPF-HSC (0.75)	4.35	4.25	3.72	14.48
PPF-HSC (1.00)	4.63	4.43	4.10	11.44

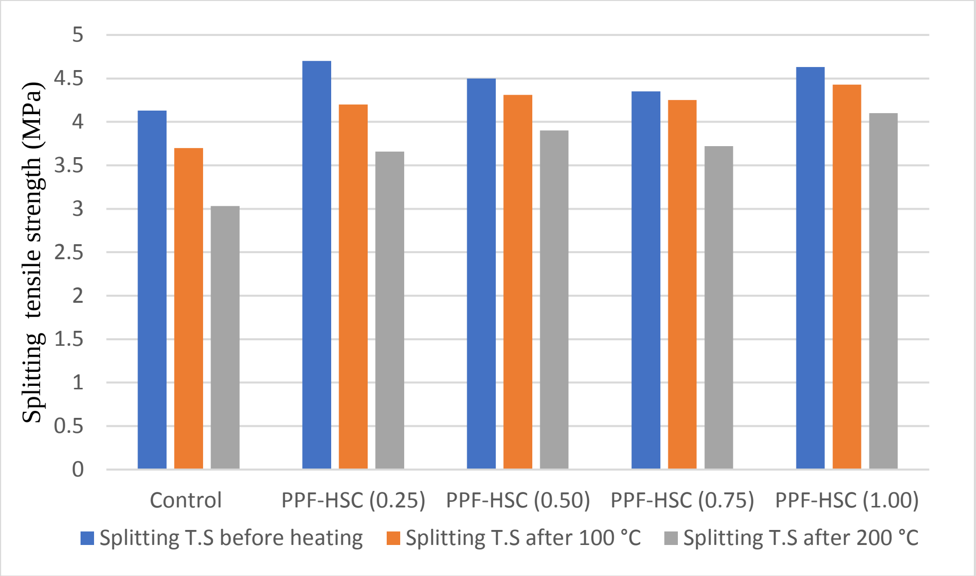

Figure 42: Description of Splitting tensile strength for PPF-HSC results after 100 °C and 200 °C

4.7.4 Relationship between Compressive Strength and UPV before and after Heating

In this section, the relationship between compressive strength and UPV from the degradation test is presented. Table 37 and 38 present the summary of the relationship for PPF-NSC and PPF-HSC, respectively. Significant relationship is observed in both cases. However, PPF-HSC showed stronger relationship than PPF-NSC. Polynomial regression showed the best relationship after 100 °C and 200 °C in NSC. Similarly, polynomial regression also showed the strongest relationship for 100 °C and 200 °C in HSC, where the linear regression in HSC with R^2 of 0.87, which showed stronger relationship between UPV and compressive results than that of NSC.

Table 37: Degradation Relationship of Compressive strength and UPV for NSC

Type of Regression	Before heating equation	R^2	Equation after 100 °C heating	R^2	Equation after 200 °C heating	R^2
Exponential	$y = 32.5e^{-0.008x}$	0.98098	$y = 26.514e^{-0.005x}$	0.77503	$y = 26.958e^{-0.004x}$	0.76688
Linear	$y = -0.1673x + 30.057$	0.98626	$y = -0.1012x + 25.896$	0.77872	$y = -0.0838x + 26.63$	0.7616
Logarithmic	$y = -9.129\ln(x) + 57.37$	0.9753	$y = -4.668\ln(x) + 39.065$	0.75993	$y = -3.734\ln(x) + 37.032$	0.75323
Polynomial	$y = -0.0038x^2 + 0.2543x + 18.568$	0.99808	$y = -0.0032x^2 + 0.1976x + 18.968$	0.80402	$y = -0.0018x^2 + 0.0776x + 23.055$	0.76806
Power	$y = 121.63x^{-0.441}$	0.96829	$y = 49.697x^{-0.223}$	0.75483	$y = 42.532x^{-0.164}$	0.75796

Table 38: Degradation Relationship of Compressive strength and UPV for HSC

Type of Regression	Before heating equation	R^2	Equation after 100 °C heating	R^2	Equation after 200 °C heating	R^2
Exponential	$y = 13.506e^{0.0047x}$	0.31496	$y = 35.798e^{-0.008x}$	0.96413	$y = 29.365e^{-0.005x}$	0.86735
Linear	$y = 0.0634x + 14.447$	0.2862	$y = -0.1707x + 31.804$	0.96604	$y = -0.1081x + 28.298$	0.87213
Logarithmic	$y = 1.8954\ln(x) + 11.102$	0.34656	$y = -11.38\ln(x) + 68.181$	0.958	$y = -6.222\ln(x) + 47.278$	0.84947
Polynomial	$y = -0.0092x^2 + 0.7992x + 10.027$	0.40508	$y = -0.0071x^2 + 0.7855x - 0.1346$	0.98611	$y = -0.0084x^2 + 0.8767x - 0.4117$	0.97114
Power	$y = 10.553x^{0.1407}$	0.37598	$y = 215.72x^{-0.562}$	0.95558	$y = 70.118x^{-0.285}$	0.84423

4.7.5 Effect of Polypropylene fibers (PPF) on Crack Development in PPF-NSC and PPF-HSC after Heating

For the mixture prepared in the laboratory, no cracks could be observed by the naked eye on the specimen surfaces, neither before nor after heating, as can be seen in Figure 43.

Figure 43: Surfaces of PPF specimens after heating

Then the microscope was used to find the development in cracks among the mixes, where no cracks were observed. This may be a result of using the pozzolanic SF in the mixes, and the PPF which refill the pores between the aggregates and cement particles preventing the growth of the cracks.

Th effect of fibers on cracks was explained by (Zhang, P., & Li, Q. F. 2013) where the PPF was able to prevent the cracks extension; reducing the magnitude of concentrated stress at the angle of crack. Also, for heating exposure while PPF is added, it has been studied by (P. Kalifa, G. Chene, C. Galle, 2001) at high temperatures (160 – 170 °C), where fiber melts then leave an inexact number of pores for the evaporated water to exit and those fibers are absorbed by cement mortar. The previous description is supported and explained in the study of (Noumowe, A. 2005), they explicate the efficiency of PPF in the concrete behavior at heat exposure, where melting PPF create small channels resulting in reducing the internal vapor pressure in concrete microstructure, thus preventing spalling.

Another point of view described by (M. Sahmaran, M. Lachemi, V.C. Li 2010), and (Noumowe, A. 2005), as they investigated the microstructure characteristic of high strength concrete after heating. they declared that PPF-concrete loses heat slower than non- fibrous concrete which leads to having less cracks in cooling process.

(Zhang, P., & Li, Q. F. 2013). Stated that the anti-cracking influence of PPF helped in reducing the number of micro-cracks within the composite. In addition, (Bagherzadeh R, Sadeghi AH, Latifi M. 2012) stated that the distributed PPF in the composite in aiding the influence of aggregates and diminish bleeding and segregation of concrete at fresh stage.

(Mirmahaleh, M. M., Shoushtari, A. M., & Haghi, A. K. 2014), declared that PPF can change the microstructure of concrete significantly as it reduces the number of voids and the micro-cracking at the interfacial zone between cement particles and aggregates.

4.8 The Effect of Polypropylene fibers (PPF) on Water Penetration Test

Water penetration test was performed on the cubes of size 150 × 150 × 150 mm then the specimens were split from the middle by applying the axial load on the specimen in the universal test machine using the half-circled supplement steel bars, then the depth of water penetrated is measured. Figure 44 and 45 illustrate the results of water penetration test of PPF-NSC, and PPF-HSC, respectively.

These results refer that there is a significant effect of fibers used in the mixes, especially in HSC, despite the effective role of pozzolans as repellant used in the mixtures where they helped in avoiding the water penetration, it can be seen clearly in PPF-HSC, the penetration was less than in the PPF-NSC, that might be attributed to the higher amount of binder used in the mix, hence it can be observed by the compressive strength which increased slightly in PPF-HSC, but decreased in NSC.

(Bošnjak, J., Ožbolt, J., & Hahn, R. 2013) concluded the relation between permeability by studying the effect of PPF on permeability at room temperature, saying that the results of water penetration within the control mix were similar to the PPF mixes. Declared that the addition of PPF does not affect the properties of concrete related to transporting process. However, at elevated temperatures the coefficient of permeability is negatively affected in PPF-concretes. On the other hand, the relationship between strength and permeability was carried out in the research of (Cui, X., Zhang, J., Huang, D., Liu, Z., Hou, F., Cui, S., & Wang, Z. 2017), stated that the strength increases when permeability decreases. Moreover, as denser concrete has lower permeability. The role of cracks in permeability was investigated in the study of (Zhang, P., & Li, Q. F. 2013): the anti-cracking property of PPF, which reduced the number of cracks in the composite blocked the channels of water in the microstructure; as a result, increase the impermeability.

Results of this research are supported by the study of (Zhang, P., & Li, Q. F. 2013). Where the PPF length was from 10 mm to 20 mm with different proportions of SF and fly ash. They deduced that adding PPF to concretes has an observable effect on permeability, where the penetration of water decreased greatly within the mixes contained PPF, fly ash, and SF. More explanation was stated in the study of (Mirmahaleh, M. M., Shoushtari, A. M., & Haghi, A. K. 2014), as nano particles such as, PPF helped in improving the mechanical properties of concrete, like water penetration resistance.

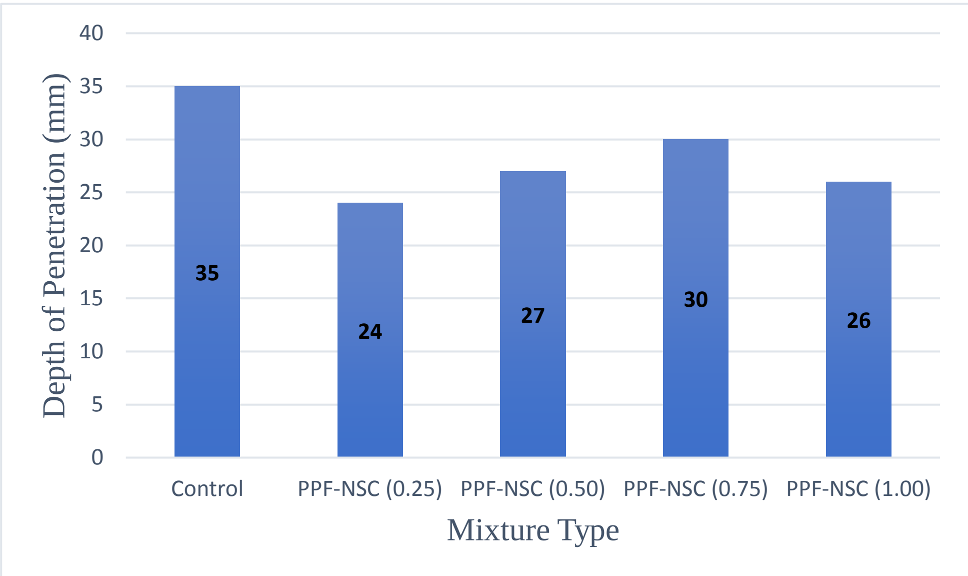

Figure 44: Water penetration test results of NSC

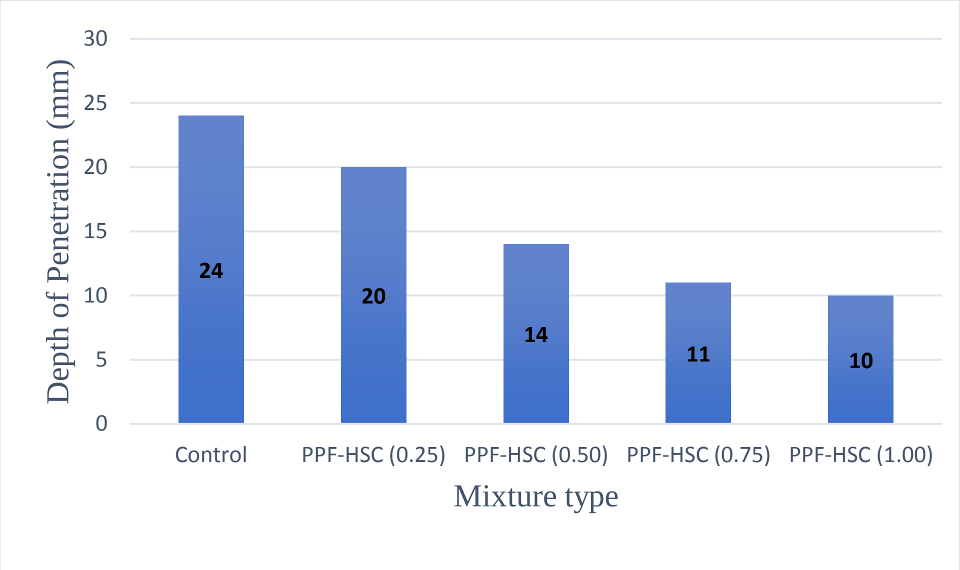

Figure 45: Water penetration test results of HSC

4.9 Effect of Polypropylene fibers (PPF) on Water Absorption Test

One of the major parameters for granting durable concrete is the absorption of water, volume of pores is expressed by porosity, where the pores and cracks are responsible for the absorbed water through the surface into the concrete. The low porous concrete is a high-quality concrete. Figures 46, and 47 show the results of water absorption in NSC and HSC, respectively after 28 days of immersed curing.

As can be seen in Figures 46 and 47, the PPF-HSC mixes showed better behavior with absorbing water after heating of 100 °C. As we mentioned before in the water penetration test, that HSC is denser than NSC, and absorbs less water. Noticing the amount of binder used in HSC mixture where the dispersing particles of SF helped in improving the microstructure of concrete with less pores and voids, less water presence is achieved. Note to mention, that low absorbing property of PPF helped in reducing the amount of water absorbed through immersing process.

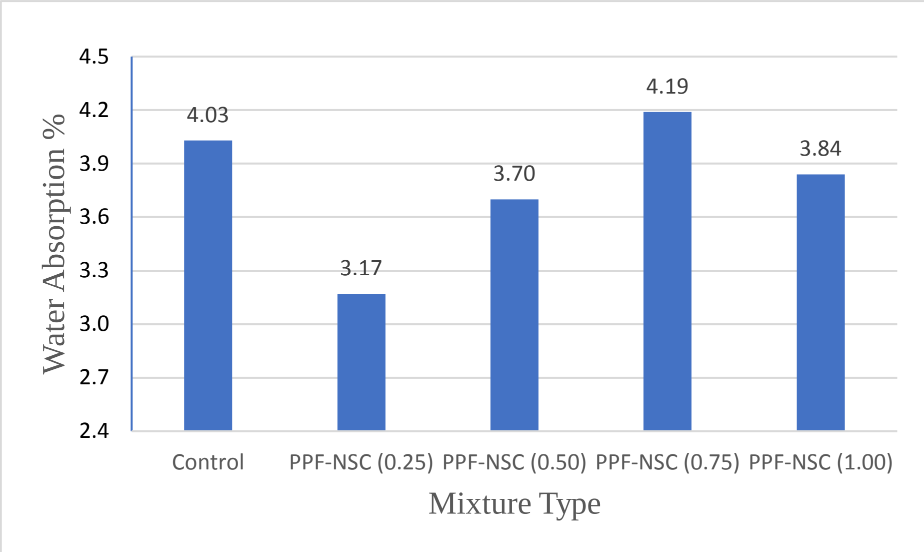

Figure 46: NSC results of water absorption test

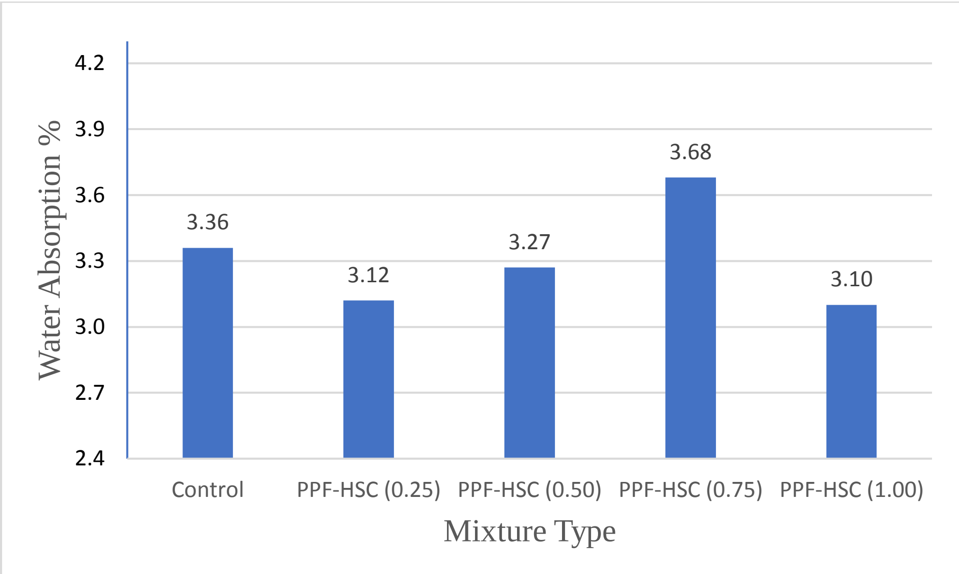

Figure 47: HSC results of water absorption test

Results of this experiment are advocated by the study of (Fallah & Nematzadeh, 2017). They investigated the effect of PPF on absorbing water by fibrous concrete, a deduction was stated; that the process of absorbing water was kept down at low volume of PPF addition. 10 % of SF was used in their mixtures, at 0.2 % of PPF the water absorption was 2.27 %, which was the least among the mixes. (Afroughsabet, V., & Ozbakkaloglu, T. 2015), also studied the effects of PPF on the mechanical properties of concrete at different volumes with 12 mm fiber length. SP and SF were added to their mixtures, as a reduction in the amount of absorbed water was observed below 0.45 % of PPF. Where the ultimate water absorption for each mix was: 0.92, 0.82, and 0.77 % for PPF volumes of 0.15, 0.30, and 0.45 %, respectively.

The difference in HSC concrete behavior between water penetration and water absorption test is may be attributed to the different conditions; penetration test was performed on a single surface where the role of binder and tips of PPF helped in reducing the amount of penetration, whereas in water absorption test, the specimens were immersed in water for 3 days and four surfaces had the chance to absorb such amount of water.

4.9.1 Relationship between Water Absorption and Compressive Strength Tests

Table 39 illustrates the relationship between water absorption and compressive strength tests by different correlations. According to results of these tests in this research and as shown in Table 39; it seems that relations are weak between these tests for PPF-NSC except the polynomial regression which shows a strong relation with R^2 = 0.6263. Nevertheless, for PPF-HSC as shown in Table 40, all regressions used to get R^2 showed good relationship, polynomial regression obviously demonstrates a strong relationship with R^2 = 0.9598 Indicates for PPF-HSC that more water absorbed by concrete specimens less compressive strength acquired by concrete specimens.

Table 39: Relationship between water absorption and compressive strength tests for NSC

	Type of Regression	Equation	R-square
NSC	Exponential	$y = 5.4343e^{-0.008x}$	$R^2 = 0.139$
	Linear	$y = -0.0281x + 5.1362$	$R^2 = 0.1432$
	Logarithmic	$y = -1.449\ln(x) + 9.3905$	$R^2 = 0.1676$
	Polynomial	$y = 0.0116x^2 - 1.1441x + 31.681$	$R^2 = 0.6263$
	Power	$y = 17.159x^{-0.392}$	$R^2 = 0.162$

Table 40: Relationship between water absorption and compressive strength tests for HSC

	Type of Regression	Equation	R-square
HSC	Exponential	$y = 54.39e^{-0.045x}$	$R^2 = 0.5574$
	Linear	$y = -0.1525x + 12.828$	$R^2 = 0.5629$
	Logarithmic	$y = -9.563\ln(x) + 42.84$	$R^2 = 0.5683$
	Polynomial	$y = 0.1821x^2 - 22.886x + 722.17$	$R^2 = 0.9598$
	Power	$y = 372709x^{-2.814}$	$R^2 = 0.5627$

4.10 Effect of Polypropylene fibers (PPF) on Drying Shrinkage

Drying shrinkage test was performed on the specimens till the measurements stopped changing, in other words, when the length between the pins is fixed; the experiment was done, and the results are presented for both mixes in Figures 48, and 49 by the percentage loss of the referenced length of specimen in per mile (‰).

According to Figures 48, and 49, the behavior of PPF-HSC is different than NSC against shrinkage (contraction). Especially at the very first days of testing, that might be attributed to the higher w/c used in NSC mixture, where evaporation took place after removing the specimens from the water tank. And might be attributed to the amount of binder used which it was higher in HSC.

The effect of PPF is obviously shown in the results shown in Figure 48 and 49 for PPF-NSC and PPF-HSC. It is also explained in the research of (Zhang, P., & Li, Q. F. 2013), since the addition of PPF on concrete restricted the effect of drying shrinkage, with the presence of SF, fly ash, and water reducing agents, where the length of fibers was between 10 and 20 mm. Others also support our findings such as (Salih SA, Al-Azaawee ME. 2008), that mixing PPF within the cement mortar reduced the drying shrinkage of the mix. It can be noticed in the PPF-NSC mix. At 1.00 % PPF the shrinkage remained restricted for the first week, and then shrinkage increased slightly till the day 20. Hence it had the best shrinking resistance. A clear reason can be given for the reduction of drying shrinkage; caused by the addition of PPF to concrete, since PPF catch up part of free water existed in the cement paste by the formation of pores resulting in increase of moisture presence for the first days that prevents the occurrence of drying shrinkage. Investigation of drying shrinkage with PPF was carried out by (Saje, D., Bandelj, B., Šušteršič, J., Lopatič, J., & Saje, F. 2010) where they used Furrowed dried fiber type in their study of 12 mm length, recording such results of this research, with reason of absorbing water by PPF.

Lower w/c in HSC mix attain to decrease the porosity in concrete where the pores will have minor amount of water after hydration; as a result, hardened concrete will have less shrinking while evaporation. on the other hand, denser concrete was unable to have more water for evaporation process which affects shrinkage as well. That happened in the control mix of HSC, where it had a better behavior against shrinkage than fibrous mixtures of HSC.

The control mixes were affected by drying in the very first hours clearly, control mix of NSC in particular; the reason was mentioned in the study of (Mangat PS, Azari MM.1984). Shrinkage creates an internal tensile stress within the matrix; PPF constrain shrinkage by shear along the fiber matrix interface where the matrix gets stiffer resulting in shrinkage reduction due to the addition of fibers. On the other hand, (Okan K, Cengiz DA. 2013) referred some information about PPF, and drying shrinkage. Explaining that PPF work as restrainer of the internal movements into the mortar by stitching the fine cracks, thus drying shrinkage is reduced

It is obvious from the presented measuring results in Figure 51 that drying shrinkage of HSC was increasing when PPF addition was increased. (Saje, D., Bandelj, B., Šušteršič, J., Lopatič, J., & Saje, F. 2010). Stated that the addition of PPF in the mixture gives a chance to snatch quantity of water by fibers from the cement paste in the initial period in particular, which means that more water might be usable into the surrounding hardened cement pastes. As drying shrinkage is taking place. In other words, it can be described that adding PPF to HSC was not effective, hence it was significantly effective at 1.00 % of PPF in NSC.

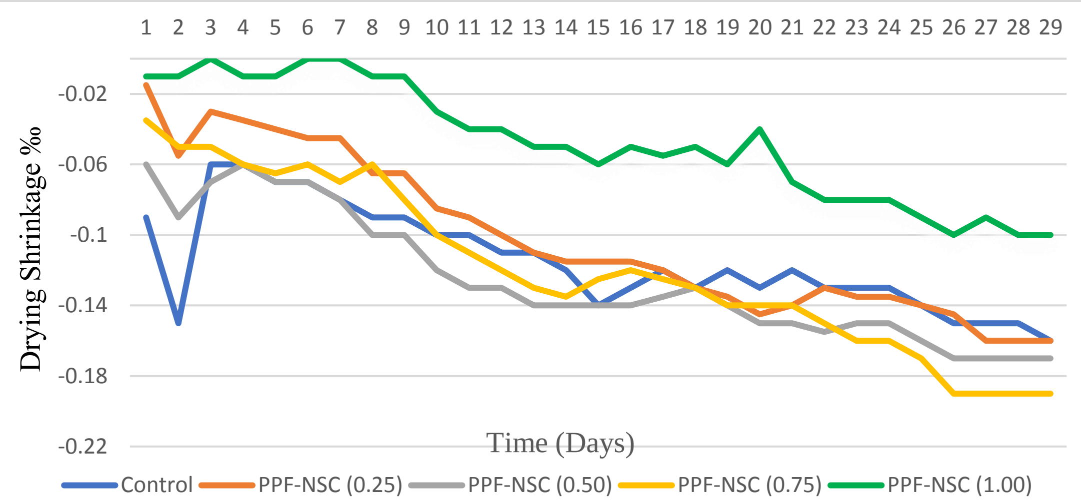

Figure 48: Drying shrinkage of PPF-NSC

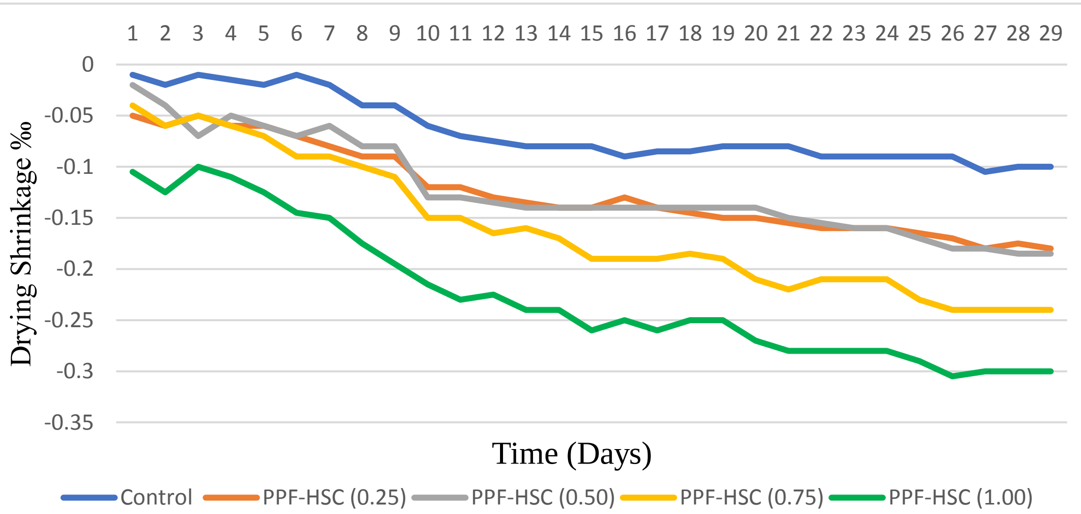

Figure 49: Drying shrinkage of PPF-HSC

4.11 Cost of Concrete and Polypropylene fibers (PPF)

PPF is a by-product material which can be used as a replacement of aggregates in concrete mixture, or as an addition by volume for concrete composite. Since it has been used as an additive in this research. The cost of concrete per meter cube increased clearly as PPF percentage increased; 0.25, 0.50, 0.75, and 1.00 % of PPF were added to NSC and HSC, C30 and C55, respectively. The C40 concrete is considered as the average cost for both concretes where one-meter cube cost 396 TL (75.4 $).

Adding PPF to concrete will increase the manufacture expense of concrete by about 76 TL (14.5 $). Table 41 illustrates the cost for different proportions of PPF were used in this research in USD ($).

Table 41: Extra cost of concrete by adding PPF with different proportions.

PPF volume added (%)	Concrete cost for meter cube ($)
0.00	75.4
0.25	80.2
0.50	85.1
0.75	90.0
1.00	94.7

As shown in Table 41, an increase in the cost of concrete as PPF was added by volume where the percentage of cost rose up by 25.6 % at 1.00 % of PPF compared to control mix. The cost of concrete increased by 6.5 % at 0.25 % of PPF, thus for PPF of 0.5 % an increase of 13.0 % was recorded in cost compared to control mix. Which can be considered as a low cost compared to control mix. All cost calculations were done according to the currency prices by mid of December 2018.

Chapter 5

CONCLUSION

In this thesis, a comprehensive experimental procedure on the addition of PPF to NSC and HSC at different proportions (0.00, 0.25, 0.50, 0.75 and 1.00 %) was performed. Using w/c ratio of 0.5 for NSC and 0.4 for HSC, 1 % of SP was used for NSC and 2 % for HSC, and 5 % of SF was used for NSC and 10 % for HSC. The effects of PPF on the mechanical properties was investigated. Parallel and cross comparison of the experimental results were performed to draw conclusions on the results of the experiments.

1. The workability of the concrete specimen was tested using slump and VeBe tests. The results of slump test show decreases in workability when PPF are added to concrete which is similar to the results of previous studies that examined the effect of PPF on slump test in concrete. The regression results show a strong relationship between the results of the slump, and VeBe which confirms the results. It can be concluded from the workability test result that addition of PPF in concrete decreases the workability of NSC more than HSC, where about 70 % reduction was recorded with 1.00 % addition of PPF to concrete.
2. The compressive strength results of our experiments showed decrease in compressive strength when PPF was added to NSC. However, compressive strength slightly increases when PPF is added to HSC. The maximum

compressive strength achieved is 63.7 MPa for PPF-HSC at PPF addition of 0.5 %. The results of compressive strength is consistent with studies in the literature such as (Mazaheripour et al., 2011) and (Fallah & Nematzadeh, 2017).

3. The splitting tensile strength results of the experiment shows increase in tensile strength compared to the control specimen in both NSC and HSC. The highest splitting tensile strength was observed for PPF-HSC (0.25) with 5.37 MPa, an increase of 5.10 % compared to the control specimen. PPF-NSC (0.25%) showed a tensile strength of 4.28 MPa with 20.56 % increase. Concluding that adding PPF to concrete was more effective in NSC for splitting strength. The splitting tensile strength results of our experiment are consistent with other studies such as (Afroughsabet & Ozbakkaloglu, 2015) and (Fallah & Nematzadeh, 2017).
4. Using regression analysis, a relationship between compressive strength and splitting tensile strength was explored. Using the 28 days results for PPF-NSC, polynomial regression analysis shows a strong relationship between compressive and splitting tensile strength of R^2 = 0.8415. The relationship between compressive strength and splitting tensile strength for PPF-HSC is not as strong as PPF-NSC because the R^2 using polynomial regression was 0.52911.
5. Added PPF on NSC, and HSC increased the flexural (rupture) strength significantly at day 7 and 28. The maximum flexural strength was recorded at PPF-HSC (0.75) of 22.95 MPa with increase percentage of 24.05 % compared to the control mix. For the NSC at 0.25 % of PPF had the maximal flexural strength of 19.63 MPa, with gaining strength of 23.46 % than reference mix.

6. Remarkable results had been observed to conclude that PPF addition above 0.50 % in particular enhances the concrete ductility. However, the literatures assured that using SF in the mixture leads to increase the brittleness of concrete.
7. Both types of concretes contain PPF showed different results, and similar ones in some experiments; finalizing the conclusion of results after, and before exposing the specimens of 100 × 100 × 100 mm to heat in the following points:

- PPF-NSC, and PPF-HSC at 1.00 % of PPF showed the least compressive strength loss after 200 °C by 14.5 %, and 8.90 %, respectively. A point deserves to be mentioned that the compressive strength loss after 100 °C was insignificant within the both mixes. PPF-HSC, and PPF-NSC specimens of 0.25 % of PPF recorded the highest compressive strength results among the fibrous mixes. However, the maximum strength percentage loss was showed by PPF-NSC (0.25) of 41.2 %.
- UPV results showed that concretes of PPF deteriorated after heating. However, ultrasonic pulse velocity remained up to 4.20 km/s in NSC, and up to 4.44 km/s in HSC, where it can be said that good concrete quality is reserved after heating. In addition, the relationship between the compressive strength and UPV results before and after heat exposure was strong.
- The addition of SF, and PPF on both concretes showed a substantial increase in splitting tensile strength before, and after heating, furthermore the splitting tensile strength of the fibrous specimens after heating remained higher than control mixes.
- The behavior of PPF under heat exposure played an essential role in the microstructure of both types of concrete, such as: cracking resistance, reducing

the interfacial voids, and releasing stresses of pore pressure build up results from evaporating and heating.

- The relationship between UPV and compressive strength before, and after heating remained strong at both mix types.
- The melting PPF at high temperatures helped to mitigate cracking and spalling within the fibrous mixtures.

8. Using SF, and PPF in the composites led to a decrease in the amount of penetrated water through the concrete surfaces Where the PPF-HSC (1.00) got water penetration depth of 10 mm less than control mix by 58.34 %.
9. Absorbing water property was higher in PPF-NSC. Where the highest amount of water absorbed was by NSC-PPF (0.75) of 4.19 % followed by 3.68 % in PPF-HSC (0.75). And HSC had less absorbing rate of water than NSC.
10. Adding PPF to the concrete was remarkable in drying shrinkage test, where it badly affected HSC, and greatly increased the shrinkage resistance in NSC. PPF-NSC (1.00) had the best behavior of shrinking, where it had the least shrinking measurement among NSC mixtures. For HSC, the drying shrinkage was increased when PPF addition increased. Where the maximum shrinking measurement was recorded at PPF-HSC (1.00) of (- 0.3 ‰).

After concluding the results and analysis of this research, a suggestion of the appropriate PPF proportion is presented below. Upon a marked property of concrete, regarding to specific conditions; a volume fraction of PPF and other concrete components are specified. According to the physical and mechanical properties in normal conditions, the following proportions are suggested with the reason:

- PPF, quantity of 0.25 % is preferred in NSC due to its peculiar results in compressive strength, splitting tensile strength, flexural strength, water penetration, water absorption and shrinking resistance. Moreover, well compacted mix with high workability, and good formability.
- PPF, quantity of 0.25 % is the better choice among the fiber mixes due to its ripe results in splitting tensile strength, compressive strength, water absorption, and drying shrinkage tests. In addition, high workable mix with desirable consistency with no bleeding or segregation.

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APPENDIX

Table a: Mix Design Table for NSC (C30)

Concrete mix design form

Job title NSC

Stage	Item	Reference or calculation	Values
1	1.1 Characteristic strength	Specified	30 N/mm² at 28 days; Proportion defective 10 %
	1.2 Standard deviation	Fig 3	4.0 N/mm² or no data ... N/mm²
	1.3 Margin	C1 or Specified	(k = ...) 1.28 × 4.0 = 5.2 N/mm²; 5.0 N/mm²
	1.4 Target mean strength	C2	30 + 5.0 = 35 N/mm²
	1.5 Cement strength class	Specified	42.5/~~52.5~~
	1.6 Aggregate type: coarse Aggregate type: fine		Crushed/~~uncrushed~~ Crushed/~~uncrushed~~
	1.7 Free-water/cement ratio	Table 2, Fig 4	0.62 } Use the lower value 0.50
	1.8 *Maximum free-water/cement ratio*	*Specified*	0.50
2	2.1 Slump or Vebe time	Specified	Slump 50-100 mm or Vebe time - s
	2.2 Maximum aggregate size	Specified	20 mm
	2.3 Free-water content	Table 3	225 kg/m³
3	3.1 Cement content	C3	225 ÷ 0.5 = 450 kg/m³
	3.2 *Maximum cement content*	*Specified*	- kg/m³
	3.3 *Minimum cement content*	*Specified*	- kg/m³
			use 3.1 if ≤ 3.2 use 3.3 if > 3.1 — 450 kg/m³
	3.4 Modified free-water/cement ratio		/
4	4.1 Relative density of aggregate (SSD)		2.7 known/assumed
	4.2 Concrete density	Fig 5	2370 kg/m³
	4.3 Total aggregate content	C4	2370 − 225 − 450 = 1695 kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 μm sieve	66 %
	5.2 Proportion of fine aggregate	Fig 6	28 %
	5.3 Fine aggregate content	C5	0.28 × 1695 = 475 kg/m³
	5.4 Coarse aggregate content	C5	1695 − 475 = 1220 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	450	225	475	405	815	
per trial mix of ... m³						

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface dry condition.

Table b: Mix Design for HSC (C55)

Concrete mix design form — Job title: **HSC**

Stage	Item	Reference or calculation	Values
1	1.1 Characteristic strength	Specified	**55** N/mm² at **28** days; Proportion defective **10** %
	1.2 Standard deviation	Fig 3	**4.0** N/mm² or no data .... N/mm²
	1.3 Margin	C1 or Specified	(k = ...) **1.28** × **4.0** = **5.2** N/mm²; **5.0** N/mm²
	1.4 Target mean strength	C2	**55** + **5.0** = **60** N/mm²
	1.5 Cement strength class	Specified	42.5/~~52.5~~
	1.6 Aggregate type: coarse Aggregate type: fine		Crushed/~~uncrushed~~ Crushed/~~uncrushed~~
	1.7 Free-water/cement ratio	Table 2, Fig 4	**0.43** } Use the lower value **0.40**
	1.8 *Maximum free-water/cement ratio*	Specified	**0.40**
2	2.1 Slump or Vebe time	Specified	Slump **50-100** mm or Vebe time **-** s
	2.2 Maximum aggregate size	Specified	**20** mm
	2.3 Free-water content	Table 3	**225** kg/m³
3	3.1 Cement content	C3	**225** ÷ **0.4** = **565** kg/m³
	3.2 *Maximum cement content*	Specified	**-** kg/m³
	3.3 *Minimum cement content*	Specified	**-** kg/m³
			use 3.1 if ≤ 3.2 use 3.3 if > 3.1 — **565** kg/m³
	3.4 Modified free-water/cement ratio		**/** — **/**
4	4.1 Relative density of aggregate (SSD)		**2.7** known/assumed
	4.2 Concrete density	Fig 5	**2380** kg/m³
	4.3 Total aggregate content	C4	**2380** − **225** − **565** = **1590** kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 µm sieve	**66** %
	5.2 Proportion of fine aggregate	Fig 6	**32** %
	5.3 Fine aggregate content	C5	**0.32** × **1590** = **510** kg/m³
	5.4 Coarse aggregate content	C5	**1590** − **510** = **1080** kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	Coarse aggregate (kg) 20 mm	Coarse aggregate (kg) 40 mm
per m³ (to nearest 5 kg)	**565**	**225**	**510**	**360**	**720**	
per trial mix of .... m³						

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface dry condition.