Experimental Study on Some Properties of Recycled Polypropylene Plastics as a Partial Replacement of Coarse Aggregate in High Strength and Normal Strength Concretes

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ABSTRACT

Previously, various studies were performed to identify safety and environmentally friendly methods for disposing of plastics. Recently, various forms of plastics have been incorporated in concrete to prevent direct contact of plastics with the environment because concrete has a longer service life. In this thesis, the effects of coarse aggregate replacement of Polypropylene as a waste material on fresh and hardened properties of normal strength concrete (NSC) and high strength concrete (HSC) was investigated. To do so, different percentages of polypropylene were replaced by various volumes (0%, 10%, 20%, 30%, 40% and 50 %) of normal and high strength concretes, with the water to cement ratio of 0.58, 0.34 for normal and high strength concrete, respectively. In addition, Superplasticizer (Glenium 27) was added to the NSC and HSC mixed by 0.3% and 2% cement weight, respectively.

Slump and VeBe time tests were done to analyse the physical properties of fresh concrete. Moreover, the influences of PP replacement in the hardened concrete were executed by performing splitting tensile strength (f_s), compressive strength (f_c) and flexural strength (f_f) tests. Rapid chloride permeability (RCP), heat degradation at 200 °C, water absorption, and non-destructive tests such as Ultrasonic Pulse Velocity (Pundit) and Schmidt hammer (rebound) were also conducted.

The results showed changes in mechanical properties of normal strength concrete and high strength concrete as the percentages of PP increases. The amount of f_s, f_c, and ff of normal and high strength concrete decreased with the increase in the amount of polypropylene at 28 days.

Furthermore, high water absorption was observed with the increasing of PP. According to the results of the Pundit test the replacement of Polypropylene increased the quality of concrete up to 50% in comparison with the control samples. It is worth noting that negative effects in f_c, f_s, ultrasonic pulse velocity, and crack development were observed after 200 °C heat exposure.

Keywords: Polypropylene (PP), Normal strength concrete, High strength concrete, workability, Mechanical properties, Non-destructive test, Water absorption, Permeability, Heat exposure

ÖZ

Geçmişte plastiklerin atılmasında güvenli ve çevre dostu yöntemler belirlemek için çeşitli çalışmalar yapılmıştı. Son zamanlarda, plastiklerin israfını ve çevreye etkilerini azaltmak için betona çeşitli plastikler eklenmiştir.

Bu tez çalışmasında, atık agrega olarak polipropilenin iri agrega ile değişiminin, normal mukavemetli (NMB) ve yüksek mukavemetli betonun (YMB) taze ve sertleşmiş özelliklerine etkisi incelenmiştir. Farklı polipropilen miktarları, normal mukavemet ve yüksek mukavemetli betona hacimsel olarak (%0, 10, 20, 30, 40 ve 50) katılmıştır ve normal mukavemetli beton için 0.58 ve yüksek mukavemetli beton için 0.34 su-çimento oranı kullanılmıştır. Ek olarak, NMB ve YMB karışımlarına sırasıyla %0.3 ve %2 (çimento oranında) süper akınlaştırıcı (Glenium 27) kullanılmıştır.

Taze betonun fiziksel özelliklerini analiz etmek için slamp ve VeBe deneyleri yapılırken, polipropilen agreglı sertleşmiş betonun mekanik özellikleri üzerindeki etkisi, basınç dayanımı deneyi, çekme dayanımı deneyi, eğilme dayanımı deneyi, Ultrasonik Darbe Hızı (pundit) deneyi (Pundit), Schmidt çekici deneyi, su emme deneyi, hızlı klorür geçirgenliği deneyi ve ısı bozulması deneyi (200 °C) yapılarak belirlenmeye çalışılmıştır.

Sonuçlara göre ise polipropilen dayanım yüzdeleri arttıkça normal dayanımlı betonun ve yüksek dayanımlı betonun mekanik özelliklerinde değişiklikler olduğunu göstermektedir. Basınç dayanımı, çekme dayanımı, normal ve yüksek mukavemetlı betonun bükülme dayanımı polipropilenin artmasıyla 28 günde düşmüştür.

Polipropilen miktarı artışı ile betonda yüksek su emme gözlemlenmiştir. Pundit deneyi, kontrol numunelerine kıyasla% 50'ye kadar polipropilen ihtiva eden betonların beton kalitesini iyileştirdiğini göstermiştir. Basınç mukavemeti, basmada yarma mukavemeti, ultrasonik hızı ve çatlak gelişimindeki negatif etki betonlar 200 °C ısıya maruz kaldıktan sonra gözlenmiştir.

Anahtar Kelimeler: Polipropilen (PP), Normal dayanımlı beton, Yüksek dayanımlı beton, Işlenebilirlik, Mekanik özellikler, Tahribatsız deneyler, Su emme, Geçirgenlik, Isıya maruz kalma

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LIST OF ABBREVIATIONS

PP	Polypropylene
HSC	High Strength Concrete
NSC	Normal Strength Concrete
CA	Coarse Aggregate
FA	Fine Aggregate
RCPA	Recycled Concrete Plastic Aggregate
SP	Superplasticizer
f_c	Compressive Strength
f_s	Splitting Tensile Strength
f_f	Flexural Strength
W/C	Water to Cement Ratio
RCP	Rapid Chloride Permeability
UPV	Ultrasonic Pulse Velocity
RD	Relative Density
NDT	Non Destructive Test
ITZ	Interfacial Transition Zone
DLBD	Dry Loose Bulk Density

Chapter 1

INTRODUCTION

1.1 Overview of Study

Plastic has turned into a fundamental part of current life, with a tremendous increase in the plastic production throughout the most recent decades all over the world. However, the generation of plastic-related waste has changed to one of the main challenges of the industries. Reusing the waste plastic seems to be a reliable solution to reduce its ecological effects.

Growing interest in using concrete leads to the utilization of great amount of wasted materials in the environment which can be widely consumed in basic products (Topcu & Şengel, 2004).

Subsequently, using waste and reused plastic for construction purposes is an effective solution for recycling the plastic waste. Therefore, the application of plastic waste in cement has gotten huge consideration lately (Gu & Ozbakkaloglu, 2016).

HSC (High Strength Concrete) has been broadly utilized, lately. Because of the better mechanical properties of HSC over ordinary concrete, using this type of concrete is more favorable, nowadays. Luckily, the majority of materials used in production of HSC are by-products. Therefore, using these materials can be helpful to produce low-cost concrete, more environmentally safe and less vitality escalated by reducing the amount of cement required (Shannag, 2000).

A meaning of HSC in the quantitative term is beyond the realm of imagination. In the North American practice, HSC is typically viewed as concrete with a minimum f_c of 45 MPa at 28 days. In the latest CEB-FIP State-of-the-art-report, HSC it is characterized as concrete possessing a minimum f_c of 60 MPa at 28 days. In many countries, concrete producers subjectively characterized HSC as concrete, if normal weight aggregate is utilized having cube strength of above 45 MPa at 28 days. Thus, the definition of HSC is relative; it relies on both the period being referred to and the area (Shannag, 2000).

Normal strength concrete (NSC) or normal weight concrete, on the other hand, is produced through mixing the two common components of water and cement under standard circumstances NSC has a setting time of 30 - 90 minutes. However, factors such as the humidity of the surrounding environment and fineness of cement may change the setting time. In this type of cement, the strength and growth begins after 7 days of 10 to 40 MPa prevalent strength values. 75 to 80 percent of the complete intensity is achieved at about 28 days (ASTM C913-18).

Although much research has been carried out on fire resistance concrete, since HSC is to some extant a new type of concrete, knowledge of fire-prone performance of HSC is restricted compared to that of NSC. The probable reason could be the dense in that cement paste prevents the humidity vapor from fleeing under elevated temperatures. As a result, a substantial pore pressure is distributed all over the concrete. Generally, the spalling problem, of course, resulted from of the unpredictable reaction of HSC to different temperature degrees in fire circumstances. In addition to spalling, it is also very essential to guarantee the security of the mechanical strength of HSC in higher heat degrees in comparison to that of the NSC (Chan, Peng, & Chan, 1996).

1.2 Aim of the Study

In this study, a reused polypropylene (PP) polymer with a distinct proportion is replaced with coarse aggregates in normal and high strength concrete by PP quantity. Influences of this concrete substitution have been explored with several laboratory experiments. These studies will report the influences of PP on the properties of fresh concrete such as slump, VeBe and unit weight of concrete, as well as the mechanical properties of hardened concrete such as f_s, f_c, f_f, Schmidt hammer, ultrasonic pulse velocity (UPV), water absorption, heat degradation and rapid chloride permeability (RCP) tests.

After performing the tests, the findings will be analyzed and compared in order to find the optimum percentage of PP replacement with normal weight coarse aggregates for both NSC and HSC.

1.3 Thesis Outline

In Chapter Two, the polypropylene substitution research on different types of concrete and its replacement with natural coarse aggregate were described (or were explained in detail).

Further, the way tests and research are conducted are discussed in Chapter Three. In Chapter Four, the outcomes of the tests are compared and summarized based on appropriate scientific reasons. Chapter Five contains the conclusion section of the thesis and an overview to further research in this area.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Plastic-derived products have been known as the most widely used products in packaging all over the globe. Nevertheless, a significant amount of plastic usage has resulted in an exponential rise in plastic waste. The recycling of plastic waste in a valuable and widely used material such as concrete tends to a proper application of plastic waste (Kamaruddin, Abdullah, Zawawi, Zainol, & Iop, 2017).

By exchanging temporary aggregate used in the preparing of concrete mixtures, additional solutions to other prospective uses of plastic waste will be achieved.

Using HSC has been steadily decreasing in the building industry due to the inferior quality and financial issues raised in using HSC in comparison with NSC which is widely used in multiple civil engineers projects. In the first exploratory research on the dwellings of concrete produced utilizing reused polypropylene (PP) coarse aggregates eight batches of concrete were produced with distinct RPA components. In addition, the impact of RPA material on elastic modulus, $f_{f,}$,$f_{s,}$ and f_c, strengthened density of each sample were explored. The findings showed that the physical characteristics of RPACs were smaller than those of concretes generated with natural aggregates(Ozbakkaloglu, Gu, & Gholampour, 2017).

There are a number of significant variables that need to be taken into account when implementing plastic waste and partial aggregate substitution. The current study, an effort is made to investigate the properties of concrete which were reported to be used in the literature. This includes the Physical characteristics of concrete including fresh density, slump value, VeBe time, mechanical properties including, f_s, f_f and f_c, rebound value, UPV, and durability characteristics including rapid chloride permeability, water absorption, and heat degradation at 200 °C.

2.2 Components of Concrete

Concrete is made of sand, water, soft and rough aggregates. It is the most common building material considering the fact that the raw materials used in the concrete are readily accessible at comparatively small cost (Yin et al., 2015). It also offers a stronger strength than any other construction material.

Concrete can actually endure greater stress, but poor tensile strength. Typically, aggregates account 65% to 80% of the quantity of the concrete which plays an important role in concrete properties such as workability, volume stability, strength and durability. In fact, aggregates take an essential part in the growth of concrete strengths that can be defined by their slump value, f_c, thermal stabilization and durability (Saikia & De Brito, 2014)

2.3 High Strength Concrete [HSC]

Higher resistance is achieved by reduction in homogeneity, micro-cracks and porosity in the Interfacial Transition Zone (ITZ) and concrete. Utilizing SP and additional cementing products like granulated ground blast furnace slag, silica fume, fly ash and artificial pozzolan can also result in higher resistance. The concept of HSC in numerical terms that is generally appropriate all over the world is not feasible. In North American practice, for instance, high strength concrete is generally regarded to have a minimum f_c of 45 MPa at 28 days. –According to CEB-FIP report on high strength concrete, a minimum 28-day f_c of 60 MPa is defined as the HSC.

In most developed nations, HSC was ambiguously defined by the concrete manufacturers as having cube strength of more than 42 MPa at 28 days by using normal weight aggregate (Shannag, 2000).

2.4 Normal Strength Concrete [NSC]

Concrete as a building material contains both normal and high strength concrete on the basis of its f_c. The compressive strength of NSC is between 20 and 40 MPa. The differentiating variables between normal and high-strength concrete have also altered throughout the years and from place to place. For 100 years, a concrete type with 28 MPa strength in compressive was regarded as the HSC. Practically speaking, normal strength concrete is the most widely utilized forms compared to HSC (Neville, 1995).

2.5 Polypropylene [PP]

Polypropylene is commonly utilized in containers, the car industry and electrical equipment. The worldwide industry for PP was around 55 million tons in 2013 (Ceresana, 2014). In addition, 7.3 million tons of PP goods, accounting for 22.8% of the whole plastic products was the 2nd most commonly used plastic form, which was manufactured in the US in 2012 (EPA, 2014) . Nevertheless, reuse percentage of PP was only limited to 0.8% (EPA, 2014) making it the lowest reused post-consumer plastics. Thus, it is plausible that using recreated PP in concrete is an appealing way to tackle the PP waste recycling issue (Ozbakkaloglu et al., 2017).

The Polypropylene properties are listed below:

- Translucent
- Toughness
- Good fatigue resistance
- Integral hinge property
- Semi-rigid
- Good chemical resistance
- Good heat resistance

PP does not pose stress-cracking issues and provides great electrical and chemical strength at greater altitudes. Although the characteristics of PP are comparable to those of polyethylene, there are particular variations.

These include reduced density, higher softening point (PP does not melt below 160 °C, polyethylene, a more prevalent plastic, anneals at around 100 °C) and greater rigidity and durability.

2.6 Workability of Concrete

The workability of concrete is described as being the ease of mixing, transporting, placing and finishing without separation. Slump test is used widely for the location. The mold for the slump test is a 305 mm elevated cone frustum. It is carried out in accordance with ASTM C 143-78. After wrapping the concrete in a cone, it is raised gently, and then the unloaded concrete will collapse. Decreased concrete height is called a slump (Siddique, Khatib, & Kaur, 2008).

A shaking panel is used to assess the rigid stability to highly moist concrete mixtures. The density of the compacted sample is evaluated by determining the mass of the strengthened sample and separating it based on its quantity (ASTM C1170/C1170M-14).

2.6.1 Efficacy of PP on Workability as a Concrete CA Replacement

Workability of both HSC and NSC mixtures reduces with a rise in the proportion of the Recycled Plastic Aggregate (RPA). This decrease can reach up to 33.3 and 2.9 per cent, respectively, in NSC and HSC combinations, primarily due to the rounded form and non-uniformity of RPA (Ozbakkaloglu et al., 2017).

2.7 Compressive Strength [f_c]

After casting concrete, it's allowed to get hard for 24 hours in the curing room. Then, demolded samples are kept in water tank for the next 27 days. Three samples are broken by using electrohydraulic press. The average of sample results have been recorded as a f_c (Pacheco-Torgal, 2018).

2.7.1 Efficacy of PP on Compressive Strength [f_c] as a Concrete CA Replacement

Compressive strength (f_c) of the distinct mixtures at 7-, 14-, 21- and 28-day with a rise in RPA level led to a reduction in f_c on every curing era for NSC and HSC mixtures. The pattern could be ascribed to the higher elastic modulus of the NAs than the RPA, lower bonding strength among cement paste and the ground of the coarse RPA, and controlled hydration of cement around the surface of RPAs which is caused due to hydrophobic pattern of the RPA (Gu & Ozbakkaloglu, 2016; Ismail & Al-Hashmi, 2008).

2.8 Splitting Tensile Strength [f_s]

One of the significant characteristics of concrete is f_s that significantly affect the magnitude of the cracks in the structural elements.

Moreover, because of its frail nature, concrete shows a reduction in stress beyond the peak point with an increase in the deformation. The immediate pressure is not expected to resist the tension. As a result, being exposed to tensile forces which are stronger than the tensile strength, concrete creates cracks. Hence, it is essential to assess the tensile strength of the concrete in order to determine the force that the concrete elements may break.

In addition, the tensile strength test on the concrete cylinder is a technique for determining the tensile strength of the concrete. The method is focused on ASTM C496 (Standard Test Method of Cylindrical Concrete Specimen) which is comparable to other standards such as IS 5816 1999.

2.8.1 Efficacy of PP on Splitting Tensile Strength [f_s] as a Concrete CA Replacement

Splitting tensile strength (f_s) of both HSC and NSC mixtures reduces with a rise in RPA levels. The fragile bond between soft RPAs and cement paste can be the result of the soft ground and hydrophobic characteristics of the RPAs, which restricts cement hydration reactions around the RPAs (Saikia & De Brito, 2014).

2.9 Flexural Strength [f_f]

Flexural strength (f_f) is also a concern in unreinforced concrete structures, such as reservoirs, which specially happens during earthquakes. Other structures, such as road and foot-bridges, are built considering the amount of f_f which involves tension strength (Neville, 1995).

In order to measure the f_f of concrete mixtures, a number of standard tests, directly and indirectly, can be conducted. Because typically there are some challenges and a great extent of complication in deriving direct dimensions of either mortar or concrete tensile strength, scientists generally use splitting, flexural, and other indirect tests. One such indirect experiments is the three-point flexural strength experiment by which the variables affecting f_f can be measured and investigated (Neville & Brooks, 1987).

2.9.1 Efficacy of PP on Flexural Strength [f_f] as a Concrete CA Replacement

With the rise in the scrap plastic proportion in these mixtures, the f_f of recycled plastic blend concrete is susceptible to decline. This pattern could be ascribed to reduction in the bond between the waste PA surface and cement particles (Rai, Rushad, Kr, & Duggal, 2012).

Flexural strength of PA concrete is normally lower than ordinary concrete with the identical W/C ratio, which is the scenario for f_c (Juki et al., 2013).

HSC and NSC mixes f_f declined as the RPA percentage increases. And can also be described by the fragile bonding between soft RPA and cement paste considering the soft ground and hydrophobic character of RPA, which limits cement hydration close the bottom of RPAs (Saikia & De Brito, 2014).

2.10 Ultrasonic Pulse Velocity [UPV]

Non-destructive concrete test is preferred to conventional compression examinations. And the implementation of UPV had been extensively researched for centuries in the non-destructive evaluation of concrete performance.

This NDT measurement has been proved to be of real importance in all constructions serving the purpose of testing and as an effective tool for inspection of concrete quality in concrete structures (Kewalramani & Gupta, 2006).

To investigate the homogeneity of concrete structure, the UPV test is performed. There are currently limited numbers of studies which evaluate the UPV (ultrasonic pulse velocity) of plastic-containing concrete. This plastic-containing concrete has reduced UPV due to pores growth.

2.10.1 Efficacy of PP on UPV as a Concrete CA Replacement

The first UPV technique was proposed by Long, Kurtz and Sandenaw (1945) to use the non-destructive test methods in order to evaluate the structure of concrete by transferring an excessive wave to move a recognized range through the concrete. Some research in earlier literature used concrete UPV test to estimate f_c, and studying the connection between UPV and f_c is essential in such research (Popovics, Song, Achenbach, Lee, & Andre, 1998).

Many factors, such as blend ratios, aggregate form, concrete age, moisture content, and others, influence pulse velocity (Popovics, Rose, & Popovics, 1990). The variables that considerably affect the concrete resistance may have little impact on UPV. As an outcome, a pulse velocity method strength assessment is not a wide spectrum technique. Therefore, the derivative relationships can be used at any moment during the delivery period for constructions produced from the same components (Mahure, Vijh, Sharma, Sivakumar, & Ratnam, 2011).

To examine the homogeneity and concrete structure, the UPV test is performed. There are currently few studies which evaluate the UPV of plastic-containing concrete. This concrete-containing plastic has reduced UPV due to pore growth.

Also UPV strength was affected by the water/cement proportion. The greater water/cement ratio puts excess water in concrete pores, resulting in the creation of vacant spaces during dehydration which eventually lead to a decrease in UPV (Sharma & Bansal, 2016).

2.11 Schmidt Hammer

One of the primary problems facing NDT is concrete resistance evaluation via non-destructive methods (NDT) on board. A huge number of experimental programs have been carried out both in the laboratory and on-site over the past 50 years, and a variety of models have been proposed to correlate concrete strength with rebound hammer calculations. It is widely agreed that none of these models can predict the concrete strength accurately with sufficient accuracy to use the evaluated value for further structural computations (Denys & Fernández-Martínez, 2014).

2.11.1 Efficacy of PP on Schmidt Hammer as a Concrete CA Replacement

A purpose of concrete rebound experiments is generally to discover a connection within an appropriate mistake between ground hardness and f_c.

Experiments have shown, however, that rebound measurements are susceptible to near-surface characteristics, throwing concerns about the test's precision in estimating f_c.

Schmidt Hammer test is affected by some factors that affect the surface hardness. These factors are moisture content, age, smoothness of surface, carbonation, and temperature of concrete. Therefore, the test is not an alternative for the actual compressive strength of concrete. Because of these variables, it has been shown that the dimensions of the rebound bar are not distinctive and the sample outcome depends on the features of the finished concrete, which in fact differs with the distinct construction parameters (Tarranza & Sanchez, 2014).

2.12 Water Absorption

The durability of concrete mainly depends on transportation characteristics that are affected by the porous structure. Transport in cemented structures is governed by three primary processes: permeability, diffusion and absorption (reference is required). Permeability is the metric of fluid flow under a gradient of stress, while diffusion is ion motion because of a gradient of intensity. Absorption can be defined as the capillary suction capability to absorb water. The quantities of pores as well as the functioning of the pore network strongly influence all three processes. A big percentage of concrete in operation is only partially immersed and capillary consumption partially influences the original consumption of air and soluble solids. As such, air consumption has been used as a significant variable in quantifying the durability of cemented systems (Castro, Bentz, & Weiss, 2011).

According to (ASTM C642-13), this experimental technique includes the determination of thickness, percentage of consumption, and percentage of voids in the hardened concrete.

2.12.1 Efficacy of PP on Water Absorption as a Concrete CA Replacement

The porosity is partially represented by water absorption features such as quantity of permeable pore and its structure. In most research, it was noted that raising the replacement frequency of coarse aggregate with waste plastic material improves absorption of water; due to the fact that natural aggregates and plastic could not be adequately combine in concrete framework and the result becomes porous (Gu & Ozbakkaloglu, 2016).

2.13 Rapid Chloride Permeability [RCP]

Reinforced concrete structures are subjected to harsh ambient and are often supposed to last for a short period of time (often 100 years or more) with little or no repair or maintenance. In order to do this, it is necessary to create a lasting framework. A popular technique of stopping such decay is to avoid chlorides from entering the building at the stage of the steel bar by using comparatively impenetrable concrete. The capacity of chloride ions to enter concrete must then be recognized for layout and quality control reasons. But, the chloride ion formation of concrete takes a long time. It is not restricted within a timeframe which could help as a quality control tool (Stanish, Hooton, & Thomas, 2001).

2.13.1 Efficacy of PP on RCP as a Concrete CA Replacement

The speed of chloride ingress inside concrete depends on pore composition of the concrete, which is influenced by variables such as materials, building methods and age. The penetrability of concrete is clearly linked to the pore composition of the cement paste matrix. This will be affected by the water-cement ratio of the concrete, the presence of additional cementing products used to subdivide the pore framework (McGrath & Hooton, 1996), and the degree of hydration of the concrete.

2.14 Heat Degradation

Concrete may be subjected to high altitudes during flames or close furnaces and reactors. Mechanical characteristics such as resistance, elasticity modulus and concrete bulk stabilization are considerably decreased during these exposures. This may lead to undesirable organizational mistakes. Therefore, the characteristics of concrete maintained after a fire are still of significance for the determination of stress carrying capacity and for the restoration of fire-damaged structures. When subjected to elevated temperatures, the chemical composition and physical structure of the concrete changes significantly. The harm to the concrete after being subjected to elevated heat can be approximately identified by watching the underside of the concrete. Thus, the evaluation of fire-damaged concrete generally begins with the graphic observation of changes in color, cracking and overlapping of concrete surfaces (Arioz, 2007).

2.14.1 Efficacy of PP on Heat Degradation as a Concrete CA Replacement

The mechanical characteristics and physical presence of recycles plastic aggregate concert's subjected to high temperatures vary from the ones subjected to ambient circumstances. In an study conducted by Ozbakkaloglu et al. (2017) there was no noticeable transformation in surface morphology of samples faced to 75 and 100 °C compared to unexposed samples, since PP melting temperature (i.e. 160 °C) is higher than these temperatures . Although, when the sample was faced to around 200 °C, the boiling of RPA led to in considerable distinct ground structure of RPAC from the control group.

The f_{cm} of both NSC and HSC control mixes fell slightly when exposed to 75 °C and 100 °C in comparison with those below ambient temperature. In contrast, when these mixes were exposed to 200 °C, significant decreases in the f_{cm} were noted. This can be attributed to a substantial amount of water vapor produced in concrete above 100 °C. A compacted concrete, however, restricts a discharge of the water vapor, which enhances pore pressure and the expansion of microcracks within the concrete. As it was noted earlier, this results in a low f_{cm} amount, in conventional concrete which is exposed to high temperatures (Phan, Lawson, & Davis, 2001).

Chapter 3

METHODOLOGY

3.1 Introduction

In this study, twelve distinct mixes were casted for two kinds of concretes with six distinct substitutes of PP with coarse aggregates proportions of 0, 10, 20, 30, 40 and 50 percentages for HSC with 0.34 w/c ratio and NSC with 0.58 w/c ratio, respectively, in accordance with the thesis objectives. In addition, the volume substitution ratio (RDpp / RDca) is 0.38 kg/m^3.

The following tests were conducted to explore the impacts of polypropylene on the mechanical characteristics of HSC and NSC on various percentages of a substitute:

1. Slump and VeBe time test
2. f_c test on 7 and 28-day
3. f_f test on 7-day
4. f_s test on 7-day
5. Schmidt hammer test
6. UPV test
7. Water absorption test
8. Heat degradation test (200 °C)
9. Rapid chloride permeability (RCP) test

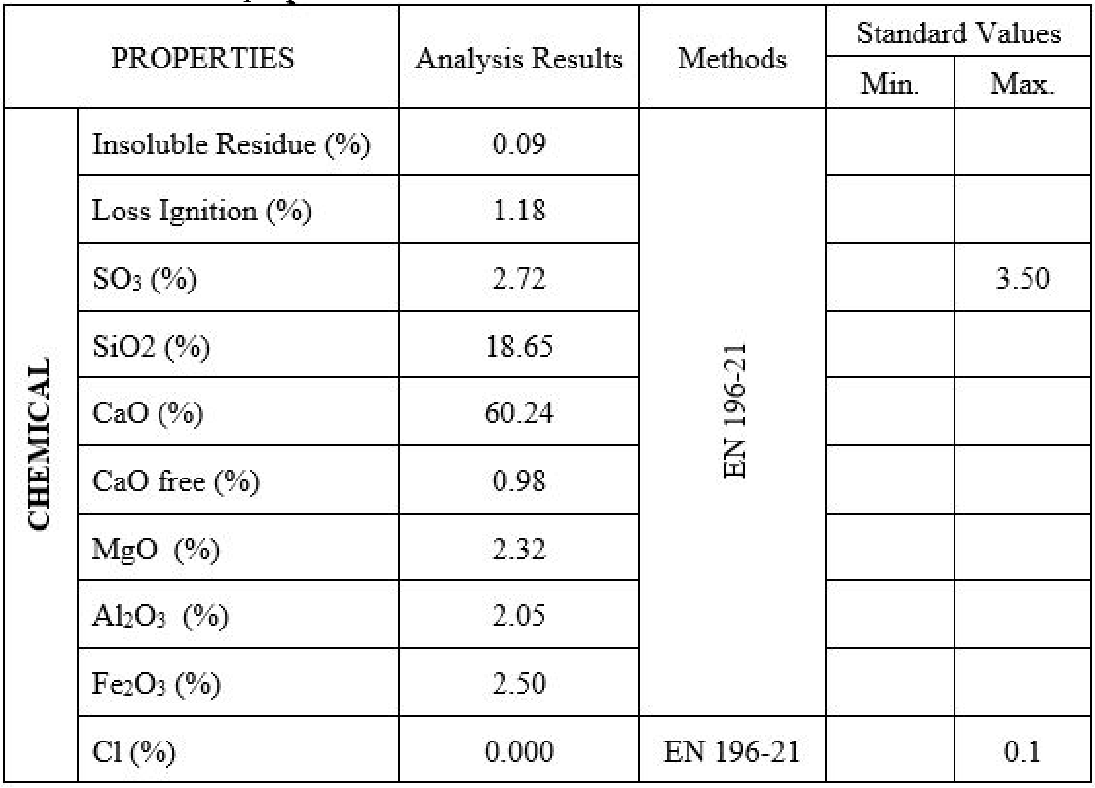
In this section, all the products used in the concrete mixing model are described. Moreover, the experiments performed in different norms as along with the investigation process and rules are also explained in detail.

3.2 Applied Material

3.2.1 Type of Cement

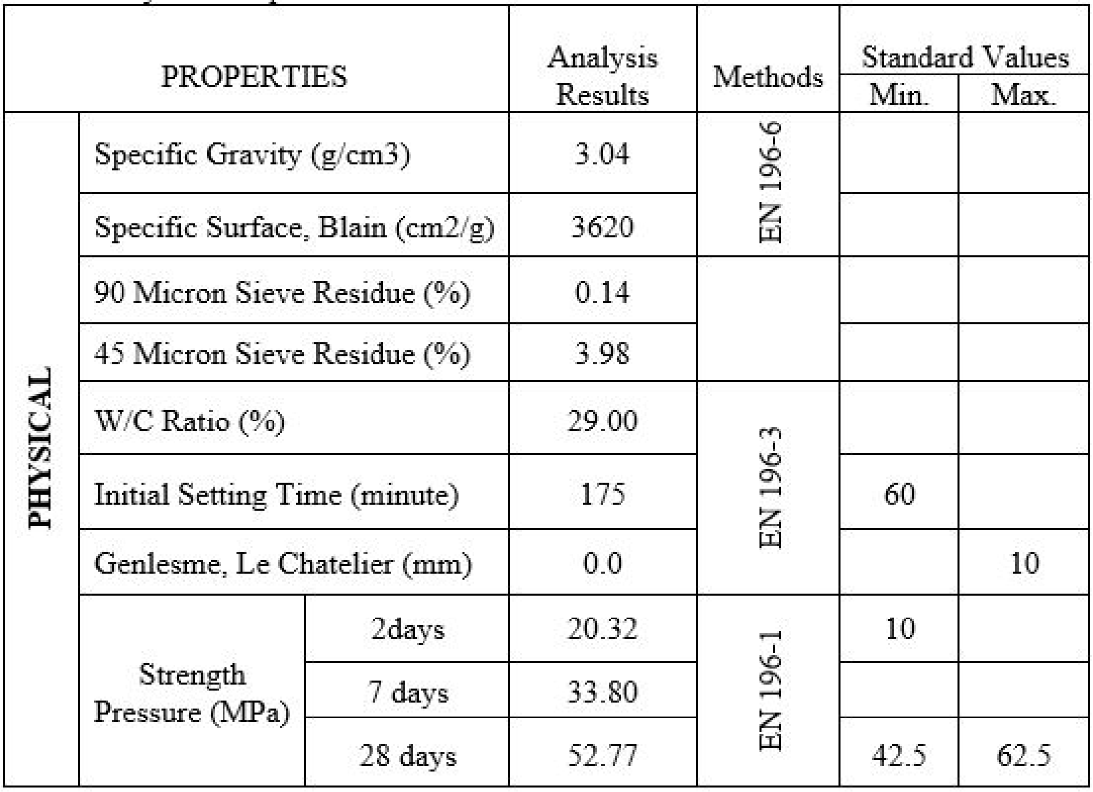
In this research, in alignment with ASTM C595-17, Portland-Slag Cement (CEM II / B-S 42.5 N) was used. This type of cement was moderately modified to withstand sulfate attack and exhibit a normal rate of hydration. Table1 and 2 show the chemical and physical characteristics of cement.

Table 1: Chemical properties of cement



PROPERTIES		Analysis Results	Methods	Standard Values	
				Min.	Max.
CHEMICAL	Insoluble Residue (%)	0.09	EN 196-21		
	Loss Ignition (%)	1.18			
	SO_3 (%)	2.72			3.50
	SiO2 (%)	18.65			
	CaO (%)	60.24			
	CaO free (%)	0.98			
	MgO (%)	2.32			
	Al_2O_3 (%)	2.05			
	Fe_2O_3 (%)	2.50			
	Cl (%)	0.000	EN 196-21		0.1

Table 2: Physical properties of cement



PROPERTIES			Analysis Results	Methods	Standard Values	
					Min.	Max.
PHYSICAL	Specific Gravity (g/cm3)		3.04	EN 196-6		
	Specific Surface, Blain (cm2/g)		3620			
	90 Micron Sieve Residue (%)		0.14			
	45 Micron Sieve Residue (%)		3.98			
	W/C Ratio (%)		29.00	EN 196-3		
	Initial Setting Time (minute)		175		60	
	Genlesme, Le Chatelier (mm)		0.0			10
	Strength Pressure (MPa)	2days	20.32	EN 196-1	10	
		7 days	33.80			
		28 days	52.77		42.5	62.5

3.2.2 Superplasticizer [SP]

Type F Poly-carboxylic high-range water reduction admixture (see Figure 1), referred to as (Master GLENIUM 27) was used in our experiment. It offers elevated strength and durability and enhances the concrete's workability. To the mixture, NSC added 0.3 percent binder for SP and HSC added 2 percent, where the w/c ratio for NSC was 0.58 and HSC was 0.34.

Figure 1: Superplasticizer MasterGlenium 27

3.2.3 Polypropylene Aggregate

The waste material Polypropylene used in this study is a by-product of recycling beach beds and ponds with one time crushed by the factory located in Nicosia, Northern Cyprus (see Figures 2 and 3). PP includes $CaCO_3$ powder that enhances concrete strength. Plastic aggregates were generated by squeezing the waste into tiny solids; their specific gravity was 1.026 kg/m^3 and polypropylene's dry loose bulk density (DLBD) is 0.524 kg/m^3. Figure 4 and Table 3, demonstrate the PP aggregate sieve analysis.


Figure 2: Factory of waste material recycling


Figure 3: Crushed waste polypropylene

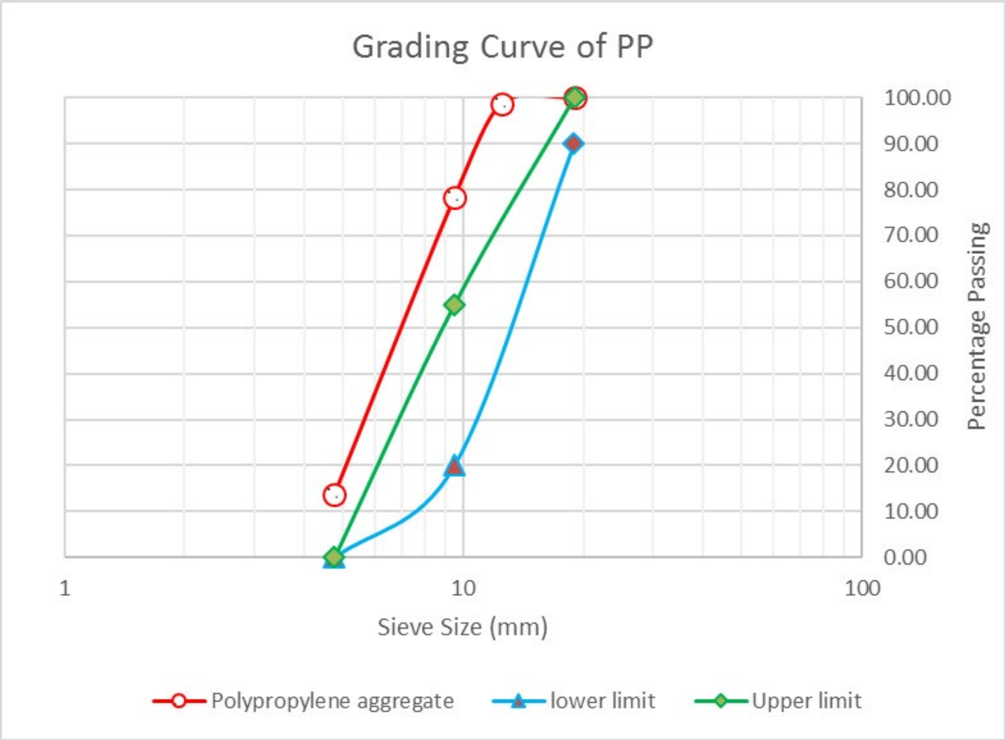


Figure 4: Sieve analysis of polypropylene

Table 3: Polypropylene sieve analysis results

			sample weight=3000				
sieve no.	**WT retained (gr)**	**individual percent**	**cumilative percent**	**percentage passing**	**ASTM C33**	**lower limit**	**upper limit**
19	0.00	0.00	0.00	100.00	90-100	90	100
12.5	38.40	1.28	1.28	98.72	0.00	0.00	0.00
9.5	612.40	20.41	21.69	78.31	20-55	20	55
4.75	1933.60	64.45	86.15	13.85	0-10	0	0
pan	410.00	13.67	99.81	0.19			
total	2994.40	99.81					

3.2.4 Fine Aggregate

The fine aggregate used in this research was crushed fine aggregate passing sieve 4.75-mm (No. 4) and almost completely maintained on 75-µm (No. 200) sieve. Crushing rock, gravel, iron blast-furnace slag, or hydraulic cement concrete formed fine aggregate (C125-19 ASTM).

The maximum size of sand was expected to be 5 mm. In this research, fine aggregates were used on concrete mixture. Analysis of the ASTM C136M-14 sieve was done to support fine aggregate gradation. Figure 5 and Table 4 Illustrate an evaluation of fine aggregate:

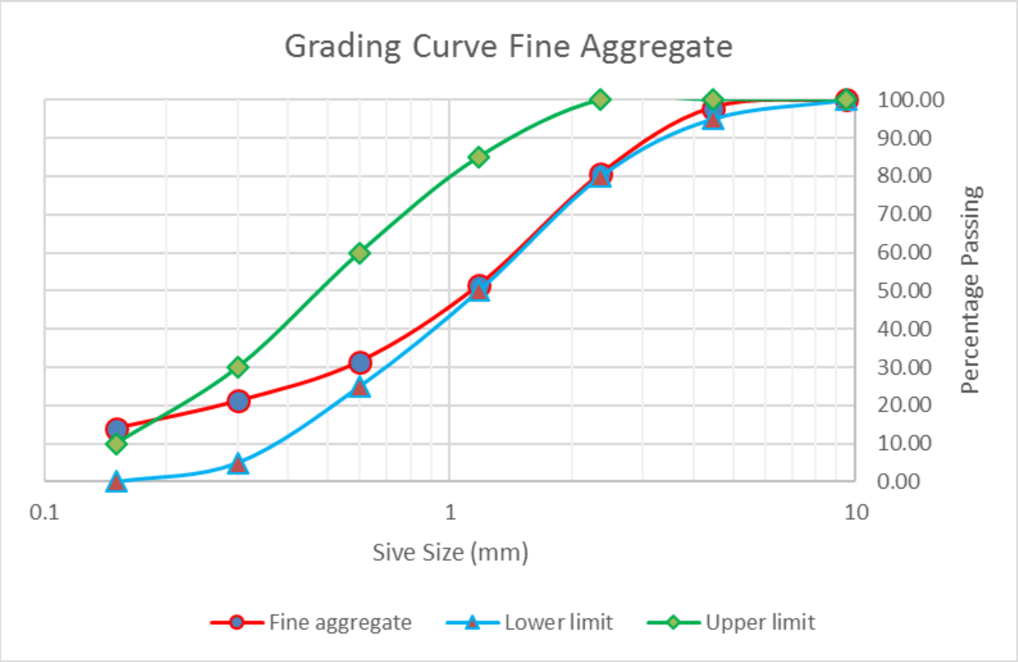


Figure 5: Sieve analysis of fine aggregate

Table 4: Fine aggregate sieve analysis results

			sample weight=1000.4 gr				
sieve no.	**WT retained (gr)**	**individual percent**	**cumilative percent**	**percentage passing**	**ASTM C33**	**lower limit**	**upper limit**
9.5	0	0.00	0.00	100.00	100	100	100
4.45	21.1	2.11	2.11	97.89	95-100	95	100
2.36	172.5	17.24	19.35	80.65	80-100	80	100
1.18	292.3	29.22	48.57	51.43	50-85	50	85
0.6	199.6	19.95	68.52	31.48	25-60	25	60
0.3	103.6	10.36	78.88	21.12	5-30	5	30
0.15	71.5	7.15	86.03	13.97	0-10	0	10
pan	137.2	13.71	99.74	0.26			
total	997.8	99.740104					

3.2.5 Coarse Aggregate

10 mm and 20 mm crushed coarse aggregates of size, were used in this research. Using ASTM C136-14 sieve analysis, the gradation of coarse aggregate was found in all dimensions according to ASTM C33M-16. Figure 6 and Table 5 demonstrate the coarse aggregate sieve analysis.

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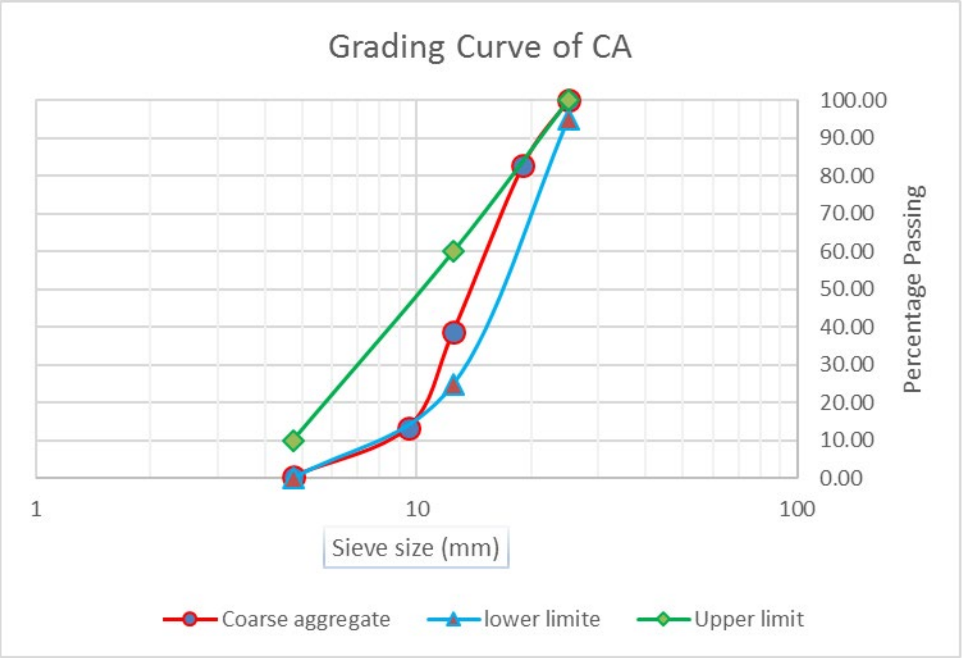


Figure 6: Sieve analysis of coarse aggregate

Table 5: Coarse aggregate sieve analysis results

			sample weight= 7500				
sieve no.	**WT retained (gr)**	**individual percent**	**cumulative percent**	**percentage passing**	**ASTM C33**	**lower limit**	**upper limit**
25	0	0.00	0.00	100.00	95-100	95	100
19	1300	17.33	17.33	82.67	0	0	0
12.5	3285	43.80	61.13	38.87	25-60	25	60
9.5	1912	25.49	86.63	13.37	0	0	0
4.75	965	12.87	99.49	0.51	0-10	0	10
pan	28	0.37	99.87	0.13	0	0	0
total	7490	99.87					

3.2.6 Mixing Water

Water used in concrete mixing should be pure and safe from harmful quantities of oils, acids, alkalis, salts, organic materials or other substances that are inconsistent with concrete or steel. (ASTM C913-18)

The water used for the mixing scheme in the concrete was potable water and the temperature of water and ambient environment were checked during the mixing time to prevent unexpected changes in f_c after 7 and 28-day.

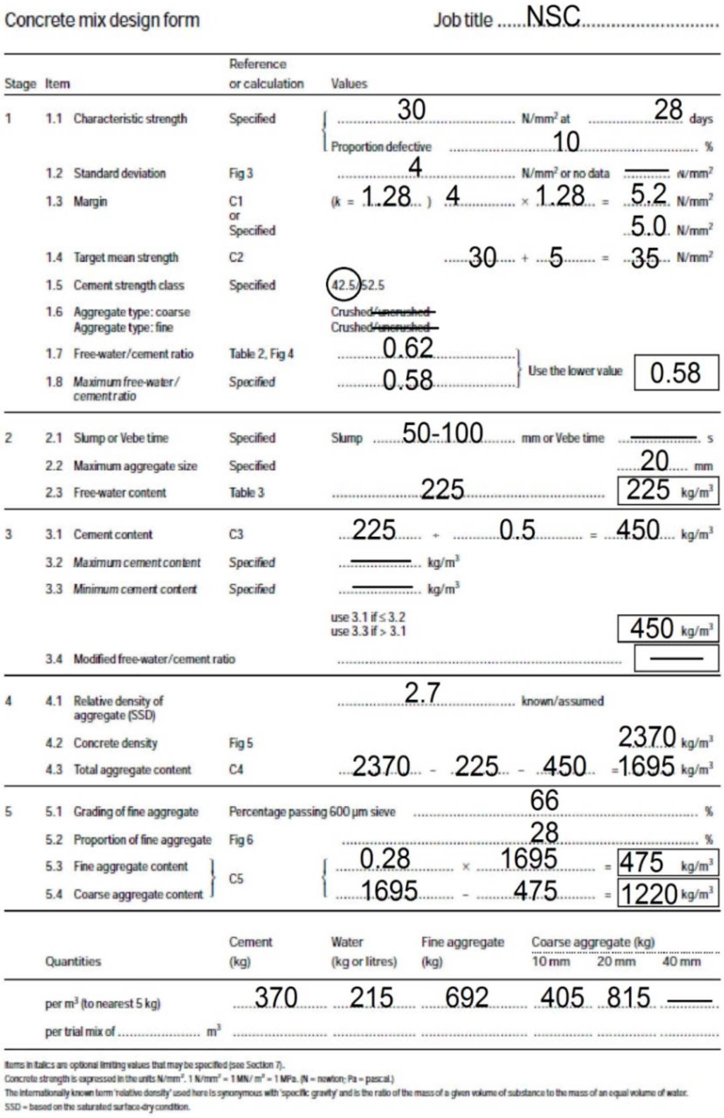
3.3 Mixing Proportion

Mix design involves calculating the proportions and amounts of the primary materials of concrete components and determines particular characteristics such as intensity, workability, formability, durability and permeability in order to achieve an appropriate concrete mixture. In this study, the BRE method for designing mixes was used (Teychenné, Franklin, Erntroy, & Marsh, 1975).

The control mix was made of two types of NSC and HSC. The first step was to replace 10% of the coarse aggregate with polypropylene, so the percentage was increased by 10 to 50. The entire quantity substitute was done by the volume. Table 6 and Figures 7 and 8; demonstrate the NSC and HSC mix design.

Table 6: Mixture design proportion

TYPE OF CONCRETE	CA	PP	RDpp	CA10	CA20	FA	W	C	SP	W/C
NSC 0.3% sp-0 PP	1220	0	0.38	405.00	815.00	692.00	215.00	370.00	1.11	0.58
NSC 0.3% sp-10 PP	1098	46.36	0.38	366.00	732.00	692.00	215.00	370.00	1.11	0.58
NSC 0.3% sp-20 PP	976	92.72	0.38	325.33	650.67	692.00	215.00	370.00	1.11	0.58
NSC 0.3% sp-30 PP	854	139.08	0.38	284.67	569.33	692.00	215.00	370.00	1.11	0.58
NSC 0.3% sp-40 PP	732	185.44	0.38	244.00	488.00	692.00	215.00	370.00	1.11	0.58
NSC 0.3% sp-50 PP	610	231.80	0.38	203.33	406.67	692.00	215.00	370.00	1.11	0.58
HSC 2% sp-0 PP	1080	0	0.38	360.00	720.00	550.00	193.00	565.00	11.3	0.34
HSC 2% sp-10 PP	972	41.04	0.38	324.00	648.00	550.00	193.00	565.00	11.3	0.34
HSC 2% sp-20 PP	864	82.08	0.38	288.00	576.00	550.00	193.00	565.00	11.3	0.34
HSC 2% sp-30 PP	756	123.12	0.38	252.00	504.00	550.00	193.00	565.00	11.3	0.34
HSC 2% sp-40 PP	648	164.16	0.38	216.00	432.00	550.00	193.00	565.00	11.3	0.34
HSC 2% sp-50 PP	540	205.20	0.38	180.00	360.00	550.00	193.00	565.00	11.3	0.34



Concrete mix design form

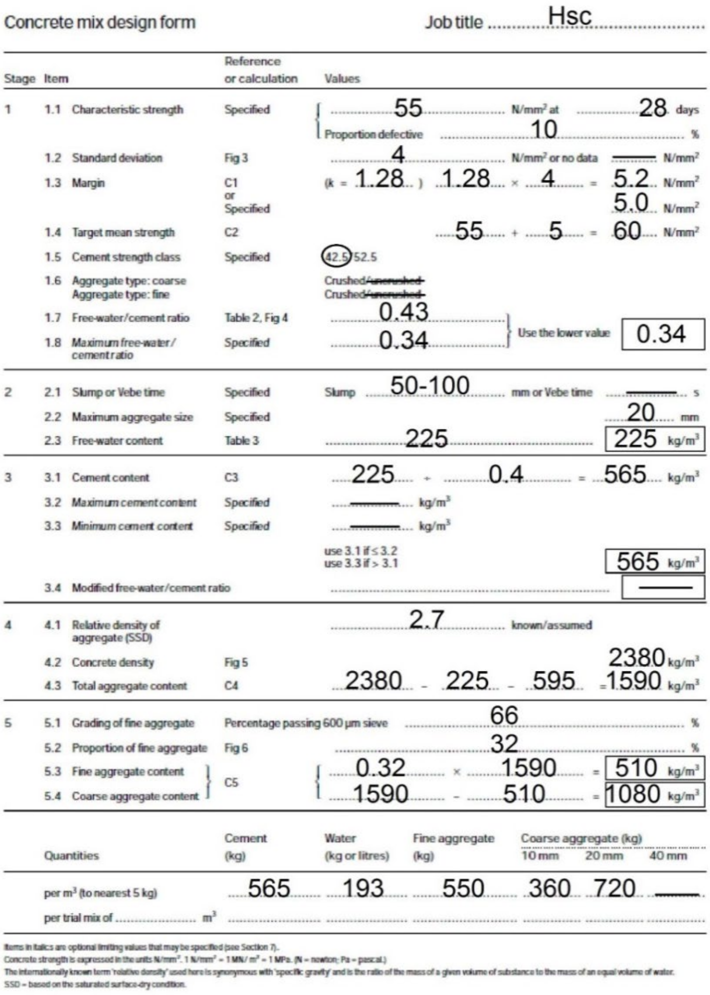
Job title NSC

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 N/mm² or no data — N/mm²
	1.3 Margin	C1 or Specified	(k = 1.28) 4 × 1.28 = 5.2 N/mm² 5.0 N/mm²
	1.4 Target mean strength	C2	30 + 5 = 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 0.58
	1.8 *Maximum free-water/cement ratio*	*Specified*	0.58
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 → 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)	370	215	692	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.

Figure 7: Mix design form of NSC



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 N/mm² or no data —— N/mm²
	1.3 Margin	C1 or Specified	(k = 1.28) 1.28 × 4 = 5.2 N/mm² 5.0 N/mm²
	1.4 Target mean strength	C2	55 + 5 = 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 0.34
	1.8 *Maximum free-water/cement ratio*	Specified	0.34
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 → 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 - 595 = 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	20 mm	40 mm
per m³ (to nearest 5 kg)	565	193	550	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.

Figure 8: Mix design form of HSC

3.4 Concrete Mixing

In the next step, coarse, fine and PP aggregates with cement were poured into the pan of the concrete mixer and then gently water was added with a superplasticizer to the mix ingredients and mixed for a minute. Each concrete mixing proportion was designed to replace polypropylene instead of coarse aggregate. The proportion of polypropylene RD to that of coarse aggregate is RDpp/RDca=1.026/2.679=0.38 kg/m3.

3.5 Fresh Concretes Tests

3.5.1 Workability (Slump, and VeBe) Tests

VeBe and Slump tests were utilized to assess the performance of concrete. The slump experiment was done by the fresh mixed concrete compacted with the rod in three phases of the cone, then the cone was pulled upwards and the concrete began to move by weight. Meanwhile, the highest concrete level and the cone height were calculated. This measure was a benchmark for concrete performance. The slump test was performed according to ASTM C143/C143M-15.

The VeBe has a vibrating table which is utilized to quantify the consistency of stiff to extremely dry concrete mixtures. Within the procedure the new concrete was pressed into a cone which was situated in a cylindrical tank in three stages by hitting concrete with 25 stroke rods at each stage and afterward dismantling the cone up to slide the concrete into the tank. At that point a plastic round plate was put on the concrete surface. With the chronometer, turned on the slider underneath is switched on. Meanwhile the timer tracked the time until the cement water became visible on the surface of the plastic plate. Thus, the time was recorded, accordingly. Within the same period of time, the performance of concrete was determined. VeBe test was performed according to ASTM C1170/1170M-14.

3.6 Casting and Curing of Specimens

In this research, three types of concrete molds were used to make the concrete specimens: Cylindrical specimens of size 100 mm diameter × 200 mm long, cubic specimens of size 150 × 150 × 150 mm and beams of size 100 × 100 × 500 mm.

All molds were saturated with mold-specific oil to allow for later demolding before utilizing plastic molds and steel cylinders. After mixing concrete, fresh concrete test started and the concrete was cast on the cubes, beams and cylinders.

In the last part of casting, the fresh concrete was vibrated for one minute by using a vibrating table. At this time, the samples were ready to be transferred to the curing room for 24 hrs.

Considering the time, every single concrete samples were moved out of the mold and floated on the curing water pool, as illustrated in Figure 9.

The temperature was around 14 ± 2 °C during the 7- and 28-day of concrete curing period.

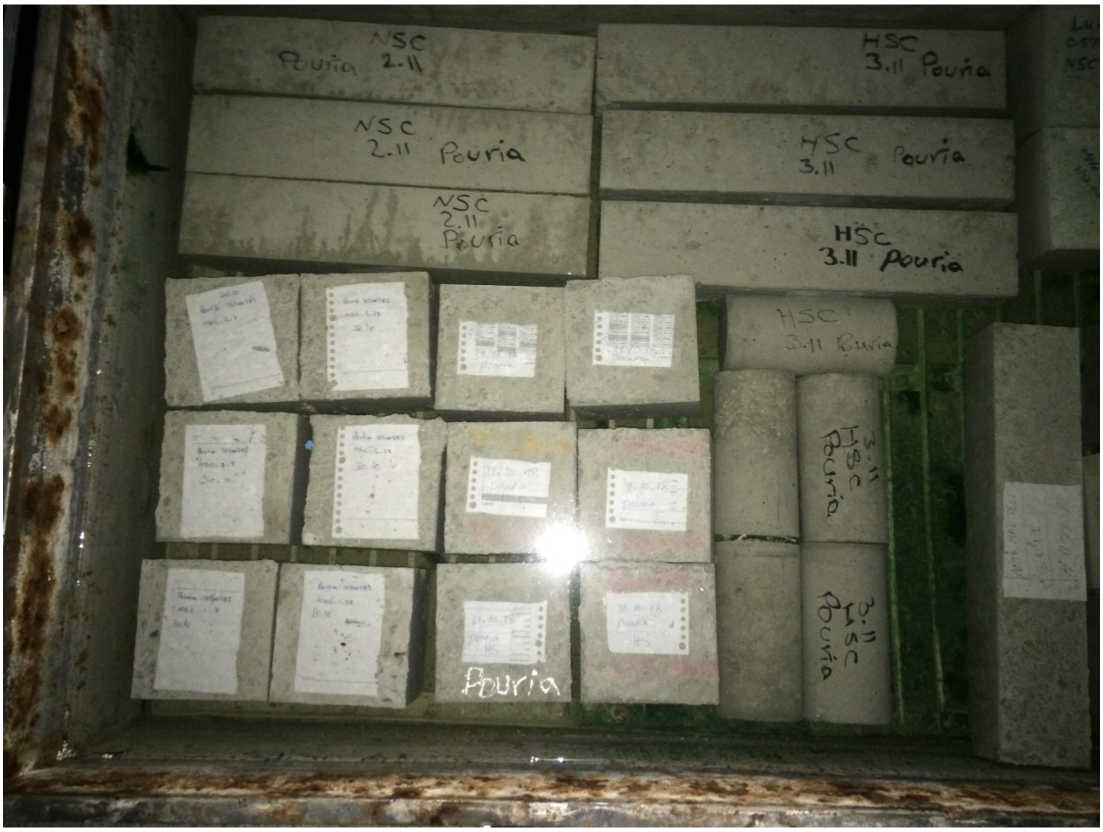


Figure 9: Curing specimens in water tank

3.7 Hardened Concrete Tests

3.7.1 Compressive Strength [f_c] Test

The f_c tests were done to perceive the efficacy of polypropylene substitute on NS and HS concrete. Due to the ASTM 32 C39/C39M – 17 Standard, f_c test was conducted using samples size of 150 × 150× 150mm. Three of the samples used on the each test, so totally, six samples were used for testing on HSC and NSC. Figure10 shows a cubic sample of concrete in the f_c testing machine.

Figure 10: Specimen failure in compressive strength

3.7.2 Flexural Strength [f_f] Test

According to ASTM C 26 1609 -2010, the f_f was tested at 28 days with the beams size of 100 × 100 × 500 mm in the concrete flexural testing machine.Figure 11 shows the f_f testing machine used.

Figure 11: Specimen failure in flexural strength

3.7.3 Splitting Strength Test

Based on ASTM C496/C496M – 11 standards, three cylindrical concrete specimens with size of 100×200 mm were used to test HSC and NSC at 28-day (See Figure 12).Three samples were used for greater accuracy in the experiments.

Figure 12: Specimen failure in splitting tensile strength

3.7.4 Schmidt Hammer Test

According to ASTM C805/C805M-18, this test method is applicable to assess the in-place uniformity of concrete, to delineate variations in concrete quality throughout a structure, and to estimate in-place strength if a correlation is developed.

Before performing concrete f_c test, it was required to place the hammer perpendicular to the sample surface and to do a hammer test for 10 times and record the units. The 6 unit difference with the average of results was omitted, and at the end, the averages of 10 units were selected as a rebound number.

3.7.5 Ultrasonic Pulse Velocity [UPV] Test

Following ASTM C597-16, the pulse velocity (V) was calculated by dividing L (the distance between transducer) by T (transit time) (See Figure13).

Figure 13: Ultrasonic pulse velocity

3.7.6 Water Absorption Test

The experiment was executed on cubic specimens in size of 150 × 150 × 150 mm to estimate the quantity of water absorbed when concrete samples is plunged into the water tank for 28 days.

After 28 days, three samples were put into the oven at 100 °C for 72 hrs. After that, they weighted and their “dry weight” was recorded. Next, the weighed samples were placed into a water tank for 24 hours. After this time, the samples were removed from the water and the water was removed from the surfaces of the samples with a cloth and their weight recorded as “wet weight”:

$Waterabsoprtion= ((wetweight - dryweight)\ dryweight)) \times 100$

3.7.7 Rapid Chloride Permeability [RCP] Test

According to ASTM C1202-19, samples with 50 mm thickness and 100 mm diameter were prepared. An electrical currents range (60 V) passed through these samples was monitored during 6 hours. The total charge passed through a sodium chloride (NaCl) solution in one end, and a sodium hydroxide (NaOH) in the other side of specimen, in coulombs, showed the resistor ability of the samples to chloride ion permeation. Figures 14 and 15 show vacuum saturation apparatus and rapid chloride permeability apparatus, respectively.

Figure 14: Vacuum saturation apparatus

Figure 15: Rapid chloride permeability apparatus

3.7.8 Heat Degradation Test (200 °C)

This test was applied at a temperature of 200 °C to study the effects of high temperatures on (f_c), (f_s), cracks development, and UPV. For this purpose, twelve cubes of size 100×100×100 mm were prepared. First, before placing the specimens under stress, f_c, f_s, and UPV were drawn. After that, the concrete specimens were placed inside an oven with a capacity of 200 °C for four hours at a heat up rate of 10°C/min. Then the oven was switched off and the samples were allowed to dry, then the tests were performed, and the modifications were reported. In addition, a microscope was used to identify the growth of micro-cracks on the sides of hot and unheated specimens (See Figures 16 and 17).

This experiment was carried out on the basis of an established fire resistance technique and was used (Albano, Camacho, Hernandez, Matheus, & Gutierrez, 2009).

Figure 16: Crack development of sample after heat exposed

Figure 17: Stereo microscope

Chapter 4

RESULT AND DISSCUTION

4.1 Introduction

In this study, the effects of different percentages of PP as a partial coarse aggregate replacement in HSC and NSC on fresh and hardened concrete properties were examined. All outcomes of the samples of both types of concrete were compared with the layout of the mixture. Slump and VeBe time tests were done to analyse the physical properties of fresh concrete. Moreover, the influence of PP replacement in the hardened concrete was executed by performing splitting tensile strength (f_s), compressive strength (f_c) and flexural strength (f_f) tests. Rapid chloride permeability (RCP), heat degradation at 200 °C, water absorption, and non-destructive tests such as Ultrasonic Pulse Velocity (Pundit) and Schmidt hammer (rebound) were also conducted

Experimental findings and results are included and discussed in this chapter.

4.2 Efficacy of PP on Fresh Properties of NSC and HSC as a Concrete CA Replacement

4.2.1 Slump Test

Figure 18 shows the results of slump test in various percentages of PP for normal and high strength concretes.

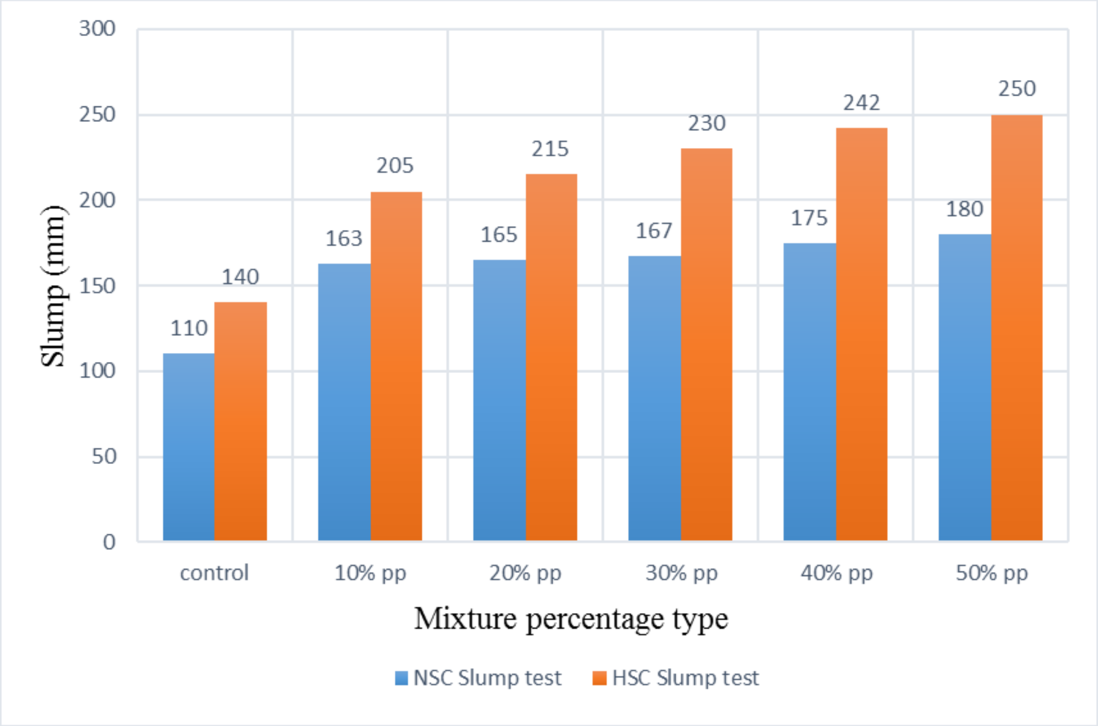


Figure 18: Results of slump test for HSC and NSC

As it can be seen from Figure 18, with an increase in the amount of PP, the slump for HSC and NSC increases. Also, the lowest of the slump in the control mix design for HSC equals 140 mm, and for the NSC is 110 mm, and the highest slump value in 50% PP for HSC and for NSC is 250 mm and 180 mm, respectively.

This trend could be explained by the water absorption capacity of various aggregates. Compared to crushed aggregates, PP particles has a reduced water absorption capacity, which contributes to higher workability (Islam, Sarwar, & Al Shafian, 2015).

4.2.2 VeBe Test

Figure 19 shows the VeBe test results of normal and high strength concretes incorporating PP at various percentages.

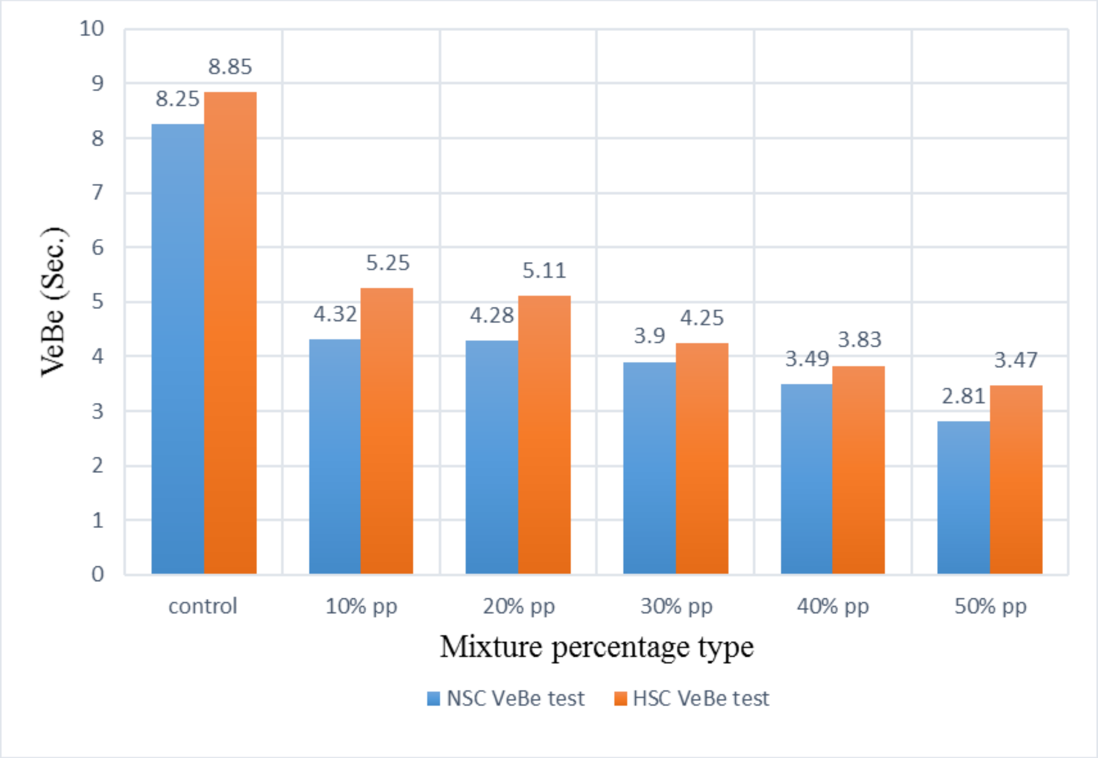


Figure 19: Results of VeBe test for HSC and NSC

As illustrated in Figure 19, by increasing the PP value, the amount of VeBe for HSC and also NSC decreases. Also, the highest value of VeBe of the control mix design and for HSC is 8.85 Sec and for NSC is 8.25 Sec and the lowest values for VeBe in 50% PP for HSC is 3.47 Sec and for NSC is 2.81 Sec, respectively.

The observed declining tendency can be ascribed not only to the spherical form with a soft ground, but also to the absorption capacity (almost null) of PP. In addition, the issue of segregation may arise when working with concrete parts defined by aggregates with distinct particular weights, particularly heavy aggregates (Choi, Moon, Chung, & Cho, 2005).

4.2.3 Unit Weight of Fresh Concrete

With respect to Figure 20, by increasing the PP replacement percentage, the unit weight of concrete value for HSC, and for NSC is descending, except in the step 30%

PP to 40% PP. Also, the highest unit weight of concrete value is in control mix design and for HSC equals 2408 kg/m^3, and for NSC it equals 2881.48 kg/m^3. The lowest value of the unit weight of concrete in the 50% PP for HSC is 2021.33 kg/m^3 and for NSC is 1913.19 kg/m^3, respectively.

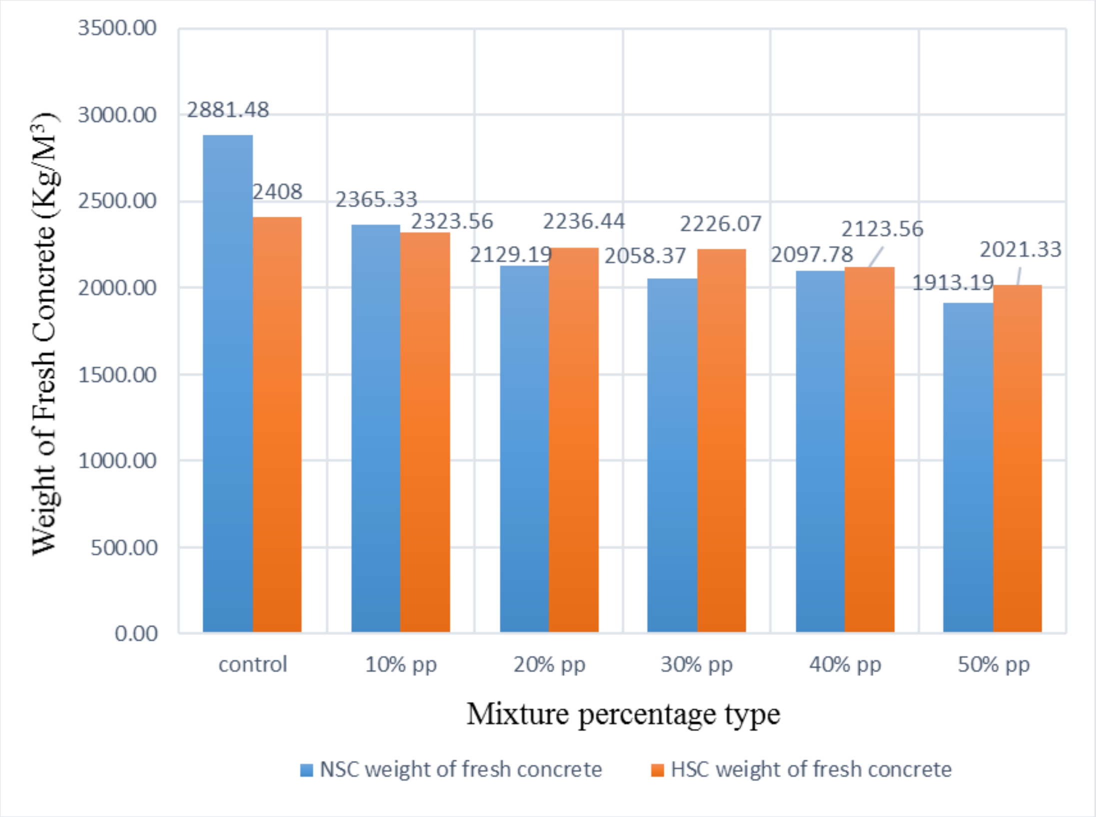


Figure 20: Unit weight of fresh concrete results for HSC and NSC

Saikia and De Brito, 2014 reported a reduction in the density of fresh concrete due to an increase in the content of plastic aggregates, as the density of plastic aggregates is very low compared to natural aggregates.

4.2.4 VeBe and Slump Test Relationship of NSC and HSC

As it can be detectable from Figure 21, in an intuitive way, in NSC, with an increase in the amount of Slump, the value of VeBe decreases.

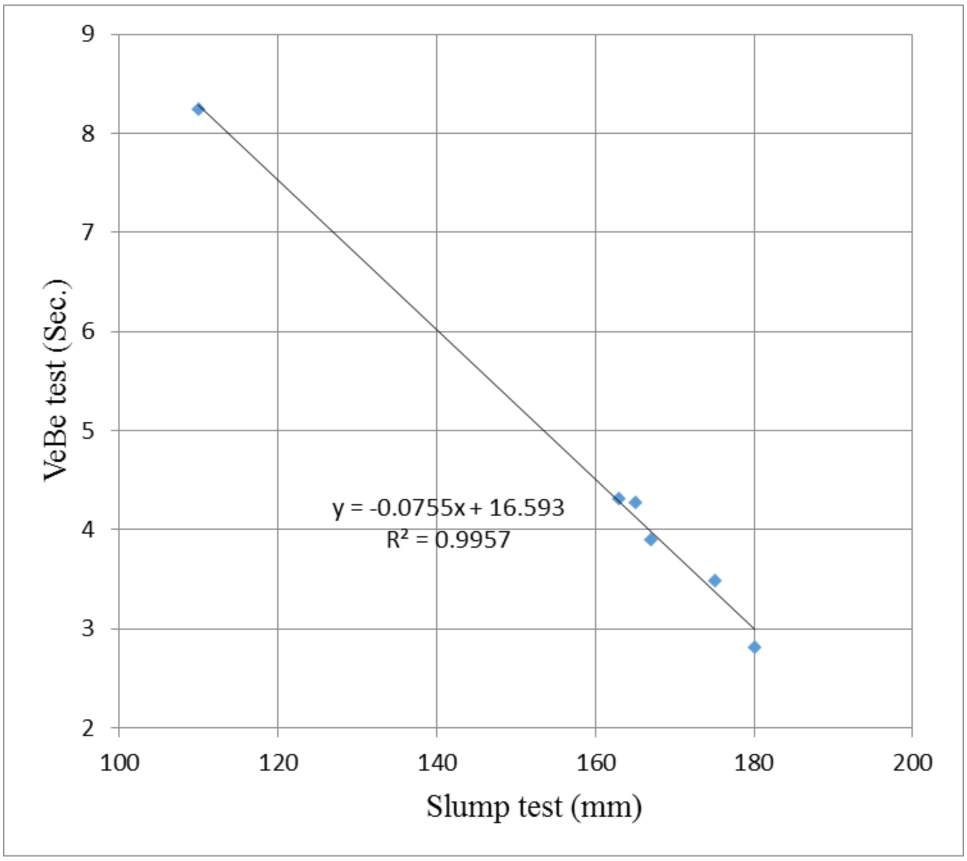


Figure 21: Slump test and VeBe test linear relationship for NSC

In order to determine the exact relationship between these two variables, Table 7 examines the types of regression models between these two properties.

Table 7: VeBe and slump test relationship equations for NSC

Concrete type	Type of Regression	Equation	R^2
NSC	Exponential	$y = 39.855e^{-0.014x}$	0.9561
	Linear	$y = -0.0755x + 16.593$	0.9957
	Logarithmic	$y = -10.52\ln(x) + 57.751$	0.9898
	Polynomial	$y = -0.0002x2 - 0.0246x + 13.116$	0.997
	Power	$y = 76061x^{-1.935}$	0.9361

The best relationship between the VeBe test and the slump test, as can be seen in Table 7 for NSC, is the polynomial function with a value of $R^2 = 0.997$.

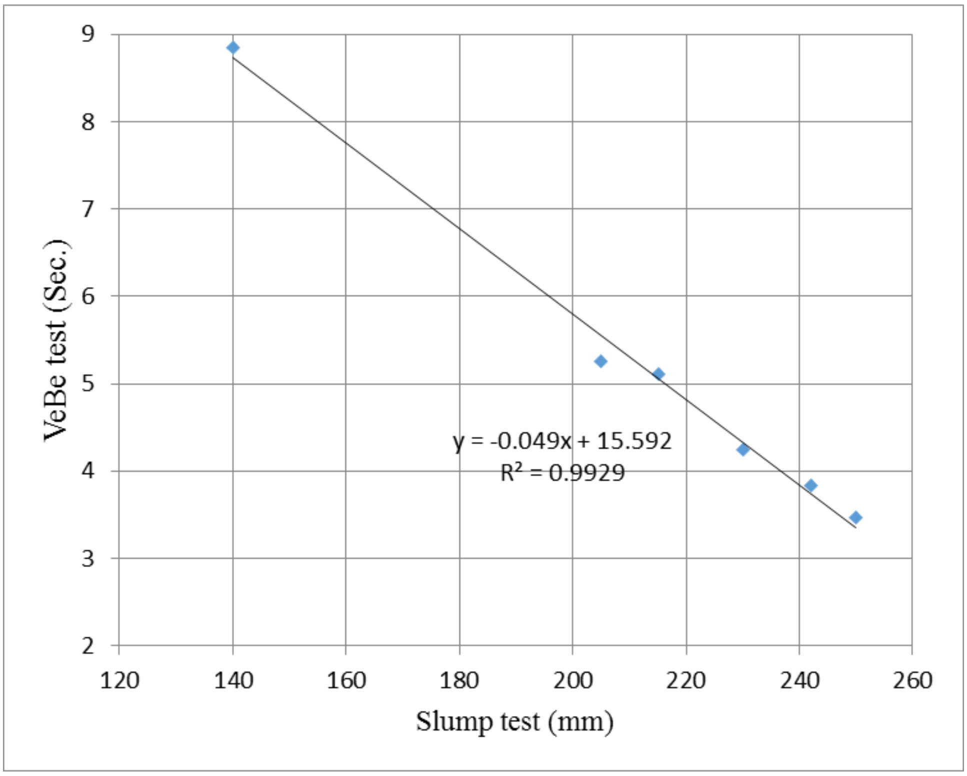
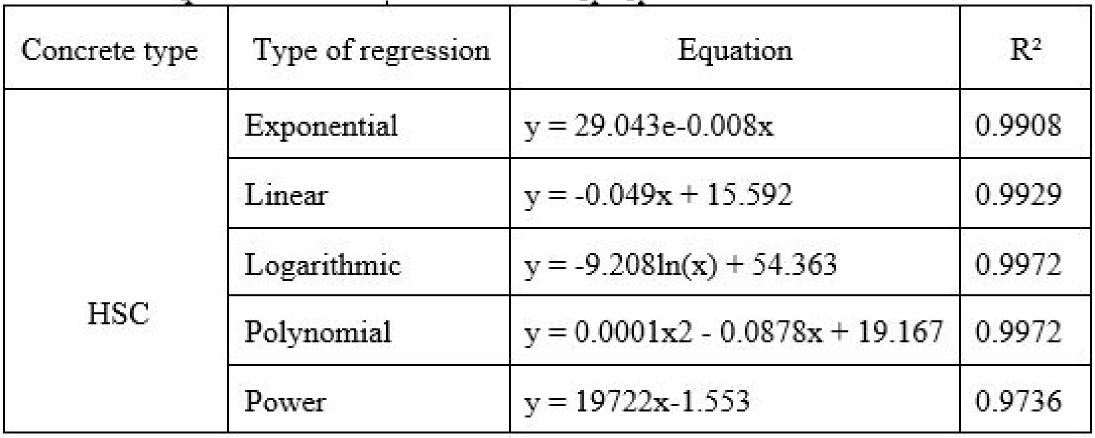


Figure 22: VeBe and slump test linear relationship for HSC

As Figure 22 demonstrates, it can be seen that intuitive decrease of the VeBe value in HSC is followed by the rise of the slump value. Table 8 examines the kinds of regression models in order to establish the relation between these two factors.

Table 8: Slump test and VeBe test relationship equations for HSC



Concrete type	Type of regression	Equation	R^2
HSC	Exponential	y = 29.043e-0.008x	0.9908
	Linear	y = -0.049x + 15.592	0.9929
	Logarithmic	y = -9.208ln(x) + 54.363	0.9972
	Polynomial	y = 0.0001x2 - 0.0878x + 19.167	0.9972
	Power	y = 19722x-1.553	0.9736

The strongest relationship between VeBe and slump, as shown in Table 8, for the HSC, is the polynomial and/or logarithmic function with a value of $R^2 = 0.9972$.

4.3 Efficacy of PP on Hardened Properties of NSC and HSC as a Concrete CA Replacement

4.3.1 Compressive Strength [f_c] Test for NSC and HSC at 7 and 28 Days

According to Figure 23, the value of f_c in NSC at 28 days is higher than 7 days. It is also shown that the f_c method in NSC for both 28 days and 7 days is decreasing, so that in the control mix layout the largest f_c in NSC for 7 days and 28 days are 28.73 MPa and 42.30 MPa, respectively, The smallest values of f_c for NSC mixes at 7 days and 28 days are 50%PP 0.3 SP, 18.77 MPa and 24.60 MPa, respectively.

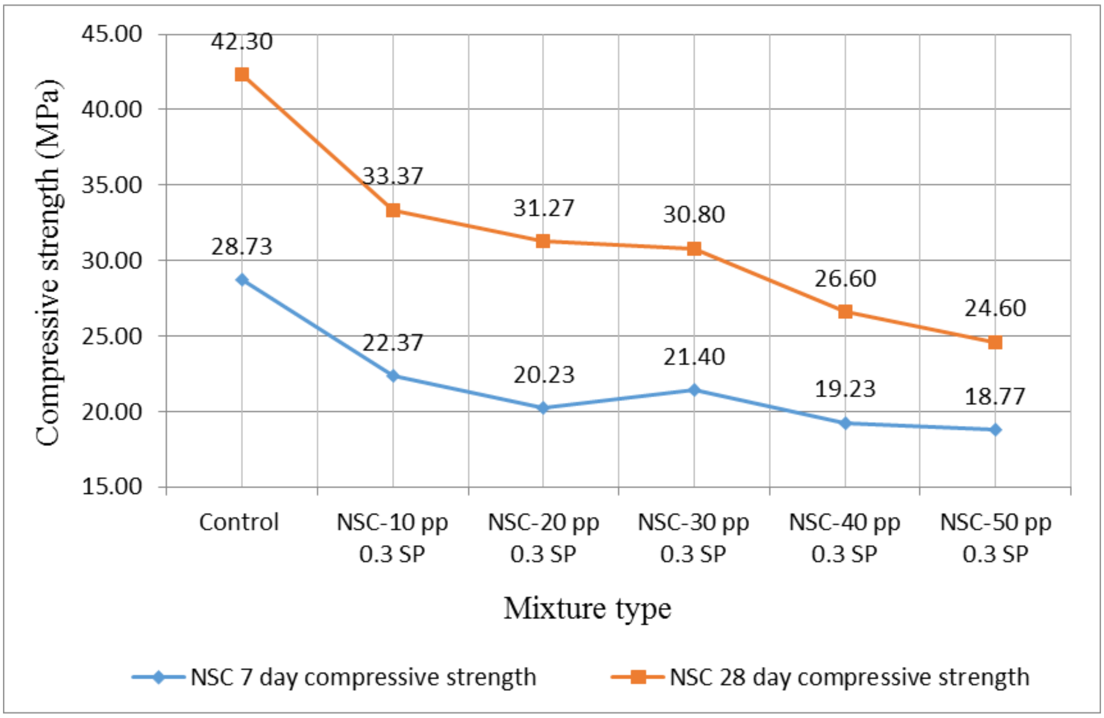


Figure 23: Results of compressive strength test for NSC at 7 and 28 days

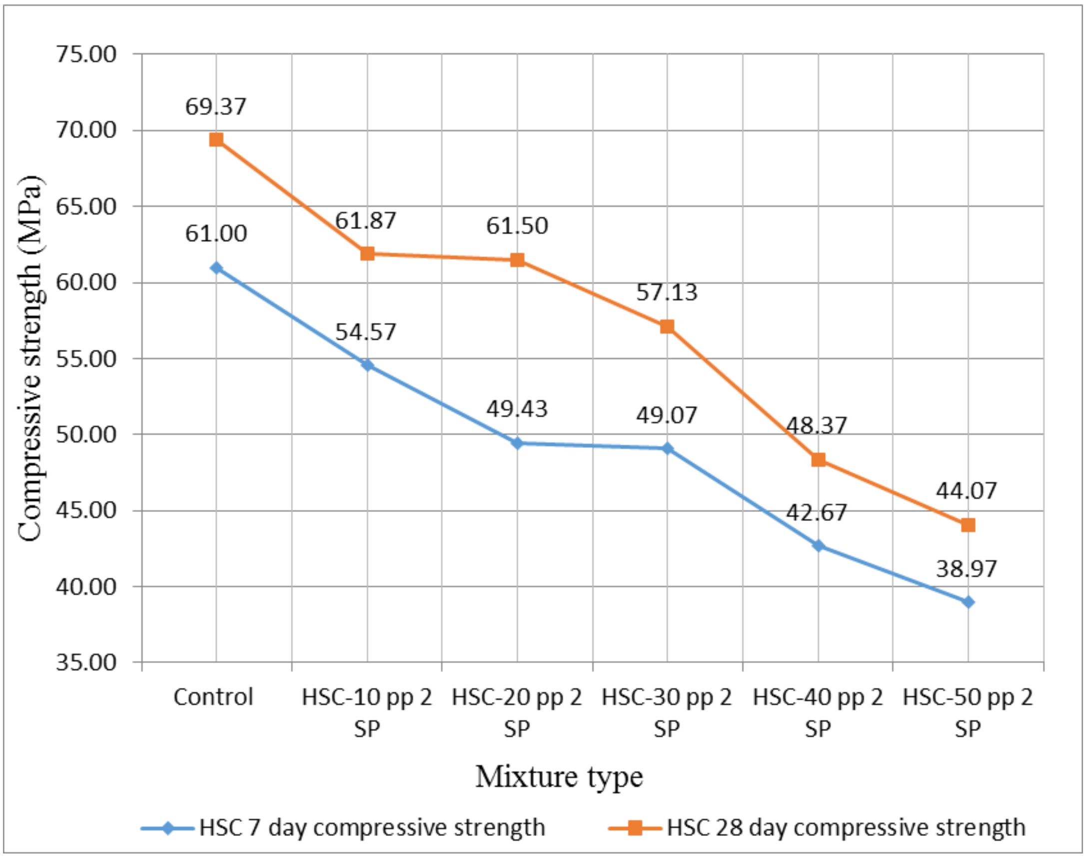


Figure 24: Results of compressive strength test for HSC at 7 and 28 days

Figure 24 shows the test results of compressive strength for HSC at 7 and 28-days. As it can be seen from Figure 24, the f_c test results at 28-days for HSC are greater than those at 7-days. Also, it is observed that at 7and 28-days, the f_c test results of HSC remains comparable and in a descending manner, so that the highest f_c value for HSC at 7 and 28-day for the control mix is 61.00 MPa and 69.37 MPa, respectively.

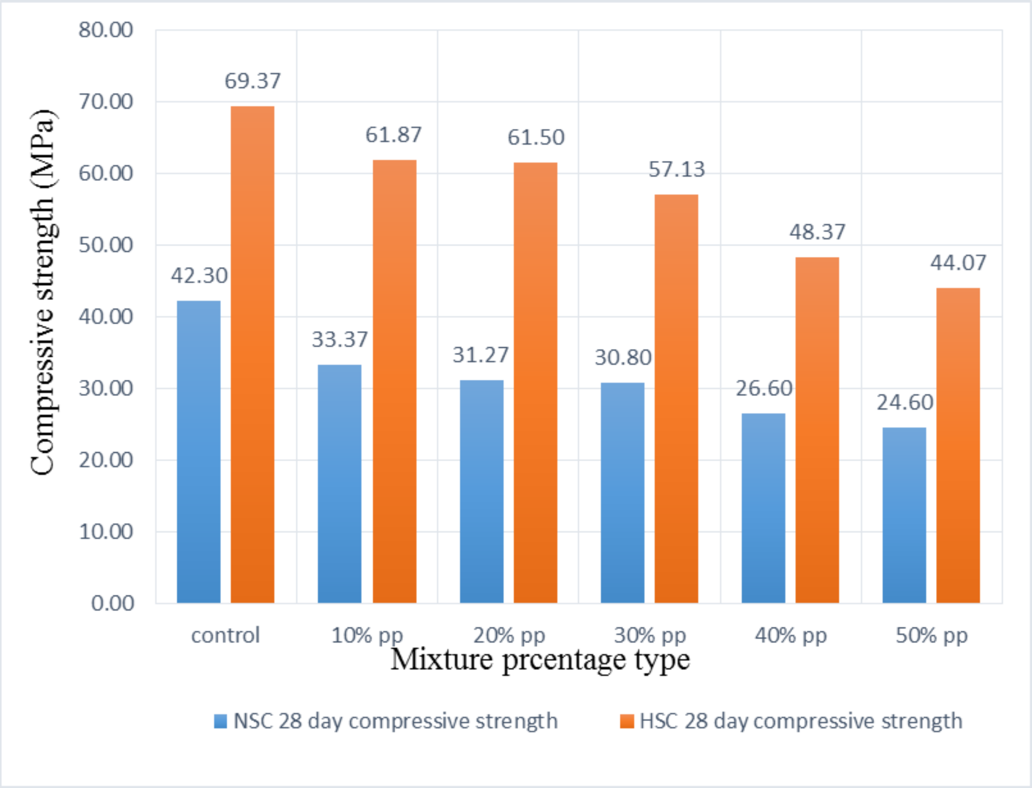


Figure 25: Results of compressive strength test for HSC and NSC at 28 days

According to Figure 25, the f_c of HSC and NSC at 28 days is decreasing as the replacement percentage of PP increases. The highest f_c at 28 days for NSC and HSC is 42.30 MPa and 69.37 MPa, respectively, for the control mixes. In addition, the lowest f_c for NSC and HSC at 28 days at a replacement level 50 % PP is 24.6 MPa and 44.07 MPa, respectively.

The factors which may be responsible for the low f_c of concrete with an increase in the percentage of plastic aggregates are: (1) the very low bond strength between the surface of the plastic waste and the paste of cement; and (2) the hydrophobic nature of the plastic waste which may inhibit the hydration reaction of cement by limiting the movement of water (Saikia & De Brito, 2012).

4.3.2 Splitting Tensile Strength [f_s] Test for NSC and HSC at 28 Days

Based on Figure 26, For NSC at 28 days, f_s decreases as the replacement level of PP increases. The highest value is for the control mix which is 3.20 MPa and the lowest value is for 50%PP - 0.3%SP and is equal to 2.30 MPa.

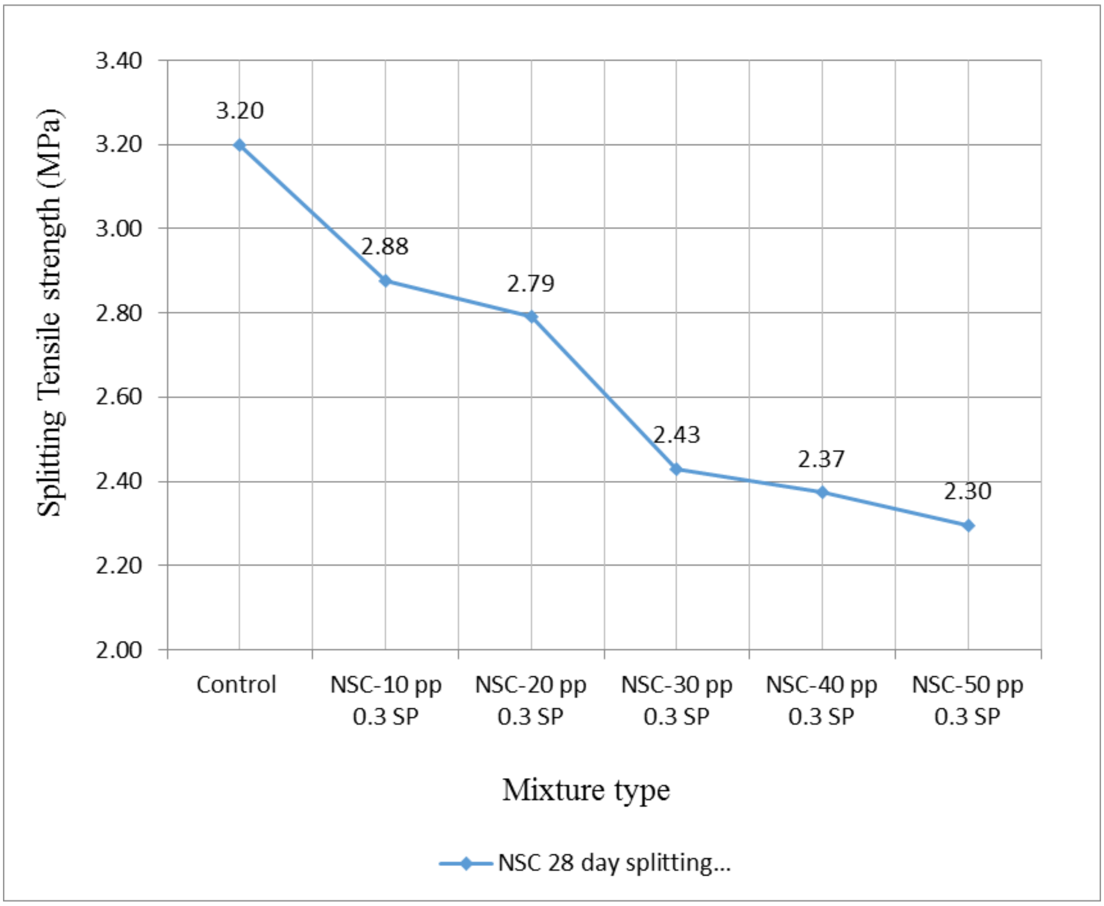


Figure 26: Results of splitting tensile strength test for NSC at 28 days

According to Figure 27, for HSC at 28-day, the amount of f_s always changes descending. The greatest amount of f_s is related to control mix design and equals 4.56 MPa, and the lowest value is related to HSC-50% PP 2 SP and equals 2.98 MPa.

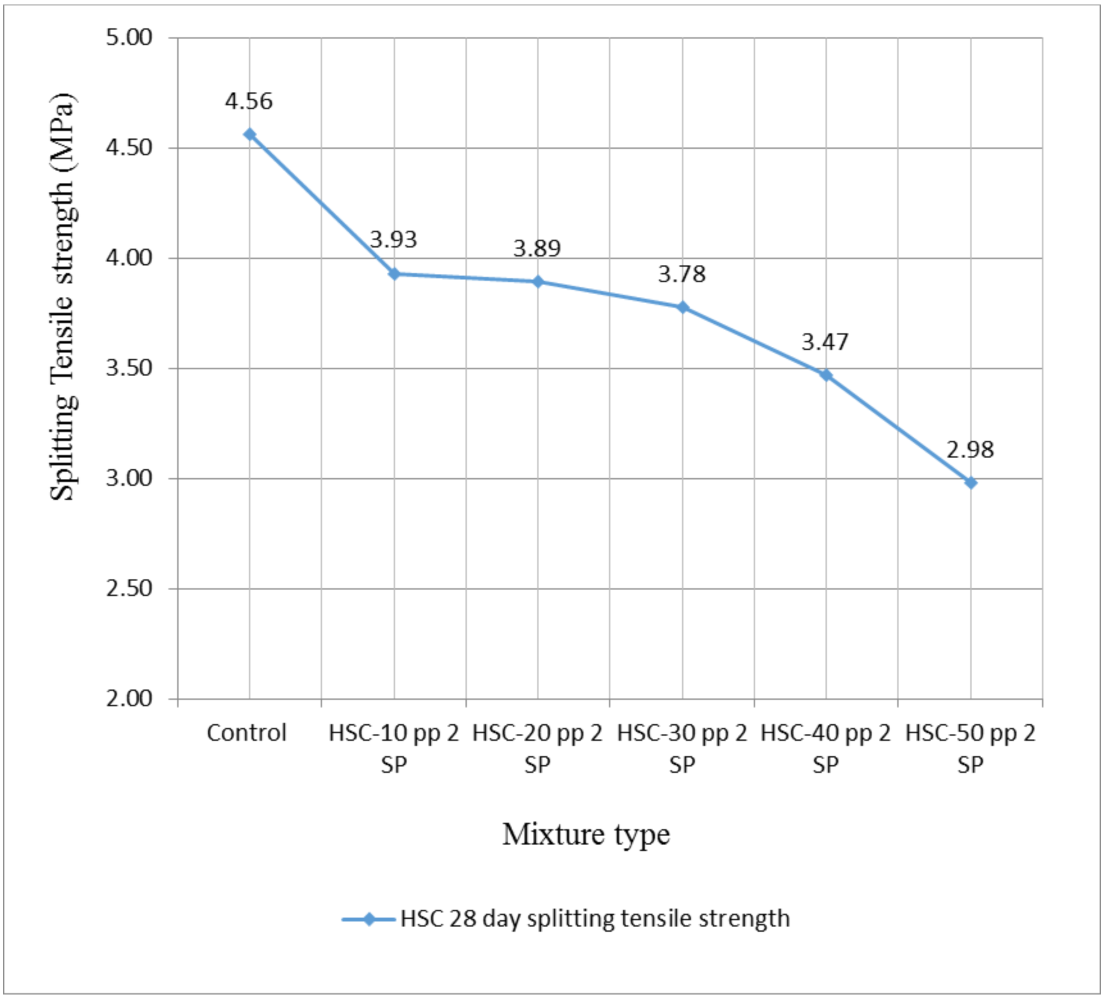


Figure 27: Results of splitting tensile strength test for HSC at 28 days

As per Figure 28, the value of tensile strength for NSC at 28 days is steadily decreasing as the replacement value of PP increases, and so is for the HSC at 28 day. The most dividing strength for NSC and HSC at 28-days is the control mix and corresponds to 3.20 MPa and 4.56 MPa, respectively. Also, the minimum f_s value for NSC and HSC at 28-days is (50% PP) 2.30 MPa and 2.98 MPa, respectively.

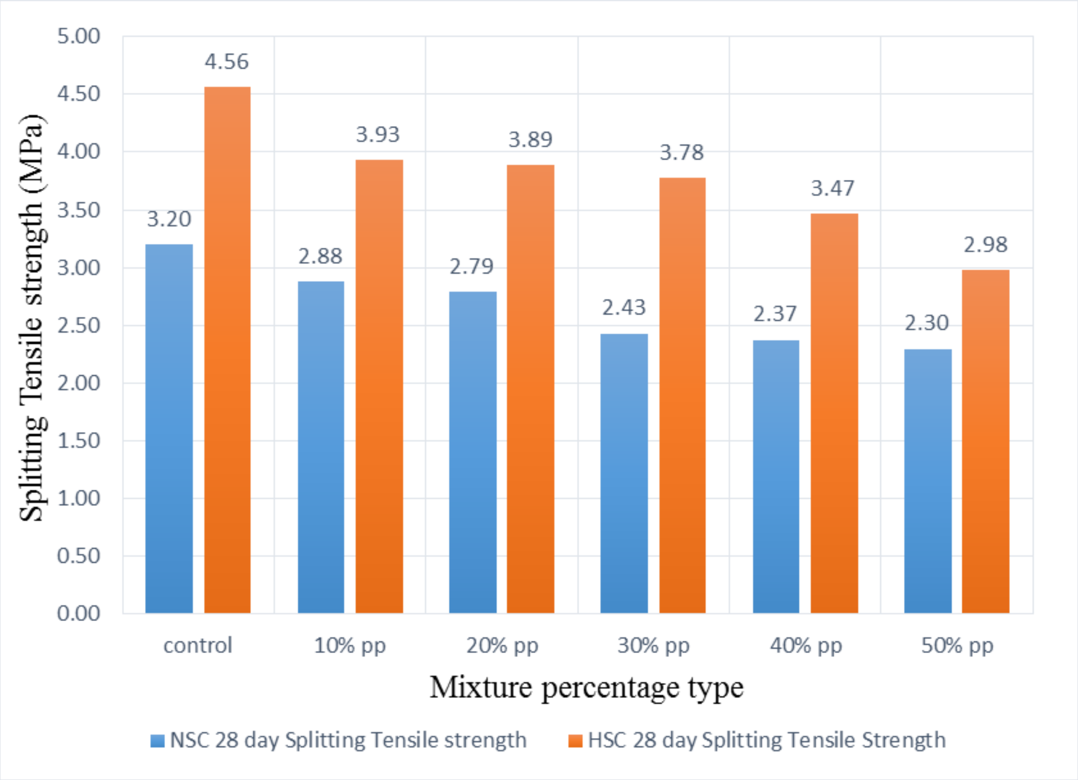


Figure 28: Results of splitting tensile strength test for NSC and HSC at 28 days

The tensile strength of the concrete is affected by the characteristics of the interfacial transition zone (ITZ) and hence the smooth surface of the PP particles and the free water collected on the PP surface could trigger a weaker bond between the PP particles and the cement paste (Saikia & De Brito, 2012).

4.3.3 Flexural Strength [f_f] Test of HSC and NSC at 28 Days

As far as Figure 29 for NSC at 28-day is concerned, the f_f value changes in a descending manner as the replacement level of PP increases. The maximum f_f value is for the control mix and equals to 4.59 MPa and the lowest value is for NSC - 50%PP - 0.3%SP and equals 2.70 MPa.

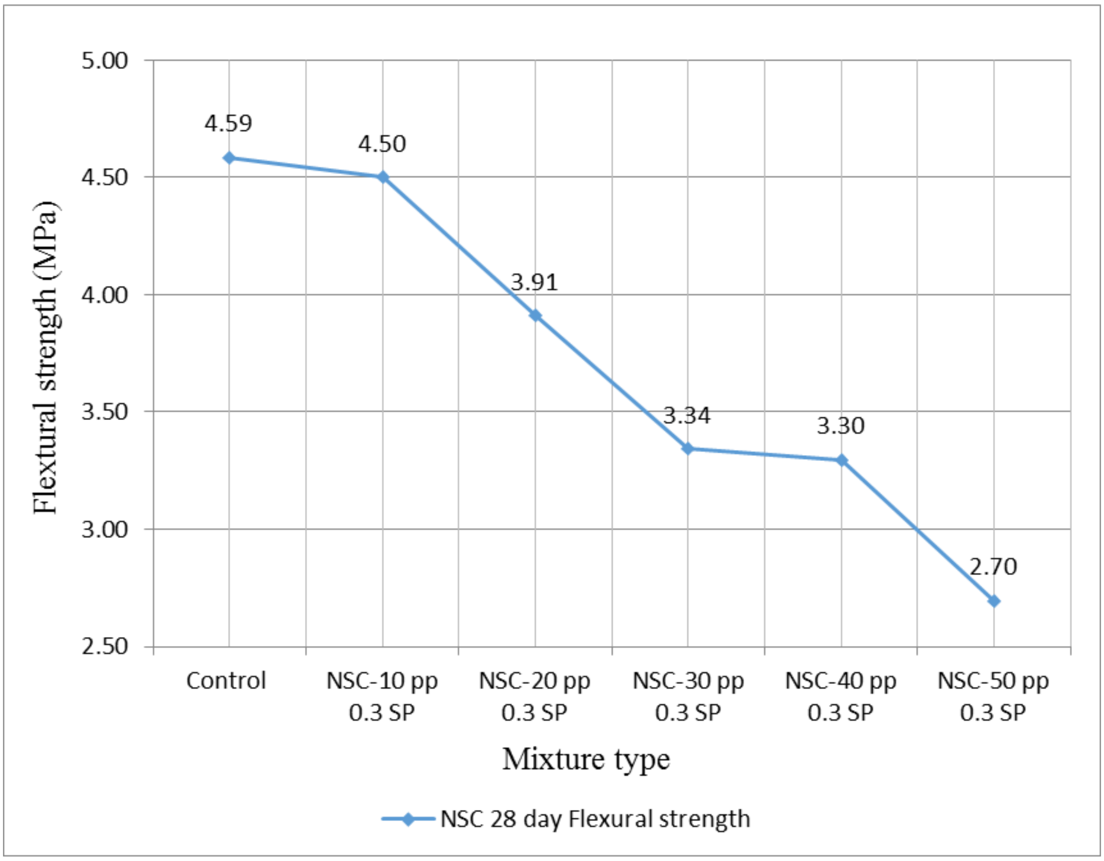


Figure 29: Results of flexural strength test for NSC at 28 days

According to Figure 30, for HSC 28 days, the value of f_f decreases as the replacement level of PP increases. The maximum f_f value is for control mix and it is equal to 5.52 MPa and its lowest value is for HSC-50%PP – 2%SP and equals to 3.09 MPa.

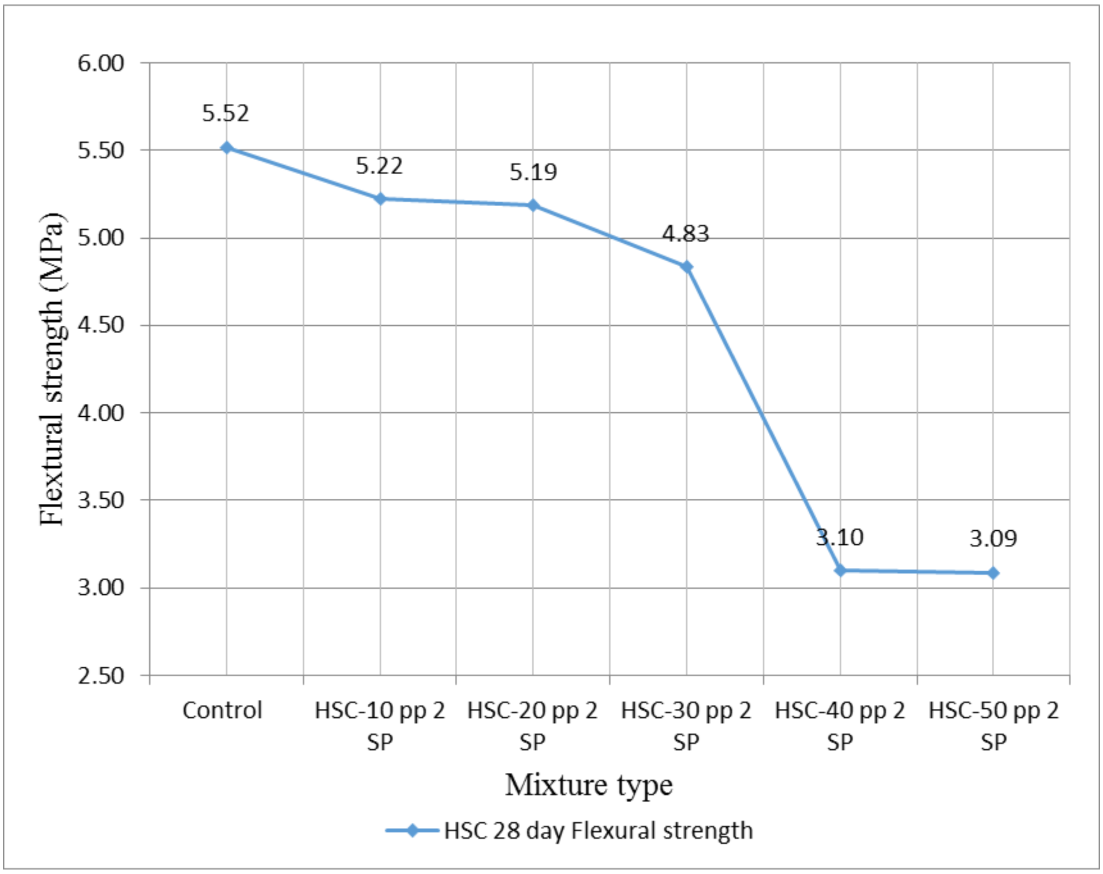


Figure 30: Results of flexural strength test for HSC at 28 days

As it is shown in Figure 31, with an increase in the amount of PP, the amount of f_f for NSC 28 days, as well as for HSC 28 days, is decreasing. The maximum strength value at 28 days for both NSC and HSC control mix is 4.59 MPa and 5.52 MPa, respectively. The minimum f_f at 28-days for NSC and HSC for replacement level of 50 % PP is 2.70 MPa and 3.09 MPa, respectively.

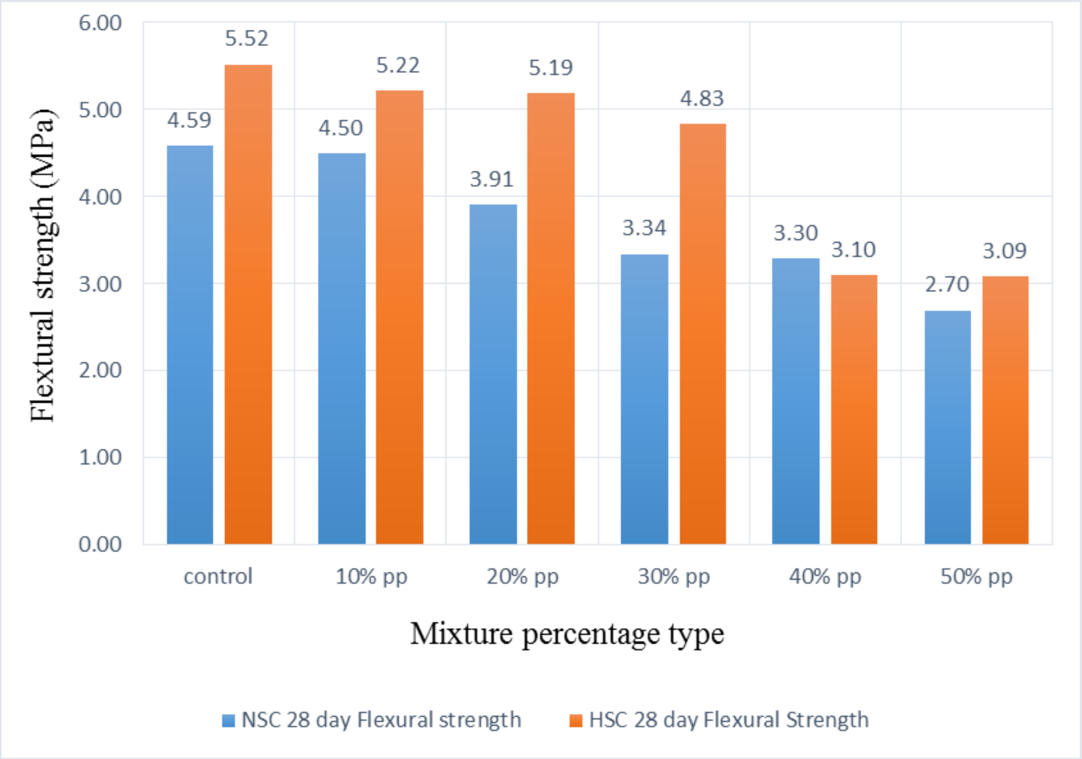


Figure 31: Results of flexural strength test for NSC and HSC at 28 days

This tendency can be ascribed to the reduction in the adhesive resistance between the ground of the scrap plastic pieces and the cement particle (Rai et al., 2012).

4.3.4 UPV Test of HSC and NSC at 28 Days

Figure 32 demonstrates that in general for NSC at 28-day, as PP replacement level increases, the UPV values decreases. The maximum UPV value is 5.039 km/sec for the control mix and the lowest UPV value is for the NSC 50%PP-0.3%SP mix which is 4.12 km/sec.

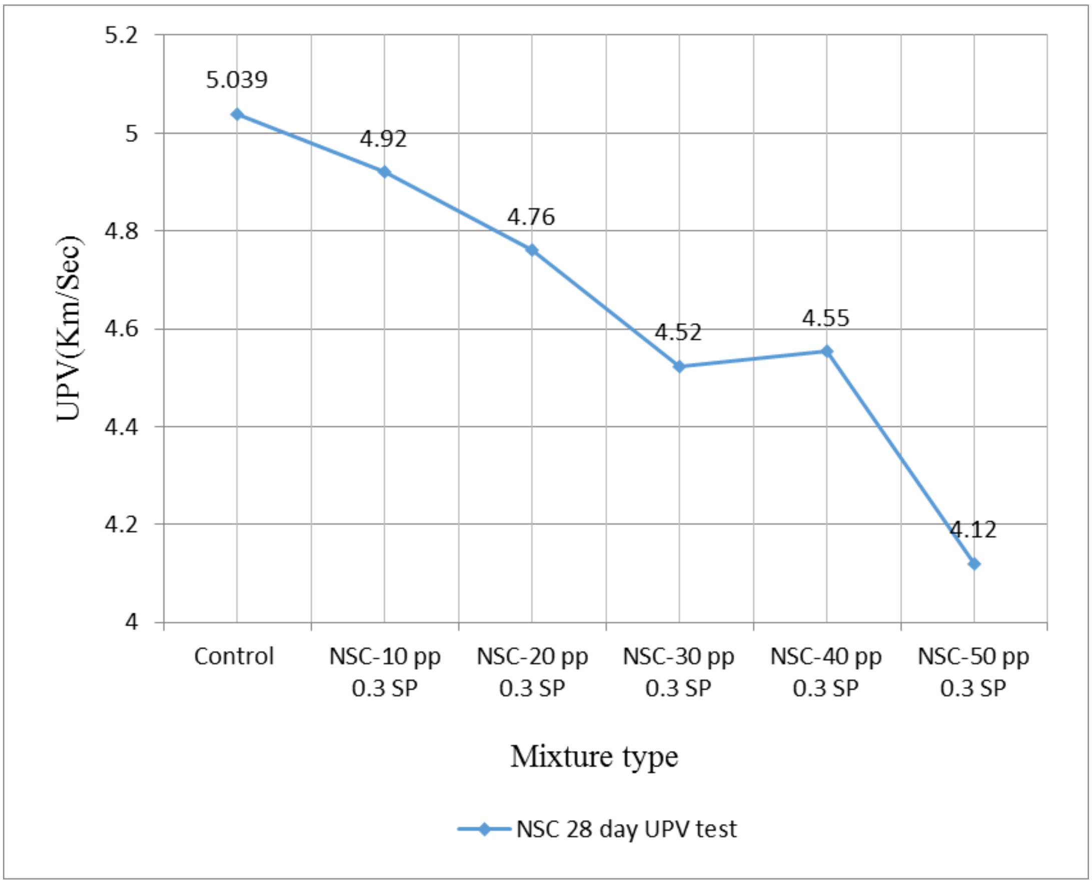


Figure 32: Results of UPV test for NSC at 28 days

Figure 33shows that for HSC at 28-days, the UPV value, except in mixes10% PP-2%SP to 20%PP-2%SP, and 40%PP-2%SP to 50%PP-2%SP, always decreases. The results show that the highest UPV value is for HSC 20%PP-2%SP which is equal to 5.06 km/sec and the lowest UPV value is for HSC 40%PP-2%SP which is equal to 4.58 km/sec.

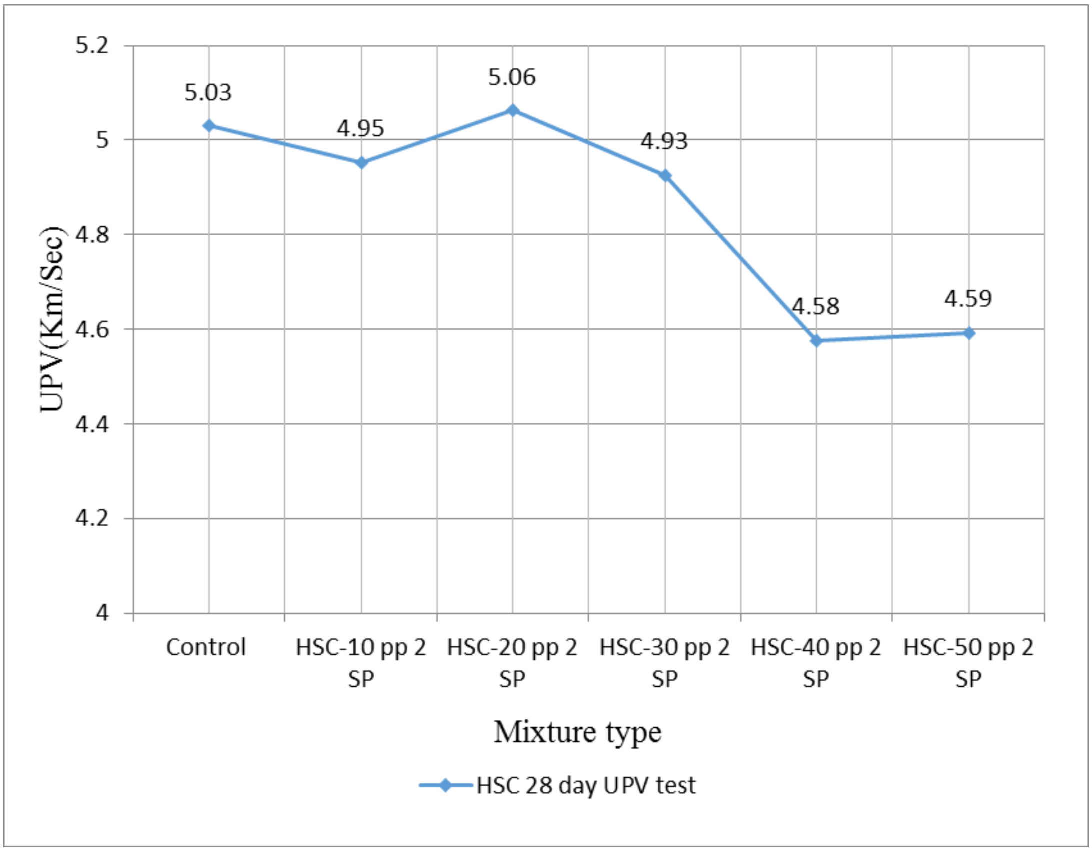


Figure 33: Results of UPV test for HSC at 28 days

According to Figure 34, except in one case, with an increase in the value of PP, the UPV value for NSC at 28-days always descends. Also, considering HSC, with an increase in the value of PP, the UPV value is, except in two cases, also descending. The highest value of UPV at 28-days in NSC is for the control mix which is equal to 5.039 km/sec and in HSC is at replacement level of 20% PP and equals to 5.06 km/sec. Also, the lowest UPV values at 28-day in NSC at replacement level of 50% PP is equal to 4.12 km/sec and for HSC at replacement level of 40% PP equals to 4.58 km/sec, respectively.

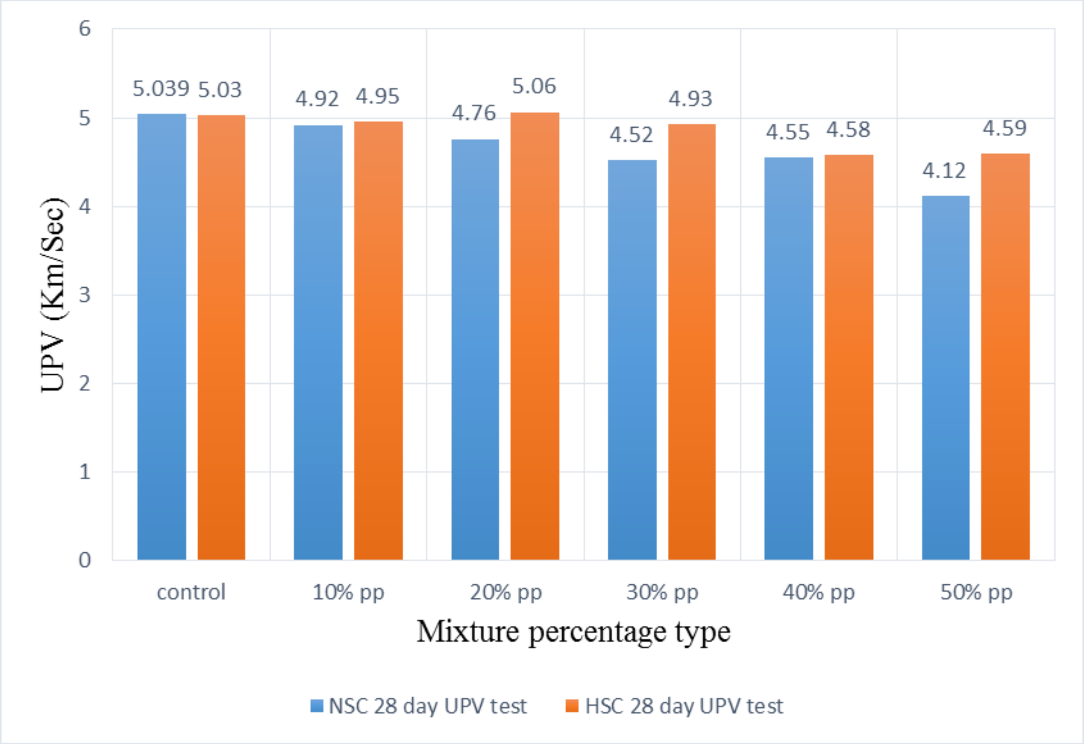


Figure 34: Results of UPV test for NSC and HSC at 28 days

Concretes are categorized as excellent, good, doubtful, poor, and very poor for 4.5 km/s and above, 3.50 – 4.50 km/s, 3.0 – 3.5 km/s, 2.0 – 3.0 km/s and 2.0 km/s and below UPV values, respectively (Whitehurst, 1951). By applying these suggested ranking methods, all concrete generated except NSC 50% PP in this study was done in excellent range of performance (Jones & Gatfield, 1955).

4.3.5 Schmidt Hammer Test of HSC and NSC at 28 Days

According to Figure 35, with an increase in PP value, Schmidt hammer values increases for NSC at 28-days, except in one case ascends (40% PP). For HSC at 28-days, except the control mix, at replacement level of 10% PP to 50% PP, with an increase in PP value, Schmidt hammer values increase. The highest Schmidt hammer value at 28-days for NSC and HSC is at replacement level of 40% PP and is 32.73 MPa and 49.20 MPa, respectively. Also, the lowest Schmidt hammer value at 28-

days for NSC is for the control mix and equals to 27.93 MPa and for HSC is at 10% PP and equals to 44.33 MPa.

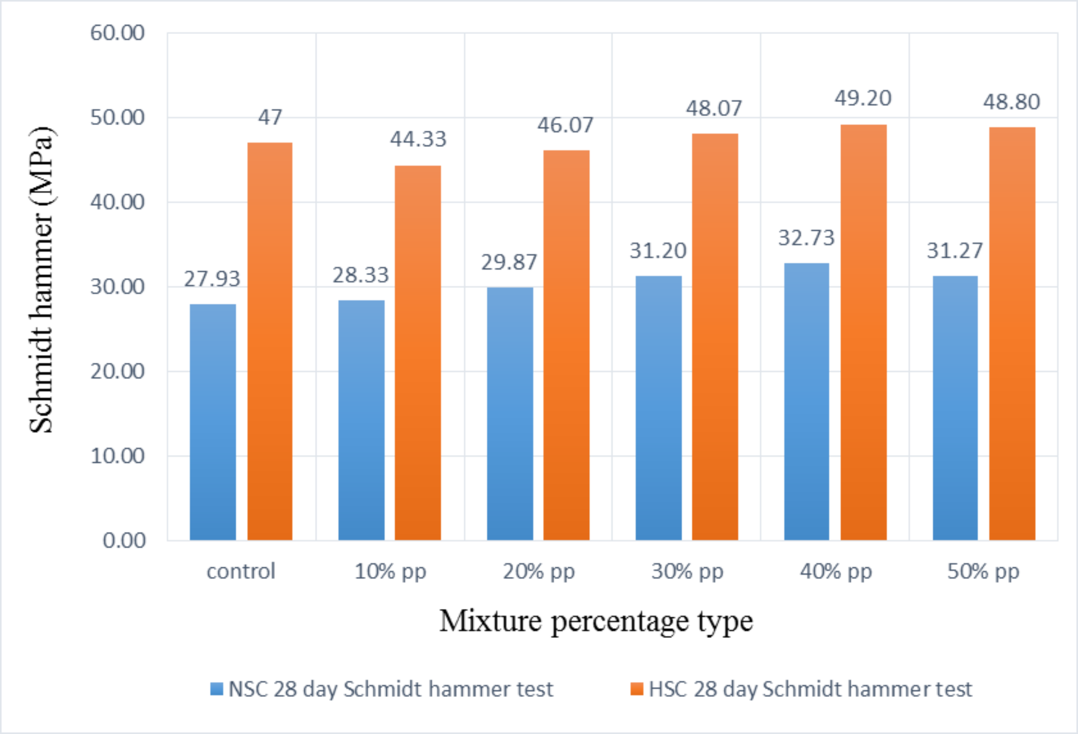


Figure 35: Results of schmidt hammer test for NSC and HSC at 28 days

Face of samples condition and the utmost size of aggregates were influenced on rebound test. But rebound test findings are not similar to the f_c outcomes and could be due to a number of factors, such as aggregate distribution, poor vibration or existence of foam on the surface of the samples (BS 1881: 201, 2009).

4.3.6 Water Absorption Test for NSC and HSC at 28 Days

The results of water absorption, shown in Figure 36, rise in moment as the proportion of PP for both NSC and HSC increases. The water absorption for NSC is greater than the water absorption for HSC, according to the results shown in this figure.

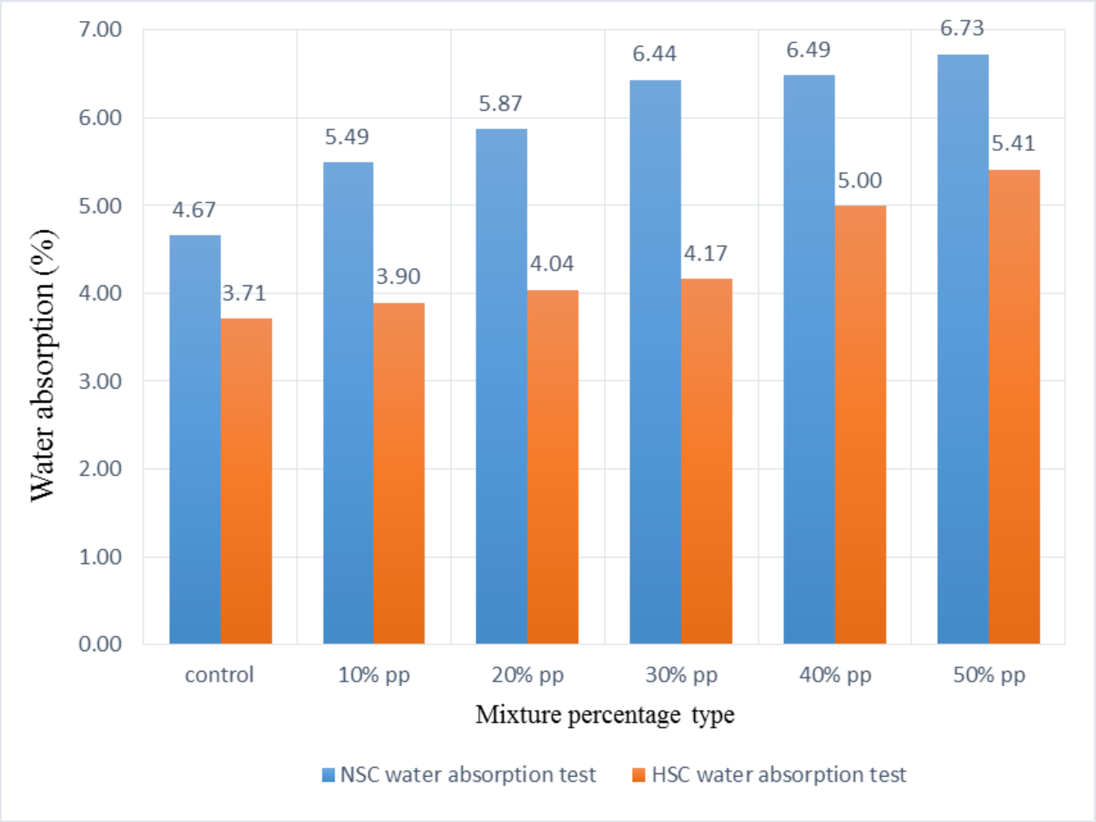


Figure 36: Results of water absorption test for NSC and HSC at 28 days

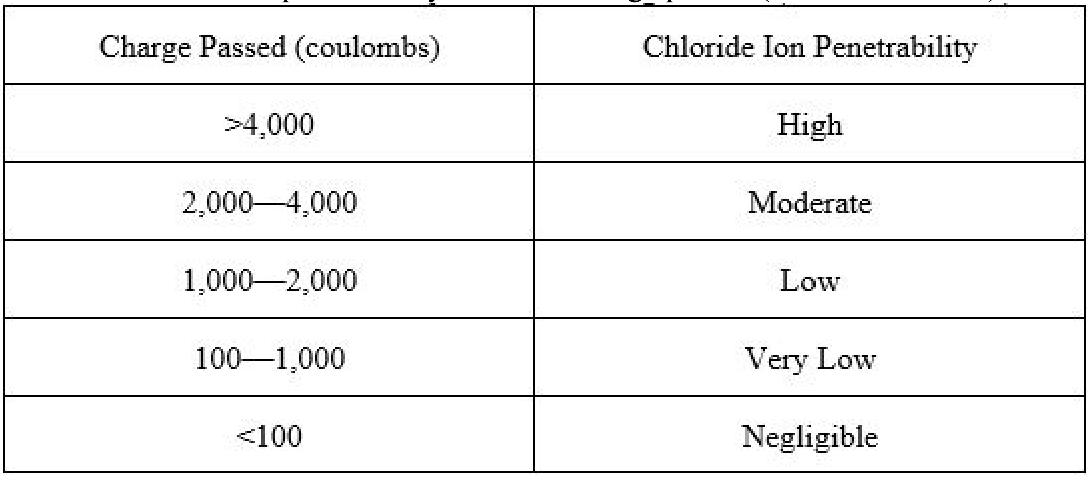
A glance at Figure 36 reveals that with a rise in the quantity of PP, the proportion of water absorption for HSC and also for NSC continues to rise. The smallest proportion of water absorption in the power system layout was 3.71 % for HSC and 4.67 % for NSC and the largest proportion of water absorption was 5.41 % for HSC and 6.73 % for NSC.

PP in absorbing of water features like a permeable pore volume and density, constitute indirect porosity. As shown in Figure 36, this upward tendency was due to the fact that plastics and artificial aggregates did not adequately combine the mixture in structure of concrete, therefore the resulting concrete became porous (Gu & Ozbakkaloglu, 2016).

4.3.7 Rapid Chloride Permeability [RCP] Test for NSC and HSC at 28 Days

According to Tables 9, 10 and 11, as well as Figure 37, a rise in the quantity of PP results in a reduction in RCP for NSC at 28-days, but as for HSC 28 days, RCP doesn’t seem to follow any particular pattern. Also, the least possible amount of RCP for the HSC is 2826 Coulombs at replacement level of 30%PP. On the other hand, the highest amount for NSC at 28-days for the control mix is 5019 Coulombs and for HSC at 28 days RCP is 5429 Coulombs for 40% PP replacement level.

Table 9: Chloride ion penetrability based on charge passed (ASTM c1202-19)



Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000—4,000	Moderate
1,000—2,000	Low
100—1,000	Very Low
<100	Negligible

Table 10: Results of RCP test on NSC at 28 days

Mixture type	RCP (Coulomb)	Change of Coulombs	Chloride Ion Penetrability
Control mix design	5019	----	High
10%pp	4843	-176	High
20%pp	2025	-2818	Moderate
30%pp	974	-1051	Very Low
40%pp	956	-18	Very Low
50%pp	602	-354	Very Low

Table 11: Results of RCP test on HSC at 28 days

Mixture type	RCP (Coulomb)	Change of Coulombs	Chloride Ion Penetrability
Control mix design	4542	----	High
10%pp	4965	423	High
20%pp	3718	-1247	Moderate
30%pp	2826	-892	Moderate
40%pp	5429	2603	High
50%pp	4943	-486	High

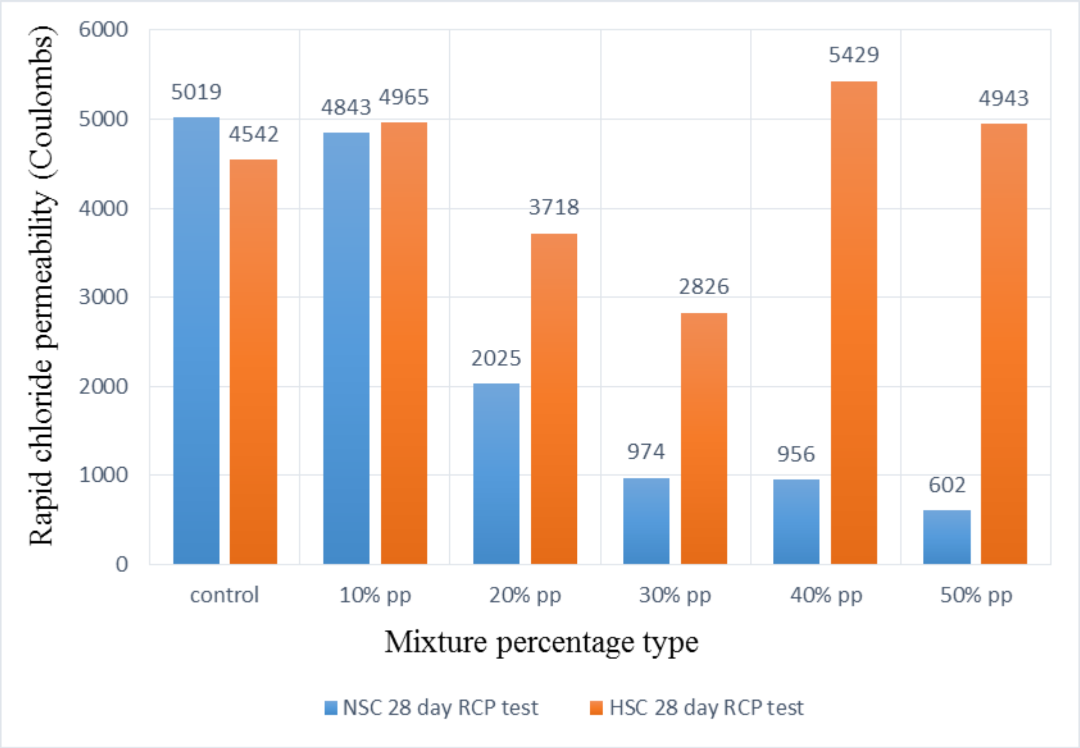


Figure 37: Results of rapid chloride permeability test for HSC and NSC at 28 days

According to the findings shown in Figure 37, HSC's RCPs at 28-days are almost all greater than NSC. In NSC, the smallest RCP was reported for PP (50%) with 602 Coulombs and in HSC, the smallest RCP was reported for PP (30%) with 2826 Coulombs.

The migration of chloride is affected by the water permeability, absorption and porosity of concrete. Silva, De Brito, and Dhir (2014) also reported that the chloride permeability of conventional concrete was lower than that of concrete containing plastic waste material. In addition, the best resistance against chloride ion penetration was observed in the concrete specimens held in the laboratory ambience.

4.3.8 Degradation Test Against Heat at 200 ˚C for NSC and HSC after 28 Days

4.3.8.1 Efficacy of PP on Compressive Strength [f_c] of Heated NSC and HSC at 200 ˚C

As it is shown in Figure 38, with an increase in the replacement level of PP, the f_c for NSC before 200 ˚C heating decreases. However, for NSC after 200 ˚C heating, it first decreases and then increases from 30% PP replacement level onwards. Also, the highest value of f_c is for the NSC control mix before 200 ˚C heating, i.e. 42.3 MPa. For NSC after 200 ˚C heating this amount is reported to be 32.47 MPa. The lowest f_c in 50% PP replacement level for NSC before 200 ˚C heating is 24.6 MPa.

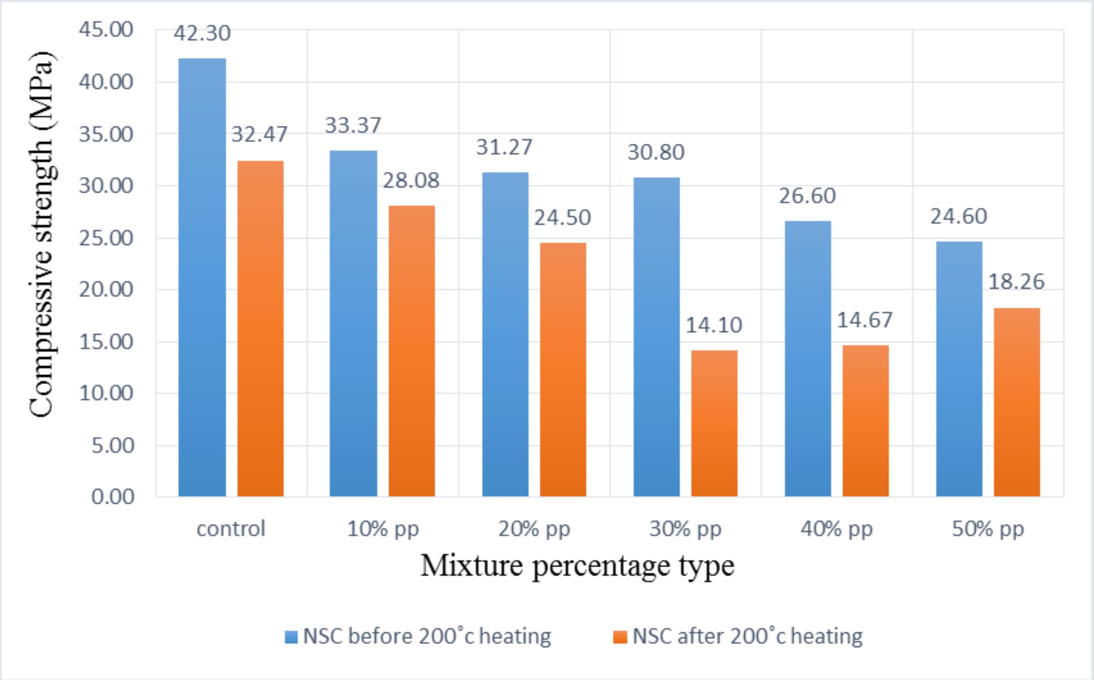


Figure 38: Results of compressive strength test before and after 200 ˚C heating for NSC at 28 days

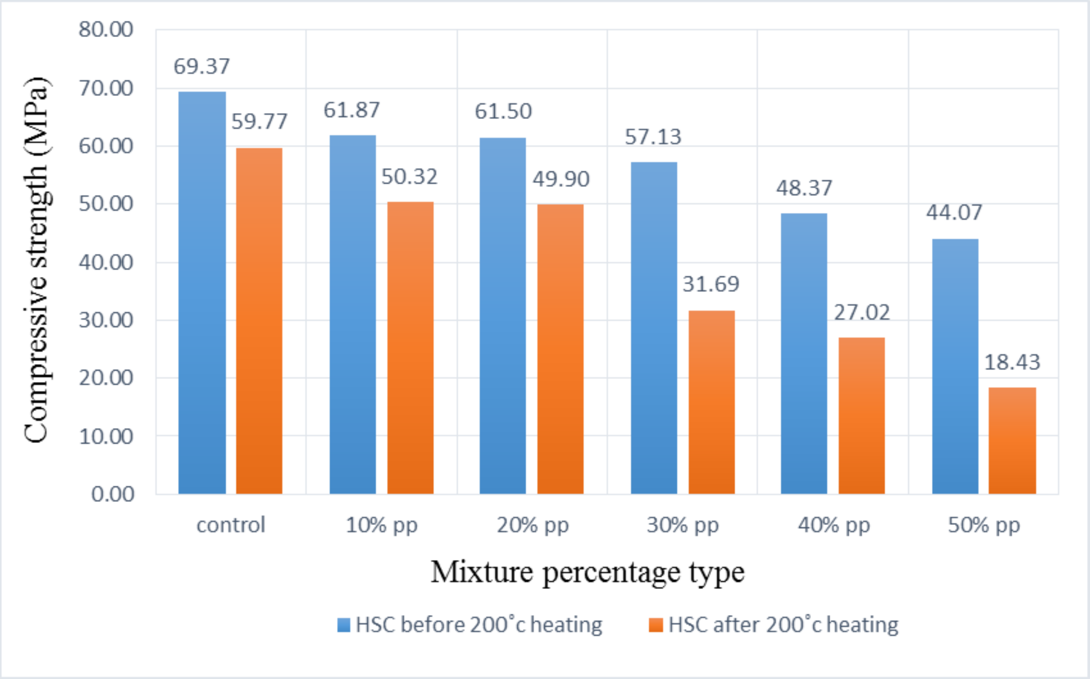


Figure 39: Results of compressive strength test before and after 200 ˚C heating for HSC at 28 days

According to Figure 39, with an increase in the replacement level of PP, the value of f_c for the HSC before and after 200 ˚C heating is always descending. Also, the highest amount of f_c in control mix for HSC before 200 ˚C heating is 69.37 MPa and after 200 ˚C heating is 59.77 MPa. The lowest value of f_c for50% PP (HSC) before 200 ˚C heating is 44.07 MPa, and after 200 ˚C heating is 18.43 MPa.

A melting point of PP was found to be above 150 ˚C (Mezghani & Phillips, 1998) Polypropylene had begun to liquefy and fill the gaps in the concrete, causing the road to increase the volume of the samples. The temperature of 200 ˚C was a factor in causing cracks inside and outside the specimens and in removing the molten plastic from the concrete. As a result, the f_c of concrete reduced with a growing proportion of polypropylene instead of a coarse aggregate in HSC and NSC.

4.3.8.2 Efficacy of PP on Splitting Tensile Strength [f_s] of Heated NSC and HSC at 200 ˚C

As shown in Figure 40, with an increase in the replacement level of PP, the value of f_s for NSC before and after 200 ˚C heating is always descending, so that from 20% PP replacement level onwards f_s values becomes zero. The highest value of f_s for control mix for NSC before 200 ˚C heating is 3.20 MPa and for NSC after 200 ˚C heating it is 2.71 MPa and the lowest $f_s$at50% PP replacement level for NSC before 200 ˚C heating is 2.30 MPa and for NSC after 200 ˚C heating is zero.

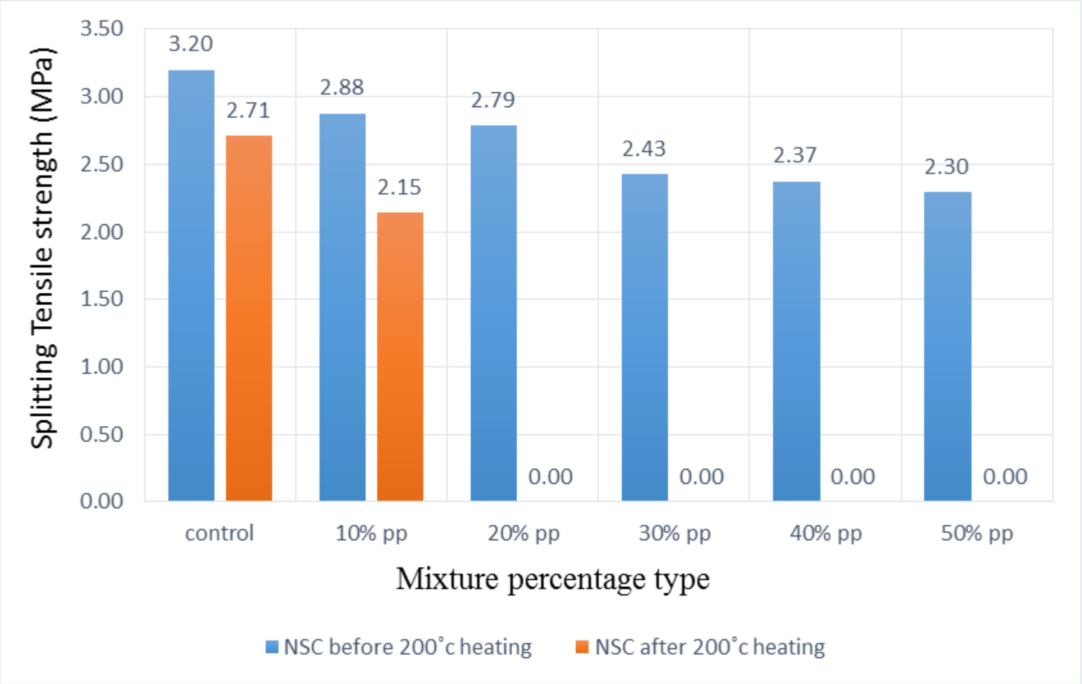


Figure 40: Results of splitting tensile strength test after and before 200˚C heating for NSC at 28 days

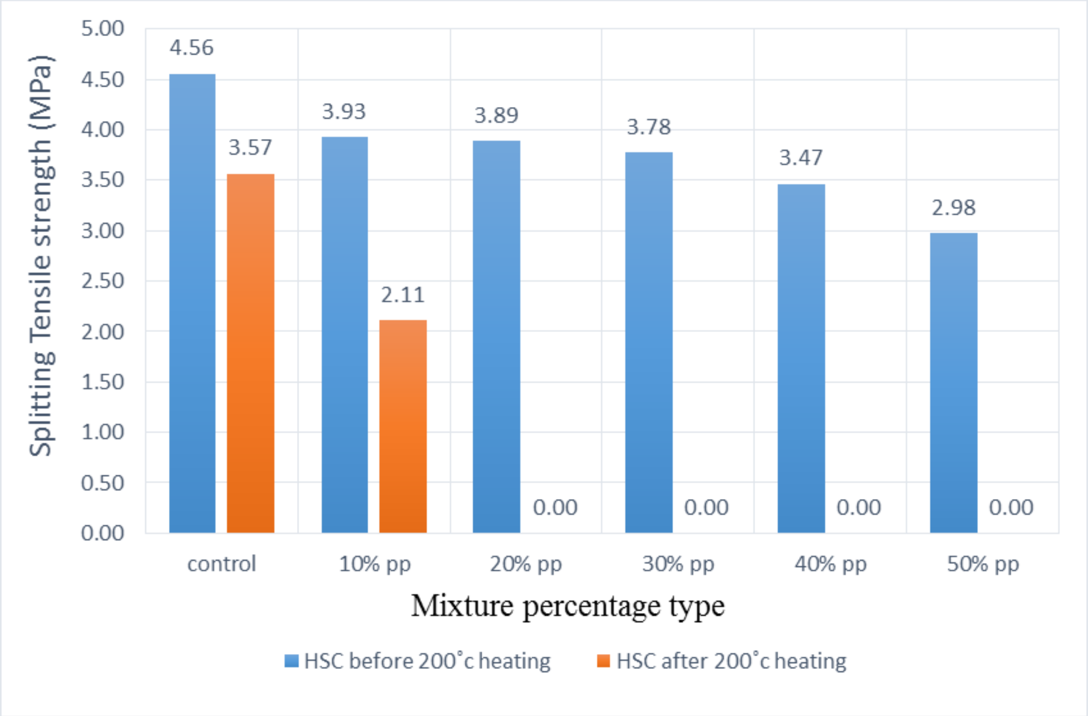


Figure 41: Results of splitting tensile strength test after and before 200 ˚C heating for HSC at 28 days

Figure 41 shows that the f_s is steadily decreasing for the HSC before and after 200 ˚C heating with an increasing of PP replacement level. Also, for HSC prior to 200 ˚C heating, it is 4.56 MPa and for HSC after 200 ˚C heating, it decreased to3.57 MPa. However, after 200 ˚C heating and beyond 20% PP replacement level, the f_s values become zero.

As illustrated, tensile strength of the heated concrete was shown to be zero after the addition of 20% polypropylene instead of a coarse aggregate. The samples were cracked at the lowest possible pressure from the concrete strength meter and no number was displayed on the concrete strength meter screen. Thus, it is recognized that lack of bonding between the internal materials, the HSC and NSC with 20% PP will no longer support any tensile strength.

4.3.8.3 Efficacy of PP on UPV of Heated NSC and HSC at 200 ˚C

Figure 42 illustrates that with an increase in the replacement level of PP, the value of UPV is descending in different steps for NSC before 200 ˚C heating and also after 200 ˚C heating , except for the 30% PP to 40% PP replacement levels,. The highest value of UPV for the control mix of NSC before 200 ˚C heating is 5.04 km/sec and after 200 ˚C heating is 4.31 km/sec and the lowest value for UPV in 50% before 200 ˚C heating is 4.12 km/sec and after 200 ˚C heating is 1.47 km/sec.

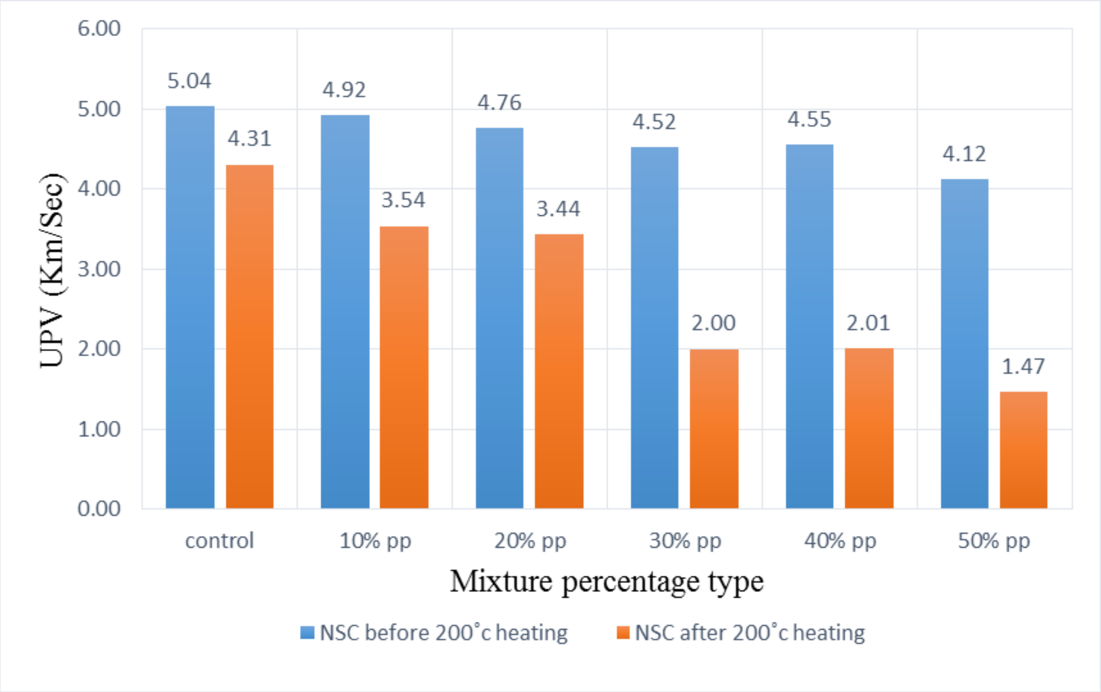


Figure 42: Results of UPV test before and after 200 ˚C heating for NSC at 28 days

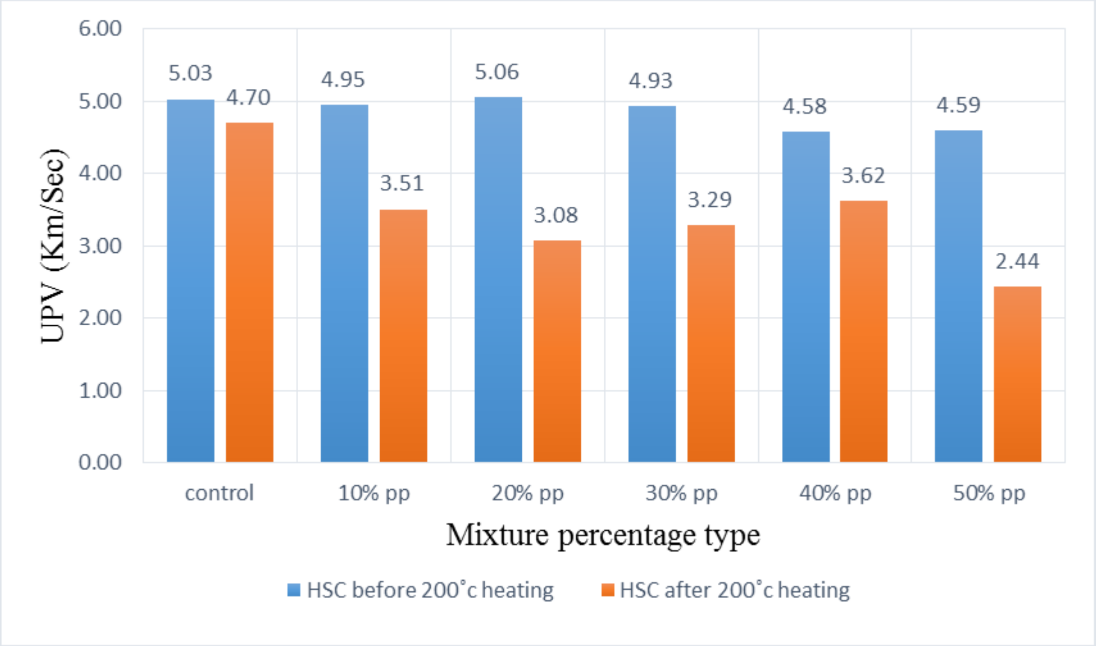


Figure 43: Results of UPV test before and after 200 ˚C heating for HSC at 28 days

According to Figure 43, for the HSC before 200 ˚C heating, with an increase in the value of PP, the UPV value decreases, with the exception of 10 percent PP to 20 percent PP and 40 percent PP to 50 percent PP replacement levels. However, after 200 ˚C heating the HSC descended first and then ascended. Also, the highest amount of UPV in control mix for HSC before 200 ˚C heating is 5.03 km/sec and after 200 ˚C heating it is 4.70 km/sec. The lowest value for UPV in 40% PP for HSC before 200 ˚C heating is 4.58 km/sec for HSC after 200 ˚C heating in 50% PP is 2.44 km/sec.

This failure of concrete performance in the HSC and NSC, UPV experiment is due to the chemical reactions that have happened between the components of the concrete blend and the degradation of the plastic components. In addition, this could be partly related to the deformation that occurred following the loss of water in high temperatures (Albano et al., 2009).

4.3.8.4 Efficacy of PP on Crack Development of Heated NSC and HSC at 200 ˚C

Figure 44a: NSC-control mix surfaces after 200 ˚C heating at 28 days

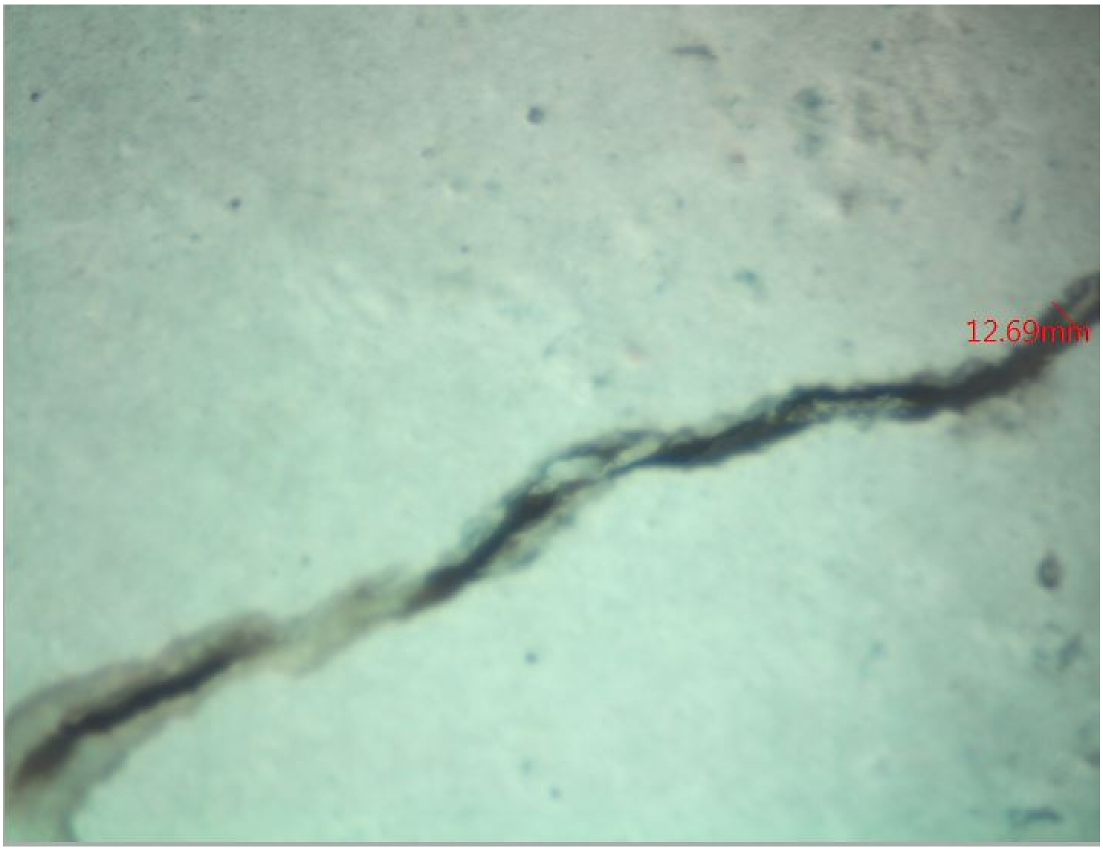


Figure 44b: NSC-10% PP surfaces after 200 ˚C heating at 28 days

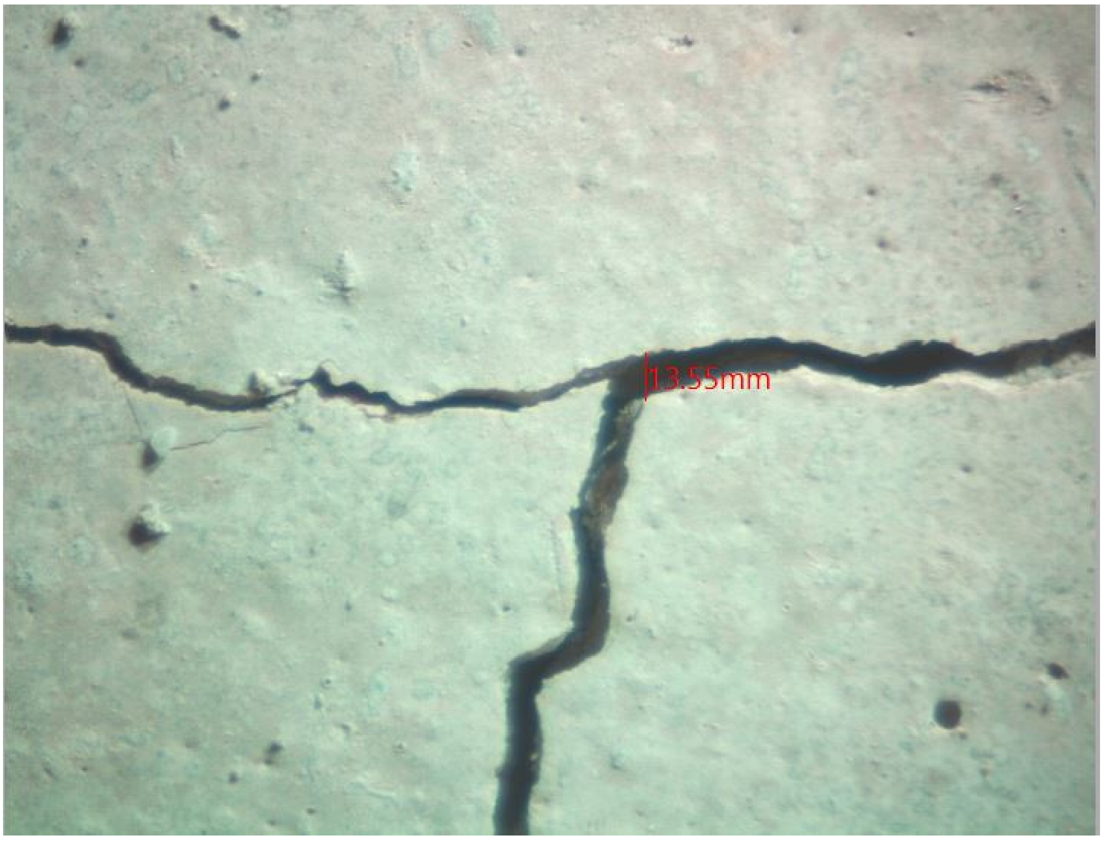


Figure 44c: NSC-20% PP surfaces after 200 ˚C heating at 28 days

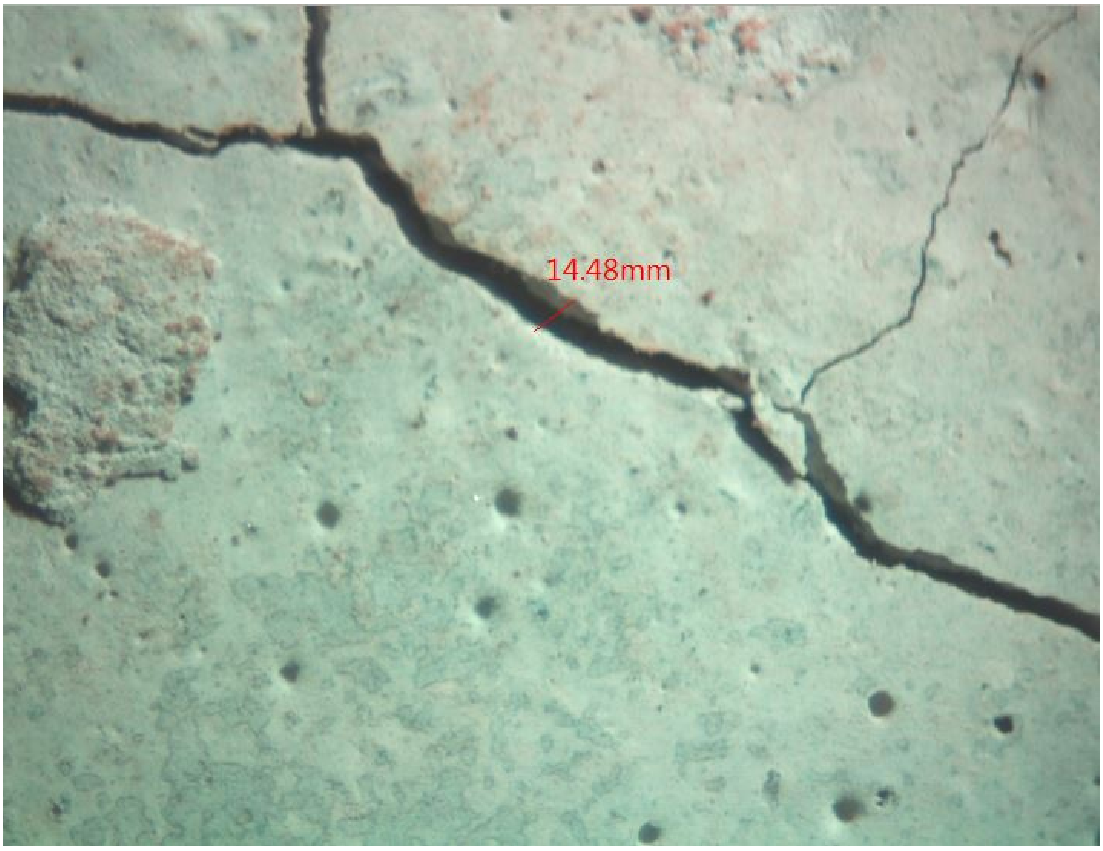


Figure 44d: NSC-30% PP surfaces after 200 ˚C heating at 28 days

Figure 44e: NSC-40% PP surfaces after 200 ˚C heating at 28 days

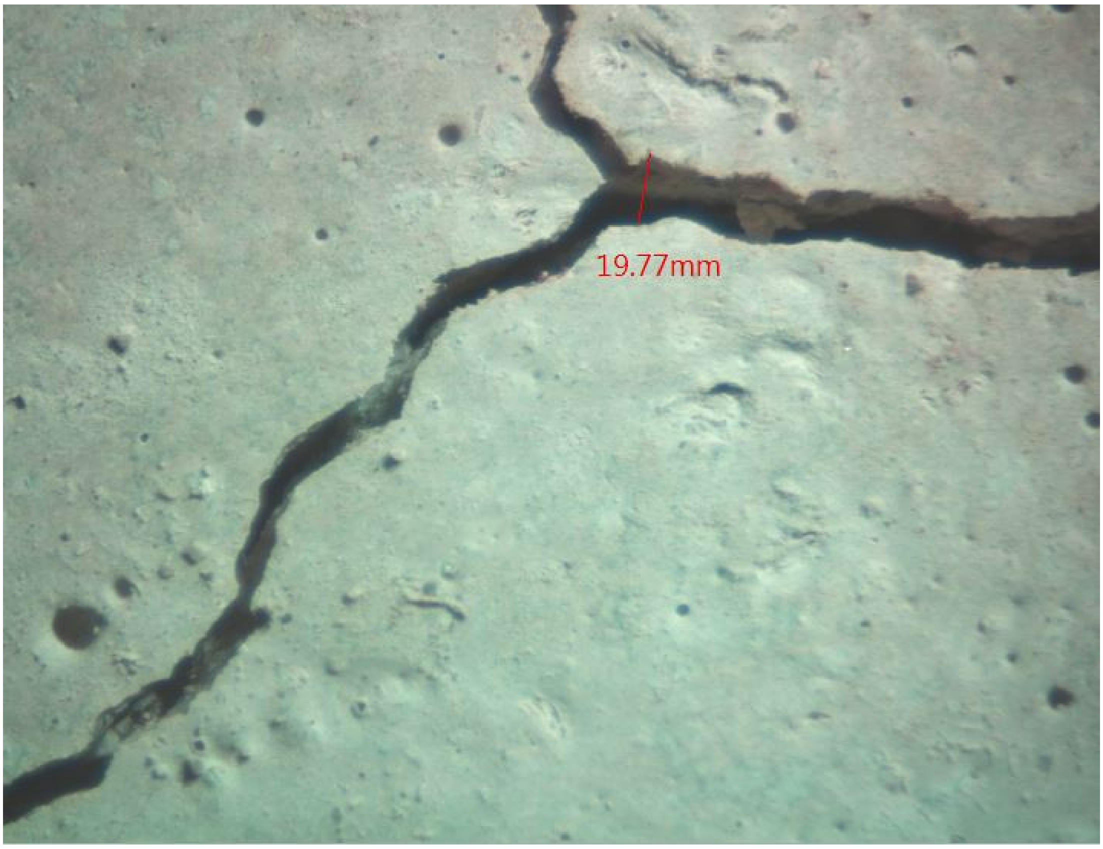


Figure 44f: NSC-50% PP surfaces after 200 ˚C heating at 28 days

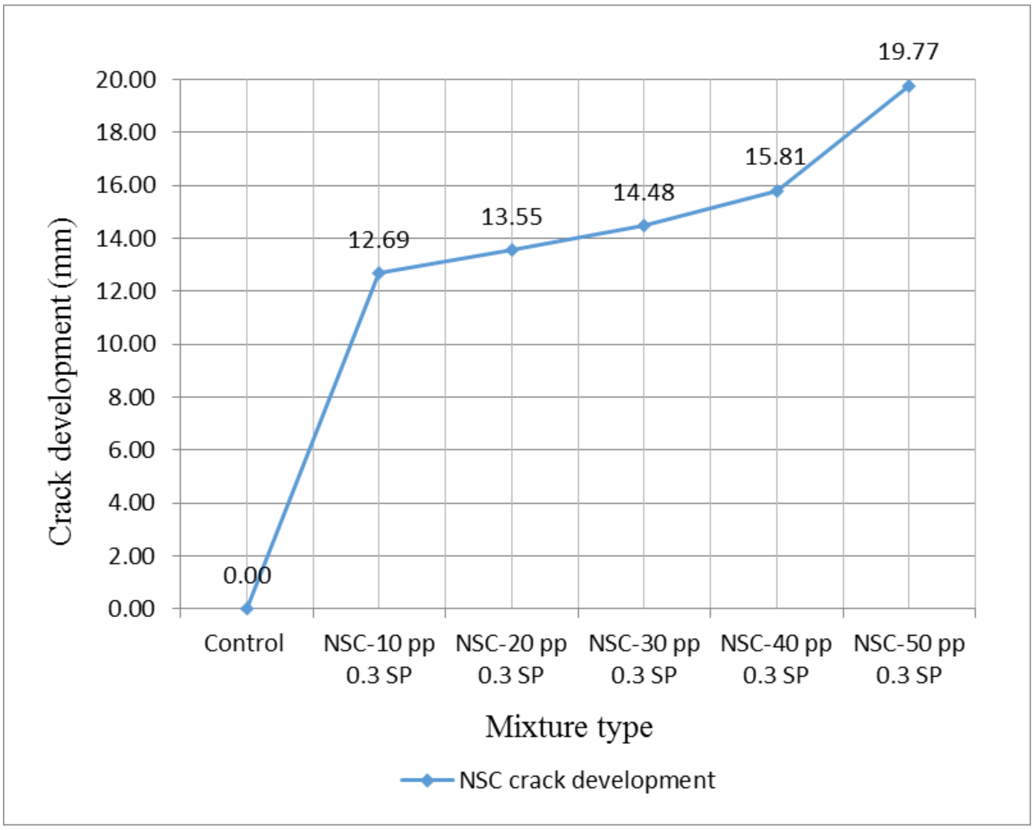


Figure 45: Crack development test results after 200 ˚C heating for NSC at 28 days

As shown in Figures 44 a, 44 b, 44 c, 44 d, 44 e, 44 f and 45, for NSC with an increase in the replacement level of PP, the crack development increases. However, this ascending change is more intense initially, but continues to be less intense gradually. The least amount of crack development is related to the control mix which is equal to zero, and its highest value is for NSC-50% PP with 0.3% SP which is equal to 19.77 mm.

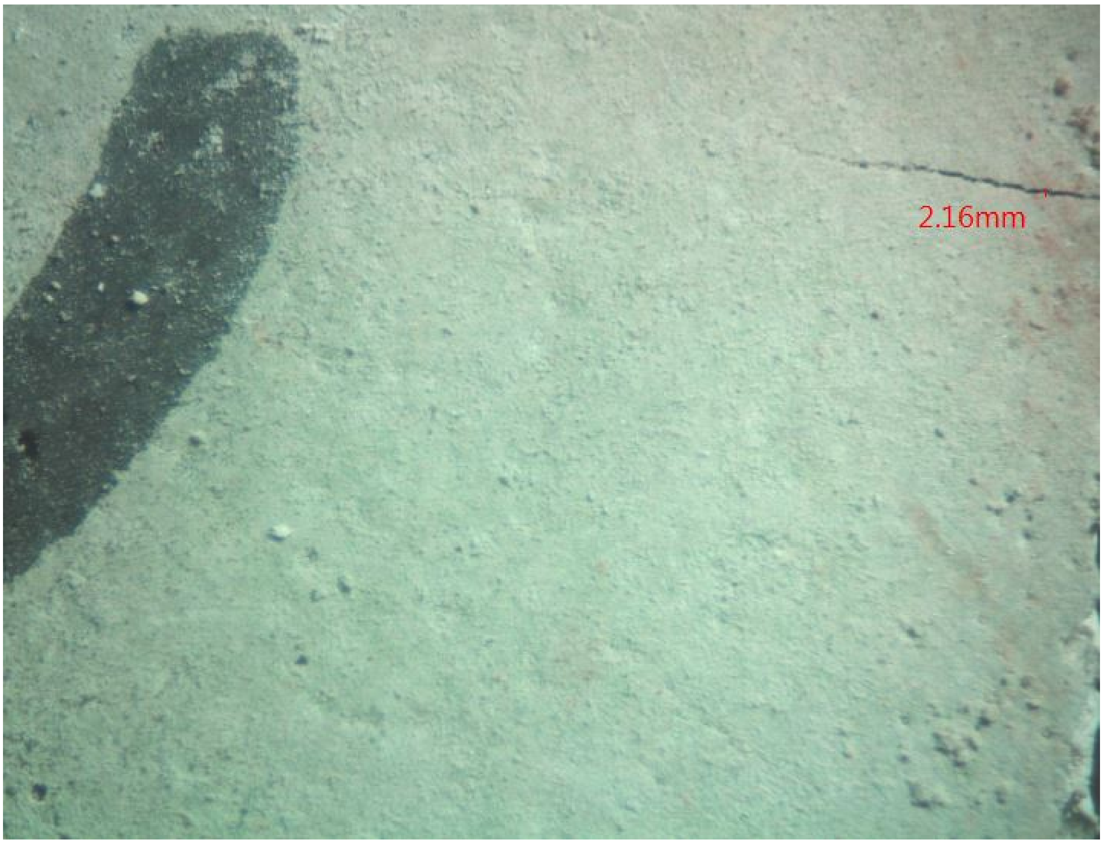


Figure 46a: HSC-control mix surfaces after 200 ˚C heating at 28 days

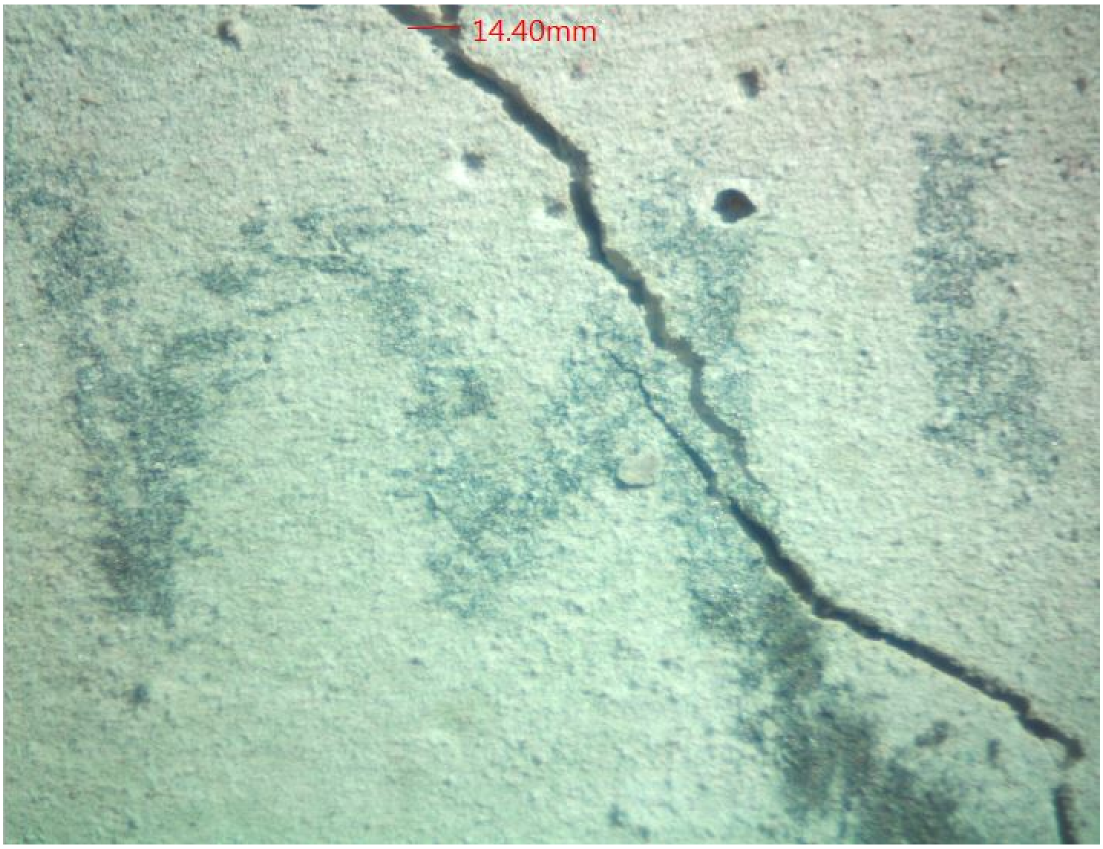


Figure 46b: HSC-10% PP surfaces after 200 ˚C heating at 28 days

Figure 46c: HSC-20% PP surfaces after 200 ˚C heating at 28 days

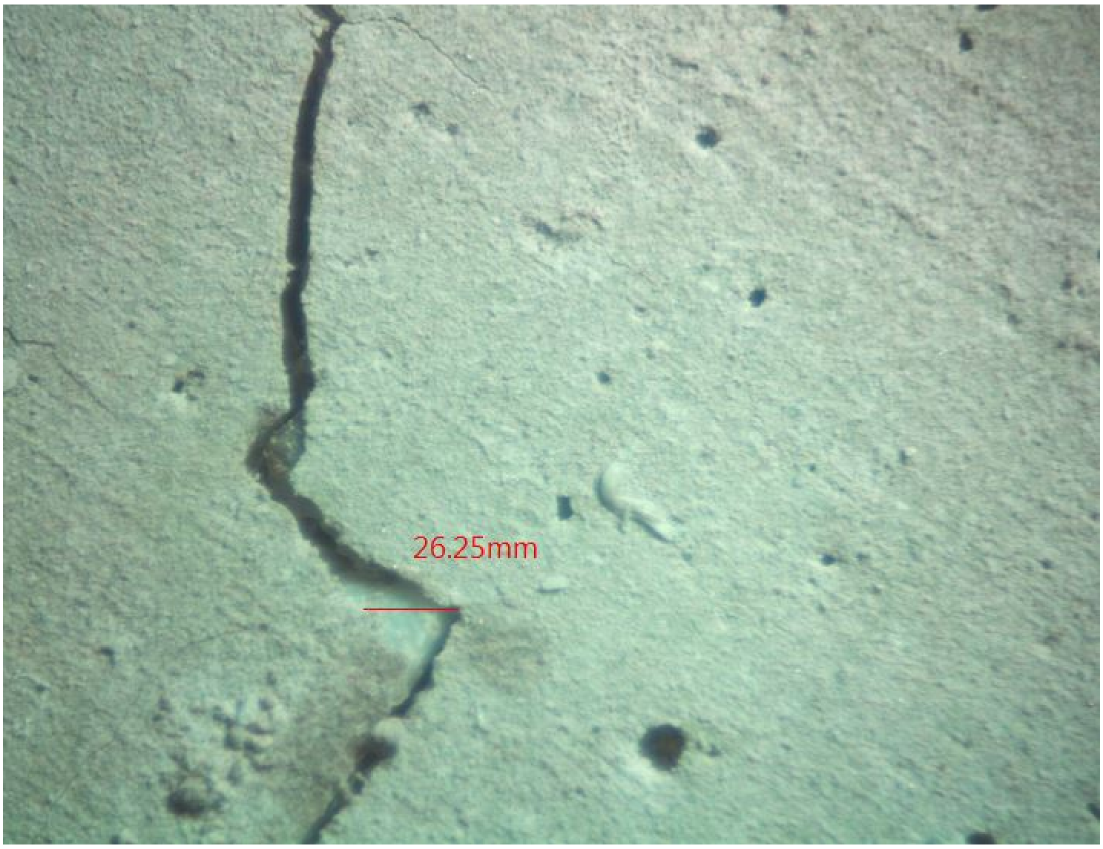


Figure 46d: HSC-30% PP surfaces after 200 ˚C heating at 28 days

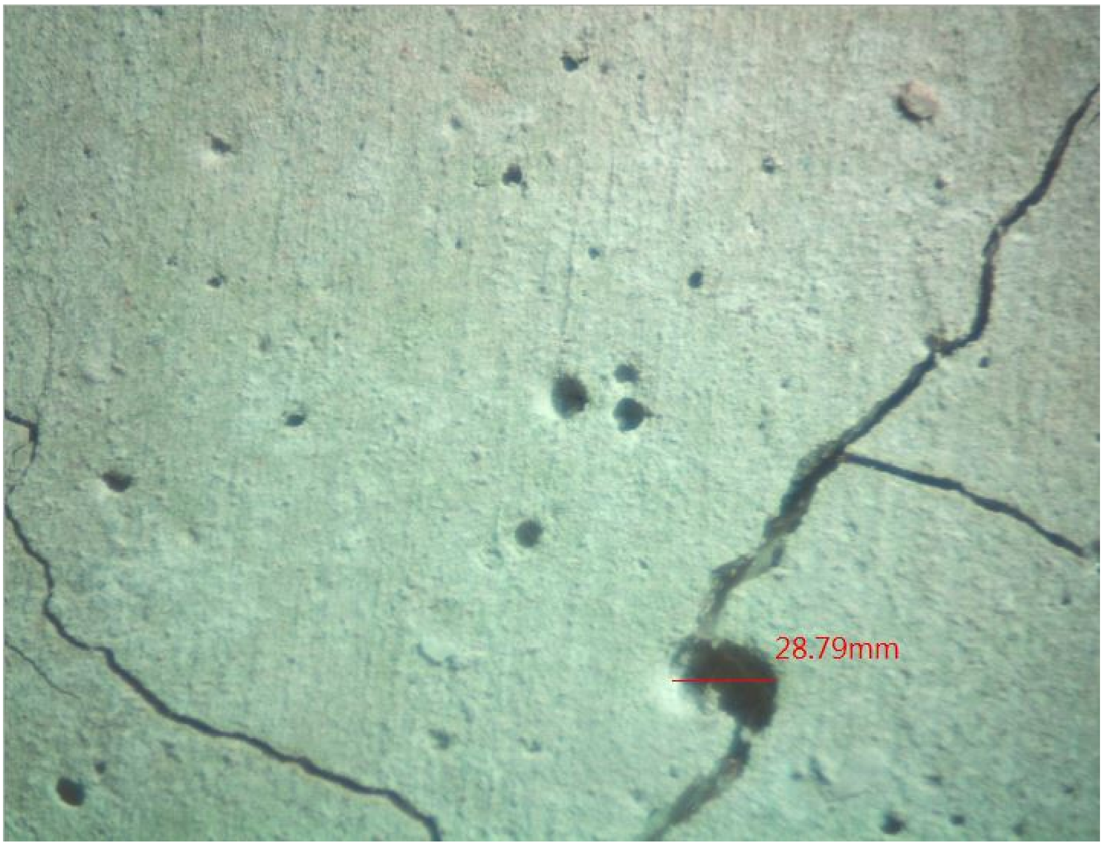


Figure 46e: HSC-40% PP surfaces after 200 ˚C heating at 28 days

Figure 46f: HSC-50% PP surfaces after 200 ˚C heating at 28 days

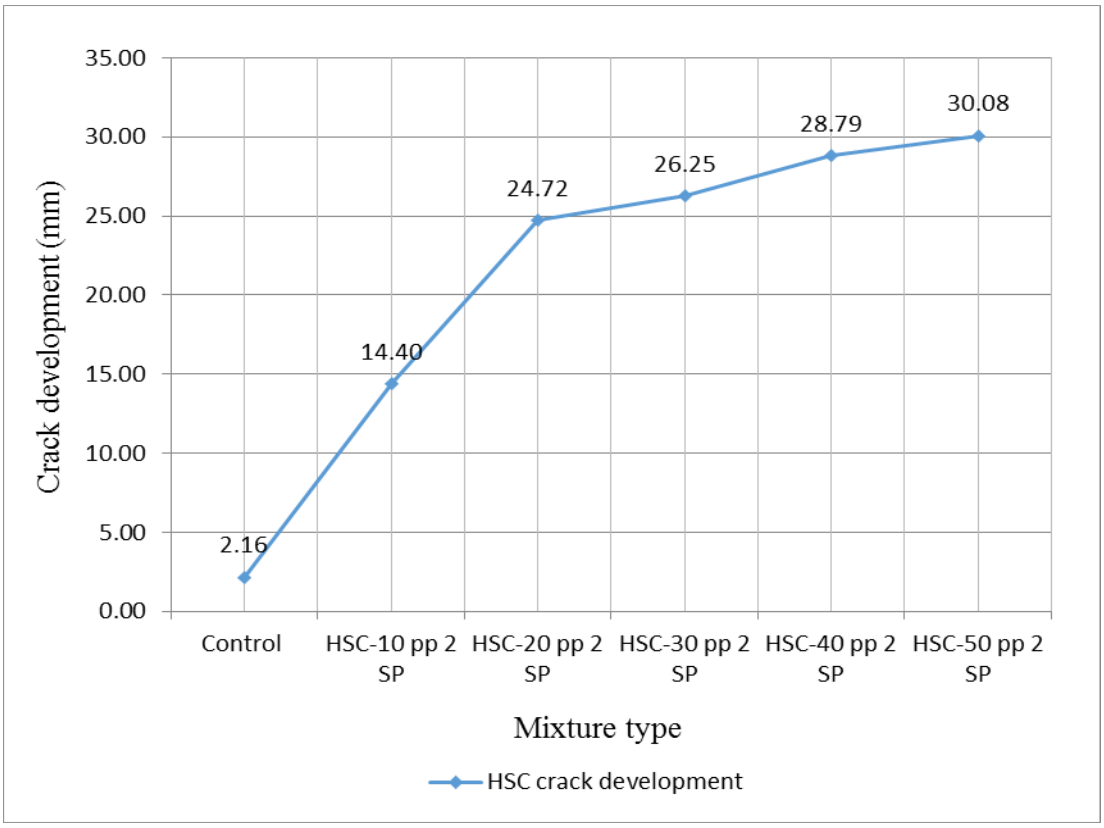


Figure 47: Crack development test results after 200 ˚C heating for HSC at 28 days

As illustrated in Figures 46 a, 46 b, 46 c, 46 d, 46 e, 46 f and 47for HSC, an increase in the replacement level of PP, the quantity of crack's growth increases. Here, too, the strength of the shift is more pronounced in the early phases, but it reduces in the subsequent phases. Furthermore, the least amount of crack development is found to be in the control mix and is equivalent to 2.16 mm and the largest value is for HSC-50 % PP with 2 % SP and equals to 30.08 mm.

Once concrete sample was exposed to 200 ˚C, which was greater than the ebullition of PP (at 150 ˚C), the PA within the specimens of HSC and NSC liquefied and extended which made large cracks on face of the concrete samples.

4.3.9 Relationship between Splitting Tensile [f_s] and Compressive Strength [f_c] Test for NSC and HSC at 28 Days

Based on the results shown in Figure 48, the f_s improves in an interactive manner in the NSC at 28-days with a rise in f_c.

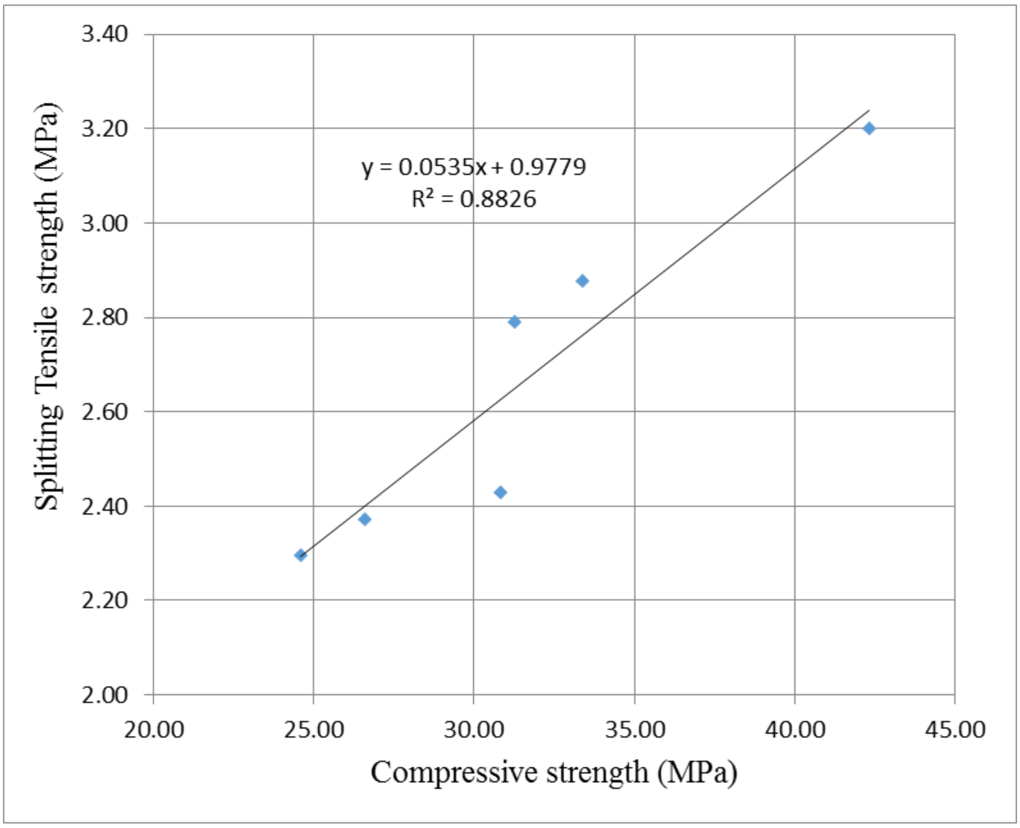
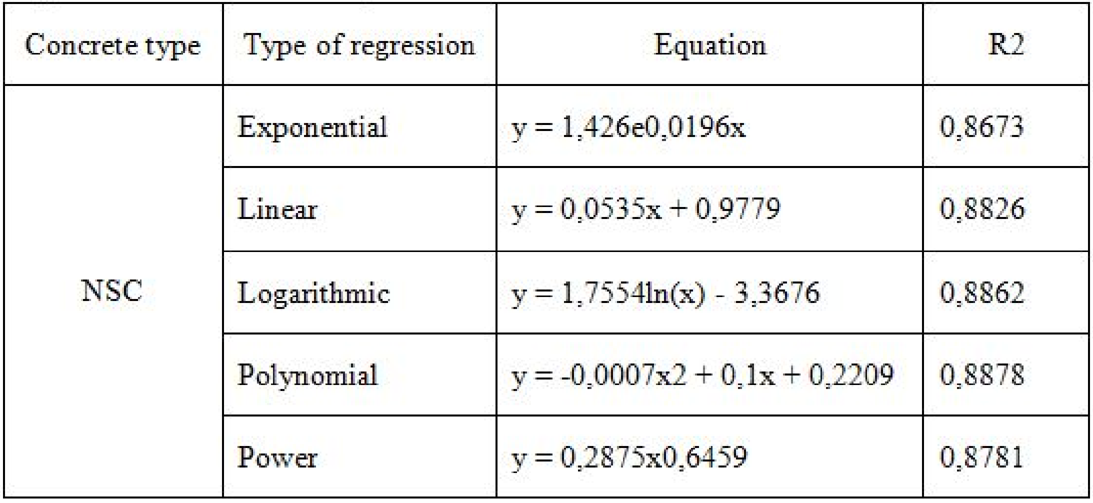


Figure 48: Compressive strength test and splitting tensile strength test linear relationship for NSC at 28 days

Table 12 illustrates the types of regression between splitting tensile and compressive strength test equations in order to determine the precise relationship between them for NSC concrete at 28 days.

Table 12: Relation between splitting tensile and compressive strength test equations for NSC at 28 days



Concrete type	Type of regression	Equation	R2
NSC	Exponential	y = 1,426e0,0196x	0,8673
	Linear	y = 0,0535x + 0,9779	0,8826
	Logarithmic	y = 1,7554ln(x) - 3,3676	0,8862
	Polynomial	y = -0,0007x2 + 0,1x + 0,2209	0,8878
	Power	y = 0,2875x0,6459	0,8781

As it can be seen in Table 12, for NSC at 28-days, the strongest relationship between *fc* and *fs* is the polynomial function and with $R^2 = 0.8878$.

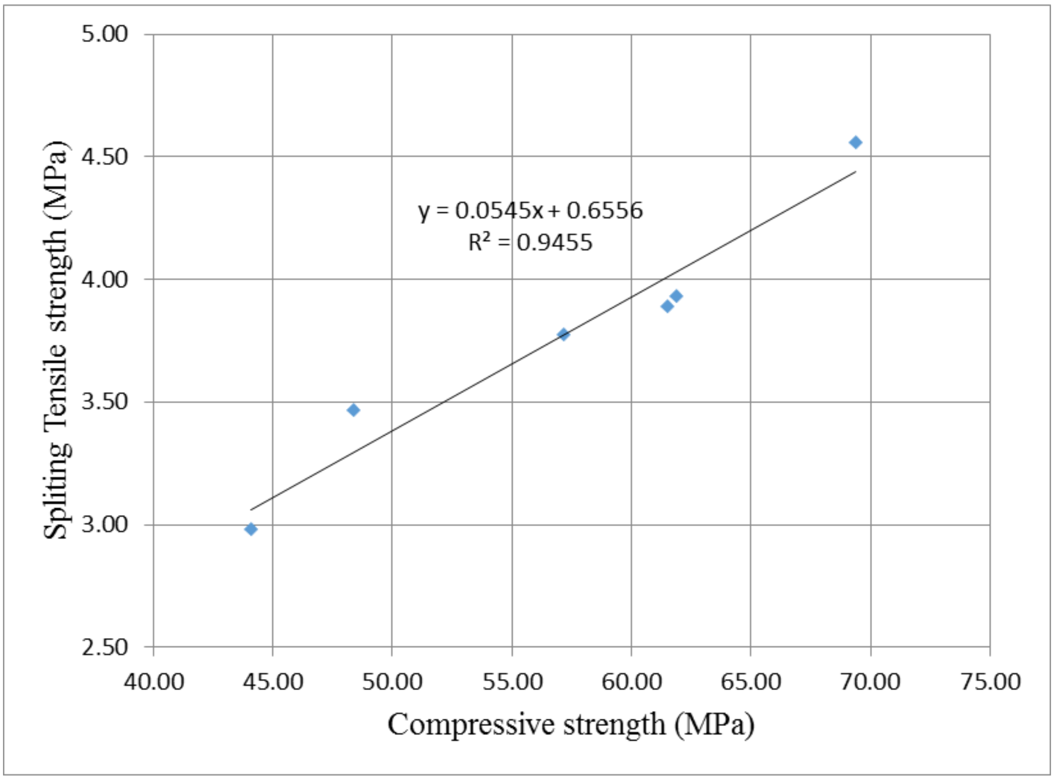
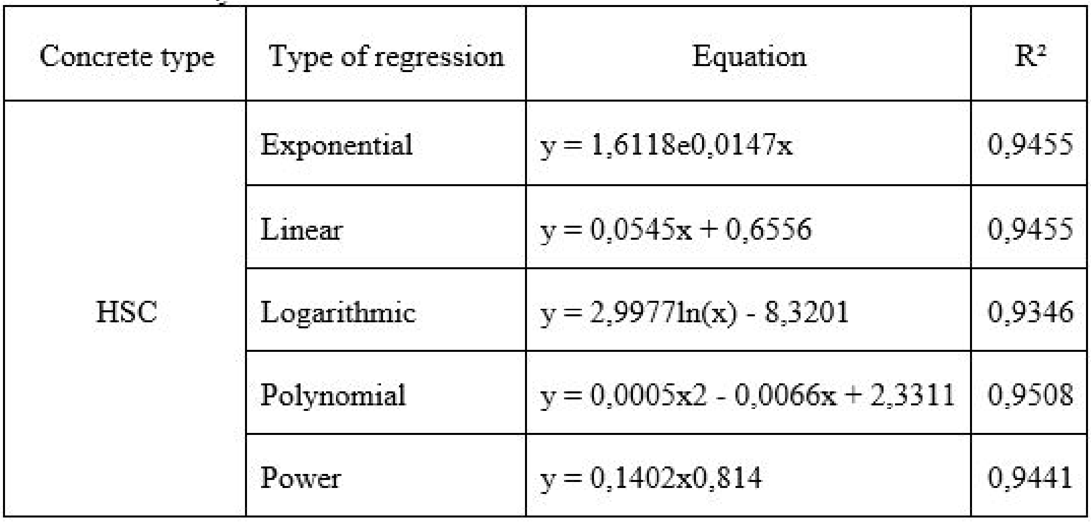


Figure 49: Splitting tensile and compressive strength test linear relationship for HSC at 28 days

Based on Figure 49, it was observed that tensile strength also improves in an interactive manner in the case of HSC at 28-days with a rise in *fc*. Table 13 shows the kinds of regression analysis between splitting tensile and compressive strength test equation in order to determine the precise relationship between them for HSC concrete.

Table 13: Relation between splitting tensile and compressive strength test equations for HSC at 28 days



Concrete type	Type of regression	Equation	R^2
HSC	Exponential	$y = 1,6118e0,0147x$	0,9455
	Linear	$y = 0,0545x + 0,6556$	0,9455
	Logarithmic	$y = 2,9977\ln(x) - 8,3201$	0,9346
	Polynomial	$y = 0,0005x2 - 0,0066x + 2,3311$	0,9508
	Power	$y = 0,1402x0,814$	0,9441

As shown in Table 13, for HSC at 28-days, the strongest relationship between f_c and f_s is the polynomial function with a value of $R^2 = 0.9508$.

4.3.10 Relationship between Flexural and Compressive Strength [f_c] Test for NSC and HSC at 28 Days

As it can be seen in Figure 50, in an intuitive way, NSC at 28-days, with an increase in the f_c, the amount of f_f also increases.

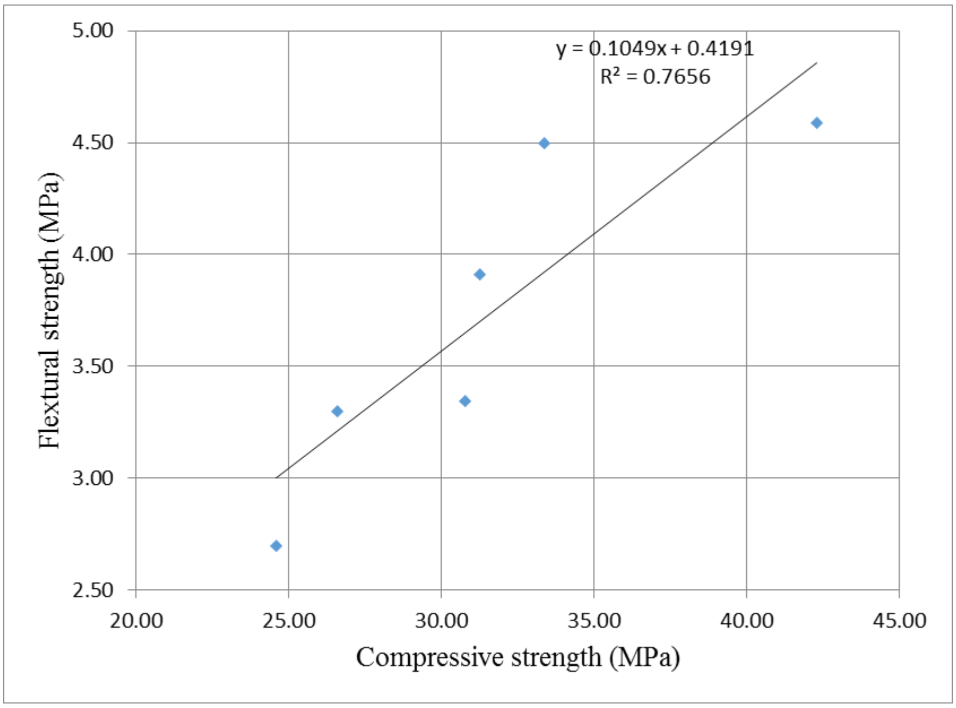
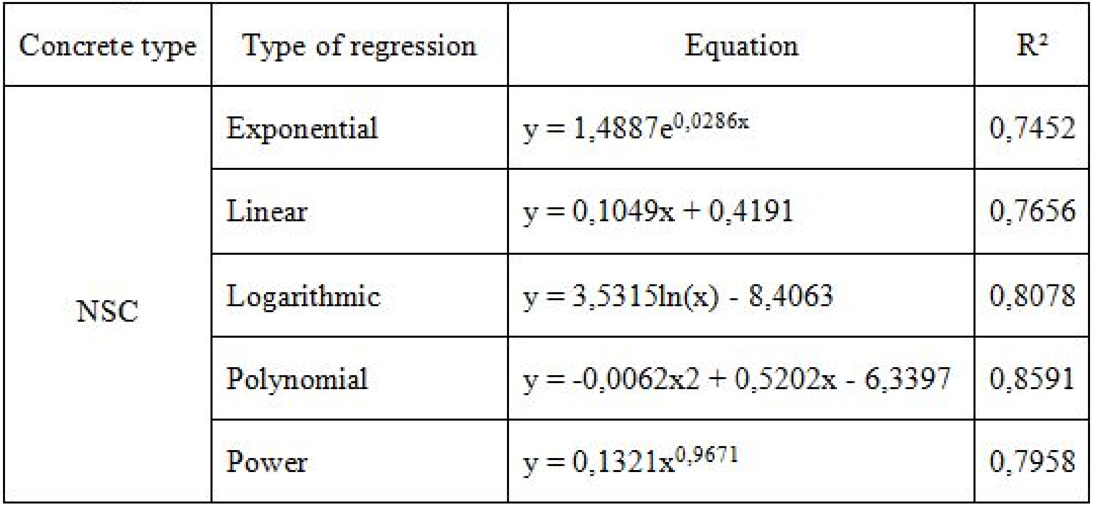


Figure 50: Flexural and compressive strength test linear relationship for NSC at 28 days

Table 14 shows the types of regression models between compressive and flexural strength test equations in order to determine the relationship between these two variables in NSC concrete at 28 days.

Table 14: Relation between flexural and compressive strength test equations for NSC at 28 days



Concrete type	Type of regression	Equation	R²
NSC	Exponential	$y = 1,4887e^{0,0286x}$	0,7452
	Linear	$y = 0,1049x + 0,4191$	0,7656
	Logarithmic	$y = 3,5315\ln(x) - 8,4063$	0,8078
	Polynomial	$y = -0,0062x2 + 0,5202x - 6,3397$	0,8591
	Power	$y = 0,1321x^{0,9671}$	0,7958

As shown in Table 14, for NSC at 28-days, the strongest relationship between f_c and f_f is the polynomial function with a value of $R^2 = 0.8591$.

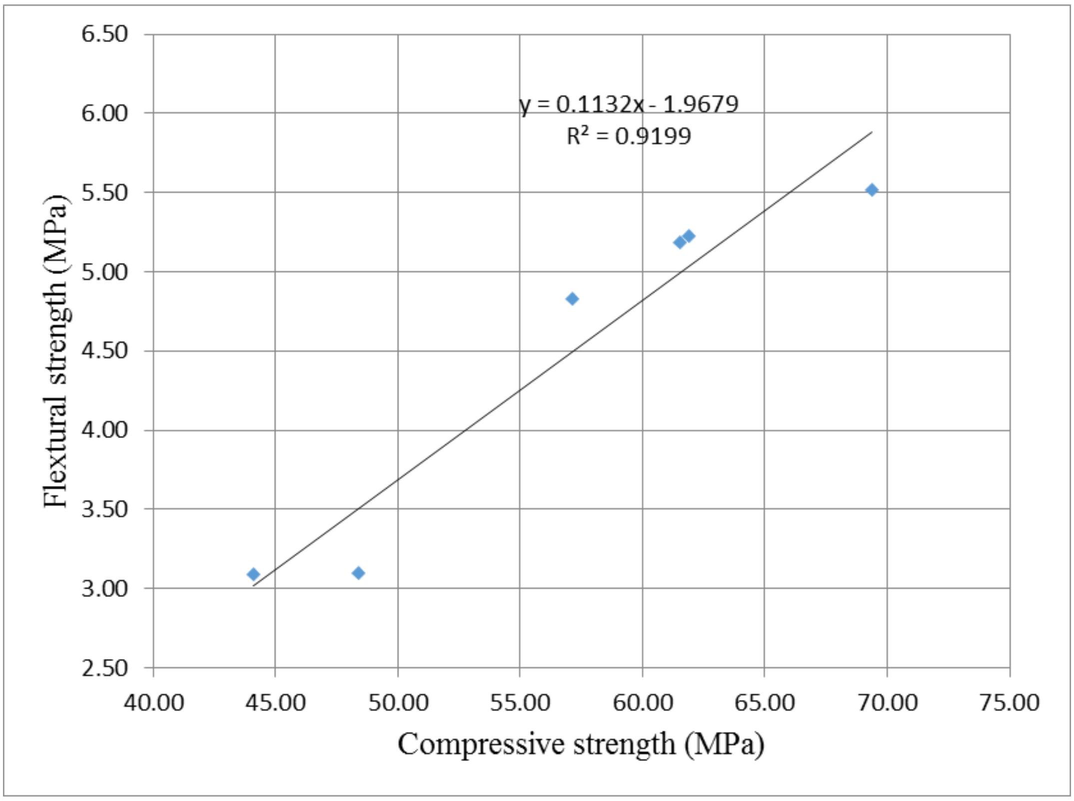
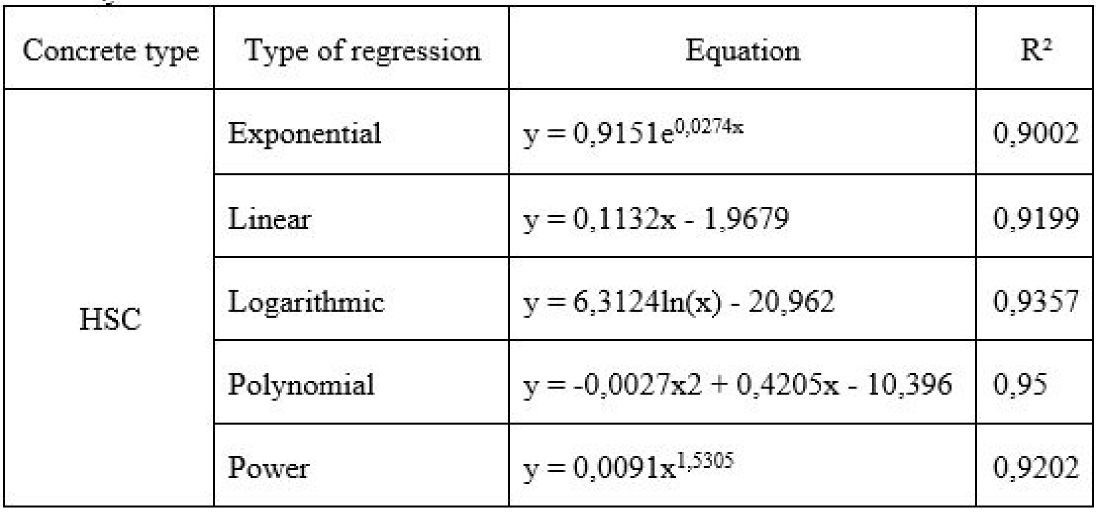


Figure 51: Flexural and compressive strength test linear relationship for HSC at 28 days

According to Figure 51, it was seen that, in an intuitive way, the HSC at 28-days, as f_c increases the value of f_f also increases. In order to determine the relationship between these two variables, Table 15 determines the types of regression models between these two properties in HSC concrete at 28 days.

Table 15: Relation equations between flexural and compressive strength test for HSC at 28 days



Concrete type	Type of regression	Equation	R^2
HSC	Exponential	$y = 0{,}9151e^{0{,}0274x}$	0,9002
	Linear	$y = 0{,}1132x - 1{,}9679$	0,9199
	Logarithmic	$y = 6{,}3124\ln(x) - 20{,}962$	0,9357
	Polynomial	$y = -0{,}0027x2 + 0{,}4205x - 10{,}396$	0,95
	Power	$y = 0{,}0091x^{1{,}5305}$	0,9202

As we can see in Table 15, for HSC at 28-days, the strongest relationship between f_c and f_f is the polynomial function with a value of $R^2 = 0.95$.

4.3.11 Relationship between Splitting Tensile [f_s] and Flexural Strength [f_f] Test for NSC and HSC at 28 Days

As shown in Figure 52, in an intuitive way, in NSC at 28-days, with the increase of f_f, the f_s also increase.

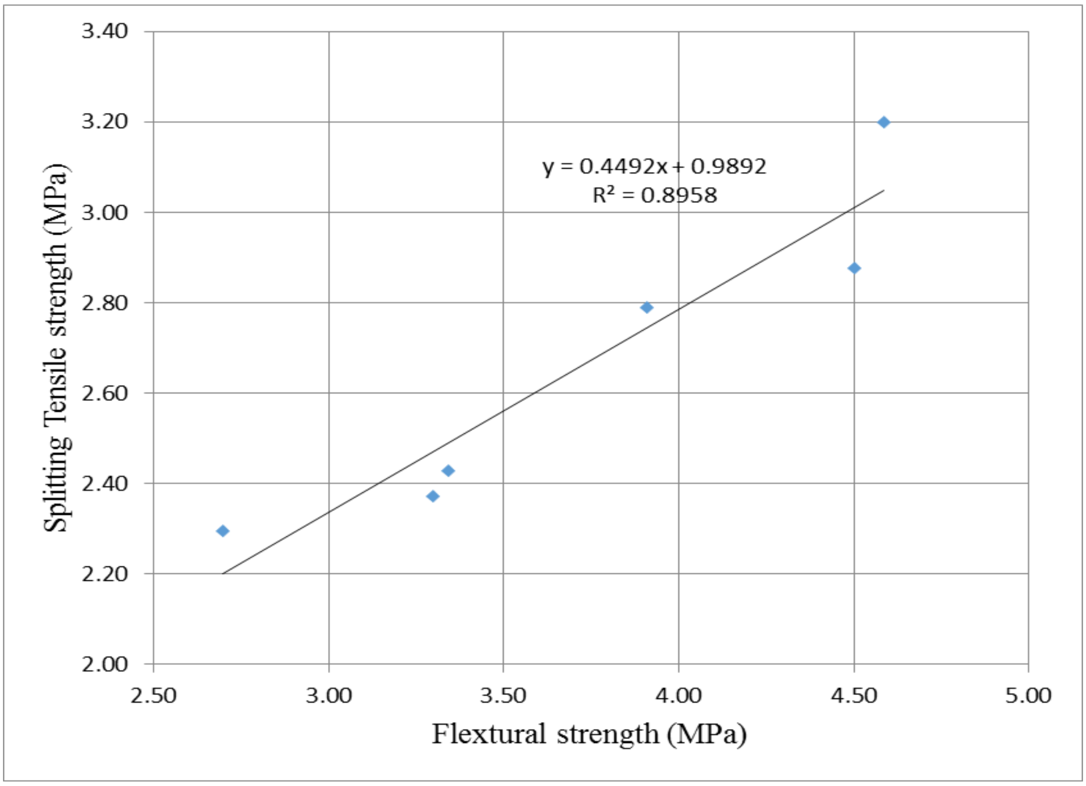


Figure 52: Flexural and splitting tensile strength tests linear relationship for NSC at 28 days

In order to determine the relationship between flexural and splitting tensile strength tests in NSC concrete at 28 days, the types of regression models between these two are shown in Table16.

Table 16: Relation equations between flexural and splitting tensile strength tests for NSC at 28 days

Concrete type	Type of regression	Equation	R^2
NSC	Exponential	$y = 1{,}4162e^{0{,}1675x}$	0,9122
	Linear	y = 0,4492x + 0,9892	0,8958
	Logarithmic	y = 1,6016ln(x) + 0,5836	0,867
	Polynomial	y = 0,1336x2 - 0,5411x + 2,7628	0,919
	Power	$y = 1{,}2151x^{0{,}5988}$	0,8871

As seen in Table 16, for NSC at 28-days, the strongest relationship between f_s and f_f is the polynomial function with a value of $R^2 = 0.919$.

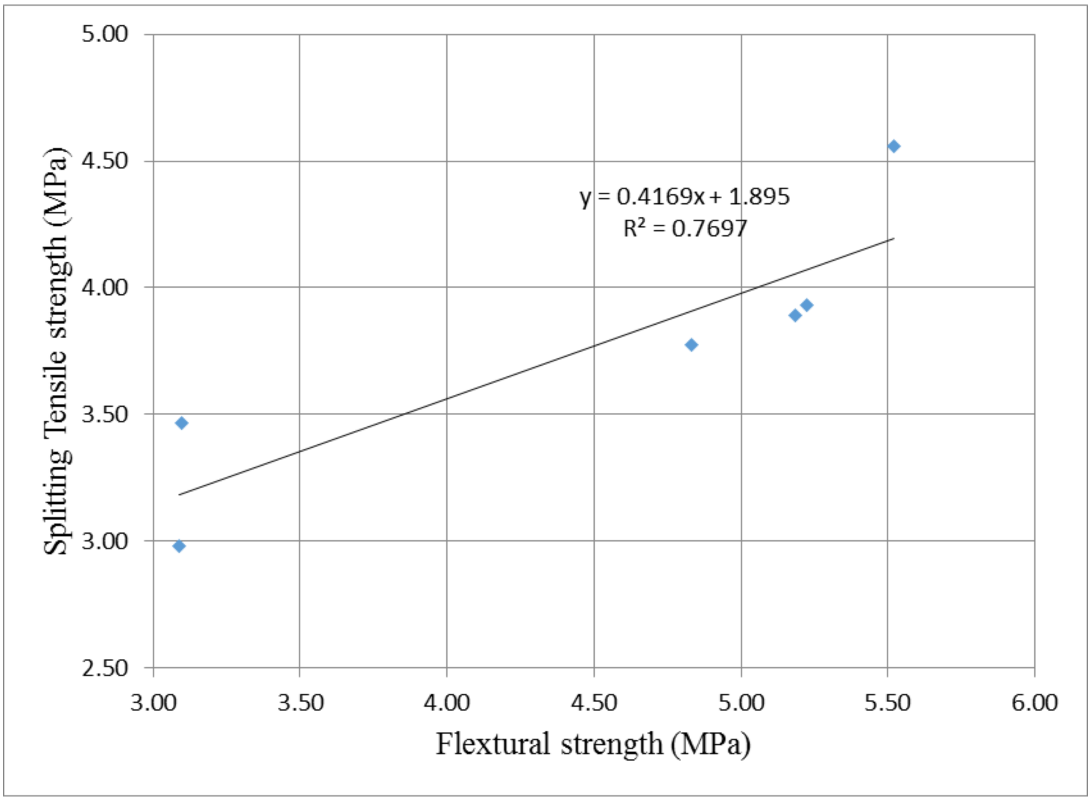
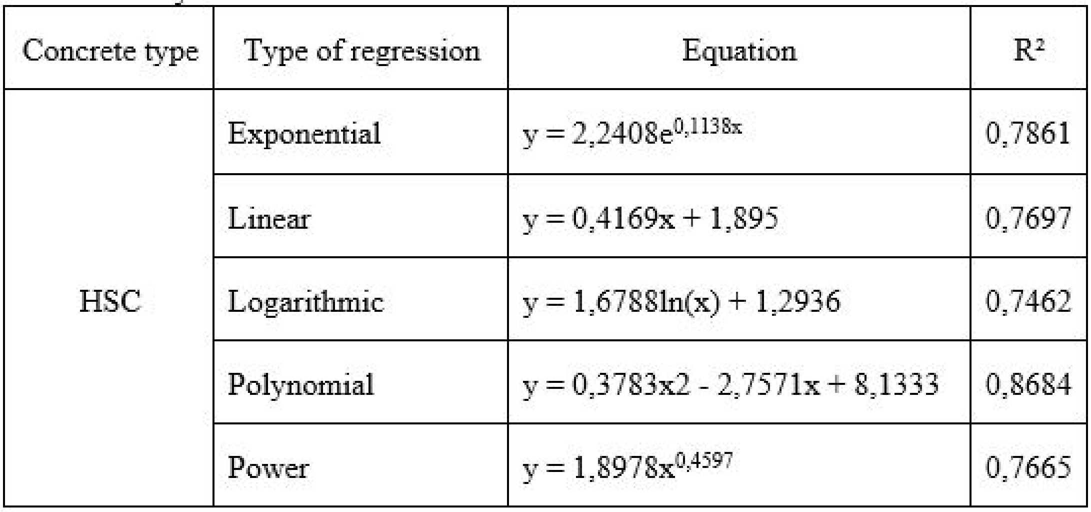


Figure 53: Flexural and splitting tensile strength test linear relationship for HSC at 28 days

As shown in Figure 53, HSC at 28-days, as f_s increases the value of f_f also increases.

Table 17 examines the types of regression designs between flexural and splitting tensile strength tests to determine the precise relationship between them in HSC concrete at 28 days.

Table 17: Relation Equations between splitting tensile and flexural strength tests for HSC at 28 days



Concrete type	Type of regression	Equation	R²
HSC	Exponential	$y = 2,2408e^{0,1138x}$	0,7861
	Linear	$y = 0,4169x + 1,895$	0,7697
	Logarithmic	$y = 1,6788\ln(x) + 1,2936$	0,7462
	Polynomial	$y = 0,3783x2 - 2,7571x + 8,1333$	0,8684
	Power	$y = 1,8978x^{0,4597}$	0,7665

As can be seen in Table 17, for HSC at 28 days, the strongest relationship between f_s and f_f is found to be the polynomial function with a value of $R^2 = 0.8684$.

4.3.12 Relationship between Compressive Strength [f_c] and Schmidt Hammer Test for NSC and HSC at 28 Days

As demonstrated in Figure 54, in NSC at 28-days, with an increase in the Schmidt hammer value, the value of f_c decreases.

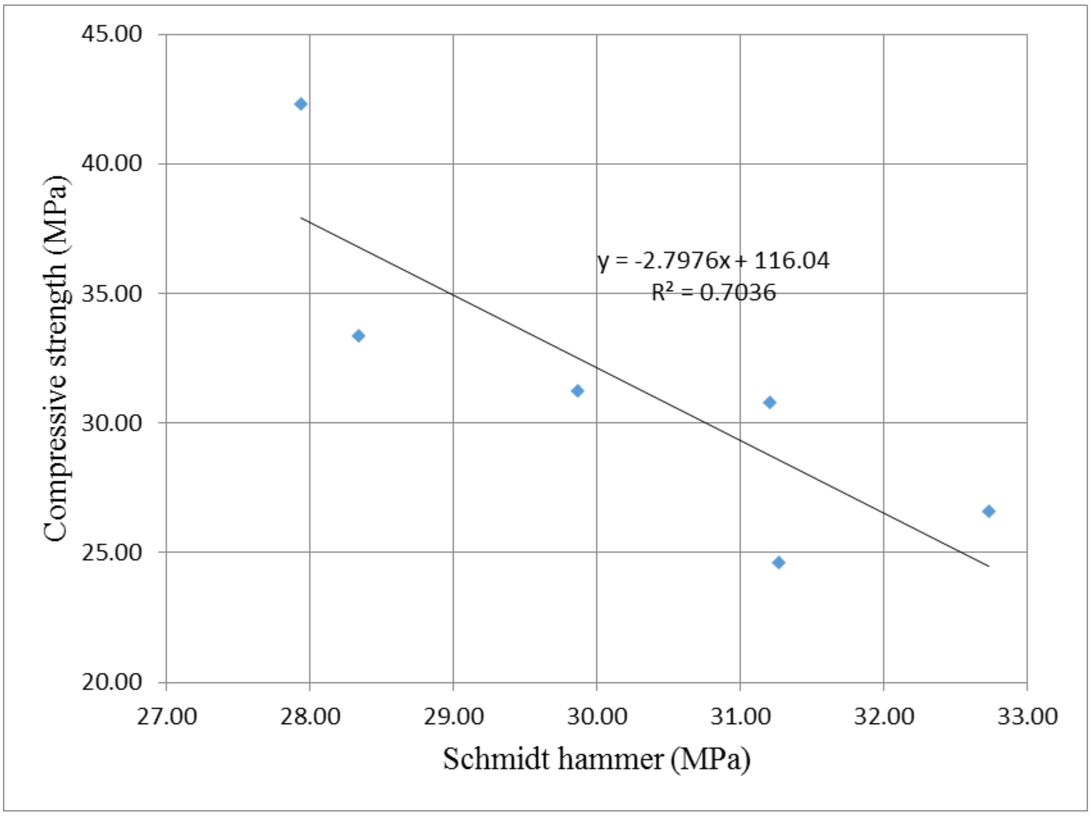


Figure 54: Schmidt hammer and compressive strength tests linear relationship for NSC at 28 days

Now, in order to determine the exact relationship between these two variables, Table 18 examines the types of regression models between these two.

Table 18: Relation equations between Schmidt hammer and compressive strength tests for NSC at 28 days

Concrete type	Type of regression	Equation	R^2
NSC	Exponential	$y = 416,46e^{-0,086x}$	0,7132
	Linear	$y = -2,7976x + 116,04$	0,7036
	Logarithmic	$y = -84,92\ln(x) + 320,82$	0,7138
	Polynomial	$y = 0,6793x2 - 43,823x + 733,51$	0,7809
	Power	$y = 222870x^{-2,606}$	0,7222

As shown in Table 18, for NSC at 28 day, the strongest relationship between Schmidt hammer and f_c is the polynomial function with a value of $R^2 = 0.7809$.

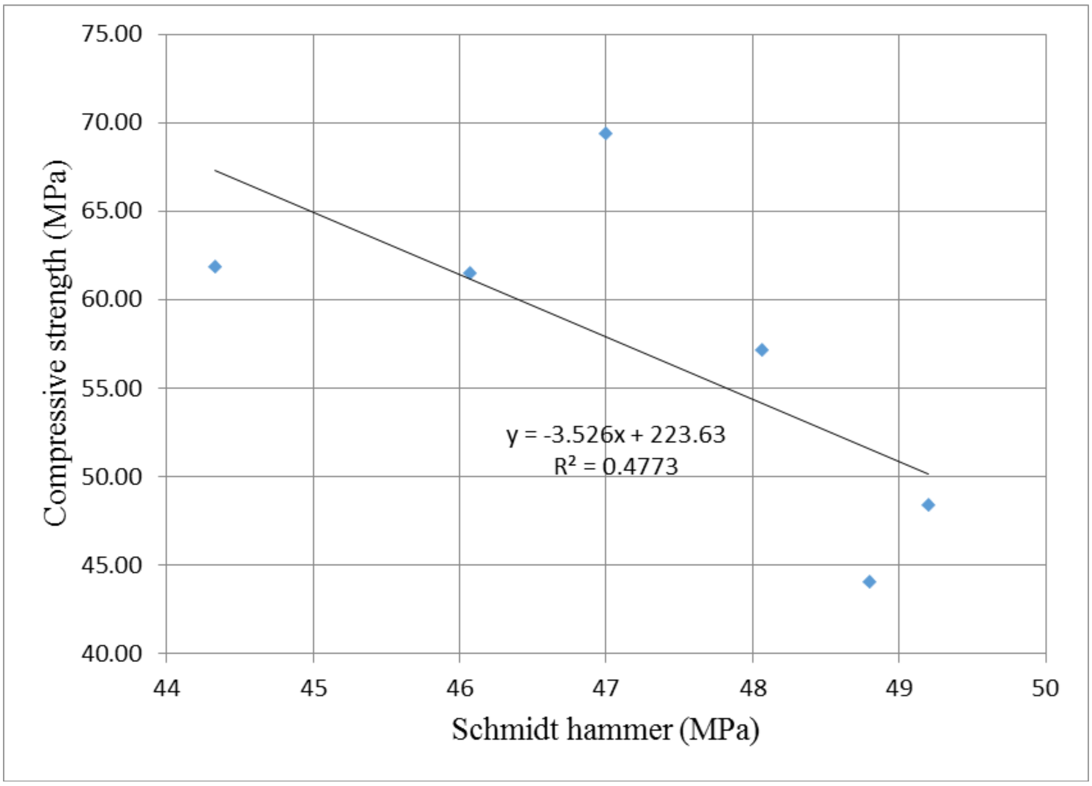
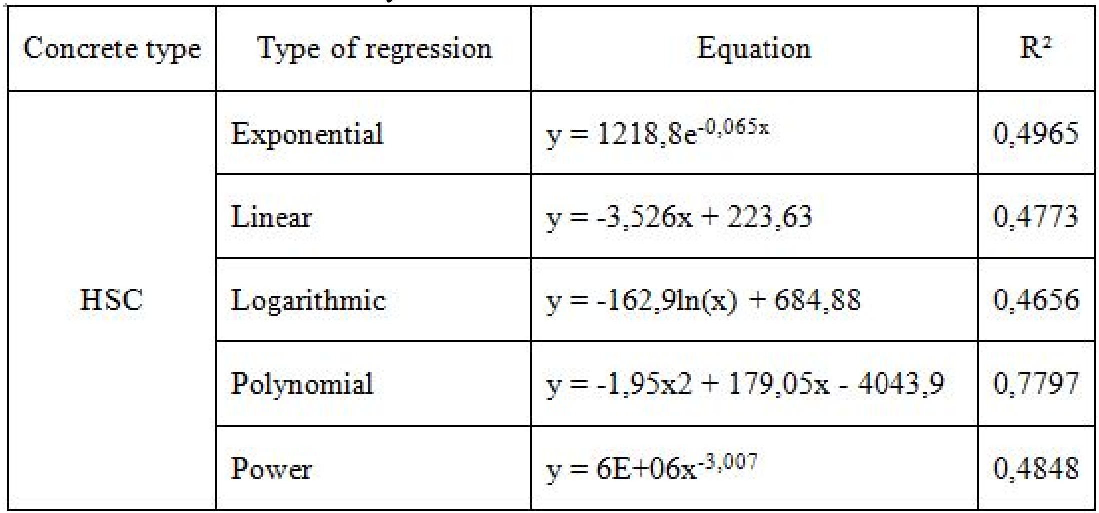


Figure 55: Schmidt hammer and compressive strength test linear relationship for HSC at 28 days

As it can be seen in Figure 55, in an intuitive way, in HSC at 28-days, with an increase in Schmidt hammer value, the f_c decreases. In order to determine the exact relationship between these two variables, Table 19 illustrates the types of regression models between them.

Table 19: Relation equations between compressive strength test and Schmidt hammer test for HSC at 28 days



Concrete type	Type of regression	Equation	R²
HSC	Exponential	$y = 1218,8e^{-0,065x}$	0,4965
	Linear	y = -3,526x + 223,63	0,4773
	Logarithmic	y = -162,9ln(x) + 684,88	0,4656
	Polynomial	y = -1,95x2 + 179,05x - 4043,9	0,7797
	Power	$y = 6E+06x^{-3,007}$	0,4848

As seen in Table 19, for HSC at 28-days, the strongest relationships between f_c and Schmidt hammer is the polynomial function with a value of $R^2 = 0.7797$.

4.3.13 Relationship of Compressive Strength [f_c] and Water Absorption Test for NSC and HSC at 28 Days

The relationship between water absorption and f_c at 28 days is further investigated using regression analysis. Table 20 and Figure 56 show the correlation between water absorption and f_c for NSC at 28-days. Table 21 and Figure 57 show the relationship between water absorption and f_c for HSC at 28-days from the experimental results.

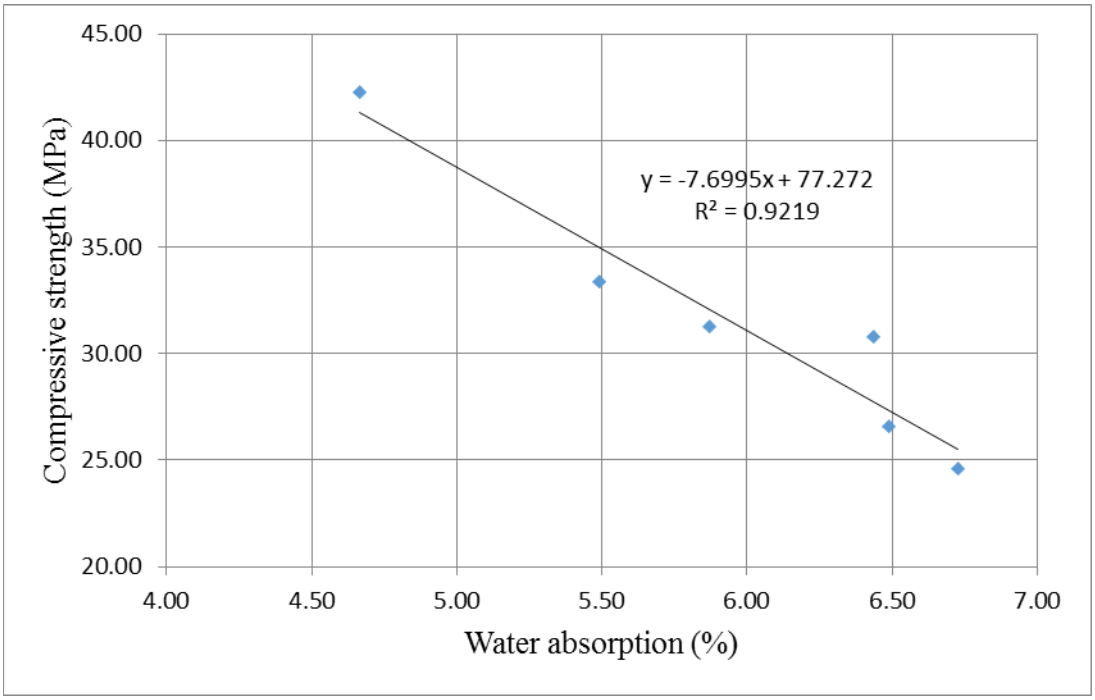
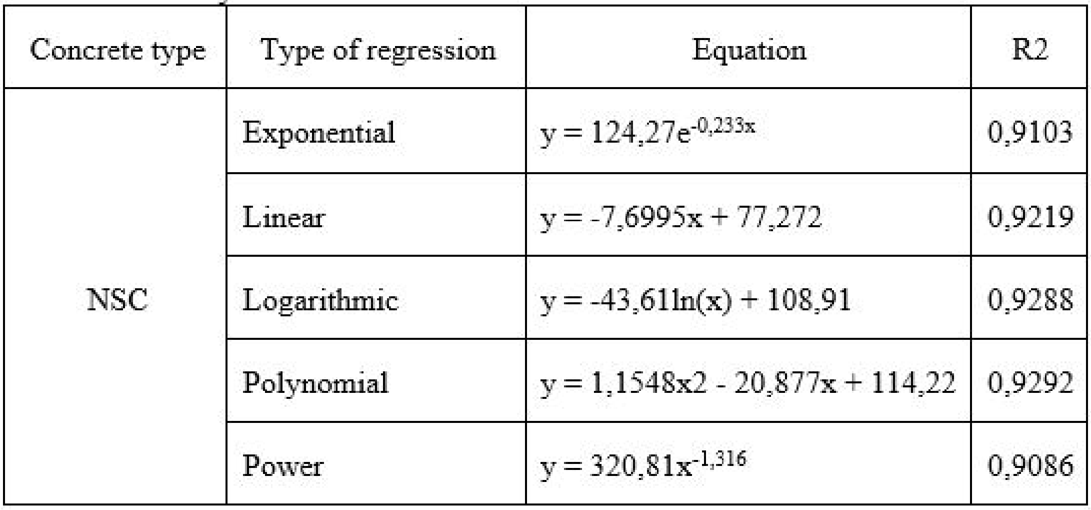


Figure 56: Compressive strength and water absorption test linear relationship for NSC at 28 days

Figure 56 shows that, in an intuitive way, in NSC at 28-days, reducing the amount of water absorption results in an increase in the amount of f_c. In order to determine the exact relationship between these two variables, we will consider a variety of regression models between these two in Table 20.

Table 20: Relation equations between compressive strength and water absorption test for NSC at 28 days



Concrete type	Type of regression	Equation	R2
NSC	Exponential	$y = 124,27e^{-0,233x}$	0,9103
	Linear	$y = -7,6995x + 77,272$	0,9219
	Logarithmic	$y = -43,61\ln(x) + 108,91$	0,9288
	Polynomial	y = 1,1548x2 - 20,877x + 114,22	0,9292
	Power	$y = 320,81x^{-1,316}$	0,9086

As seen in Table 20, for NSC at 28 days, the strongest relationship between water absorption and *fc* is the polynomial function with $R^2 = 0.9292$.

The relationship between water absorption and *fc* for HSC at 28-days will be discussed further in this section.

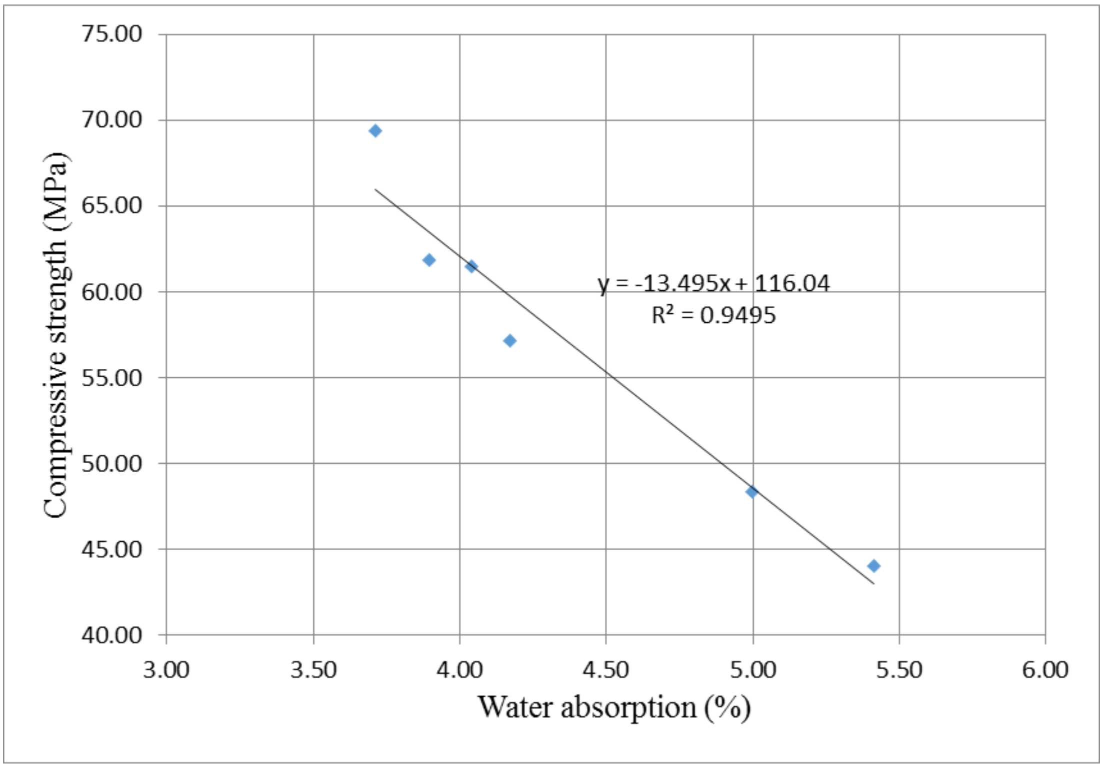
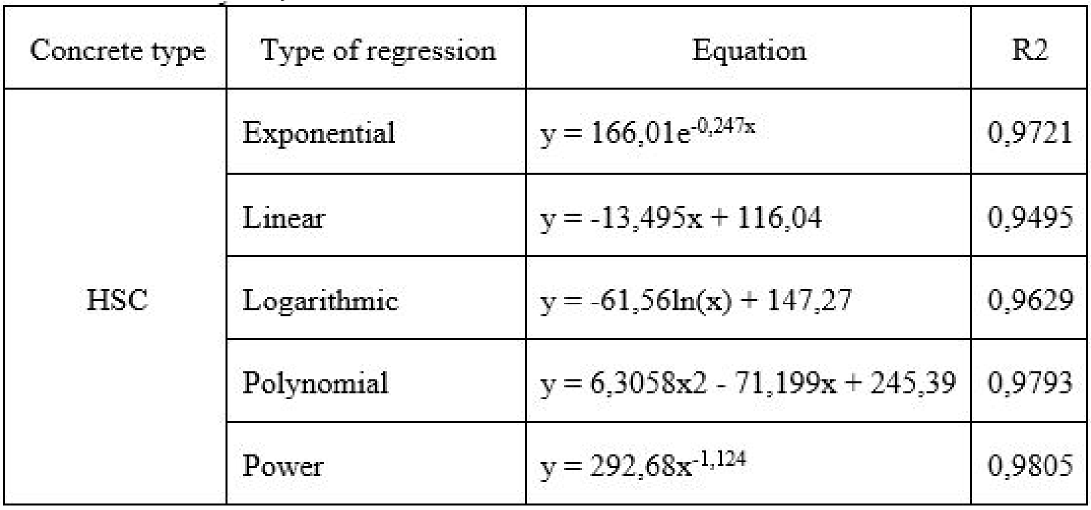


Figure 57: Water absorption and compressive strength test linear relationship for HSC at 28 days

As it is demonstrated in Figure 57, in an intuitive way, for HSC 28 day, reducing the amount of water absorption results in an increase in the amount of *fc*. In order to determine the relationship between these two variables, we will consider a variety of regression models between these two in Table 21.

Table 21: Relation equations between water absorption and compressive strength tests for HSC at 28 days



Concrete type	Type of regression	Equation	R2
HSC	Exponential	$y = 166{,}01e^{-0{,}247x}$	0,9721
	Linear	$y = -13{,}495x + 116{,}04$	0,9495
	Logarithmic	$y = -61{,}56\ln(x) + 147{,}27$	0,9629
	Polynomial	$y = 6{,}3058x2 - 71{,}199x + 245{,}39$	0,9793
	Power	$y = 292{,}68x^{-1{,}124}$	0,9805

As shown in Table 21, for the HSC at 28 day, the strongest relationship between water absorption and f_c is the Power function with a value of $R^2 = 0.9805$.

4.3.14 Relationship of Compressive Strength [f_c] and Ultrasonic Pulse Velocity [UPV] Tests for NSC and HSC after 200˚C Heating at 28 Days

As illustrate in Figure 58, for NSC at 28-days, with an increase in the amount of UPV, the amount of f_c increases as well.

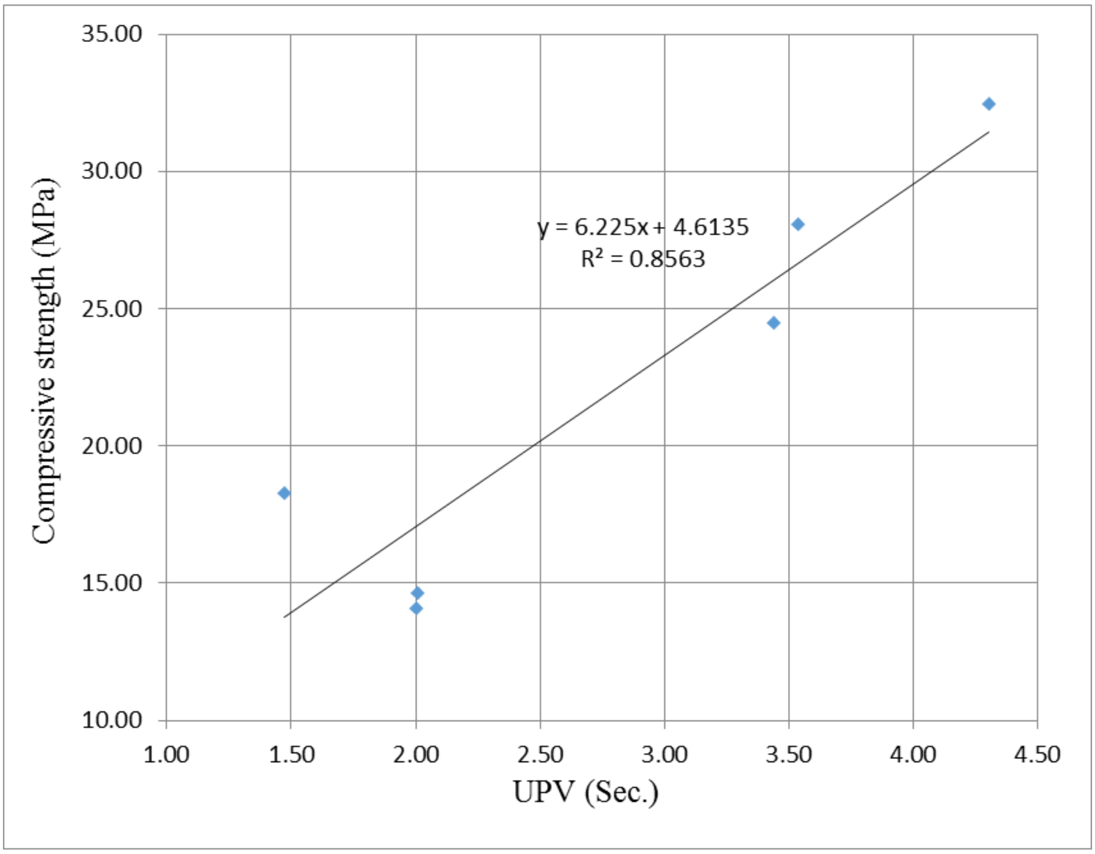


Figure 58: Compressive strength test and UPV test linear relationship for NSC after 200 ˚C heating at 28 days

In order to determine the exact relationship between these two variables, we will examine the types of regression models between them in Table 22.

Table 22: Relation equations between compressive strength test and UPV test for NSC after 200˚c heating at 28 days

Concrete type	Type of regression	Equation	R^2
NSC	Exponential	$y = 9{,}5498e^{0{,}2809x}$	0,8155
	Linear	$y = 6{,}225x + 4{,}6135$	0,8563
	Logarithmic	$y = 15{,}704\ln(x) + 6{,}9944$	0,7734
	Polynomial	$y = 2{,}4092x2 - 7{,}5622x + 21{,}816$	0,9164
	Power	$y = 10{,}637x^{0{,}7083}$	0,7358

As we can see in Table 22, for NSC at 28 day, the strongest relationship between UPV and *fc* is the polynomial function with R² = 0.9164.

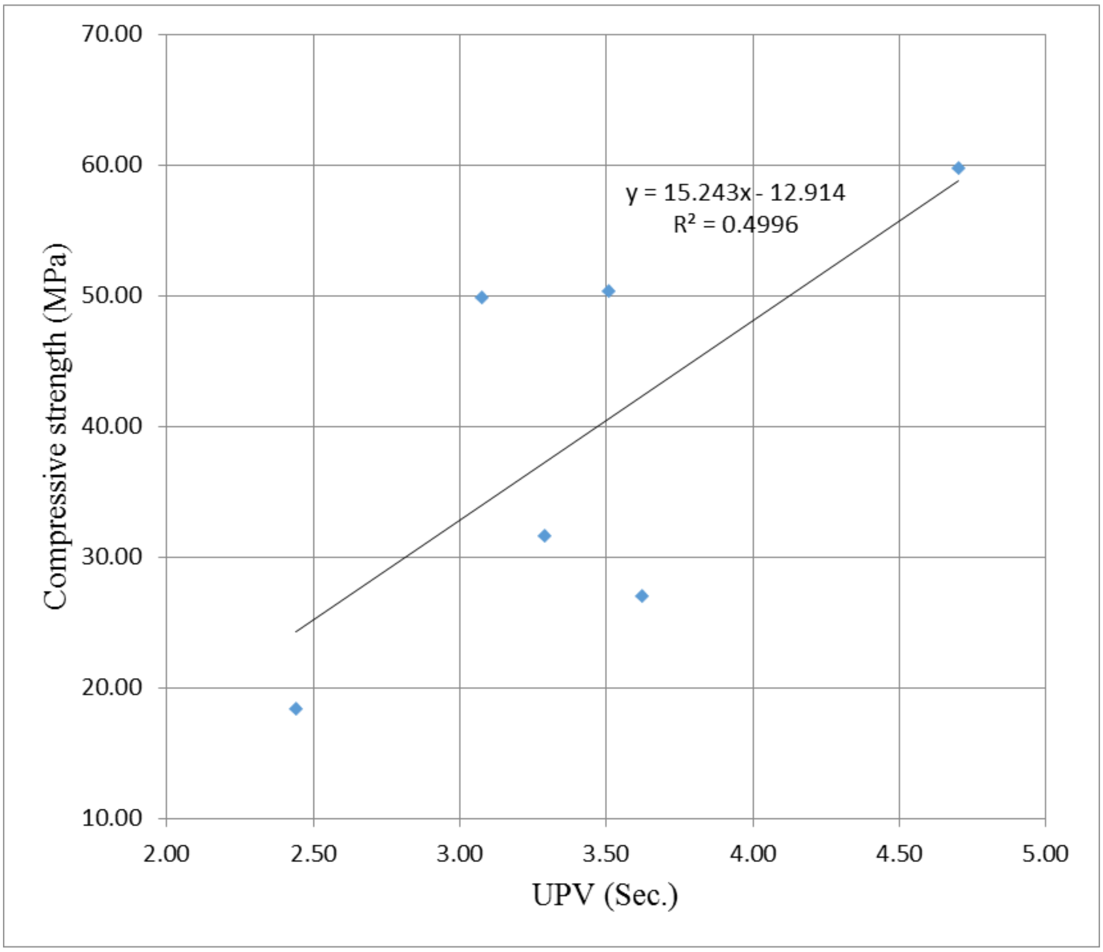
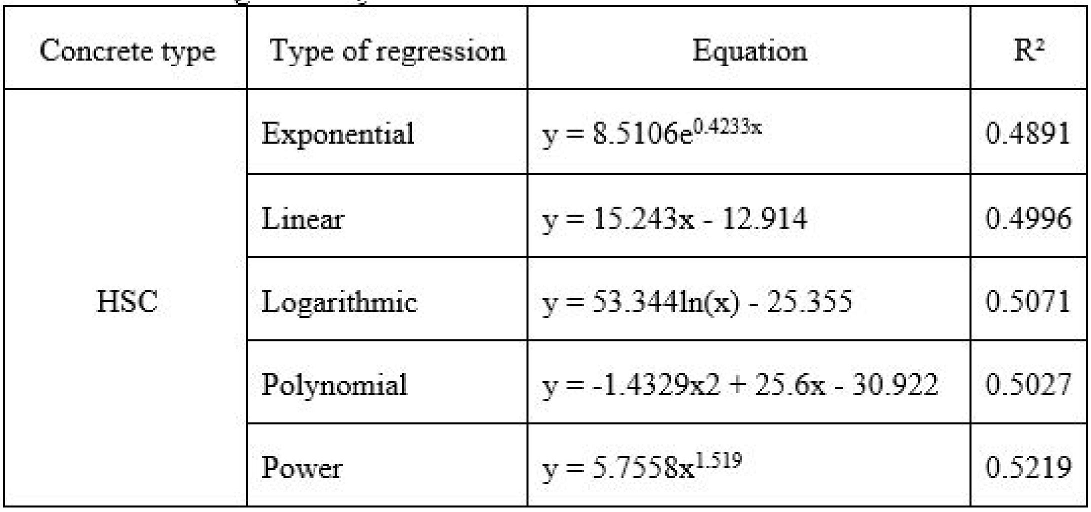


Figure 59: Compressive strength test and UPV test linear relationship for HSC after 200 ˚C heating at 28 days

As it can be seen in Figure 59, in an intuition way, with an increase in the UPV value at 28-days, the value of *fc* increases. Table 23 illustrates different relationships between *fc* and UPV for HSC after heat exposure at 200 ˚C. From the test results based on regression analysis, the best fit is the power relationship between UPV and *fc*.

Table 23: Relation equations between compressive strength and UPV test for HSC after 200˚C heating at 28 days



Concrete type	Type of regression	Equation	R²
HSC	Exponential	$y = 8.5106e^{0.4233x}$	0.4891
	Linear	$y = 15.243x - 12.914$	0.4996
	Logarithmic	$y = 53.344\ln(x) - 25.355$	0.5071
	Polynomial	$y = -1.4329x2 + 25.6x - 30.922$	0.5027
	Power	$y = 5.7558x^{1.519}$	0.5219

As seen in Table 23, also for HSC 28-day, the strongest correlation of $f_c$and UPV is calculated as Power with $R^2 = 0.5219$.

Chapter 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion of Thesis

In this research six different replacement percentages namely 0, 10, 20, 30, 40, 50% with 0.38 proportion of PP-to-CA were utilized as partial replacements by the volume of normal crushed limestone coarse aggregate. A w/c ratio of 0.58 for NSC and 0.34 for HSC, 0.3 % of SP were used for NSC and 2 % for HSC. The influences of waste PP on mechanical and physical properties of concrete were investigated. The findings and conclusions are summarized as follows:

1. The workability of the concrete specimen was tested using slump and VeBe tests. The results of the slump test showed an increase in workability when PP were replaced into concrete. This is in line with the results of previous studies that examined the effects of PP on slump test in concrete. The regression results between slump and VeBe showed a strong relationship confirms the findings. The workability test result revealed that replacing PP instead of coarse aggregate in concrete increases the workability of NSC more than HSC, where about 61 % increase was recorded with 50 % replacement of PP. Islam et al. (2015) and Choi et al. (2005) came up with the same results conducting slump and VeBe tests, noting that the absorption of water in PP was less than crushed aggregate which led to higher workability.

2. The unit weight of fresh concrete results of our experiments showed decrease in unit weight of concrete when PP was used in NSC and HSC. The low unit weight of concrete was observed for NSC-50%PP and HSC-50%PP with 1913.19 kg/m^3, 2021.33 kg/m^3 a decrease of 66% and 84% compared to the control mix samples. Because the density of PA is less than natural ones, the density of fresh concrete was less than an ordinary one reported by (Saikia & de Brito, 2014).
3. The f_c results of our experiments showed decrease in f_c when PP was replaced in coarse aggregates of NSC and HSC with 58% and 63% difference to the control mix design, respectively. These findings are similar to the findings of Saikia and De Brito (2012). The reason is discussed to be due to the low bonding between cement paste and plastic aggregates. In addition, reduction in hydration of cement paste which is associated with limited water movement in plastic ambience led to low amount of f_c.
4. According to the results, the f_s decreases as the PP particles content increases, when the loss of strength reached 72 % for NSC and 65% for HSC compared to the control mix at 50 % replacement of PP particles with coarse aggregate.
5. It was also found that the replacement of PP in NSC, and HSC resulted in a significant decrease in the flexural strength at 28 days. The minimum flexural strength (f_f) was recorded at NSC-50% PP of 2.70 MPa with a decrease percentage of 58.82 % compared to the control mix. While, HSC at 50% of PP had the minimum f_f of 3.09 MPa, with losing strength by 55.97% than reference mix. According to Saikia and De Brito, (2012), low amount of f_s and f_f could be attributed to the smooth surface and hydrophobic characteristics of PP which decreases bonding strength between particles.

6. As PP content in the concrete increases the UPV of samples decreases, because the high rate of voids and cracks that have been formed after replacement of HSC and NSC aggregates by PP. A result of UPV shows an excellent rang of concrete quality categorized by Whitehurst (1951) with increasing percentage of the PP replacement.
7. Schmidt hammer test is for prediction of f_c test, but this test was designed for conventional concrete, so it may have different results from f_c for other concretes. But the results of rebound hammer showed a 10.68%, 3.68% increase in NSC and HSC, respectively, by increasing the percentage of PP up to 50%. Unfortunately, the literature does not provide enough information about Schmidt hammer test results regarding concrete having PP replacement with coarse aggregate.
8. Our findings showed that replacing coarse aggregates with PP had a negative effect on water absorption capacity up to 50% PP replacement level for NSC and HSC. This findings are similar to Gu and Ozbakkaloglu (2016) results.
9. According the rapid chloride permeability experiments in this study, although PP had no effect on HSC up to 50%, but it had a negative effect on NSC. Based on Silva et al. (2014),the concrete containing plastic waste material had higher chloride permeability than the conventional concrete which is not obtained in the results of the present study.
10. The heat degradation (200 ˚C) results showed a negative effect on f_s, f_c, and UPV and crack development. This effect is because melting point of PP is 150 ˚C, lower than 200 ˚C. So, PP had melted through the pores and has separated the concrete material samples.

5.2 Future Research Recommendations

1. This study was performed using coarse aggregate replacement by waste PP. In future studies the employed percentages can change and waste plastic material can be replaced by other materials.
2. Two different types of concrete were used in this experimental study. It could be also worth to study the other types of concrete.
3. Studying the influence of PP on the creep and shrinkage is also recommended.
4. Additives for having higher values in strength results can also be used in future studies.
5. Non-destructive tests on waste material aggregates in concrete are suggested to be used in further research.

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