# Effects of Polyvinyl Chloride as a Partial Aggregate Replacement on Mechanical Properties and Behavior of Self Compacted Concrete

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# ABSTRACT

These days, concrete is one of the main construction materials used the world ever. Aggregates are considered the most important component of concrete volume because they account for three quarters of the volume of any normal concrete. All over the world, more than 22 million tons of polyvinyl chloride (PVC) are presently produced per year. Such a large level of PVC production has a negative effect on environmental pollution in the society. For this reason, in this thesis, the waste plastic light weight aggregate PVC was tested examined as a replacement for natural aggregate in six different percentages starting from 0, 10, 20, 30, 40 and 60%. The study also examined the production of self-compacting concrete (SCC) at a constant water binder ratio of 0.45, using Master Glenium 27 as 1.7% of the mixture and silica fume at 10% of the weight of the cement.

The workability of the SCC was tested with L-box, V-funnel flow time and slump flow methods. Results showed that the PVC plastic content successfully achieved SCC until a 60% ratio. They also show that, the use of PVC waste plastic as a partial replacement of natural aggregate has negative effect on the physical and mechanical properties of concrete, including: flexural strength, compressive strength, splitting tensile strength, weight, and ultrasound pulse velocity before and after degradation.

**Keywords:** Self Compacted Concrete (SCC), Polyvinyl chloride (PVC), Workability, Silica fume, Flexural strength, Compressive strength, Splitting tensile strength, Mechanical Properties, Durability against heat.

# ÖZ

Günümüzde, dünyanın heryerinde beton en önemli yapı malzemesi olarak kullanılmaktadır. Agregalar, normal bir betonda, toplam hacmin yaklaşık %75'ini kapladıklarından dolayı, agregalar önemli beton bileşiği olarak kabul edilmektedirler. Diğer taraftan, her yıl dünyada, 20 milyon tondan fazla polyvinyl chloride (PVC) üretilmektedir. Bu kadar yüksek miktarda PVC üretimi, çevresel hava kirliliğini arttırarak olumsuz yönde etkilemektedir. Bu nedenle, bu deneysel çalışmada, atık plastic PVC küçük parçalara bölünerek, hafif agrega sınıfında kabul edilerek belirli oranlarda agrega yerine kullanılmaktadır. Agrega yerine betona katılmış olan atık PVC parçacıkları toplam hacmin %( 0, 10, 20, 30, 40 ve 60)'I kadardır. Üretilen tüm kendiliğinden yerleşen beton KYB'larda su/bağlayıcı (s/b) oranı 0.45 olarak alınmıştır. Bunun yanısıra, KYB tipi olarak üretilmiş olan tüm karışımlara, çimentonun ağırlığının %10'u kadar silis dumanı katılmıştır. Silis dumanı ve çimento ağırlık toplamlarının %1.70'i kadar da süperakışkanlaştırıcı (Gelenium 27) katılmıştır. Karışımların işlenebilirlik tayini için sırasıyla L-box, V-funnel, and slump flow deneyleri yapılmıştır. Fiziksel özeliklerin (işlenebilirlik, özgül ağırlık) tayininden sonra mekanik (yarmada çekme, basınç ve eğilme dayanımları ve de tokluk) ve sıcaklık (100˚C ve 200˚C) değişimine karşı dayanıklılık testleri yapılmıştır.

Atık PVC parçacıklarının, KYB katılmasının bazı değerlerde düşüşe yol açtığı gözlemlenmiştir. Bunlar, çekmede yarma, basınç ve eğilme dayanımları; ve de işlenebilirlik özeliklerinde azalma ve de iç çatlaklarda artiş olarak açıklanabilir.. Diğer taraftan, atık PVC parçacıklarının KYB da agrega yerine kullanılmasının;

betonun sünekliğini ve tokluğunu arttırdığı, beton ağırlığını azalttığı ve de çevre dostu beton üretme konularında avantaj sağladığı tesbit edilmiştir.

**Anahtar Kelimeler:** Kendiliğinden yerleşen beton (KYB), polyvinyl chloride (PVC), İşlenebilirlik, Silis dumanı, çekmede yarma dayanımı, basınç dayanımı, eğilme dayanımı, Mekanik özelikler, Isı dayanıklılığı.

# DEDICATION

In all my heart, I devote this study to all my family My relatives and friends, I like to thank My mother and father who did not tire despite all the sacrifice they made to me for getting more success

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| | |
|---|---|
| C | Cement |
| CA | Coarse aggregate |
| E | Modulus of elasticity |
| FA | Fine aggregate |
| ITZ | Interfacial transition zone |
| $S_C$ | Compressive strength |
| St | Splitting tensile strength |
| Sf | Flexural strength |
| SCC | Self Compacted Concrete |
| SCC00PVC | SCC with 0% PVC replacement |
| SCC10PVC | SCC with 10% PVC replacement |
| SCC20PVC | SCC with 20% PVC replacement |
| SCC30PVC | SCC with 30% PVC replacement |
| SCC40PVC | SCC with 40% PVC replacement |
| SCC60PVC | SCC with 60% PVC replacement |
| W | Water |
| W/b | Water-binder ratio |

# Chapter 1

# INTRODUCTION

## 1.1 General Background

Concrete is a main construction material, it is a composite material that consists of cement water and aggregates (fine and coarse), aggregates are considered as the most important components in concrete volume. For example, in normal concretes about three-quarters of the volume is occupied by the aggregates. The most important functions of using both fine and coarse aggregates are to provide bulk to the concrete, to increase the density and volume stability, to contribute in workability and uniformity of concrete mixes.

Generally, it is considered that aggregates quality is important in concrete mixing. Not only because the aggregates limit the strength of concrete, but, with undesirable aggregate properties cannot produce a strong, durable and structural performance concrete. Both physical properties and mechanical behavior of aggregates greatly influence fresh and hardened properties and behavior of concrete (A. M. Neville, 2011).

On the other hand, nowadays recycling of waste materials poses a major problem for countries and municipalities worldwide. So, using or recycling these waste materials in construction industry at all and especially in concrete has attracted a lot of interest worldwide due to the increased disposal costs and environmental concerns (Senhadji et al., 2015; Kou et al., 2009; Haghighatnejad et al., 2016). Polyvinyl chloride or PVC is one of the most problematic waste materials. More than 20 million tons of PVC is being produced per year all over the world (Brown et al., 2000). For years, the PVC waste has been burned which caused the environmental pollution. But, today social awareness is finding the new methods of recycling PVC wastes. Like, using PVC as a replacement to either fine and/or coarse aggregates in concrete production will be beneficial behavior in environmental friendly concrete production (Yap et al., 2001)

## 1.2 Problem Statement

Nowadays, the world environment is facing to a very serious crisis because of waste materials and conventional ways of recycling or utilizing these waste materials. On the top of these materials is polyvinylchloride (PVC) which has a great role in causing environmental pollution, also, until now there is not a very property way to reusing and/or recycling it. So by thinking towards using PVC in construction industries may be a perfect way to recycling in a high amount and at the same time it can be a safe and economical way.

## 1.3 Significance of the Study

This research is focusing on finding out the best way to utilizing the waste PVC in construction industries in order to release the environment from this material in a safe and economical way. It is important to find out the critical effects of PVC as an aggregate substitution, on mechanical and physical properties and long term durability of SCC concrete.

## 1.4 Objectives of the Study

This thesis aims to investigate the effects of replacing a part of coarse aggregate with PVC, on concrete performance. The objectives to be studied are:

- Effects of polyvinylchloride (PVC) on fresh concrete properties.
- Influence of PVC on concrete compressive, splitting tensile and flexural strengths,
- Effects of polyvinylchloride (PVC) on flexural toughness,
- Ultra sound pulse velosity readings before and after loading the specimens,
- Long term durability-degradation tests againts heat,
- The optimum amount of PVC waste plastic replaced to aggregates,
- Conclusions and recommendations for further research.

## 1.5 Organization of the Experimental Study

This thesis is organized into five chapters as follow:

Chapter one is introducing the thesis subject, significance and objectives, while chapter two is about theoretical background and literature review of the study. Chapter three is containing the material and experimental procedure and description. Analysis of experimental results and discussions can be found in chapter four and finally, conclusions and recommendations for further research can be found in chapter 5, which is the last.

# Chapter 2

# THEORETICAL BACKGROUND AND LITERATURE REVIEW OF THE STUDY

## 2.1 Introduction

Everyday, million tons of waste materials are generated and collected from manufacturing processes, service industries and municipal wastes, etc. As a result, waste management has been concerned as a major solution to this problem especially in the developing countries. For this purpose, in the last 10 years, the researchers had studied some researches related to using these waste materials in construction industries. One of the most concerned issues was utilizing waste materials in concretes as a replacement material to coarse aggregates to be used in buildings, bridges, roads, pavements, etc.

Using waste materials in construction industries is a partial solution to environmental and ecological problems, also, benefits in reducing the cost of concrete manufacturing and it has some indirect benefits such as saving energy, reduction in landfill cost, and protecting the environment form possible pollution effects. In addition, utilizing these materials may improve physical, mechanical and durability properties of mortar and concrete, which are difficult to achieve by using conventional materials only (Brown et al. 2000).

## 2.2 Aggregates in Concrete

Generally, fine and coarse aggregates occupy 60% to 75% by volume and 70% to 85% by mass of concrete which strongly influences the concrete property in both fresh and hardened statues. At the same time the aggregate is much cheaper than cement, so, by using aggregates as much as possible in concrete, maximum economy is obtained. The most commonly used aggregate types are the natural aggregates which are taken from natural resources without any change in their natural statuses during production except for washing, grading and crushing. For example, usually natural rushed or uncrushed fine and coarse aggregates are used in concrete production. The unit weight of concrete produced by natural aggregates is between 2160 to 2560 kg/m$^3$.

### 2.2.1 General Classification of Aggregates

With the purpose of finding the best materials and best ways to produce suitable concrete for construction projects with best physical and mechanical properties, lower cost, at the same time environmental friendly, we have to deal with all component (raw) materials. It is known that aggregates are the main parameters of concrete mixing production; so, studying the properties and types of aggregates can be a right step towards producing aimed concrete. For this purpose, this section focusses on the best classifications of concrete aggregates.

### 2.2.2 According to Particle Size

Normally, the size of aggregate particles that are used in concrete ranges from tens of millimeters down to less than one-tenth of millimeter in diameter. Actually, the maximum size used varies, in concrete mixes, particles of different sizes are combined and distribution of the particles according to their sizes refers to grading. The alternative to obtain good quality concrete, always manufacture classified aggregates at least in two groups, the main division being between fine aggregate, often called sand. For instance, according to ASTM standards, the division is made at No. 4 ASTM sieve or 4.75 mm openings, in which fine aggregates pass through this sieve and the retains become coarse aggregate, which comprises of materials at least 5 mm in size.

### 2.2.3 Petrological Characteristics Classification

Based on formation, there are two types of aggregates, first, human made aggregates which is known as artificial aggregates, this kind mostly used for producing special concrete properties for special case concretes. For example, light weight aggregates used to produce low dense or permeable concrete. Natural aggregates which are divided into two types, normal aggregates and crushed aggregates are made from natural rocks. So, the petrographic classification categorizes aggregates according to component materials and compounds of parent rocks.

Neville (1987) showed that, from the petrographic point of view, based on component materials and characteristics of parent rocks, aggregates can be divided in too many groups. Such as; Basalt, Flimt, Gabro, Granite, Volcanic rocks, Hornfeles, Limestone, Porphyry, Quartzite, Schist groups.

### 2.2.4 Surface Texture or Shape Classification

Surface texture or shape classification is one of the most important classification of concrete aggregate, because the surface texture and shape has a great influence on both mechanical and physical properties (Li, 2011; Abdullahi, 2012; Hachani, Kriker, & Seghiri, 2017; Zhou et al, 1995; Neville,1987).

There are many kinds of surface and texture classification, each reasercher or each standard has divided aggregates into many catagories and sub catagories in order to measure or study the effects of surface texture and shape of aggregates on both fresh and hardened properties of concretes. For example, Claisse (2016) classified aggregates into the catagories: Rounded, Irregular, Flaky, Angular, Elongated. On the other hand, Neville1 (987) stated that, in US sometimes aggregates are classified into the following catagories as: Well rounded, Rounded, Sub rounded, Sub angular and Angular.

## 2.3 Effect of Aggregates on Physical Properties and Mechanical Behavior of Concrete

As it is cleared, aggregates are the important components of concrete body, also, it should have some influences of concrete's physical and mechanical properties. Previous sections show the effects of aggregates on concrete in both fresh and hardened status.

### 2.3.1 The Influence of Aggregate on Workability of Fresh Concrete

According to previous studies, the aggregate's shape and texture can influence the workability of fresh concrete mixtures. As it is mentioned, at the same cement content and with the same *w*/*b* ratio, aggregates with rough surface texture or angular shape result in lower workability. On the other hand, aggregates with smooth surface texture and spherical shape result in higher workability (Li, 2011).

Vilane and Sabelo (2016) argued that, the workability (slump test) was directly proportional to the aggregate size. For example, the workability (slump) for the 9.5 mm, 13.2 mm and 19 mm coarse aggregate sizes were 10 mm, 13.5 mm and 20 mm, respectively for constant w/c (0.5) and same mix proportion (1:2:4).

It increased from 10.0 mm, 13.5 mm to 20.0 mm for the 9.5 mm, 13.2 mm and 19.0 mm, respectively. As the slump increased, the concrete becomes more workable.

### 2.3.2 Effect of Aggregate Properties on Compressive Strength of Concretes

Generally, the strength of concrete aggregates is relatively higher either than the mortar and the transition zone (ITZ), lying between the matrix (cement past or mortar) and aggregates. So it can be stated that, effect of aggregate properties on compressive strength is not the main parameter.. However, if the strength of the aggregate is lower than the strengths of the other two phases (ITZ and matrix), strength of the concrete decreases (Zhang, 2011).

According to previous researches, aggregate influence concrete strength by surface characteristics (texture and angularity). The surface characteristics of coarse aggregates effect the strength of concrete by influencing bonding quality between aggregates and cement paste. However, when quantity of water is needed to be increased to be able to achieve the same workability, will result in the increase of water-cement ratio and therefore strength will decrease. When the water-cement ratio is less than 0.4, the strength of the concrete with crushed stones will be 38% higher than that of the concrete produced with gravels. For the mixes produced with higher water-cement ratio, however, their difference will not be that obvious.

In terms of surface texture, Li showed that, the aggregate shape and texture can influence the bonding and compressive strength of concrete. At the same *w*/*c* ratio and with the same cement content, aggregates with angular shape and rough surface texture lead to a better bond and better mechanical properties. On the other hand, aggregates with spherical shape and smooth surface texture result in a lower bond and lower mechanical properties (Li, 2011).

Aggregate size effect is studied by Kozul, and Darwin (1997). They found that, there is no considerable effect of aggregate size on the compressive strength of normal and high-strength concretes. On the other hand, Vilane and Sabelo (2016) found that; the compressive strength increased with increasing aggregates size (19.0 mm, 13.2 mm and 9.5mm)

In another study which was about aggregate type, (Abdullahi (2012)) it is found that, compressive strength of normal strength concrete is affected by the aggregate type. For example, in concretes containing crushed granite lowest strength is developed at all ages, while, highest compressive strength is achieved from crushed quartzite, followed by concrete produced with river gravel.

### 2.3.3 The Influence of Aggregate on Tensile Strength

There is a general belief that, when crushed aggregates are used instead of rounded aggregates will result in a higher tensile strength concrete because the rounded shape aggregate which has a weaker bond with the matrix than the crushed ones, is eliminated by increasing the workability and by this way decreasing the mixing water requirement. Thus; with lower water/cement ratio, higher strength is obtained in concrete. Laboratory test of strength determination was found that rounded aggregate provides more flexural and tensile strengths (46% and 38% at 28 days) than crushed aggregates (Hachani, Kriker, & Seghiri, 2017).

### 2.3.4 The Influence of Aggregate on Modulus of Elasticity

Many researchers focused on the effects of coarse aggregates on elastic modulus. For example, Tia et all indicated that, coarse aggregate is one of the main elements of concrete and they argued that the variation in coarse aggregate content or coarse aggregate types will affect the elastic modulus of concrete (Tia et al. 2005).

Tia et al Zhou et al argued that, using different types of course aggregates can substantially influence the modulus of elasticity of concrete (Zhou et al., 1995). Moreover, Neville (1987) showed that, concretes with higher aggregate content result in a higher modulus of elasticity for the same concrete strength, and indicated that concretes with normal weight aggregate has a higher elastic modulus than hydrated cement paste.

## 2.4 Aggregate Replacement Materials

### 2.4.1 Waste Glass

Glass is an inorganic solid material that is usually translucent as well as hard, brittle, and impervious to the natural elements. Glass has been made into practical and decorative objects since ancient times, and it is still very important in applications as disparate as housewares and building construction.

Waste glass is one of the most polluting waste materials for the world environment, it is one of the material it can be used in concrete production as a partial aggregate or partial cement replacement material, for this purpose many researches studied the effects of utilizing waste glass on mechanical and phisycal properties of concrete and morter (Srivastava, V. et al 2014; Newes and Zsuzsanna 2006; Park, S. B, et al 2004).

According to some previous reasearches, glass is one of the waste material that can be some mechanical and phesical properties of concrete mixtures. Fore Example, Adaway and Wang (2015) demonstrate that glass aggregate up to 30% as fine aggregate replacement exhibits higher compressive strength development than traditional concrete. Also, using glass as aggregate replacement in concrete has issue with ASR (alkali-silica reaction). When the silica of glass chemically reacts with naturally occurring hydroxyl ions in the cement, silica gel is formed and causes cracks in the cement at it absorbs water (Sato, S., et al. 2004).

### 2.4.2 Waste Plastics

Industrial activities associated with significant amounts of non-biodegradable solid waste, waste plastic is among the most prominent polluting waste materials, using this waste material (waste plastic) in concrete mixes as a partial aggregate replacement is an attractive alternative because it helps to reduce the cost of concrete manufacturing as well as reduce the waste recycle cost. For this purposes many researchers studied the effects of plastic aggregate on mechanical properties and behavior of concrete.

Ismail and Al-Hashmi (2008) demonstrated that, waste plastic lead to decrease the compressive strength and tensile strength of concretes to below the values for the reference concrete, this can be attributed to the reduction of the adhesive force between the cement paste and the plastic waste surface. In addition, plastic waste is a hydrophobic substance which may restrict the hydration of cement.

#### 2.4.2.1 Waste Tyres

When vehicle tyres reach the end of their usable life, they can still find some use as a replacement for course aggregate in concrete mixes. Crumb rubber is a car or truck tyre that is ground up between the sizes of 3 - 10 mm. This mix has very poor compressive strength due to its high air content. It is believed that when this rubber is mixed with the concrete air becomes trapped within it. One benefit to the addition of this alternative is that the rubber keeps the concrete from shattering in failure.

#### 2.4.2.2 Waste PVC

According to some previous reasearches, PVC is one of the waste material that can be used as an aggregate replacement in concrete mixtures (Senhadji, et al. 2015; Haghighatnejad, et al. 2016). This thesis will study the possibility of using crushed PVC as a replacement material for coarse aggregates according to some physical and mechanical properties of concretes.

## 2.5 Influence of Recycled PVC Aggregates on Workability of Concrete Mixes

Workability is one of the important physical characterestics of concrete mixtures and it is influenced by aggregates, any changes in both fine and coarse aggregates in quantity and type has respective effect on the workability. So replacing aggregates with waste PVC is a kind of change in aggregate type may have an effect on workability of fresh concrete.

In Senhadji, et al. (2015) study, they used polyvinylchloride (PVC) waste obtained from scrapped PVC pipes as a partial replacement of both sand and coarse aggregates in the proportions of 30, 50, and 70% by volume. They found that workability was improved as the replacement ratio increased. Addition to these, they said that, it was capable of reducing the unit water content to improve strengths. Wile, Haghighatnejad, et al. (2016) found that, 20%, 30%, 40% and 50% substitution of natural sand with PVC decreases the workability in terms of slump value of normal concrete, and they concluded that this decrease was because of sharp edges of PVC aggregates.

## 2.6 Influence of Recycled PVC Aggregates on the Mechanical Properties of Hardened Concrete

Some previous studies established that using waste PVC as fine and coarse aggregates negatively affect some mechanical properties of concrete mixtures.

### 2.6.1 Influence of Recycled PVC Aggregates on Compressive Strength of Hardened Concrete

Compressive strength is one of the important mechanical properties of concrete which is negatively affected by consuming waste PVC as fine and coarse aggregates.

Haghighatnejad, et al. (2016) stated that, presence of PVC aggregate as a fine aggregate (sand) replacement in concrete mixes reduces the compressive strength at the ages of 3, 7, 28 and 90 days and they found that for 50% PVC incorporation, the highest reduction was attained for all curing conditions. Also, Senhadji, et al. (2015) concluded that, using PVC in concrete to replace 50% and 70% of coarse aggregates significantly reduce the mechanical strengths.

Kou, et al. (2009) studied the effects of different volume replacements of sand by PVC granules on the fresh and hardened properties of the concrete. They found that with an increase in sand (fine aggregate) replacement ratios by PVC granules, the compressive strengths were reduced.

### 2.6.2 Effect of Reused PVC Aggregates on Tensile Strength of Hardened Concrete

The following studies argued that tensile strength of concretes made with PVC aggregates were found to decrease.

Siddique, Khatib and Kaur, (2008) determined that concrete containing plastic aggregates exhibited more ductile behaviour than concrete made with conventional aggregates and they found that the splitting tensile strength for concrete containing 10% plastic aggregates was decreased by 17%.

Kou, et al. (2009) demonstrated that, replacement of sand by PVC granules decreased the tensile strength property of the concrete. They stated that, with an increased replacement the splitting tensile strength was reduced for all tested concretes.

Haghighatnejad et al (2016) demonstrate that, with an increase in the recycled PVC aggregate content at 28-days of curing age the splitting tensile strength of mixtures decreased.

### 2.6.3 Influence of Recycled PVC Aggregates on Modulus of Elasticity of Hardened Concrete

As it is clear, , Neville (1987) argued that, there is a great relationship between E and compressive strength, hence any parameter that affects the strength of concrete, it affects the elastic modulus as well .Furthermore, coarse aggregate is the main factor ınfluencing modulus of elasticity (E) of concrete. So, any variation in coarse aggregate types or coarse aggregate replacement with other materials will result in the change of elastic modulus of concrete (Tia et al. 2005)**.**

Haghighatnejad, et al. (2016), tested the E of concretes in which natural sand was replaced as 20%, 30%, 40% and 50% with recycled PVC aggregate under different curing conditions. They found that there is a clear inclination of E concretes at 28-days of curing age regardless of the curing type used.

# Chapter 3

# LITERATURE REVIEW

## 3.1 Introduction

In this experimental study, six different 0.45 w/b mixes were produced by replacing six different percentages (0, 10, 20, 30, 40 and 60 %) of waste plastic PVC to coarse aggregate. The main goal was to determine the effects of substituted PVC instead of coarse aggregates on mechanical behavior and the long term durability of concrete against heat. The names and details of the performed tests are defined below:

- Fresh concrete (SCC) tests: Slump test, L-box test, V-Funnel test
- Compressive, split tensile and flexural strength tests,
- Ultra sound pulse velocity readings before and after loading the specimens,
- Ultra sound pulse velocity readings before and after 100˚C and 200˚C heat treatments,
- Degradation tests against 100˚C and 200˚C heat treatments
- This chapter also contains a description of the materials utilized in the tests
- Outlined above and moreover, clarifies the ASTM standard codes or any other Standards that were used in experimentation.

## 3.2 Materials Used

The materials utilized in the experiments for this research are characterized in the following sections.

### 3.2.1 Cement

CEM II Slag Portland cement of 32.5 grades was used in this study. This kind of cement has been modified to withstand a direct sulfate attack. It generally produces less heat and has a slow rate of hydration. The chemical and physical analysis of this cement is illustrated in Table 3.1

Table 3.1: Physical and Chemical Analysis of Cement - CEM II/B-M 32,5

| **Portland Cement (CEM II/B-M 32,5 )** | | | | |
|---|---|---|---|---|
| Properties | | | Analysis Results | Methods |
| Chemical Analysis | Insoluble Residue (%) | | 0.10 | EN 196-2 |
| | Loss on ignition (%) | | 10.88 | |
| | $SO_3$ (%) | | 2.24 | |
| | $SiO_2$ (%) | | 18.72 | |
| | CaO (%) | | 60.44 | |
| | CaO free (%) | | 1.00 | |
| | MgO (%) | | 2.00 | |
| | $Al_2O_3$ (%) | | 4.04 | |
| | $Fe_2O_3$ (%) | | 2.56 | |
| | $C_l$ (%) | | 0.00 | EN 196-21 |
| PROPERTIES | | | Analysis Results | Methods |
| Physical Analysis | Specific Gravity (g/cm$^3$) | | 3.00 | EN 196-6 |
| | Fineness: specific surface (cm$^2$/g) | | 4.007 | |
| | 90 Micron Sieve Residue (%) | | 0.26 | |
| | 45 Micron Sieve Residue (%) | | 5.24 | |
| | Water/Cement Ratio (%) | | 28.00 | EN 196-3 |
| | Initial Setting Time (minutes) | | 18.5 | |
| | Pressure Strengths (MPa) | 3 days | 15.78 | EN 196-1 |
| | | 7 days | 29.86 | |
| | | 28 days | 41.33 | |

### 3.2.2 Mixing Water

Drinkable tap water, which is free from acids, alkalis, oils and organic materials, was used for all concrete mixtures and the curing process.

### 3.2.3 Fine Aggregate

Machine-crushed fine aggregate with a maximum size of 5 mm in diameter, which is called sand, was used in this study. To find out gradation based on the ASTM standard, C136M-14 sieve analysis was performed and controlled by C33/C33M-16 of ASTM standard as shown in Figure 3.1 and Table 3.2

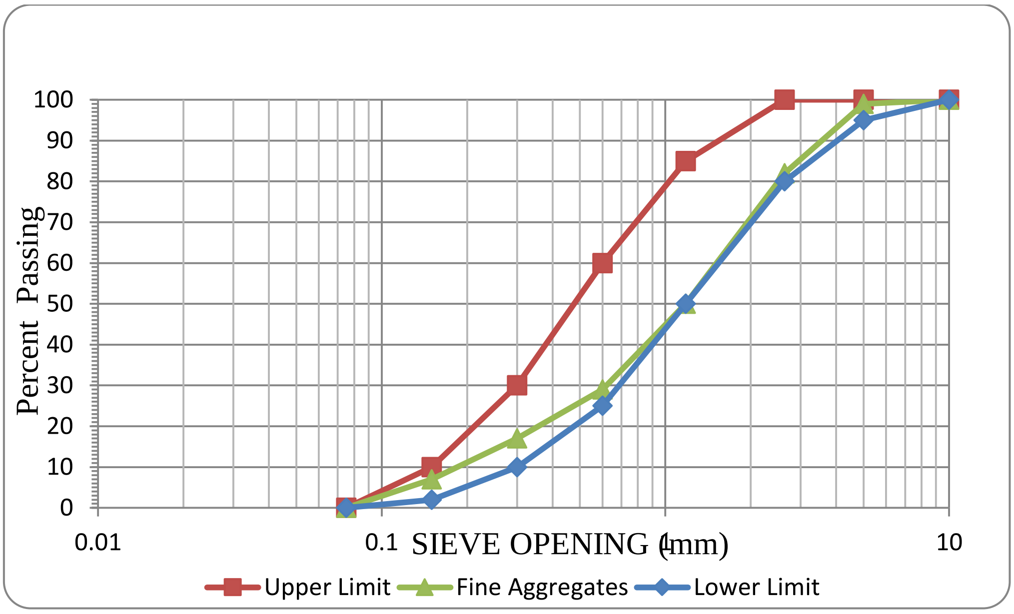


Figure 3.1: Sieve Analysis of Fine Aggregate

### 3.2.4 Coarse Aggregates

Crushed coarse aggregates were used in these tests as gravel with a maximum aggregate size of 10 mm in diameter. Grading of coarse aggregate was done according to standard ASTM C136M-14 and controlled by ASTM C33M-16 as shown in Figure 3.2.

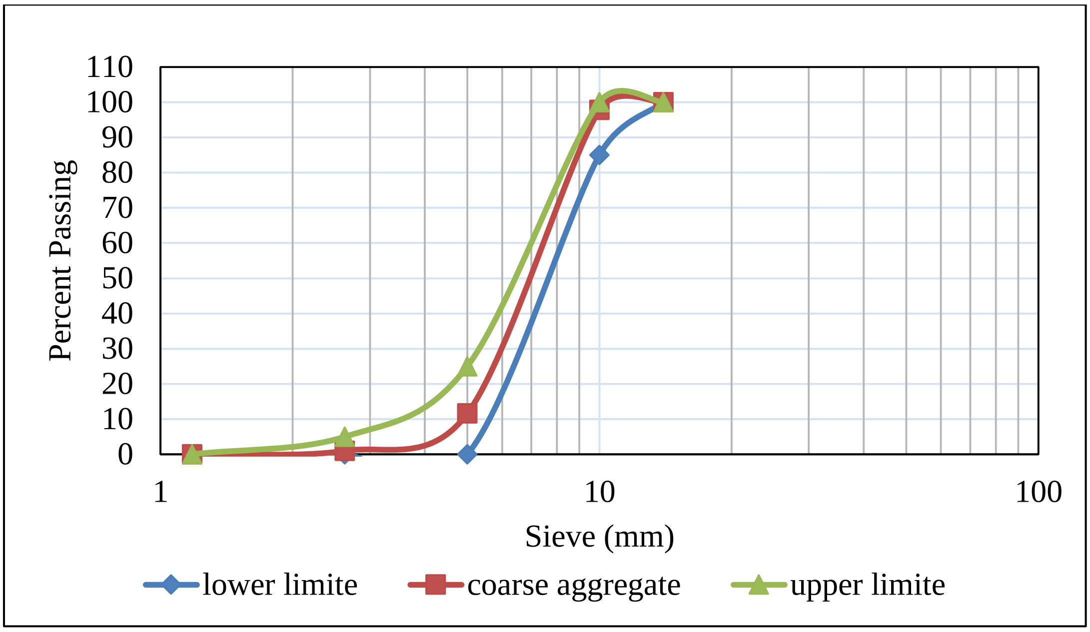


Figure 3.2: Sieve Analysis of Coarse Aggregates

### 3.2.5 PVC Waste Plastics Replaced to Coarse Aggregate

In five different produced mixes, PVC Plastic waste, crushed into 10 mm maximum size was used as a replacement to coarse aggregate in five different proportions. The PVC waste plastics (PVCWP) typically could be obtained from waste pipes, window framing, floor coverings, roofing sheets, and cables. In this study, the PVCWP replaced to coarse aggregates were obtained by crushed waste window frames having a density of 1350 kg/m$^3$. The waste windows were cleaned and washed to remove paper, nylons, and other undesired materials. After drying, they were manually broken using a hammer, after which they were crushed with a rotating processor machine.

Figure 3.3: PVC Waste Plastics Crushed To 10 mm Maximum Size

### 3.2.6 Silica Fume

In this experimental study, silica fume is used as an additive to concrete in order to improve the concrete properties in terms of long term durability. The amount of silica fume used for all six different concrete mixes produced with differing proportions of PVC waste plastics 0, 10, 20, 30, 40 and 60 % was equal and 10 % of the cement weight to achieve self-compacting concrete. Chemical and physical properties of silica fume can be followed from Table 3.4 and Figure 3.4, respectively.

Table 3.2: Chemical and Physical Characteristics of the Silica Fume

| Property | Amount |
|---|---|
| $SiO_2$ | 82.20% |
| $AL_2O_3$ | 0.50% |
| $FE_2O_3$ | 0.42% |
| CaO | 1.55% |
| MgO | 0.00% |
| $SO_3$ | 3.03% |
| Loss of ignition | 5.66% |
| Fineness | 29000 ($m^2$/kg) |
| Specific gravity | 2.2 |

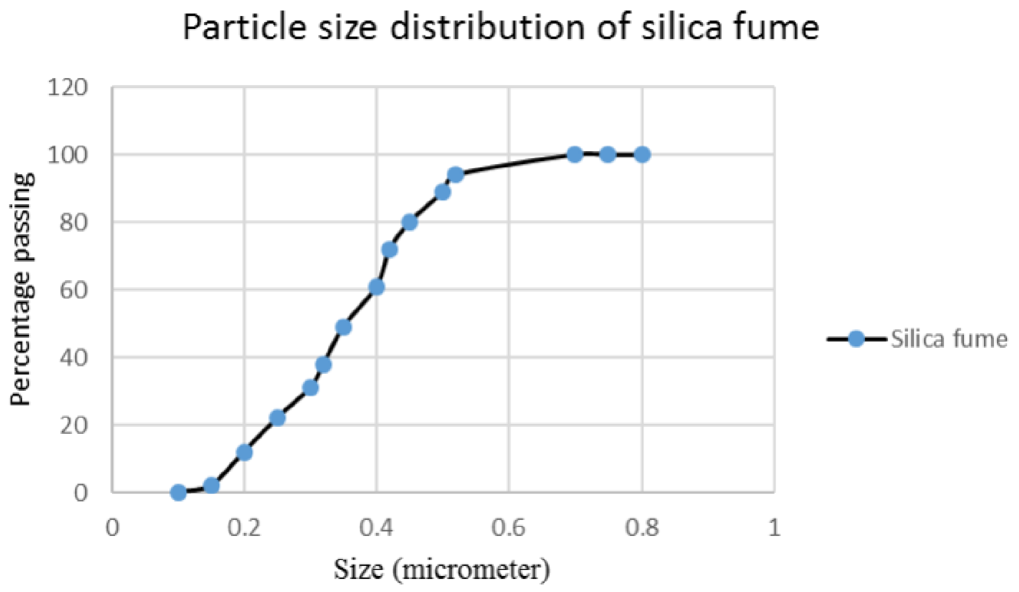


Figure 3.4: Particle Size Distribution of Silica Fume

### 3.2.7 Super-plasticizer

Produced through the modification of polycarboxylic ether polymers, Master Glenium 27 is an admixture used for the experiments in this study. The Master Glenium 27 was used as 1.7 % of the binder (SF + cement) at different ratios 10 %, 20, 30, 40 and 60 %. This water reducing admixture was created specifically to satisfy the demand for durability, high strength, and slump retention required by the ready-mix concrete industry. It is also an essential ingredient in the production of ‘self-compacting concrete’ due to its superb dispersion effect.

Master Glenium 27 the perfect admixture for the ready-mix concrete industry. The lower water/cement ratio required by the admixture does not significantly impact it is workability retention, thus permitting the production of high quality concrete.

The benefits offered by Master Glenium 27 include:

- Self-compacting concrete.

- The absence of segregation or bleeding.

## 3.3 Mix Design

The mix design can be defined as the calculation of the amounts and proportions of the main component materials of concrete mixes for the required characteristic strength, specific material properties, and workability, in order to get the best concrete mix. The performed mix designs for this study are as shown in Table 3.5

Table 3.3: Quantities and Proportions of 0.45 W/C Ratio Concrete Mixes Ingredients

| Concrete Type | PVC (%) | C (kg/$m^3$) | PVC (kg/$m^3$) | W (kg/$m^3$) | FA (kg/$m^3$) | | CA (kg/$m^3$) | SP. (kg/$m^3$) | SF (kg/$m^3$) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 3mm | 5mm | | | |
| SCC 00PVC | 0 | 400 | 0.000 | 198 | 915 | 915 | 812,0 | 7.7 | 40 |
| SCC 10 PVC | 10 | 400 | 40.28 | 198 | 915 | 915 | 734.4 | 7.7 | 40 |
| SCC 20 PVC | 20 | 400 | 79.65 | 198 | 915 | 915 | 658.6 | 7.7 | 40 |
| SCC 30 PVC | 30 | 400 | 120.82 | 198 | 915 | 915 | 579.2 | 7.7 | 40 |
| SCC 40 PVC | 40 | 400 | 161.13 | 198 | 915 | 915 | 502.6 | 7.7 | 40 |
| SCC 60 PVC | 60 | 400 | 241.70 | 198 | 915 | 915 | 346.6 | 7.7 | 40 |

GP: Waste Glass Powder; C: Cement; FA: Fine Aggregate; CA: Coarse Aggregate SP: Super Plasticizer SF: Silica Fume

## 3.4 Experimental Study: Performed Experiments and Procedures

In order to test the effects of replacing aggregate with PVC waste plastics in six different proportions 0, 10, 20, 30, 40 and 60 %, six different 0.45 w/c concrete mixes depending on six proportions of PVC waste plastics incorporated with silica fume and super plasticizer have been designed. At the end, experimental results of each sample, whereas crushed coarse aggregate is substituted with PVC waste plastic in five different ratios, were compared with the result of the control one produced only with crushed aggregate.

### 3.4.1 Concrete Mixing Procedure

The blender equipment is one of only a few components used to simplify the mixing process, which also includes the stacking method, the discharge method, the mixing time, and the mixing energy.

The blending and weighing were done based on the British Standard. In each batch, aggregate, cement, silica fume and plastic PVC mixed together in a laboratory mixer. After approximately 30 seconds, water was gradually added to the blend and the blending process continued for approximately 3 minutes to achieve a homogenous paste. In this step, the workability test (slump test) was carried out on fresh concrete. After testing the workability, the concrete was put back into the mixer and remixed for a few seconds to fill the molds (BS 1881: Part 125: 1986, 2009).

### 3.4.2 Fresh Concrete Tests - Self-compacting Concrete

The purpose of this experiment was to determine how the properties of fresh self-compacting concrete (SSC) are affected by the partial replacement of coarse aggregate with plastic waste in its production. The workability properties of each of the mixes were determined in terms of time, slump flow, L-box, and V-funnel.

### 3.4.2.1 Slump flow – Workability of Concrete

In order to determine the effects of PVC waste plastic replacement to coarse aggregate on the workability of fresh concrete, the slump test has been performed. As a SCC requirement; each measured slump value should be between 500-700 mm. Slump test is prepared and performed according to the ASTM C143/C143M 15a standard (Figure 3.4).

Figure 3.5: Slump Test Apparatus

### 3.4.2.2 V-funnel – Flowability of Concrete

The V-Funnel apparatus is used to estimate the flow period of freshly mixed self-compacting concrete. First, the machine is filled totally with concrete without tamping, after that, the stopwatch is adjusted before opening the door. The stopwatch is started when the trap door is opened and records the time of discharge for complete flow; the passing time is also recorded. This duration should be between six to twelve seconds in order to have self-compacting concrete. Figure 3.5 illustrate's the V-Funnel test apparatus.

Figure 3.6: V-funnel Test Apparatus

### 3.4.2.3 L-Box – Viscosity of Concrete

Approximately 14 liters of concrete is necessary to make increase the regularity of the tests. First, fixed the machine level on stable earth and ensure that the down gate could open easily and then close it.

After that, soak the interior surface of the machine and drain any excess water, then fill the vertical area of the device with the concrete. Lift the sliding door and allow the concrete to stream out into the horizontal section. At the same time, begin the stopwatch and record the time for the concrete to reach into the even. When the concrete stops streaming, the separations 'H1' and 'H2' are measured. The Calculation of H2/H1 should be less or break even with one to have self-compacting concrete. (EFNARC, 2005. Specification and Guidelines for self-compacting concrete.)

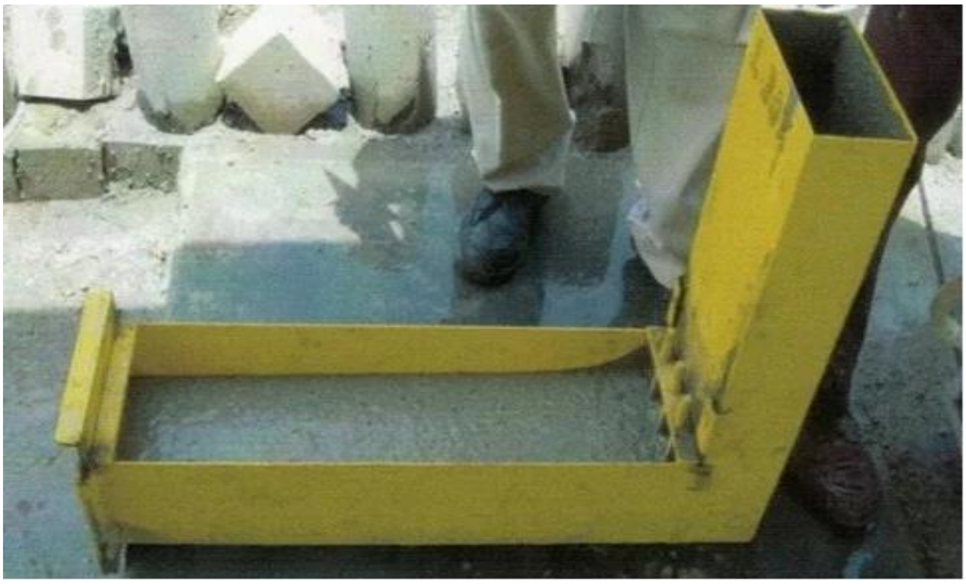


Figure 3.7: L Box Test Apparatus

### 3.4.3 Specimen Preparation and Curing

In this stage of the experiments, different shapes and sizes of specimens were prepared in order to perform the hardened concrete tests. These are cylinders with 100 × 200 mm long, cubes with 150 × 150 × 150 mm, cubes with 100 × 100 × 100 mm, and also beams with 500 × 100 × 100 mm were produced for each concrete mix. Before placing the concrete in the molds, the molds were washed and coated in oil in order to avoid a chemical reaction between the concrete and steel molds and also to ease specimen casting. After finishing the slump test, the concrete was mixed for 45 more seconds. After which, the molds were immediately filled completely with concrete. They were then placed on a vibration machine in order to compact the concrete, as shown in Figure 3.7. Afterwards, the samples were stored in the drying room and became molded after twenty-four hours.

Figure 3.8: Standard Compaction of Specimens

After de molding, directly the samples were placed to the curing water tank at a normal temperature around 25 ℃ for 28 days until the day of testing, as it is shown in Figure 3.8.

Figure 3.9: Standard Curing of Specimens – Curing Tank

## 3.5 Hardened Concrete Tests

In order to determine the effects of PVC waste plastic replacement to coarse aggregate on hardened SCC performance, the following hardened SCC tests are performed respectively.

### 3.5.1 Compressive Strength ($S_c$)

To examine the impact of replacing aggregate with PVC waste plastics on the Sc, the cube specimens with 150 × 150 × 150 mm were prepared and cured up to 28 days until testing, corresponding to the ASTM C39/C39M – 17 standard details. The average of at least three specimens was taken for each measurement throughout the whole study.

### 3.5.2 Splitting Tensile Strength ($S_t$)

To determine the impact of replacing aggregate with PVC waste plastics on St, the cylindrical specimens with 100 × 200 mm were prepared and subjected to standard water curing for 28 days. After 28 days of water curing, the specimens were subjected to the splitting tensile test according to ASTM C496/C496M – 11. In addition, each test was repeated on three specimens and the average results were taken.

Figure 3.10: Splitting Tensile Strength Test Machine

Figure 3.11: Crushed Specimen after Splitting Test

### 3.5.3 Flexural Strength Test ($S_f$)

The beams 100 × 100 × 150 mm were prepared and tested for Sf and toughness measurements. Three-point loaded Sf equipment was loaded with a constant deformation rate of 0.05 mm/min based on the standard (ASTM C 1609, 2010). The pressure was exerted without shock and increased constantly until the first crack, after which no more loads were applied. The maximum load that samples with stood before the first crack was used to evaluate the flexural strength (Figure 3.12)

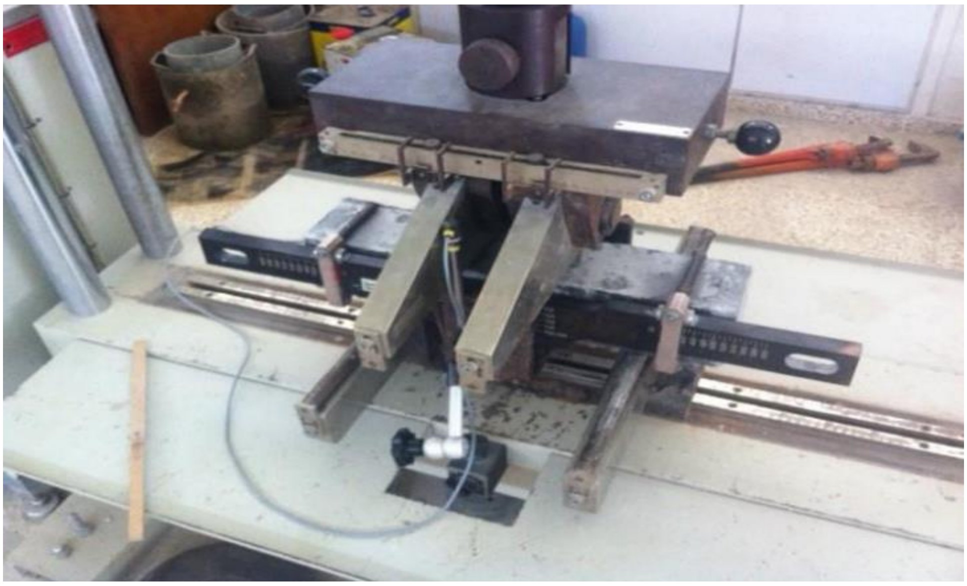


Figure 3.12: Flexural Strength Test Machine

### 3.5.4 Ultra Sound Pulse Velocity Readings (UPV)

A Pundit test was performed to determine the presence of defects within the concrete either before or after loading and/or guess the compressive strength of concrete without destroying the samples. This test evaluates the time that an ultrasonic wave takes to travel through the concrete between two points of the sample based on the standard (BS 1881: Portion 201, 2009). The cubic specimens were prepared and subjected to test after 28 days of curing for this test. The PUNDIT performance is presented in Figure 3.13.

Figure 3.13: PUNDIT machine

### 3.5.5 Degradation Against Tests Heat.

Degradation of polymers is a molecular deterioration as a result of overheating. At high temperatures, the components of the long chain backbone of the polymer can begin to be broken and react with one another to change the properties of the polymer. Thermal degradation can present an upper limit to the service temperature of plastics as much as the possibility of mechanical property loss. Thermal degradation generally involves changes to the molecular weight of the polymer and typical property changes include reduced ductility, chalking, color changes and cracking. (Albano, C., Camacho, N., Hernandez, M., Matheus, A., Gutierrez, A., 2009)

When performing a degradation text, the weight and ultra sound velocity of the samples are first measured. After which, they are put in the oven on a gradual heat at ten percent per minute up to a hundred or two hundred degrees for four hours. The oven is then turned off while the samples are left to cool in it to cool for six hours.

Following the six hour cooling period, the samples are taken out and weighed again, while an ultrasonic test is also performed after degradation to determine the effects of the test. The oven apparatus used in the degradation test is shown in Figure 3.14.

Figure 3.14: The Oven Apparatus

### 3.5.6 Stereo Microscope Detections

After the specimens were exposed to high temperatures by degradation, the use of a microscope was necessary to take a clear image of the surface of the specimens to determine the presence of any cracks due to degradation, and to compare the effects of cracks made by each increase in temperature and waste plastic replacement percentage. Moreover, the microscope was also used to measure the diameter of those cracks. Figure 3.14 show the microscope apparatus used in this study.

Figure 3.15: Stereo Microscope Instrument

# Chapter 4

# EXPERIMENTAL RESULTS AND DISCUSSION

## 4.1 Analyses of Experimental Results

This chapter outlines the fresh and hardened properties of six different 0.45 w/b SCC mixes. Effects of PVC waste plastics replaced to coarse aggregate in five different proportions 0, 10, 20, 30, 40 and 60 %, on some physical, mechanical and thermal properties were examined by performing the required experiments (chapter 3). The test results were tabulated in tables and/or drawn in charts using the Microsoft Office 2016.

## 4.2 Effects of PVC Waste Plastics on Workability: Slump, V-Funnel, and L-box

The fresh concrete properties (Slump, V-Funnel, and L-box) of all six different SCC mixes are shown in Table 4.1. The six different 0.45 w/b SCC mixes; produced by replacing coarse aggregates with PVC waste plastics in six different proportions 0, 10, 20, 30, 40 and 60 % and also by adding 1.75 % of cement weight Glenium super plasticizer and 10% silica fume to all mixes. As it is clear either from the table 4.1 and/or, figures 4.1-4.3, PVC waste plastic replacement has a great influence on the workability properties of SCC fresh concrete.

The workability measurements for control SCC mix (No – 0 % replacement of PVC waste plastics) are as: The slump flow was 650 mm which is in the range of (500-700) mm, the V-funnel flow time was recorded as 7 seconds which is also in the acceptable range – (7-12) seconds, and finally the L-box ratio $H_2/H_1$ for the same mix was found to be 0.90 mm which is again in the range 0.80-1.00. At this stage, it can be decided that, the control mixture satisfied SCC requirements in terms of workability.

When workability results of other SCC mixes, where coarse aggregate replaced with PVCWP are examined, it can be seen that; SCC requirements has been satisfied up to 60 % replacement (Table 4.1).

The improvement of workability between 0 and 60 % was due to the non-absorption of the waste plastic PVC. Concrete including PVC aggregate had more free water, and no bleeding or segregation in all the mixtures and the slump flow increased as a result

Table 4.1: Workability Measurements of 0.45 W/b SCC Mixes

| | Slump Flow (mm) | | V-Funnel (second) | | L-Box (H2/H1) | | |
|---|---|---|---|---|---|---|---|
| Mixture Name | Results | Limits | Results | Limits | Results | Limits | SCC |
| SCC00PVC | 650 | 500-700 | 7.00 | 6-12 | 0.90 | 0.8-1 | Satisfied |
| SCC10PVC | 670 | 500-700 | 7.50 | 6-12 | 0.94 | 0.8-1 | Satisfied |
| SCC20PVC | 690 | 500-700 | 7.55 | 6-12 | 0.95 | 0.8-1 | Satisfied |
| SCC30PVC | 700 | 500-700 | 7.70 | 6-12 | 1.00 | 0.8-1 | Satisfied |
| SCC40PVC | 700 | 500-700 | 8.10 | 6-12 | 1.00 | 0.8-1 | Satisfied |
| SCC60PVC | 665 | 500-700 | 8.60 | 6-12 | 0.82 | 0.8-1 | Satisfied |

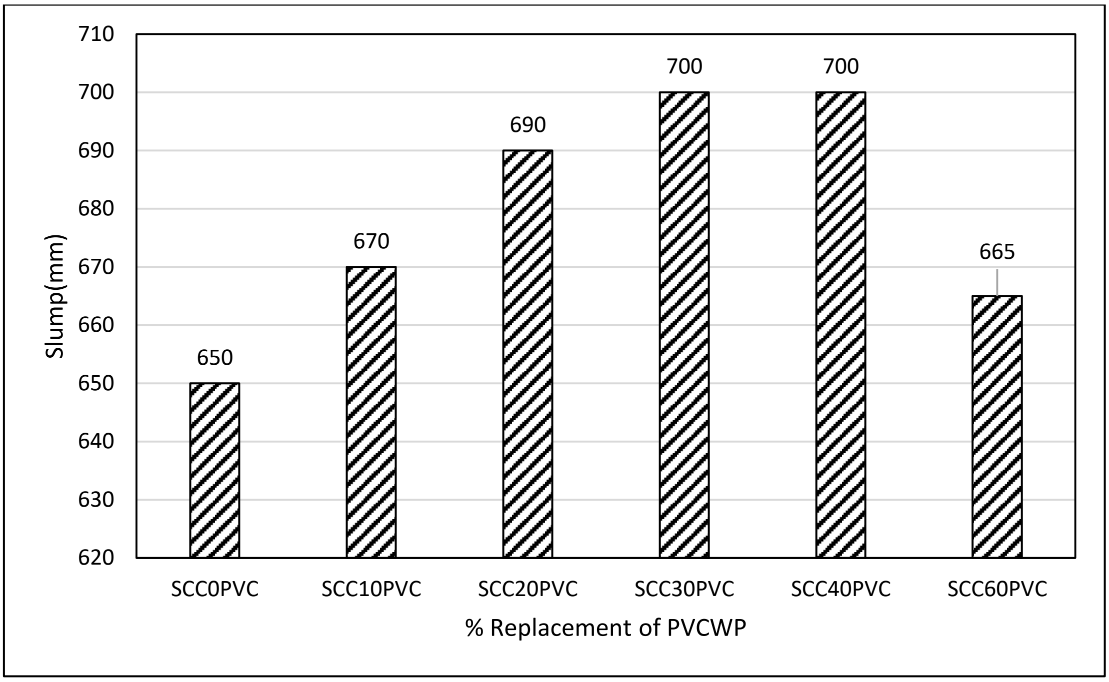


Figure 4.1: Effect of PVC Waste Plastic Replacement to Coarse Aggregate on Slump Flow

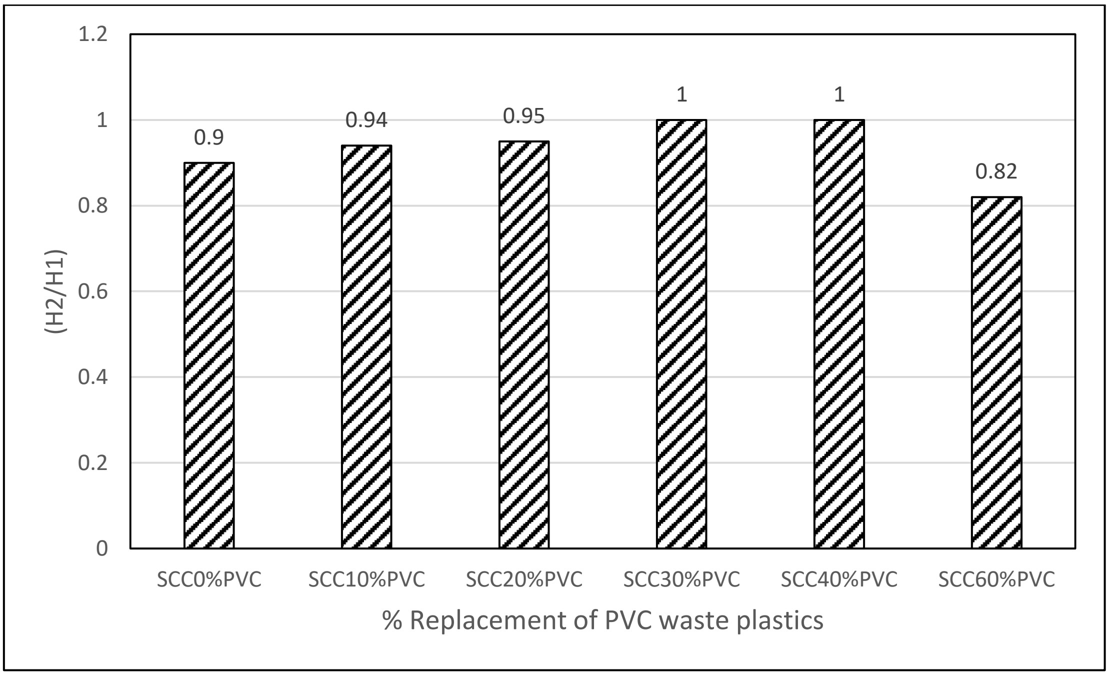


Figure 4.2: Effect of PVC Waste Plastic Replacement to Coarse Aggregate on L-Box Values

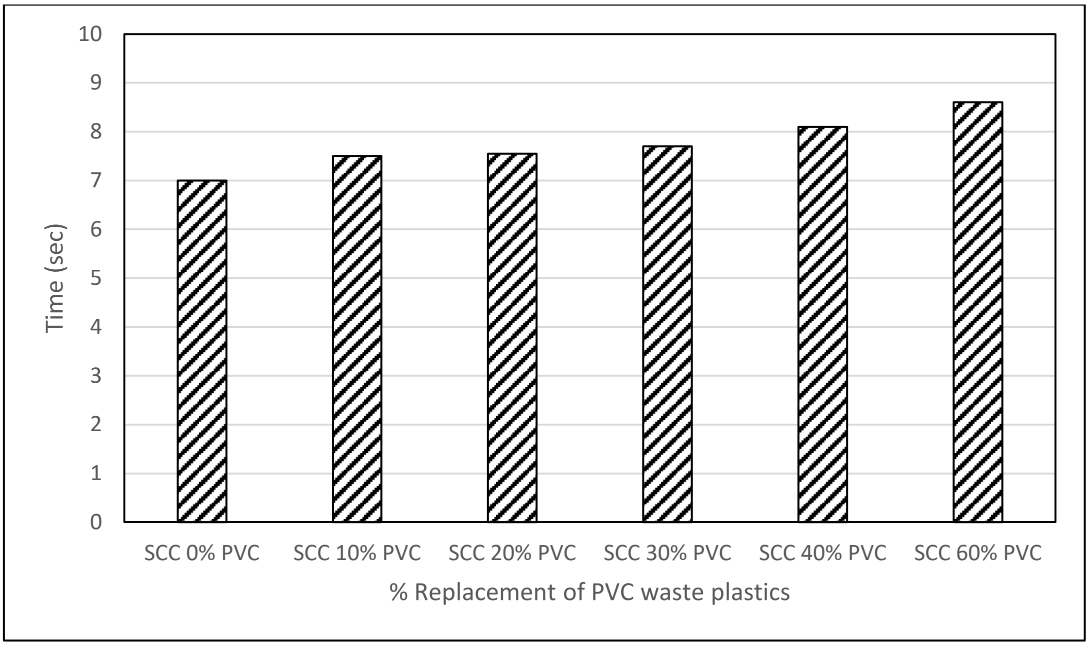


Figure 4.3: Effect of PVC Waste Plastic Replacement to Coarse Aggregate on Viscosity of SCC

## 4.3 Effects of PVC Waste Plastics on Compressive Strength of SCC

The compressive strength ($S_C$) test results of six different SCC mixes are tabulated in Table 4.2 and also figured in Figure 4.4. PVC waste plastic replacement decreased the 28 – days $S_C$ of all SCC mixes and this decrement is much more beyond 30 % PVC waste plastic replacement.

Table 4.2: Effects of Different Proportions of PVC Replacement on $S_C$

| Mixture Name | 28-days $S_C$ (MPa) | % Change in $S_C$ (MPa) |
|---|---|---|
| SCC00PVC | 59.63 | - |
| SCC10PVC | 57.30 | -3.91 |
| SCC20PVC | 55.00 | -7.77 |
| SCC30PVC | 55.93 | -6.20 |
| SCC40PVC | 48.70 | -18.30 |
| SCC60PVC | 45.60 | -23.50 |

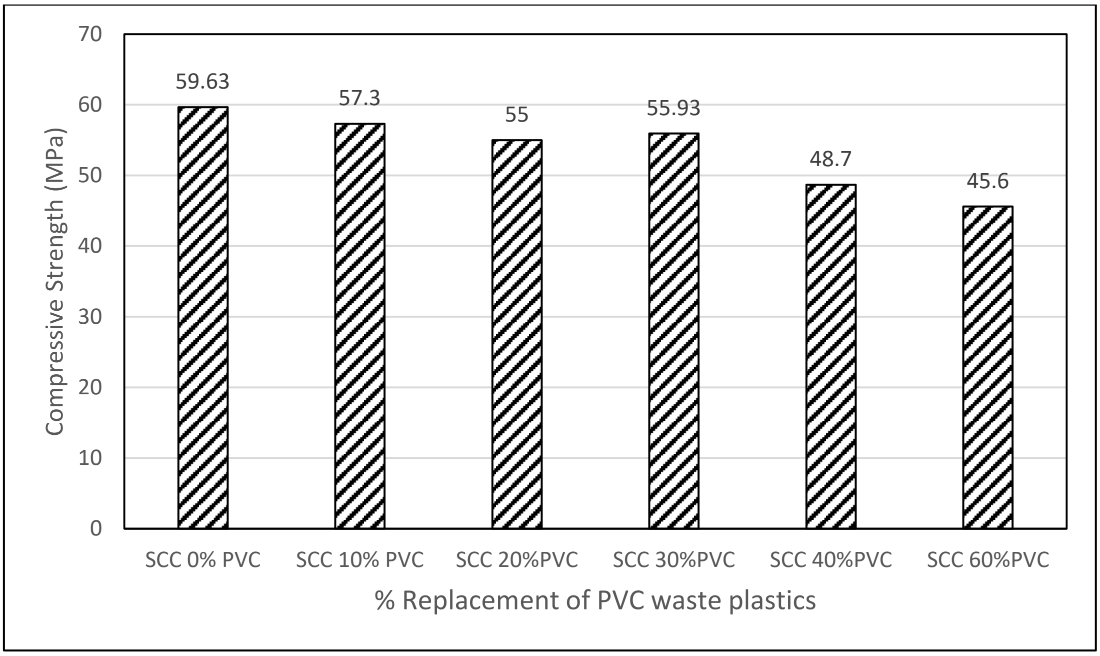


Figure 4.4:Effect of PVC Waste Plastic Replacement to Coarse Aggregate on $S_c$

The amount of reduction in $S_C$ values of PVC replaced mixes relative to control specimens showed difference with increased PVC amount. While up to 30 % replacement, decrement in $S_C$ was uniform and not so high, beyond that point it is about twice of them. For a 10 % aggregate substitution, the $S_C$ of SCC specimens has a reduction of up to 3.91 % relative to the control. For a 20 % aggregate substitution, the $S_C$ diminishes by about 7.77 % from the control and with a 30% substitution, the 28-days $S_C$ decreases as 6.2 % amount. On the other hand, when the substitution percentage is increased to 40 % and 60 %, the 28 - days $S_C$ decrease by 18.3 % and 23.5 %, respectively.

This reduction in $S_C$ can be attributed to the aggregate and aggregate - matrix bond properties, since there is no difference in the matrix quality of all 0.45 w/b mixes. The mechanical properties of PVC aggregates are much lower than the crushed ones and the interfacial Transition Zone (ITZ) between aggregates and the matrix is weaker when PVC aggregates are used. At this stage, when crushed aggregate is replaced with PVC waste plastics; differences in aggregate mechanical properties, bond strength and structure of ITZ should be taken into consideration. The lower strength and modulus of elasticity of PVC aggregates will directly reduce the Sc. On the other hand, the smooth surface and non-absorbent characteristics of PVC aggregates will play an important role in the formation of weaker bond and ITZ structure relative to crushed aggregates. When smooth surface PVC aggregate is used; first, ITZ thickness will be higher due to increased wall effect, second, initial defects (pores and cracks) will increase since water cannot be absorbed by PVC aggregates.

## 4.4 Effects of PVC waste Plastics on Splitting Tensile Strength

The splitting tensile strength (St) test results of six different SCC mixes are given in Table 4.3 and Figure 4.5.

Table 4.3: Effects of Different Proportions of PVC Replacement on 28 days St

| Mixture Name | 28 days St (MPa) | Load (KN) | Change in St (%) |
|---|---|---|---|
| SCC00PVC | 4.995 | 157.10 | - |
| SCC10PVC | 4.560 | 143.25 | -8.7% |
| SCC20PVC | 4.310 | 135.60 | -13.7% |
| SCC30PVC | 4.28 | 134.60 | -14.3% |
| SCC40PVC | 4.200 | 132.10 | -15.9% |
| SCC60PVC | 4.150 | 130.50 | -16.9% |

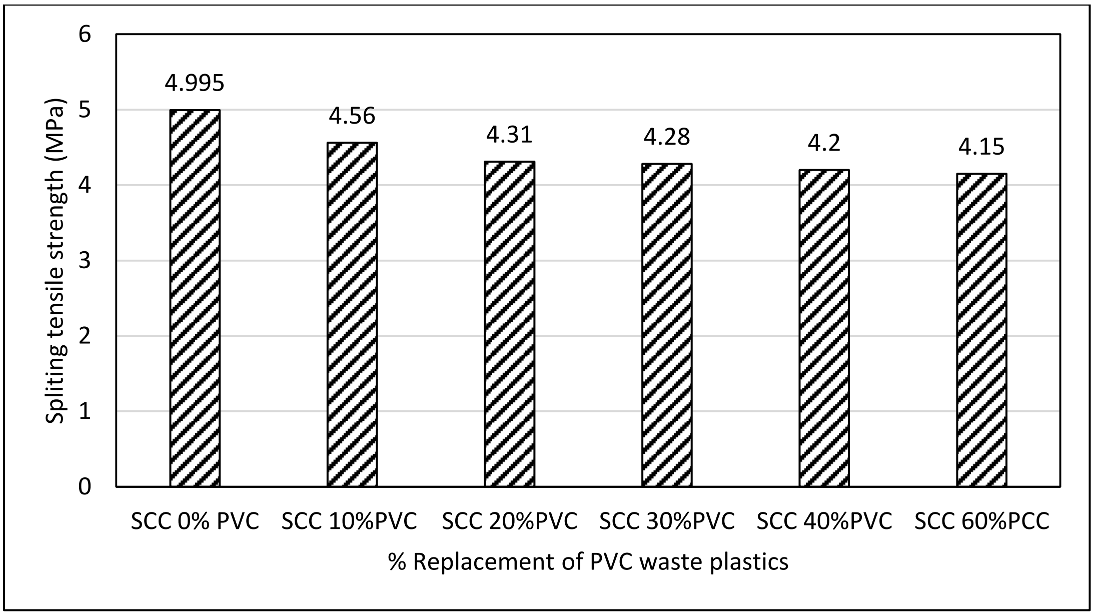


Figure 4.5: Effect of PVC Waste Plastic Replacement to Coarse Aggregate on $S_t$

The splitting tensile strength results were evaluated at 28 days. From the information given in table below, it can be concluded that, St is equally affected by PVC substitution as with compressive strength. There is a reduction in St with regard to the increasing ratio of the PVC replacement included comparing with the control specimens. There was a decrease in the St for concrete containing 10, 20, 30, 40 and 60 % PVC waste plastic aggregates. The reduction rate was -8.7% on the first substitution of PVC by 10 %. For a 20 % substitution of PVC, St also decreased by -13.7 %. Subsequently, replacing 30 % of PVC caused a -14.3 % reduction of the St, which similarly reduced by -15.9 % and -16.9 % PVC 40 % and PVC 60 %, respectively.

The reduction in 28 – days St is much more uniform than that of 28 – days Sc. Similar to $S_C$, reduction in St can be attributed to the bond strength and ITZ properties of all 0.45 w/b mixes. The weakness of ITZ between aggregates and the matrix increases when PVC aggregates are used. Because, when crushed aggregate is replaced with PVC waste plastics; the smooth surface and non-absorbent characteristics of PVC aggregates play an important role in the formation of weaker bond and ITZ structure. Since ITZ becomes larger and weaker due to increased wall effect, and therefore initial defects (pores and cracks) St Values decrease with increased PVC replacement.

## 4.5 Relationship between Compressive and Splitting Tensile Strengths

In a similar trend to that observed for splitting tensile strength, compressive strength also decreased over the course of the 28-days. It can be seen from Table 4.4 that the different relation factor $R^2$ in order to express St as a function of $S_C$ and drawn the best one linear relationship in the form of $y = 0.0091x^{-}0.9091x+26.708$ and the best relation R2= 0.9211. Figure 4.6 shows the polynomial relationship between $S_C$ and St containing PVC aggregate; it is obvious from the figure that as compressive strength decreases, splitting tensile strength also decreases as well.

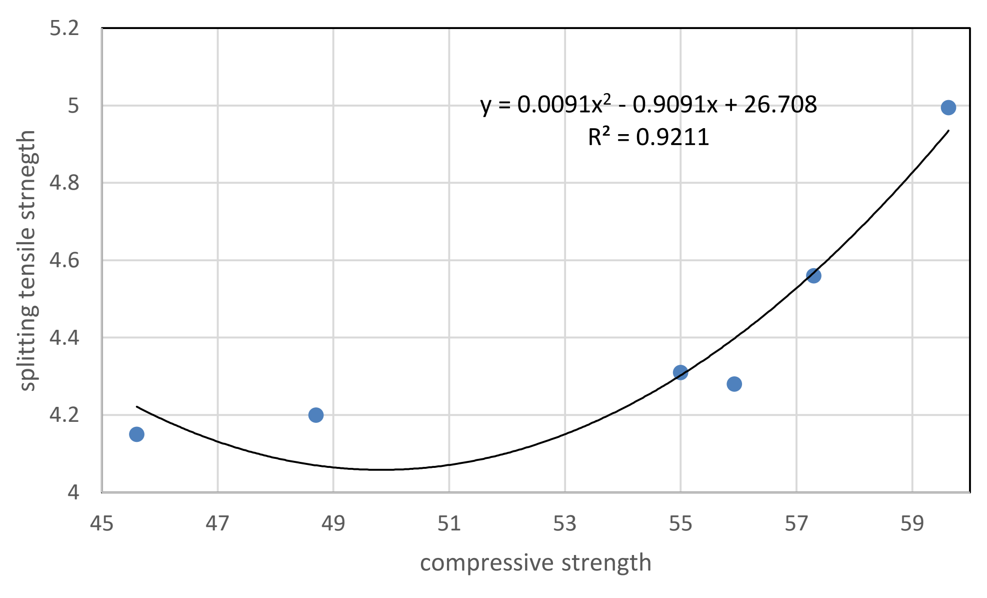


Figure 4.6: Relationship between Compressive Strength and Splitting Tensile Strength

Table 4.4: Relationship Equations between Compressive Strengthand Splitting Tensile Strength

| Concrete Type | Regression type | Equation | $R^2$ |
|---|---|---|---|
| Concrete PVC | Exponential | $y=2.5338e^{0.0013x}$ | 0.6403 |
| | Linear | $Y=0.0464x +1.9249$ | 0.622 |
| | Logarithmic | $Y=2.3616Ln(x)-4.9808$ | 0.5939 |
| | Polynomial | $Y=0.0091 x^2-80.9091x+26.708$ | 0.9211 |
| | Power | $Y=0.5153x^{0.5252}$ | 0.6125 |

## 4.6 Effects of PVC Waste Plastics on Flexural Strength and Toughness

The results for the flexural strength ($S_F$) and toughness of SCC with plastic waste aggregate replacement from 0 % PVC until 60 % were tested on beam specimens with 500 × 100 × 100 mm and presented in Table 4.4 and Figure 4.7. It is clear that the $S_F$ of the control sample (11.493MPa) was higher relative to that of the aggregate percentage replacement of PVC.

The 28day $S_F$ is 11.493 MPa at control with 0% plastic replacement. With a 10 % PVC replacement in the mixture, the strength declines to 9.684 MPa. When the percentage of PVC waste plastic rose up to 20 %, the Sf decreases further to 9.477 MPa and continues decreasing at 30, 40 and 60 % to reach the lowest strength value of 9.225 MPa.

These results show that $S_F$ reduces with each increase in the proportion of PVC replacement. The resulting reductions, however, are relatively small and can be attributed to bonding between cementitious materials and aggregates, and the decrease in adhesive strength between the cement paste and plastic waste surface.

According to the figure below, the load of the beams in all PVC proportions initially goes up to the maximum but begins to drop immediately after, thus indicating a lack of ductility and deflection.

Table 4.5: Flexural Strength Values of 6 Different SCC Mixes

| of Mixture Name | Load (KN) | $S_F$ (MPa) | (%) Loss of $S_F$ |
|---|---|---|---|
| SCC00PVC | 12.77 | 11.493 | - |
| SCC10PVC | 10.76 | 9.684 | -15 |
| SCC20PVC | 10.53 | 9.477 | -16 |
| SCC30PVC | 10.45 | 9.405 | -17.59 |
| SCC40PVC | 10.36 | 9.324 | -18.3 |
| SCC60PVC | 10.25 | 9.225 | -19.17 |

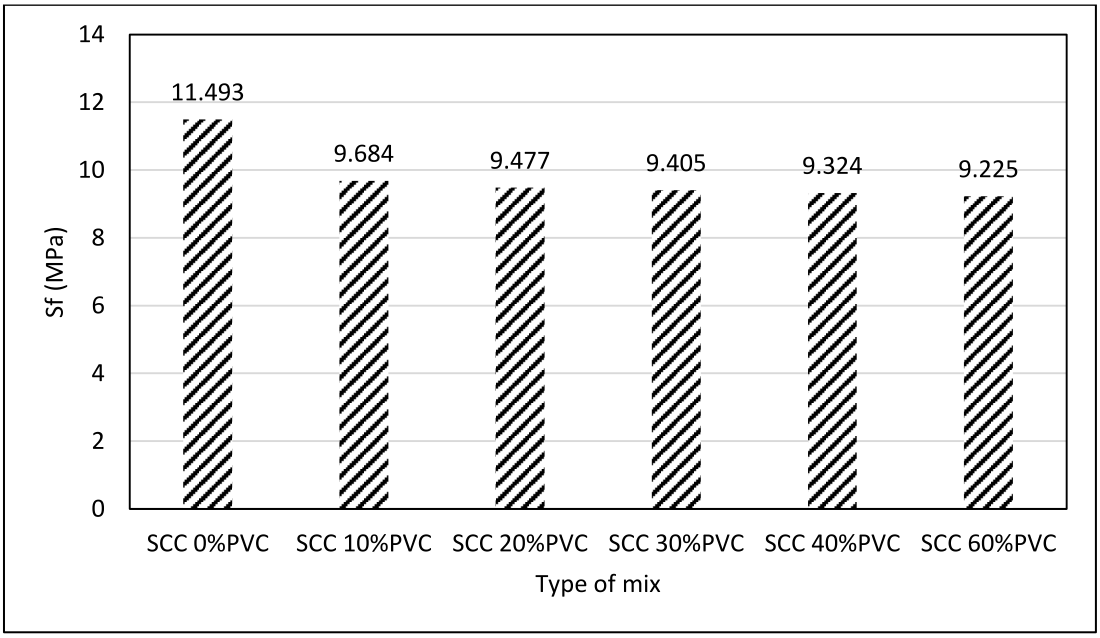


Figure 4.7: Effect of PVC Waste Plastic Replacement to Coarse Aggregate on $S_f$

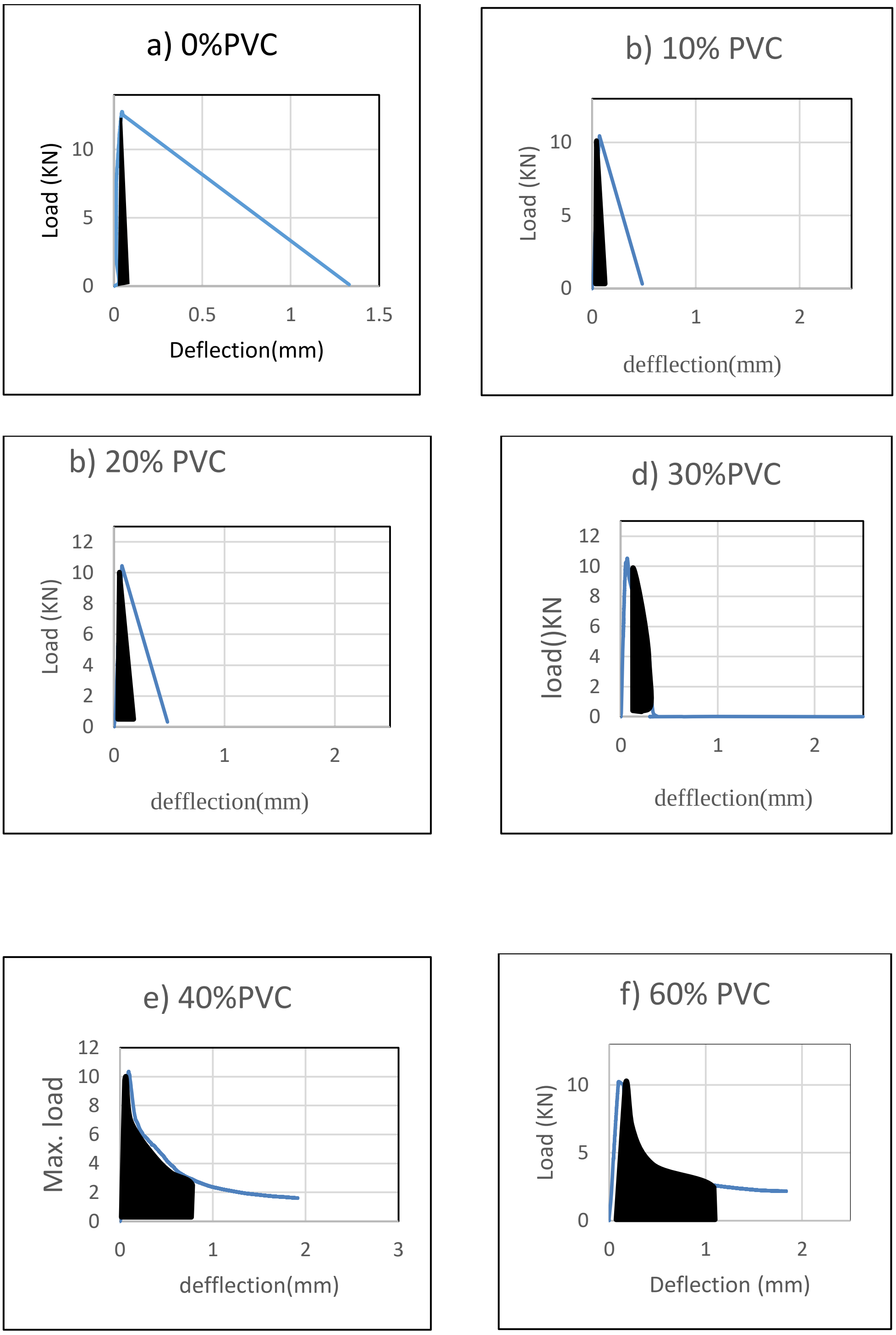


Figure 4.8: Effect of PVC Waste Plastic Replacement to Coarse Aggregate on Flexural Toughness

## 4.7 Relationship between Flexural and Compressive Strengths

It is evident from an overall comparison of all the tests that there is indeed a relationship between the $S_F$ and $S_C$ of concrete. In this respect, some formulations have been designed in Table 4.5 to evaluate $S_C$ as a function of $S_F$. The best polynomial equations are normally in the form of $Y=0.0284\ x^2 - 2.8729x + 81.349$ and the best relation $R^2 = 0.8356$.

Fig. 4.9 shows the relationship between the $S_C$ and $S_F$ of concrete containing PVC waste plastic aggregates. Overall, the results indicate that when $S_C$ diminishes, $S_F$ diminishes as well.

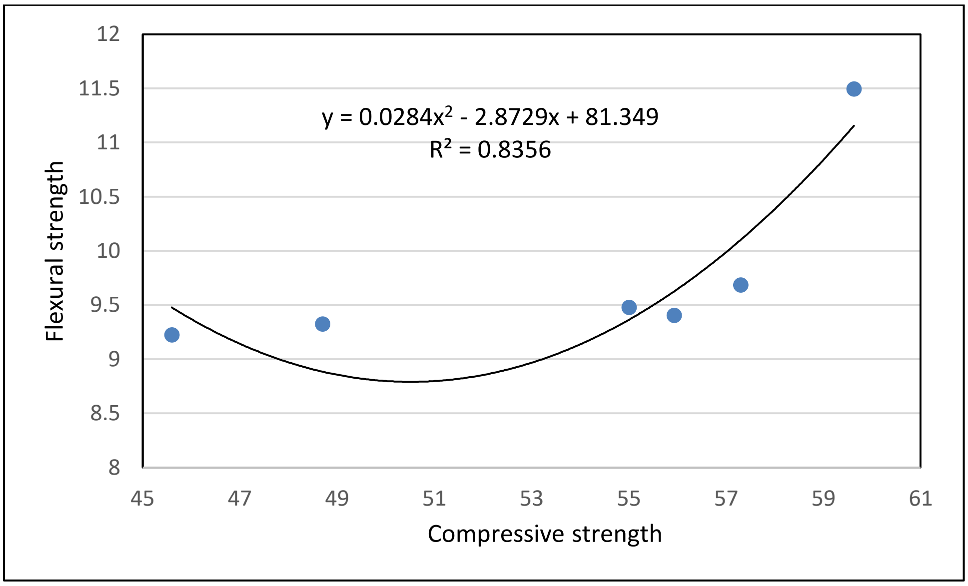


Figure 4.9: Relationship Equations between Flexural Strength nd Compressive Strength

Table 4.6: Relationship Equations between Flexural Strengthand Compressive Strength

| Concrete type | Regression type | Equation | $R^2$ |
|---|---|---|---|
| SCC Concrete PVC | Exponential | $y=5.586e^{0.0104x}$ | 0.455 |
| | Linear | $Y=0.1056x+4.0967$ | 0.4127 |
| | Logarithmic | $Y=5.3325\ Ln(x)-11.449$ | 0.4127 |
| | Polynomial | $Y=0.0284x^2-2.8729x+81.349$ | 0.8356 |
| | Power | $Y=1.2148x^{0.5232}$ | 0.4281 |

## 4.8 Effects of PVC Waste Plastics on Degradation of SCC Against Heating

Three test cube samples 100 × 100 × 100 mm containing six different proportions 0, 10, 20, 30, 40 and 60 % of waste plastic PVC were tested for their residual compressive strength, splitting tensile strength, weight and ultrasound pulse velocity before and after being exposed to temperatures of 100 and 200 °C.

### 4.8.1 Effects of PVC waste Plastics on Weight Loss of SCC Specimens due to Heating

This test was to determine the weight of the concrete specimens with PVC plastic aggregate before and after heating 100 and 200 ℃, this weight of the specimens was measured after 28 days. The weight at zero percent of substitution was reduced from 2.343 kg before heating to 2.32 kg at 100 ℃ to 2.16 Kg after 200 ℃, secondly the weight at 10 % replacement before heating was 2.342 kg, which further decreased to 2.328 kg at the first heat exposure100 ℃ and continued to decrease at the second heat to 2.11 kg. It can be seen that the weight continually decreases with increases in plastic substitution and the rate of temperature heating, and at about 20 % substitution, the weight decreases from 2.3 kg to be 2.27 kg and 2.056 kg before and after heating, respectively. Similarly, the weight decreases at 30 % from 2.23 kg to 2.21 kg and 2.06 kg after heating at 100 and 200 ℃ respectively. These results demonstrate that the weight will continually decline up until 40 and 60 % PVC replacement as shown in Table 4.5, leading to a reduction in the overall weight of the samples.

In addition to causing a reduction in the weight of the specimens, replacing the normal aggregate with plastic light weight also caused a reduction in weight due to the evaporation of free water inside the specimens following an increase in temperature.

Table 4.7: Effect of Degradation Test and Different Proportion of PVC on Weight

| Mix | Weight(Kg) before heating | Weight (Kg)after heating at 100℃ | Weight(Kg) after heating at 200℃ | % Loss |
|---|---|---|---|---|
| SCC00PVC | 2.343 | 2.327 | 2.160 | - |
| SCC10PVC | 2.342 | 2.328 | 2.110 | 0.04 |
| SCC20PVC | 2.300 | 2.276 | 2.056 | 1.835 |
| SCC30PVC | 2.234 | 2.217 | 2.068 | 4.652 |
| SCC40PVC | 2.226 | 2.209 | 2.062 | 4.993 |
| SCC60PVC | 2.127 | 2.105 | 2.029 | 9.218 |

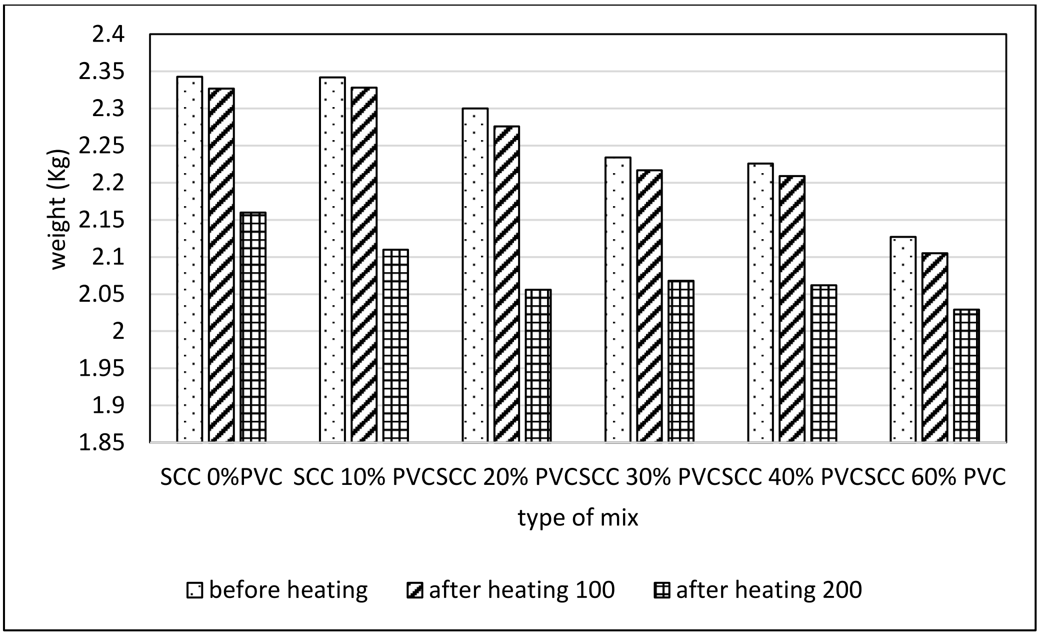


Figure 4.10: Effect of Degradation Test and Different Proportion of PVC on Weight

### 4.8.2 Effects of PVC Waste Plastics on Ultrasound Pulse Velocity Readings

The Ultrasonic Pulse Velocity (UPV) methods are designed to classify and draw voids, cracks, and other damage in concrete, wood, stone, ceramics.

At 0 % replacement PVC, the velocity was 4.82 Km/s. This velocity decreased at the initial 10% PVC replacement to become 4.46 Km/s and continued to decease with each increase of the replacement to 20, 30, 40 and 60 % to become 4.4 Km/s, 4.29 Km/s, 4.16 Km/s and 4 Km/s, respectively.

When the concrete specimens are also exposed to raise temperature, the result shows an affected reduction in ultrasonic pulse velocity with increasing temperature as shown in Table 4.6 and Figure 4.10. The velocity decrease, from 4.81 Km/s to 4.5 Km/s at first heating (100 ℃), continued to diminish to 4 Km/s at the second heating (200 ℃).

Furthermore, at 10 % replacement, the velocity decreased after the two heating from 4.46 Km/s to 4.37 Km/s at 100 ℃, and to 3.7 Km/s at 200 ℃ as shown in Table of results. In addition, the velocity at 20 % PVC replacement also decreased from 4.4 Km/s before heating to 4.18 Km/s after heating 100 ℃, and decreased further to 3.5 Km/s by the second heating at 200 ℃. The velocity continued decreasing in all percentages at the two heating temperatures. The loss in pulse velocity is due to the combination of the effects of loss of water, internal cracking appearing on the concrete surface (shown in table 4.11), as well as the variations in the microstructure of the paste on heating, leading to chemical decomposition. The bonding between aggregate and binder has been weakened because of the heat. (And the wave pass through many different material (normal aggregate, PVC plastic, cement) caused decrease the velocity

Table 4.8: Ultrasound Pulse Velocity (UPV) before and after Heating

| Mix | Velocity (Km/s) before heating | Velocity (Km/s) after heating 100℃ | Velocity (Km/s) after heating 200℃ | % Loss |
|---|---|---|---|---|
| SCC00PVC | 4.82 | 4.50 | 4.00 | - |
| SCC10PVC | 4.46 | 4.37 | 3.70 | 7.468 |
| SCC20PVC | 4.40 | 4.18 | 3.53 | 8.713 |
| SCC30PVC | 4.29 | 3.97 | 3.25 | 10.995 |
| SCC40PVC | 4.16 | 3.80 | 3.10 | 13.692 |
| SCC60PVC | 4.00 | 3.04 | 2.90 | 17.012 |

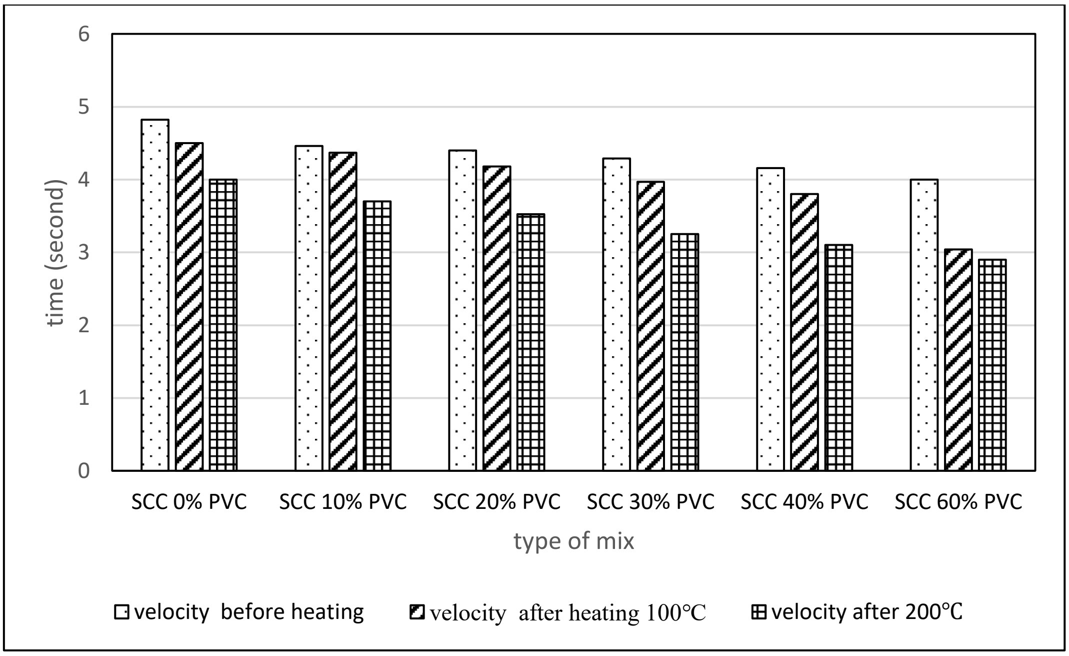


Figure 4.11: Ultrasound Pulse Velocity before and after Heating

Figure 4.12: Presence of Surface Cracks

### 4.8.3 Effect of Degradation Test and Different Proportion of PVC on Compressive Strength Loss:

The experiment results are provided in Table 4.9 shown the impact of compressive strength before and after heating temperature on small cubes 100 × 100 × 100 mm with six different proportion of plastic replacement at two different heating 100 and 200 ℃. From this Table, before heating the specimen, the compressive strength at 0 % replacement was 70.3 MPa. This strength decreased after heating at 100 ℃ to 67.3MPa and decreased yet again with increasing temperature to 200 ℃ to become 61.3 MPa. Additionally, this compressive strength was reduced to 66.4MPa before heating at 10 % PVC replacement and continued decreasing after the two heating at 100 and 200 ℃, respectively to become 63.85 MPa and 58.3 MP. As such, it appears that temperature heating and PVC replacement with aggregate had a negative impact on the concrete’s compressive strength. It appears as though every rise in replacement percentage and heating temperature exerts a greater influence on compressive strength in the entire replacement ratio 20, 30, 40 and 60 %, Table 4.9 show that the increase in heat leads to a reduction in compressive strength.

The second heating 200 ℃ has more effect on compressive strength of concrete than first heating 100 ℃, this comparison defined that evaporation of water inside concrete specimens and producing of cracks has a significant effect on the reduction of compressive strength of the concrete .

Table 4.9: Compressive Strength before and after Heating to 100 and 200 ℃

| Mix | $S_C$ (MPa) before heating | Load (KN) | $S_C$ (MPa) after heating 100 ℃ | Load (KN) | % Loss | $S_C$ (MPa) after heating 200 ℃ | Load (KN) | % Loss |
|---|---|---|---|---|---|---|---|---|
| SCC00PVC | 75.5 | 703 | 67.35 | 673.5 | 10.794 | 61.30 | 613.0 | 18.807 |
| SCC10PVC | 66.4 | 664 | 63.85 | 638.5 | 3.84 | 58.63 | 586.3 | 11.701 |
| SCC20PVC | 62.5 | 625 | 57.90 | 579.0 | 7.36 | 55.70 | 557.0 | 10.88 |
| SCC30PVC | 60.8 | 608 | 56.05 | 560.5 | 7.812 | 54.75 | 547.5 | 10.032 |
| SCC40PVC | 59.3 | 593 | 56.00 | 560.0 | 5.564 | 52.50 | 525.0 | 11.467 |
| SCC60PVC | 52.7 | 527 | 46.80 | 468.0 | 11.195 | 44.30 | 443.0 | 15.939 |

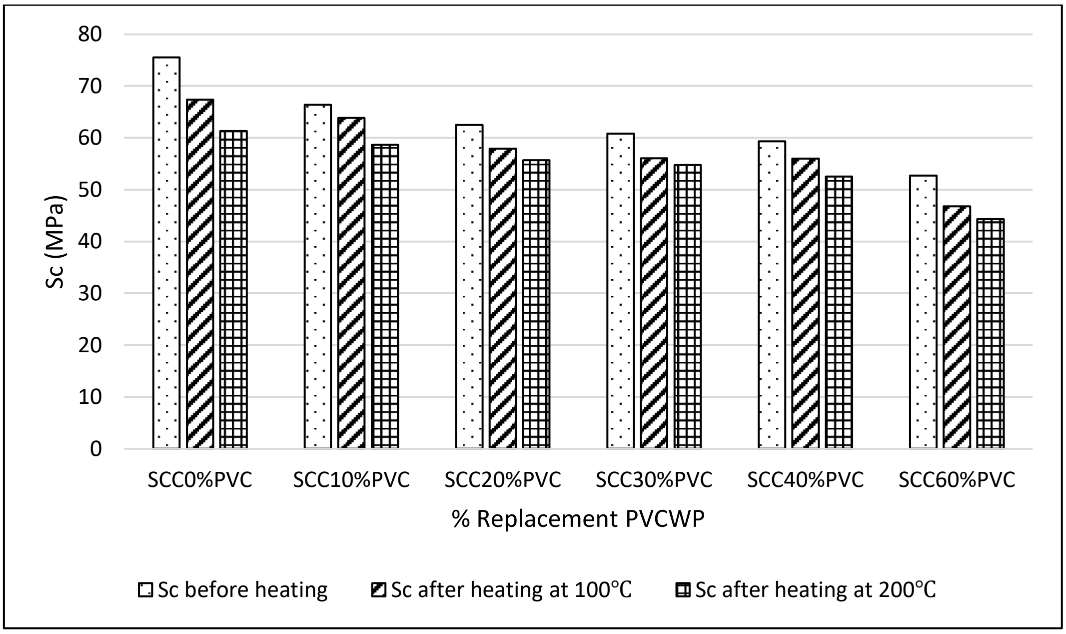


Figure 4.13: $S_c$ before and after Heating

### 4.8.4 Effect of Degradation Test Against Heat on the Splitting Tensile Strength.

St was tested as a function of six different proportion PVC replacement and different temperature heating before and after 100 and 200 ℃ at 28 days after curing, and the results are shown in Table 4.9.

When the concrete specimens were exposed to high temperatures, the splitting tensile strength values show decreases in all concrete mixes during the initial temperature exposure (100 and 200 ℃). Table 4.10 and Figure 4.14 show the splitting tensile strength values in concrete mixes at age 28 days in comparison to the residual splitting tensile strength of the control mix values. The splitting tensile strength for a control mix before heating was 4.339 MPa and decreased to 4.255 MPa after the first heating (100 ℃) and also decreases to 3.79 MPa at second heating (200 ℃).

In concrete mixtures with a 10 % PVC replacement, compared to the control mixture value, the strength is reduced from 3.96 MPa before heating to 3.83 MPa and 3.46 MPa after increasing the temperature to 100 and 200 ℃, respectively. Additionally, The 3.74 MPa strength before heating at 20 % PVC is reduced after the two heating's at 100℃ and 200℃ to become 3.64MPa and 3.41 MP, respectively. For 30% replacement, the splitting strength again achieved a decrease after the heat: before heating it was 3.71MPa and became 3.6MPa after 100 ℃ heating and 3.29MPa after heating at on 0 and 200 ℃, similarly on 40 and 60 %. It appears that temperature heating and PVC replacement with aggregate had a negative impact for concrete splitting, with same the effect on the compressive strength.

Table 4.10: Splitting Tensile Strength before and after Heating 100 and 200 ℃

| Mix | St (MPa) before heating | Load (KN) | St (MPa) after heating 100 ℃ | Load (KN) | St (MPa) after heating 200 ℃ | Load (KN) | % Loss |
|---|---|---|---|---|---|---|---|
| SCC00PVC | 4.34 | 68.20 | 4.26 | 66.90 | 3.79 | 59.50 | 12.62 |
| SCC10PVC | 3.96 | 62.26 | 3.83 | 44.40 | 3.46 | 54.30 | 12.63 |
| SCC20PVC | 3.74 | 58.80 | 3.64 | 56.45 | 3.41 | 53.50 | 8.82 |
| SCC30PVC | 3.71 | 58.29 | 3.60 | 56.59 | 3.29 | 51.80 | 11.32 |
| SCC40PVC | 3.64 | 57.20 | 3.53 | 55.40 | 3.05 | 47.90 | 16.20 |
| SCC60PVC | 3.60 | 56.60 | 3.26 | 51.25 | 3.00 | 47.10 | 16.67 |

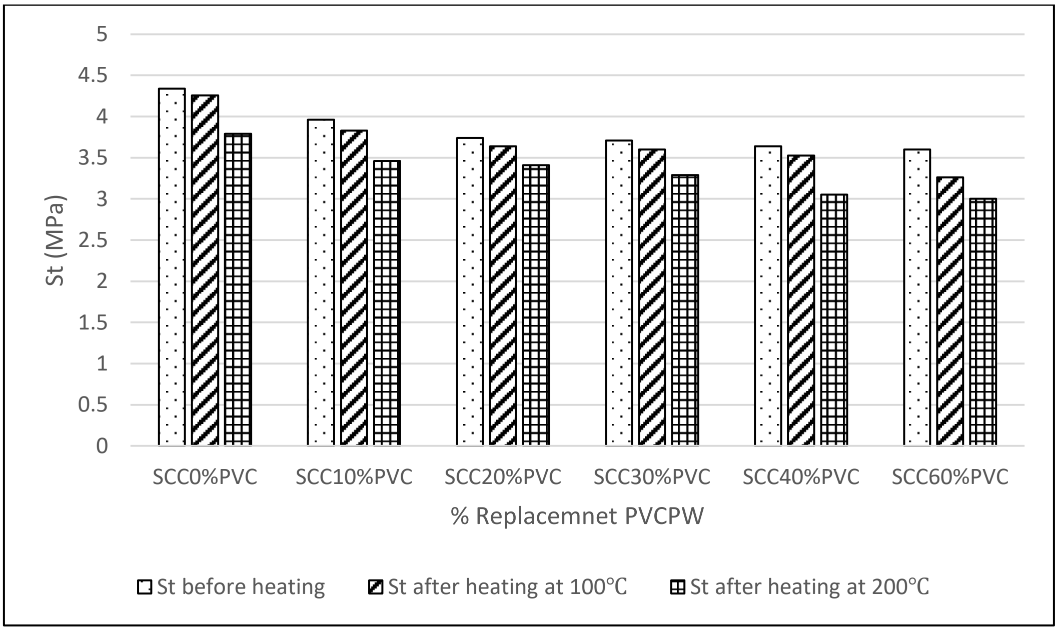


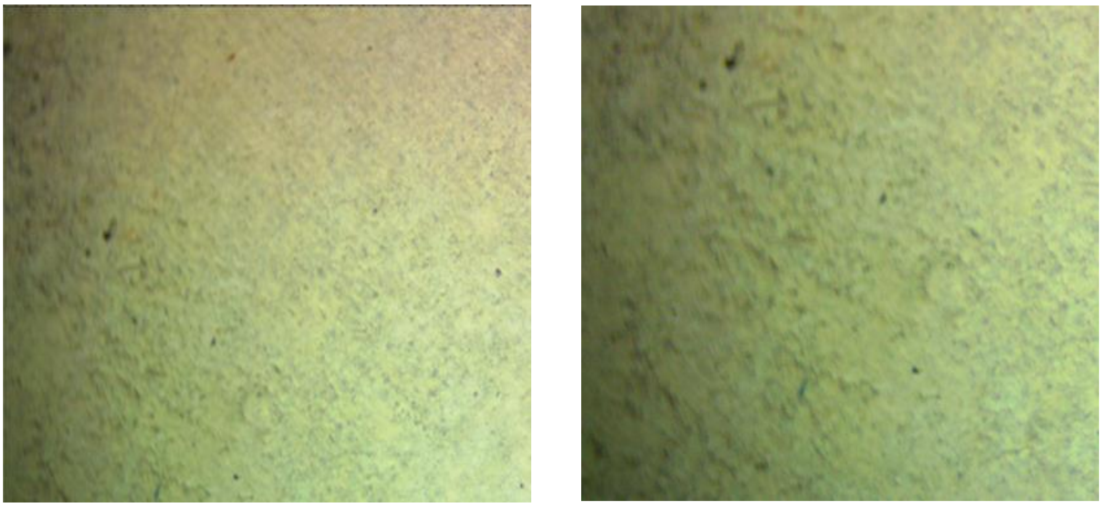
Figure 4.14: $S_t$ before and after Heating 100 and 200 ℃

### 4.8.5 Effect of Degradation Test against Heating on Surface Cracks of Specimens

After the specimens were exposed to heat temperatures, cracks appeared on the surface of specimens from evaporating water and melting of plastic inside the concrete. This process led to an increase in interior stresses and changed the form of the specimens, consequently resulting in the presence of cracks. During the tests, visible cracks appeared on the specimens when temperatures increased to 100 ℃ and 200 ℃ as is shown in Figure 4.15. The increased loss of moisture at 200 ℃ resulted in the presence of more extreme cracking in terms of number and size of cracks when compared to cubes exposed to 100 ℃.  The diameter of the cracks increased with the temperature and percentage of plastic waste content. As such, it is clear that there is a relationship between the increased temperature and plastic content, and the cracks. The diameter of the specimens' cracks increase from 0.27 mm at 10 % PVC to 0.42 mm at 6 0% PVC after heating at a 100 ℃, with the diameter of the cracks increasing after heating at 200 ℃ from 0.58 mm at 10 % PVC to 0.98 mm at 60 % PVC as shown in Table 4.9. There was an absence of cracks on the surfaces of the specimens made from the control mixes.

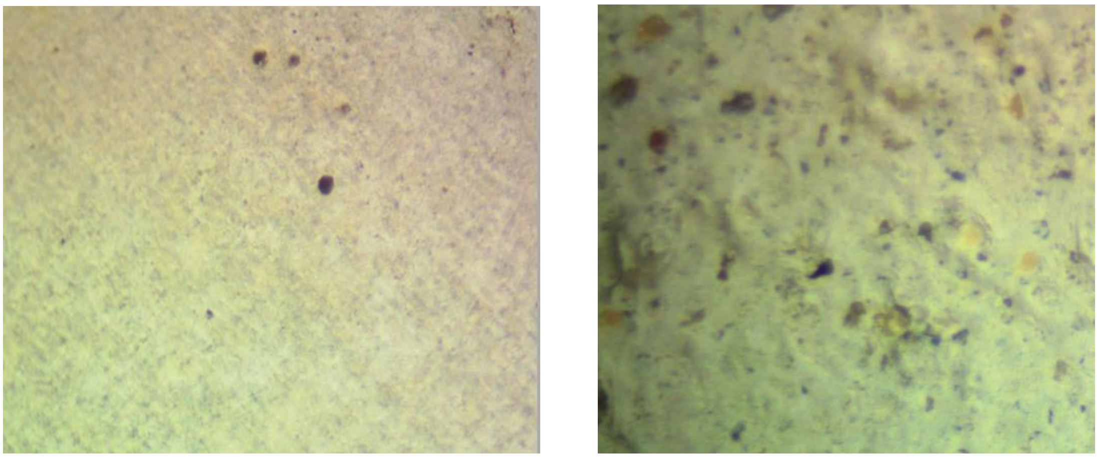
Table 4.11: Effect of Heat Temperature on Surface Cracks of Specimens

| mix | Cracks (mm) Before heating | Cracks (mm) After heating 100℃ | Cracks (mm) after heating 200℃ |
|---|---|---|---|
| SCC00PVC | No crack | 0.00 | 0.00 |
| SCC10PVC | No crack | 0.27 | 0.58 |
| SCC20PVC | No crack | 0.28 | 0.68 |
| SCC30PVC | No crack | 0.33 | 0.76 |
| SCC40PVC | No crack | 0.42 | 0.92 |
| SCC60PVC | No crack | 0.42 | 0.98 |



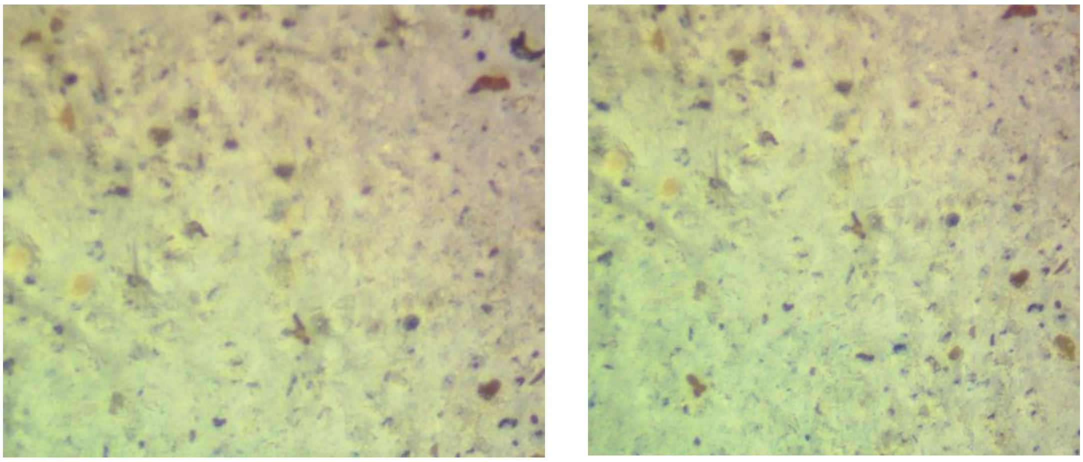
A) 0%PVC BEFORE HEATING

B) 10%PVC BEFORE HEATING



C) 20%PVC BEFORE HEATING

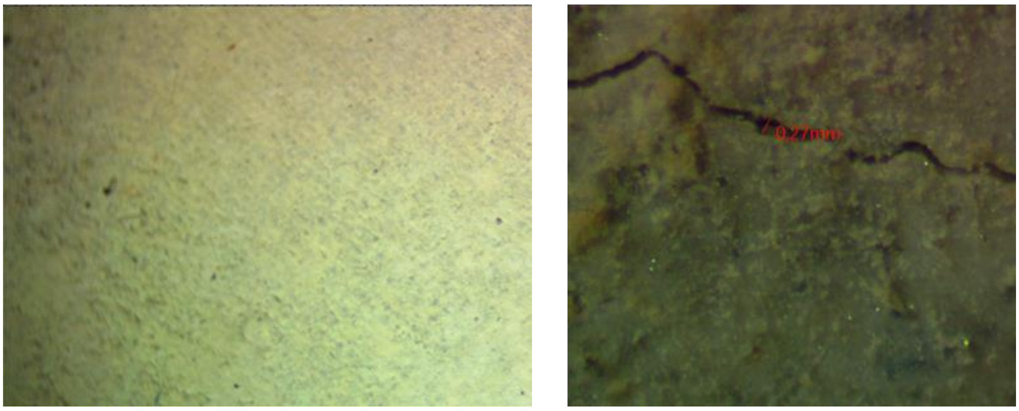
D) 30%PVC BEFORE HEATING



E) 40%PVC BEFORE HEATIG

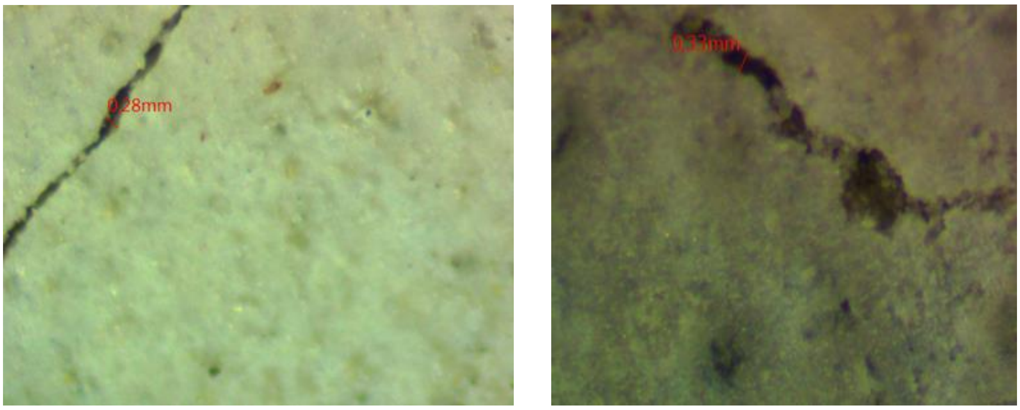
F) 60%PVC BEFORE HEATING

Figure 4.15: Craks before Heatin



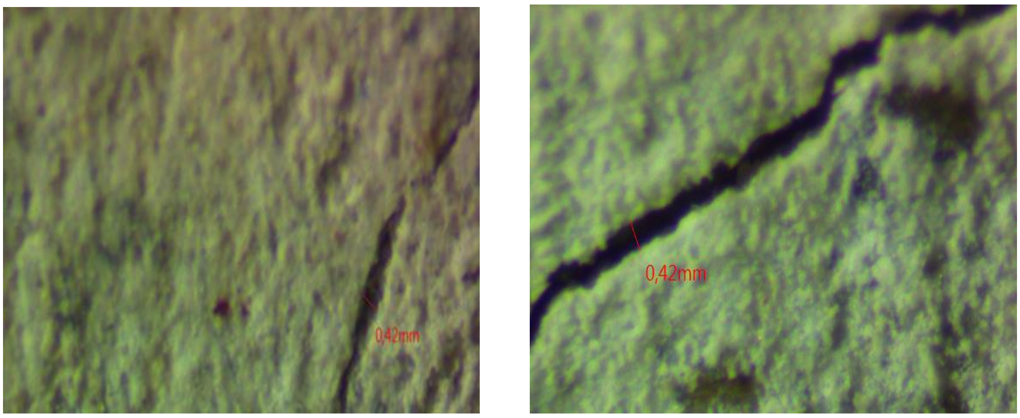
A) 0%PVC AFTER 100°C

B) 10%PVC AFTER100°C



C) 20%PVC AFTER 100°C

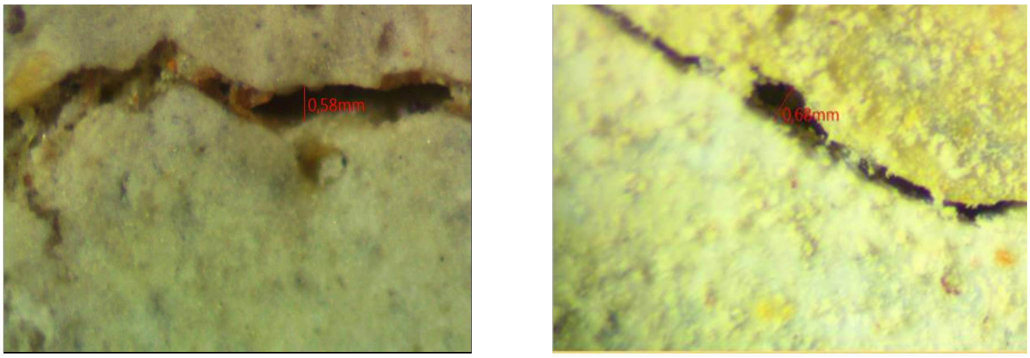
D) 30%PVC AFTER 100°C



E) 40%PVC AFTER 100°C

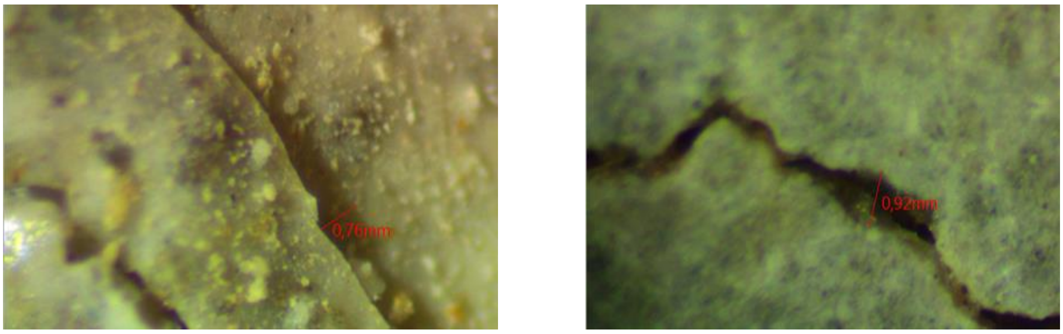
F) 60%PVC AFTER 100°C

Figure 4.16: Craks after Heating at 100°C



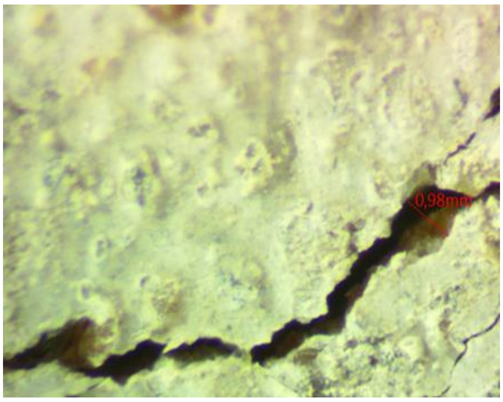
A) 10%PVC AFTER 200°C

B) 20%PVC AFTER 200°C



C) 30%PVC AFTER 200°C

D) 40%PVC AFTER 200°C



E) 60%PVC AFTER 200°C

Figure 4.17: Craks after Heating at 200°C

# Chapter 5

# CONCLUSIONS AND RECOMMENDATION

## 5.1 CONCLUSIONS

The main objective of this study has been to investigate the use of six different ratios of natural aggregate replacement with plastic PVC in concrete, and the creation of self-compacting concrete. These six different replacement ratios 0, 10, 20, 30, 40 and 60 % were selected and tested while the 0 % replacement of the aggregate with plastic PVC was used as a control.

The study involved tests of mix workability, compressive strength, splitting tensile strength, ultrasound pulse velocity and weight before and after degradation, in addition to a flexural strength test.

- The presence of PVC granules in the mixture improved the workability and achieved self-compacting concrete up until a 60 % replacement. As such, PVC plastic waste can be used up until 60 % aggregate replacement when making SCC.
- The compressive strength and splitting tensile strength were reduced by the use of PVC plastic replacement in all proportions before and after heating.
- While the flexural strength decreased by -19.17 % as the PVC aggregate content increased from 0 % to 60 % in the mixes, there was no significant decrease in the flexural, and no ductility.

  - The weight of the specimens reduces with increases in the PVC plastics waste, and also reduces after the two heatings at 100 and 200℃.
  - The velocity was 4.82 Km/s. This velocity decreased in the replacement at 10, 20, 30, 40 and 60 % of plastic waste from 4.82 Km/s to 4 Km/s. Moreover, the result shows an affected reduction also with increasing temperature at 100 and 200 ℃.
- There is a reduction in strength during the replacement of natural aggregate with plastic aggregate waste PVC. This reduction in strength was caused by the presence of cracks on the concrete surface, which increased during heating at 100 and 200 ℃. Additionally, when the temperature heating is increased, the number and diameter of the cracks also increased.

## 5.2 RECOMMENDATION

Research the combined effect of waste PVC particles as a partial replacement with sand, and the glass powder as a partial replacement with cement on the physical, mechanical and rheological properties of concrete.

The influence of using waste PVC particles on the mechanical behavior of fiber reinforced concrete.

# REFERENCES

Abdullahi, M. (2012). Effect of aggregate type on compressive strength of concrete. *International Journal of Civil and structural engineering*, 2(3), 782.

Adaway, M., & Wang, Y. (2015). Recycled glass as a partial replacement for fine aggregate in structural concrete–Effects on compressive strength. *Electronic Journal of Structural Engineering*, 14(1), 116-122.

Albano, C., Camacho, N., Hernandez, M., Matheus, A., & Gutierrez, A. (2009). Influence of content and particle size of waste pet bottles on concrete behavior at different w/c ratios. *Waste Management*, 29(10), 2707-2716.

Arioz, O. (2007). Effects of elevated temperatures on properties of concrete. *Fire Safety Journal*, 42(8), 516–522.

Behnood, A., & Ziari, H. (2008). Effects of silica fume addition and water to cement ratio on the properties of high-strength concrete after exposure to high temperatures. *Cement & Concrete Composites*, 30(2), 106–112.

Brown, K., Holland, M., Boyd, R., Thresh, S., Jones, H., & Ogilvie, S. (2000). Economic evaluation of PVC waste management: A report produced for the European Commission Environment Directorate. *Retrieved September, 24*, 2007.

Chen, L. J., Jun, H. E., Chao, J. Q., & Qin, B. D. (2009). Swelling and breaking characteristics of limestone under high temperatures. *Mining Science and Technology (China)*, 19(4), 503-507.

Dali, J. S., & Tande, S. N. (2012, August). Performance of concrete containing mineral admixtures subjected to high temperature. *In 37th Conference on Our World in Concrete and Structures, Singapore, August*.

Elkhadiri, I., Palacios, M., & Puertas, F. (2009). Effect of curing temperature on cement hydration. *Ceram Silik*, 53(2), 65-75.

EN12390, B. S. (2009). Testing hardened concrete, part 3: compressive strength of test specimens. *British Standard, Brussels, Belgium*, 1-22.

Foti, D. (2011). Preliminary analysis of concrete reinforced with waste bottles PET fibers. *Construction and building materials*, 25(4), 1906-1915.

Hachani, M. I., Kriker, A., & Seghiri, M. (2017). Experimental study and comparison between the use of natural and artificial coarse aggregate in concrete mixture. *Energy Procedia*, 119, 182-191.

Haghighatnejad, N., Mousavi, S. Y., Khaleghi, S. J., Tabarsa, A., & Yousefi, S. (2016).Properties of recycled PVC aggregate concrete under different curing conditions. *Construction and Building Materials*, 126, 943-950.

Haghighatnejad, N., Mousavi, S. Y., Khaleghi, S. J., Tabarsa, A., & Yousefi, S. (2016). Properties of recycled PVC aggregate concrete under different curing conditions. *Construction and Building Materials*, 126, 943-950.

Ismail Z.Z., AL-Hashmi E.A., Use of waste plastic in concrete mixture as aggregate replacement”, *Waste Management* 28 (2008) 2041–2047.

Ismail, Z. Z., & Al-Hashmi, E. A. (2008). Use of waste plastic in concrete mixture as aggregate replacement. *Waste Management*, *28*(11), 2041-2047

Kou, S. C., & Poon, C. S. (2009). Properties of self-compacting concrete prepared with recycled glass aggregate. *Cement and Concrete Composites*, 31(2), 107-113.

Kou, S. C., Lee, G., Poon, C. S., & Lai, W. L. (2009). Properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes. *Waste Management*, 29(2), 621-628.

Kozul, R., & Darwin, D. (1997). *Effects of Aggregate type, size, and content on concrete strength and Fracture Energy*. University of Kansas Center for Research, Inc..

Li, Z. (2011). *Advanced concrete technology*. John Wiley & Sons.

Madandoust, R., & Mousavi, S. Y. (2012). Fresh and hardened properties of self-compacting concrete containing metakaolin. *Construction and building materials*, 35, 752-760.

MALAK, K. R. (2015). Use of waste plastic in concrete mixture as aggregate replacement. *International Journal of Engineering, Education And Technology (ARDIJEET)*, *3*(2).

Mors, R., & Jonkers, H. (2017). Effect on Concrete Surface Water Absorption upon Addition of Lactate Derived Agent. *Coatings*, 7(4), 51.

Neville, A. M. (1995). *Properties of concrete* (Vol. 4). London: Longman.

Neville, A. M., & Brooks, J. J. (1987). *Concrete technology*. London: Pearson.

Park, S. B., Lee, B. C., & Kim, J. H. (2004). Studies on mechanical properties of concrete containing waste glass aggregate. *Cement and concrete research*, *34*(12), 2181-2189.

Roy, D. K. S., & Sil, A. (2012). Effect of partial replacement of cement by silica fume on hardened concrete. *International Journal of Emerging Technology and Advanced Engineering*, ISSN, 2250-2459.

Saha, A. K., & Sarker, P. K. (2016). Expansion due to alkali-silica reaction of ferronickel slag fine aggregate in OPC and blended cement mortars. *Construction and Building Materials*, 123, 135-142.

Sahmaran, M., Yurtseven, A., & Yaman, I. O. (2005). Workability of hybrid fiber reinforced self-compacting concrete. *Building and Environment*, 40(12), 1672-1677.

Saikia, N., & de Brito, J. (2012). Use of plastic waste as aggregate in cement mortar and concrete preparation: A review. *Construction and Building Materials, 34*, 385-401.

Sakr, K., & El-Hakim, E. (2005). Effect of high temperature or fire on heavy weight concrete properties. *Cement and Concrete Research*, 35(3), 590–596.

Sanjuan, M. A., Argiz, C., Gálvez, J. C., & Moragues, A. (2015). Effect of silica fume fineness on the improvement of Portland cement strength performance. *Construction and Building Materials*, 96, 55-64.

Sato, S., Nonaka, T., Ogata, H., & Hattori, K. (2004). Investigation on alkali-silica reaction utilizing waste glass in concrete and suppression effect by natural zeolite.

Senhadji, Y., Escadeillas, G., Benosman, A. S., Mouli, M., Khelafi, H., & Ould Kaci, S. (2015). Effect of incorporating PVC waste as aggregate on the physical, mechanical, and chloride ion penetration behavior of concrete. *Journal of Adhesion Science and Technology*, 29(7), 625-640.

Siddique, R., Khatib, J., & Kaur, I. (2008). Use of recycled plastic in concrete: a review. *Waste management*, 28(10), 1835-1852.

Srivastava, V, Gautam, S. P., Agarwal, V. C., & Mehta, P. K. (2014). Glass Wastes as Coarse Aggregate in Concrete. *J. Environ. Nanotechnol*, *3*(1), 67-71.

Thakur, J., & Kumar, N. (2011). DES, AES and Blowfish: Symmetric key cryptography algorithms simulation based performance analysis. *International journal of emerging technology and advanced engineering*, 1(2), 6-12.

Topcu, Ilker Bekir, Turhan Bilir, and Tayfun Uygunoğlu. "Effect of waste marble dust content as filler on properties of self-compacting concrete." *Construction and Building Materials* 23.5 (2009): 1947-1953.

Vilane, B. R. T., & Sabelo, N. (2016). The Effect of Aggregate Size on the Compressive Strength of Concrete. *Journal of Agricultural Science and Engineering*, *2*(6), 66-69.

Yap, S. P., Alengaram, U. J., & Jumaat, M. Z. (2013). Enhancement of mechanical properties in polypropylene–and nylon–fibre reinforced oil palm shell concrete. *Materials & Design*, 49, 1034-1041.

Yap, S. P., Alengaram, U. J., & Jumaat, M. Z. (2013). Enhancement of mechanical properties in polypropylene–and nylon–fibre reinforced oil palm shell concrete. *Materials & Design*, 49, 1034-1041.

Zhang, H. (Ed.). (2011). *Building materials in civil engineering*. Elsevier.

Zhang, W., Qian, H., Sun, Q., & Chen, Y. (2015). Experimental study of the effect of high temperature on primary wave velocity and microstructure of limestone. *Environmental Earth Sciences,* 74(7), 5739–5748.

Zhu, W., & Gibbs, J. C. (2005). Use of different limestone and chalk powders in self-compacting concrete. *Cement and Concrete Research, 35*(8), 1457-1462.