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Eco-Efficient Preplaced Recycled Aggregate Concrete Incorporating Recycled Tire Waste Rubber Granules and Steel Wire Fibre Reinforcement

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ABSTRACT

With increasing world population and urbanization, the depletion of natural resources and generation of waste materials is becoming a considerable challenge. As the number of humans has exceeded 7 billion people, there are about 1.1 billion vehicles on the road, with 1.7 billion new tires produced and over 1 billion waste tires generated each year. In the USA, it was estimated in 2011 that 10% of scrap tires was being recycled into new products, and over 50% is being used for energy recovery, while the rest is being discarded into landfills or disposed. The proportion of tires disposed worldwide into landfills was estimated at 25% of the total number of waste tires, which represents fire hazards and grounds for breeding of disease carrying mosquitoes. Moreover, waste generated during construction and demolition in the United States in 2014 was about 353.6 million tons. This is expected to increase worldwide with ageing civil infrastructure. Recycling tire rubber and demolition concrete as recycled concrete aggregate (RCA) poses technological challenges. Tire rubber tends to float during concrete mixing and placing due to its lower density, while RCA tends to absorb mixing water, causing loss of workability and shrinkage stresses.

In the present study, tire rubber and tire steel-wire along with RCA can be preplaced in the formwork, eliminating the problems above. Subsequently, a flowing grout is injected to fill inter-granular voids. This preplaced aggregate concrete (PAC) offers multiple sustainability advantages. It incorporates about 50% more coarse aggregate than normal concrete, thus reducing the demand for cement and the associated greenhouse gas emissions from cement production. The dense granular skeleton of PAC has a unique stress transfer mechanism, which better resists shrinkage and thermal contraction stresses due to the physical contact between granular particles. Moreover, the mixing and pumping energy of concrete and the associated labour are greatly reduced since only the smaller grout fraction is mixed and injected.

In this experimental study, 21 eco-efficient preplaced aggregate concrete mixtures were made with recycled concrete aggregate, along with 10%, 20%, 30%, 40% and 50% of scrap tire rubber, and 0%, 0.25%, 0.5% and 1.0% of tire steel-wire fibre. The mechanical properties of specimens from each mixture were explored, including compressive, tensile and flexural strengths, elastic modulus, post-crack behaviour, and impact resistance. While tire rubber decreased the mechanical strength and elastic modulus, combined tire rubber and steel-wire fibres provided the preplaced aggregate concrete with superior post-crack behaviour, higher toughness and better impact resistance. The Weibull distribution was found to be an effective tool for predicting the impact resistance of PAC mixtures. It is believed that the proposed sustainable technology of preplaced recycled aggregate concrete incorporating recycled tire rubber and tire steel-wire fibres can offer an eco-efficient construction procedure for pavements, sidewalks, road barriers, and other non-structural concrete. Further refinements, including the use of effective supplementary cementitious materials or geo-polymer grout can further enhance the mechanical strength and overall eco-efficiency of this technology.

Key Words

Preplaced aggregate concrete; recycled concrete aggregate; two stage concrete; sustainability; natural aggregate; recycling; tire rubbers; steel-wire; cement; grout; flowability; mechanical properties; dynamic; impact resistance; ductility; toughness; sustainability; eco-efficient; construction.

CO-AUTHORSHIP STATEMENT

This thesis was prepared according to the integrated-article layout designated by the Faculty of Graduate Studies at Western University, London, Ontario, Canada. All the work stated in this thesis including experimental testing, data analysis, statistical modeling, and writing draft manuscripts for publication was carried out by the candidate under the supervision and guidance of Dr. M.L. Nehdi. Any other co-author (if applicable) assisted in conducting the experimental program and/ or revision of the initial draft of the manuscript. The following publications have been submitted for publication to peer-reviewed technical journals:

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DEDICATION

This Thesis is dedicated to:

My Father: Abdulwahab Alfayez and My Mother: Salwa Alohali
For their prayers, sacrifices and encouragements. My past, present and future accomplishments belong to them.

My Sister: Athary
For the years she taught me Math and Science, and for being a great company during our scholarship programs, I wish her all the best in her Astronomy & Astrophysics post graduate studies.

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For their support and being always wonderful brothers, I wish them all the best in their futures.

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May their souls rest in eternal peace.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

ACI	American concrete institute
ASTM	American society for testing and materials
ANOVA	Analysis of Variance
a	Parameter dependent of the mixture fluidity
b	Average width of a specimen at fracture (mm)
c	Parameter dependent of efficiency of flushing pipe (m^3/min)
C_3A	Tri-calcium aluminate
$CaCo_3$	Calcium carbonate
C_4AF	Tetra calcium alumino-ferrite
CaO	Calcium oxide
C_3S	Tricalcium silicate
C_2S	Dicalcium silicate
d	Diameter of the PAC/TSC cylinder (mm)
E	Modulus of elasticity of PAC/TSC (GPa)
e	Parameter dependent of the type of excavation bottom
$\mathcal{E}$	Strain
ε_2	Longitudinal strain produced by S_2
$\mathcal{E}_2$	Longitudinal strain produced by stress Q_2
ECCO	Environmental Council of Concrete Organizations
f	A constant with a value of 9.806 x 10^{-3}
$f'c$	Compressive strength of PAC/TSC (MPa)
f_t	Tensile strength of PAC/TSC (MPa)
Fo	Distribution density function
$f(n)$	Weibull distribution function
$FN(n)$	Cumulative distribution function
GGBFS	Ground granulated blast furnace slag
GPa	Giga-Pascal
h	Falling height of the steel mass in (mm)

HRWRA	High range water reducer admixtures
i	Failure order number
IE	Sustained impact energy in Joule
I_5	Toughness index at $3\delta_1$
I_{10}	Toughness index at $5.5\delta_1$
I_{20}	Toughness index at $10.5\delta_1$
I_{30}	Toughness index at $15.5\delta_1$
kN	kilo-Newton
L	Span length (mm)
l	Length of the PAC/TSC cylinder (mm)
LN	Probability of survivorship function
MPa	Mega-Pascal
MSE	Mean square due to error
$MS_{Treatment}$	Mean square due to treatments
N	Total number of observations
n	Specific value of a random variable N
Ni	Number of blows
$N1$	Number of impacts to induce first visible crack
$N2$	Number of impacts to induce first visible failure
OPC	Ordinary Portland cement
P	Maximum applied load in Newton
PAC	Preplaced aggregate concrete
Q_2	Stress corresponding to 40% of the ultimate compressive load (MPa)
$Q1$	Stress corresponding to a longitudinal strain ε_1 of 50 millionths (MPa)
R	Modulus of rupture (MPa)
R_2	Coefficient of determination
R_{5-10}	Residual strength factors for deflection interval ($3\delta_1$- $5.5\delta_1$)
R_{10-20}	Residual strength factors for deflection interval ($5.5\delta_1$- $10.5\delta_1$)
R_{20-30}	Residual strength factors for deflection interval ($10.5\delta_1$- $15.5\delta_1$)
RCA	Recycled concrete aggregate

S	Rate of shrinkage depending on the relative humidity of the ambient atmosphere
St	Shrinkage after time of drying (t)
$\mathcal{S}o$	Final shrinkage in relation to the percentage of cement paste in the concrete
S_2	Stress corresponding to 40% of the ultimate load of the concrete
S_1	Stress corresponding to a longitudinal strain of ε_1 at 50 millionths
SS	Micro-silica sand
SSE	Sum of squares due to error
SST	Total corrected sum of squares
SSTreatments	Sum of squares due to reinforcing the specimens
s/b	Sand-to-binder ratio
s/c	Sand-to-cement ratio
SiO_2	Silicon dioxide
SCMs	Supplementary cementitious materials
T	Splitting tensile strength in MPa
TSC	Two-stage concrete
u	Scale parameter
w	Mass of the steel hammer in kg
w/b	Water-to-binder ratio
w/c	Water-to-cement ratio
yij	jth observations taken under factor level of treatment i
µm	Micrometer
ρ	Percentage of cement paste in the concrete
σ	Stress
δ_1	Deflection at the first crack
δ_2	Deflection at the peak load
α	Shape parameter
α_1	Significance level

Chapter 1

1. RUBBERIZED AND STEEL-WIRE FIBRE-REINFORCED PREPLACED RECYCLED AGGREGATE CONCRETE

1.1. INTRODUCTION

The dramatic worldwide increase in waste tire stockpiles is a subject of major environmental concern. It has led to initiating substantial research on sustainable approaches to valorize such huge amounts of discarded tire wastes in various applications. Recycling wasted tire rubber and steel-wire cord components in construction applications can be implemented in green construction technology with potential applications in pavements, sidewalks, and many other non-structural concrete infrastructures.

Several studies have been conducted to create alternative and ecofriendly methods to recycle tire-rubber wastes. The unique properties of rubber make it a promising material that could be used in construction. Its various applications in the civil engineering realm are increasingly being explored. In particular, the application of using tire rubber as an aggregate and tire steel-wire as fibre reinforcement in concrete is promising. Rubber is considered a high strain capacity material that could help improve the ductility of concrete and prevent the initiation and propagation of micro-cracks (e.g. Turatsinze *et al*., 2005; Topcu, 1995). However, higher rubber content can compromise the compressive strength and workability of concrete (Taha *et al*., 2008).

The utilization of waste tire steel-wire fibers can significantly improve the tensile strength of concrete (e.g. Altun and Aktas, 2013; Mohammadi *et al*., 2008), as well as inhibit micro-crack formation and growth (Aslani 2013; Naghibdehi *et al*., 2014). Furthermore, waste tire steel-wire fibers have higher strength and stiffness when compared to waste tire chips or crumb rubber (Li *et al*., 2004; Neocleous, *et al*., 2006; Ghailan 2005). Steel fibre-reinforced concrete typically displays higher toughness and enhanced post-crack behavior when compared to normal concrete. Thus, recycled steel-wire fibers could impart similar benefits.

Using recycled tire rubber and steel-wire in preplaced aggregate concrete (PAC), also known as two-stage concrete, is of particular interest (Najjar et al., 2016). The PAC technique produces a different form of concrete than conventional concrete. It consists of preplacing a higher amount of coarse aggregate in the formwork, which is closely in contact with one another, hence the alternative name, “skeleton concrete” (Abdelgader, 1996). The aggregate skeleton is then injected with a highly flowable grout to fill inter-granular voids.

The mechanical properties of preplaced, aggregate concrete are affected by the properties of the preplaced aggregates and the grout used (Abdul Awad, 1988; Abdelgader, 1999). The mechanism of resisting external loads by PAC is different from that of conventional concrete. In the latter, the entire concrete matrix resists the load. In preplaced aggregate concrete, the aggregate absorbs and transfers the stress throughout its contact points and gets bonded to the cementitious matrix (Nowek *et al*., 2007). Additional advantages of this functioning characteristic of preplaced aggregate concrete include the following: less shrinkage strain and cracking, better resistance to thermal contraction, possibility to produce enhanced mechanical and durability performance, and resistance to harsh exposure conditions (Abdelgader *et al*., 2015). However, substantial research needs to be conducted on the PAC technology in order to capture the emerging techniques that can make the process more sustainable, while deploying advances in concrete technology in PAC design and production (Abdelgader and Gorski, 2003).

1.2. RESEARCH OBJECTIVES

The primary objectives of this thesis are to develop eco-efficient preplaced recycled aggregate concrete including scrap tire granules and steel wire fibres with precise focus on sustainable pavement and sidewalk construction. The specifics objectives include:

1) Elevating the awareness on the negative environmental impact of disposing tire waste and the potential of valorizing it in construction engineering applications.
2) Introducing green concrete technology having superior ability to use large volumes of recycled concrete aggregate (from demolition waste) and recycled tire waste.
3) Exploring key engineering properties of the eco-efficient concrete produced in order to motivate the construction industry to implement it, while having confidence in its mechanical strength and durability.

4) Making such concrete highly eco-efficient, not only in terms of its very high recycled content, but also via achieving substantial gains in reducing the energy and labour required for its production.
5) Deploying statistical tools, such as analysis of variance (ANOVA) and Weibull distribution to predict key engineering properties of this material.

1.3. THESIS OUTLINE

This thesis has been created based on the integrated article format and established through the thesis command guide of Western University's School of Graduate and Postdoctoral Studies. The thesis consists of five core chapters representing its rationale and findings.

Chapter 1 presents a concise introduction of the study, while delivering the main objectives of conducting this research.

Chapter 2 exhibits an overview of literature on the existing evidence and rationale of the study, emphasizing global and environmental concerns that led to the recent research motivations. The need for introducing tire waste materials in various Portland cement concrete applications, as part of sustainable and green project goals is described by displaying its effects on concrete properties and reviewing positive and negative outcomes of using recycled coarse aggregates and recycled tire waste combinations in concrete manufacturing. This chapter also highlights the PAC mixture proportions and its effects on the overall PAC functioning.

Chapter 3 provides a detailed description of the investigated preplaced aggregate concrete and its mixture proportioning with specific volume fractions of recycled granulated tire rubber particles and steel-wire cord dispersed within a recycled concrete aggregate skeleton. The chapter describes the mixing of grout, casting of specimens, curing procedure, test methods used, collected test data, and mechanical strength performance of test specimens.

Chapter 4 explores the dynamic properties of specimens from the produced eco-efficient concrete through conducting an experimental impact resistance test using a standard drop weight method, while evaluating failure mechanisms. The beneficial effects of recycled steel-wire fibre on the impact behavior of rubberized and non-rubberized TSC specimens are also discussed. The chapter captures statistical analysis of variance (ANOVA) and Weibull distribution function of the impact test data in order to statistically analyze the results and possibly develop statistical predictive tools of impact test results.

Chapter 5 summarizes the findings of the study, advocates specific recommendations, and discusses the need for future research.

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Chapter 2

2. OVERVIEW ON SUSTAINABLE DEVELOPMENT OF PREPLACED AGGREGATE CONCRETE TECHNOLOGY CONTAINING RECYCLED TIRE WASTE

2.1. Background

The dramatic increase in tire waste stockpiles worldwide has caused substantial environmental damage and harmful impacts on human health and natural resources. Since landfilling and burning of tire releases potentially hazardous substances from these tires, the soil and groundwater can become polluted (Thomas and Gupta 2015; Gesoglu and Güneyisi,2011; Yung *et al*., 2013; Eldin and Senouci,1994). This negative outcome accelerates the need for inventing efficient methods for discarding tire waste, such as recycling and utilizing it in concrete construction, geotechnical works, pavements, and marine reef projects (Segre and Joekes, 2000), instead of disposing it in landfills. The outcome of the incorporation of recycled tire rubber particles in concrete has shown some promising features. These include the ability to provide sound, heat, and waterproofing insulation, benefiting various construction and building applications.

In addition, the performance of rubberized concrete can be improved significantly in terms of its toughness, brittleness, crack resistance, deformation, energy absorption capacity, and freeze-thaw resistance as compared to that of conventional concrete. In addition to rubber waste, the inclusion of recycled steel fibers obtained from steel-wire cords of tires can enhance concrete toughness, tensile and flexure strength, thus delaying cracks and better resisting failure. Of particular interest is integrating these waste materials into concrete constituents using the preplaced aggregate concrete technique. The PAC technique can also use recycled concrete aggregate (demolition concrete turned into aggregates), thus expanding on the innovation of green concrete technology with better physical and mechanical properties, while having positive environmental footprint, and cost-efficient engineering impacts.

2.2. Problem Context

The rapid development of the automobile production and transportation industries increased tire consumption, resulting in a massive amount of tire waste needing to be discarded annually. By 2030, the total number of discarded tires annually in the world is expected to reach 1.2 billion tires (Al-Mutairi *et al*., 2010). In the last 20 years, many developed countries with large population have issued several governmental policies that aim to reprocess landfilling treatments due to the tire landfill sites being hazardous to human health as well as to the environmental with negative economic impacts. Disposing used tires in landfills is no longer acceptable, as the number of available landfill sites is becoming limited. Consequently, recycling scrap tires in a safe way that guarantees no negative impact on the environment has also been a challenge. The complexity of rubber chemical composition delays its degradation process, causing harm to natural resources surrounding the landfills and tire fires that could damage neighboring facilities (Fadiel *et al*., 2011).

As reported by many studies, the worldwide production of waste tires is nearly 1 billion tons. This makes recycling tire wastes extremely necessary. The same studies show that the United States and Japan have almost 290 and 110 million waste tire rings, respectively. The study also illustrated that 30% of waste tires in Canada and the US were transferred to landfill sanitary centers, which causes environmental and health issues due to possible fires and infestation with mosquitos and rats (Shafabakhsh *et al*., 2014). India has been experiencing a huge environmental and social crisis as a result of the rapid growth of waste materials disposed into the air, water, and the ground from industrial sources such as power houses, colliery pits and demolition. Also, the government of India has been working on green concepts to reuse waste materials. For example, the use of such materials has doubled the production of cement. These materials are used in the construction of road pavements, aggregate production, and as fillers in concrete (Kolisetty and Chore, 2013).

The European Union reacted to the environmental crisis regarding tire stockpiles by banning the landfilling of whole tires in July 2003. They also banned shredded tires in July 2006 (Evans and Evans, 2006). The government of China also developed a green plan, “Twelfth Five-Year Plan”, directed at the construction industry. The policy was based on reusing the recycled rubber as solid waste, as part of the Chinese building evaluation standard, in order to protect the environment by reducing pollution (Lijuan *et al*., 2014). With the help of this policy, tire waste rubbers were used in asphaltic concrete mixes and road construction as a fill material (Eldin and Senouci, 1992; McQuillen *et al*., 1988).

The civil engineering research field has found that the recycling process and inclusion of tire waste, including rubber particles and steel fibres, is suitable and can be an efficient part of green concrete production. This process has promising environmental and economical benefits as it reduces natural resource consumption and the cost of construction. Tire rubber waste can also be recycled as a waterproofing and insulation material. Concrete is considered as the most useful construction material, although it has some limitations in its mechanical and physical properties, which are related to hardening and curing, low tensile strength, ductility, energy absorption, high shrinkage, and cracking. In this regard, several studies have highlighted the use of recycled tire rubber in the improvement of some of these weak characteristics of concrete (Wang *et al*., 2000). However, incorporating these materials in construction requires rigorous studies of both the materials' intrinsic and extrinsic properties, in order to achieve safe and optimal use. The use of crumb rubber as a modified material, such as in asphalt, has been investigated in many studies and is implicated in increasing pavement life, reducing maintenance cost, traffic noise and environmental pollution (Shafabakhsh *et al*., 2014).

2.3. Tire Waste Incorporation Objectives

Reusing and recycling waste materials provide protection for the environment, while reducing the cost of the projects and creating additional jobs in various industries. The reuse of waste materials can be applied to residential and industrial sectors where the consumption of original construction materials is high. These sectors participate in providing a productive, efficient and sustainable future. The main aim of recycling waste materials is to reduce damage to the Earth's crust and green lands by relieving the waste load in disposal sites. The construction industry plays an important role in environmental protection by reusing recycled concrete stones and bricks in its projects. The reuse of waste materials can create innovative design by varying the resources and cost of materials used in construction to move toward a sustainable environment. This provides environmental protection from hazardous and solid waste products (Kolisetty and Chore, 2013).

Compared to conventional concrete, the properties of rubberized concrete are promising in terms of cost effectiveness, sound and thermal insulation, water absorption reduction, protection against acid, and resistance to load and temperature changes, as well as being efficient in impact and tensile strength. In addition, rubberized concrete has various uses in highway projects, as it has been found that adding rubber contents in concrete mixtures reduces plastic cracking and shrinkage, absorb sound and earthquake waves (Kumaran *et al*., 2008). Rubber-modified concrete has been widely used in various applications as major elements of buildings, such as in precast sidewalk panels, non-load bearing walls, and precast roofs for green buildings (Tomosawa *et al*., 2005). Furthermore, it can be used in developing roadways, recreational courts, pathways, and skid-resistance ramp projects (Kamil *et al*., 2005). In architectural applications, rubberized concrete can perform in low strength structures, such as nailing concrete and wall panels, while fixing the ground of railroads (Topcu, 1995). Furthermore, concrete with rubber content can replace normal concrete for its use in lightweight architectural units, such as lightweight concrete walls and building facades (Khatib and Bayomy, 1999). Rubberized concrete has a high resistance to harsh weather where it can be used in areas with occurrence of freezing and thawing cycles. It can also be placed in larger sheets than conventional concrete (Kumaran *et al*., 2008). When using a single slab of rubberized concrete in tennis courts for example, the courts no longer have section lines after the curing process. Rubberized concrete can also be involved in many lightweight structures, such as roofing tiles, and can be poured in airport runways, industrial floorings and in some structural elements (Kaloush *et al*., 2004).

Over the last 20 years, researchers have been rigorously exploring effective ways to recycle used tires. One such breakthrough is to crush these tires to achieve the rubber aggregates’ size, as well as use them and their steel fibres in cement-based materials and concrete (Garrick, 2005; Hernández *et al*., 2007; Khatib and Bayomy, 1999; Sukontasukkul and Chaikaew, 2006). Many studies conducted in the civil engineering field have explored the use of rubber aggregates as an important part in producing concrete to help avoid poor deformation capacity, while improving the tensile strength performance and the energy absorption capacity of the concrete (Ozbay *et al*., 2011). Furthermore, tire rubber particles play an important role in enhancing the deformation and energy absorption capacity of concrete (Eldin and Senouci, 1993; Khatip and Bayomy, 1999; Topcu, 1995). Many projects have been conducted in the civil engineering field to potentiate the sustainable use of environmentally-friendly raw materials and solid waste materials as an aggregate part of cement concrete (Shu and Baoshan, 2014). Accordingly, the use of tire rubber is being explored in different engineering applications such as geotechnical works, pavements, fuel for cement kilns, reefs in marine environments, and aggregates in cement-based products (Segre and Joekes, 2000). Using concrete with the addition of rubber material is advantageous in increasing skid resistance during freezing conditions, improving flexibility and crack resistance, while reducing traffic noise (Lijuan *et al*., 2014).

2.4. Environmental and Sustainability Motivation

Disposing waste tires can hardly be achieved because tires are not biodegradable, not to mention how burning them affects air quality, the soil and vegetation in that area. Huge amounts of water mixed with oil are often generated leading to pollution of soil and ground water; hence, developing an innovative and efficient plan for tire disposal is paramount. This green plan can include reusing tire rubber waste in asphalt concrete pavements, which eventually starts producing different types of plastic and rubber components, adding waste rubber materials as fuel for cement kilns, and using tire rings to create artificial reefs in marine environments (Fadiel *et al*., 2011). In addition, one of the possible solutions to recycling tire rubber and fibers is their use as an aggregate or filler in concrete components. This process is deemed to be environmentally and economically favorable, since it turns this waste into a valuable resource (Kumaran *et al*., 2008). Thus, using rubber concrete promises to reduce pollution and save natural resources that will lead to positive economic and social impacts (Liu *et al*., 2013).

2.5. Tire Waste Concrete Common Proportioning

2.5.1. Recycled Tire Waste Materials

Recycled tire rubber granules are obtained by shredding scrap tires in relation to the required particle sizes, terminologies (**Table 2.1a**) and properties (**Table 2.1b**), as recycled waste tire particles, defined by ASTM D-6270, has a standard practice for the use of scrap tires in civil engineering applications. The weight of these tires generally ranges from 9.071 kg to 45.359 kg (Siddique and Naik, 2004). Manufacturing tires requires major materials that include natural & synthetic rubber (14%), carbon black (28%), steel (14%-15%), fabric, filler, accelerators and antiozonants (16%-17%) (**Table 2.1c**). The major chemical composition of waste tire rubber consists of carbon black (29%) and additives (13%), as introduced in Error! Reference source not found., complex chemical mixtures including extender oil (1.9%), elastomers, polyisoprene, polybutadiene and styrene butadiene (Black and Shakoor, 1994; Benda, 1995). Different tires can have different intrinsic compositions. Automobile tires, for example, have a significantly different composition than truck tires. This difference is most significant in the contents of natural and synthetic rubber. In general, recycled rubber can be classified into the three following main categories:

(a) Shredded rubber, also known as chipped rubber, is used to partially replace gravel. Manufacturing this category requires the tire to be shredded in two stages. The first stage produces rubber with a length of 300-430 mm and a width of 100-230 mm. The second stage cuts the length to 100-150 mm. Shredded particles can be acquired by continuing the process of shredding, which leads to the production of rubber particles with a size around 13-76 mm.

(b) Crumb rubber has particles with a size of 0.425-4.75 mm and can be used to substitute the sand portion in concrete production. This type of rubber is produced by turning the big rubbers into smaller particles, where the variety of rubber particle size is mainly dependent on the mills used and the temperature level.

(c) Ground rubber particles are manufactured through the micro milling process, which produces a particle size that ranges from 0.075 to 0.475 mm. The size of equipment plays an important role in reducing the size of particles. The process is subjected to magnetic separation and screening. This type of recycled tire rubber can be used as a filler to partially replace cement in concrete production (Ganjian et al., 2008).

2.5.2. Ordinary Portland Cement

Ordinary Portland Cement (OPC) is generally produced by mixing and burning clay with limestone (Calcium Carbonate, $CaCO_3$) at a high temperature (1400-1450°C) in a kiln to separate carbon dioxide molecules from the calcium carbonate molecules and produce calcium oxide (CaO) or lime. This can be regarded as a part of the calcination process. Lime must be mixed with silicates (SiO_2) and various chemical compounds to produce a hard substance known as cement “clinker”.

Clinker is then ground with gypsum into a fine powdery material containing hydraulic calcium silicates to finally produce OPC. The production of different types of cement is almost similar; however, they are basically manufactured to meet several chemical and physical requirements (**Table 2.2**) for specific measures and applications with accordance to ASTM C150 (Standard Specification for Portland Cement). Cement type I with an approximate specific gravity and surface area of 3.15 g/cm^3 and 371 m^2/kg, respectively, has been commonly considered in most of the concrete research industry because it provides excellent durability and strength. The quality of cement binding refers to the chemical reaction between cement and water, also known as cement hydration. The process significantly controls the porosity of the cement paste and affects the strength of concrete. In fact, the hydration process begins with the mix of cement, water, and four cement chemical compositions that include tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetra calcium aluminoferrite (C_4AF). These chemical compositions intensify the mass and hydration stages by moderating the setting and gaining of strength properties of cement paste (Neville, 1996). Consequently, the strength of concrete reflects the bonding quality of the hydrated cement paste structures.

2.5.3. Silica Sand

Sand is considered as one of the purest natural fine aggregates among the concrete constituent materials (Orchard, 1979). Silica sand is made of silicon and oxygen, which happen to be the most available elements in the Earth's crust, given the chemical formula SiO_2. Silica consists of a high percentage of quartz grains, which is the second most common mineral on the Earth's surface. Hence, silica sand, commonly known as industrial sand, differs significantly from construction sand due to its high silica content of up to nearly 99.5% of SiO_2. These factors provide promising physical and chemical properties (**Table 2.3**) (British Geological Survey, 2009).The wide varieties of silica inclusions refer to its high durability, heat and chemical attack resistance that support its utilization in glass and ceramic industries (Kerai and Vaniya, 2015), not to mention its valuable incorporation in cement mortars. However, considering the physical characteristics, including grain size gradations as shown in **Table 2.4** and **Figure 2.1**, is such an important step to achieve industrial requirements. Ottawa silica sand's mining process began around the 1860s (US Silica) and is considered as one of the most useful types of sand in North America. The largest silica production plant is in Ottawa, Illinois, annually producing 2.2 million tons. Its soft round grains, low consolidation, high chemical resistance and consistency are factors of being considered in concrete production under ASTM C778 (standard specification for standard sand).

Table 2.1:Typical terminologies, properties and compositions of tire wastes

(a) Terminology for recycled waste tire particles referring to ASTM D-6270		
Classification	Lower Limit (mm)	Upper Limit (mm)
Chopped Tire	Unspecified dimensions	Unspecified dimensions
Rough Shred	50×50×50	762×50×100
Tire Derived Aggregate	12	305
Tire Shreds	50	305
Tire Chips	12	50
Granulated Rubber	0.425	12
Ground Rubber	-	<0.425
Powdered Rubber	-	<0.425

(b) Recycled tire materials Properties (Bdour and Al-Khalayleh,2010)			
Material	Tire chips (%)	Crumb rubber (%)	Steel cords (%)
Rubber volume	95-99	99-100	35-75
Steel volume	1.5-8	0	35-75
Density (g/cm^3)	0.8-1.6	0.7-1.1	1.5-3.9

(c) Essential compositions of tires (Rubber Manufacturers' Association, 2000)		
Composition weight (%)	Automobile Tire (wt%)	Truck Tire (wt%)
Natural Rubber	14	27
Synthetic Rubber	27	14
Carbon black	28	28
Steel	14-15	14-15
Fabric, Filler, Accelerator, and Antiozonants	16-17	16-17

(d) Chemical compositions of waste tire rubber (Bekhiti et al.,2014)	
Material	Mass Percentage (%)
Rubber	54
Textile	2
Carbon black	29
Oxidize zinc	1
Sulfur	1
Additive	13

Table 2.2: Chemical composition and physical properties of OPC (ASTM C150)

Compounds (%)	Formula	Short form	Cement (% Wt)	Main compounds (Borgue's equation)	Short form	%Wt	Function
Lime	CaO (Calcium oxide)	C	64.35	Tricalcium silicate	C_3S	63.5	Initial set and early strength gain
Silica	SiO_2 (Silicon dioxide)	S	20.08				
Alumina	Al_2O_3 (Aluminum oxide)	A	4.63	Dicalcium silicate	C_2S	8.92	Strength gain beyond 7 days
Iron Oxide	Fe_2O_3 (Iron/ferric oxide)	F	2.84				
Magnesia	MgO (Magnesium oxide)	M	2.07	Tricalcium aluminate	C_3A	6.69	Moderate sulfate resistance
Sulfite	SO_3 (Sulfur trioxide)	S	2.85				
Potassium Oxide	K_2O	K	---	Tetra calcium alumino-ferrite	C_4AF	12.9	Hydration gain
Sodium Oxide	Na_2O	N	---				
Physical Properties of OPC							
Loss of ignition (%) = 2.56							
Surface area (m^2/kg) = 371							
Specific gravity (g/cm^3)= 3.15							

Table 2.3:Chemical and Physical analysis of silica sand (US Silica)

Chemical Compositions of Silica Sand			
Compounds (%)	Formula	Short form	Silica sand (% Wt)
Silica	SiO_2 (Silicon dioxide)	S	99.7
Iron Oxide	Fe_2O_3 (Iron/ferric oxide)	F	0.020
Alumina	Al_2O_3 (Aluminum oxide)	A	0.06
Lime	CaO (Calcium oxide)	C	<0.01
Magnesia	MgO (Magnesium oxide)	M	<0.01
Sodium Oxide	Na_2O (Sodium Oxide)	N	<0.01
Potassium Oxide	K_2O	K	<0.01
Physical Properties of Silica Sand			
Color	White	Grain shape	Round
Melting point (ºC)	1704.4	Fineness modulus	1.47
Loss of Ignition	1	Absorption capacity (%)	0.28
Bulk density (g/cm^3)	1.56	Minimum Dry Density (kg/m^3)	1446
Specific Gravity	2.65	Maximum Dry Density (kg/m^3)	1759

Table 2.4: Typical Ottawa silica sand particle size gradation (US Silica)

U.S Mesh	Sieve size (mm)	%Retained		% Passing
		Individual	Cumulative	Cumulative
No.16	1.180	0	0	100
No.30	0.600	2	2	98
No.40	0.425	28	30	70
No.50	0.300	45	75	25
No.100	0.150	23	98	2
Pan	--	2	100	0

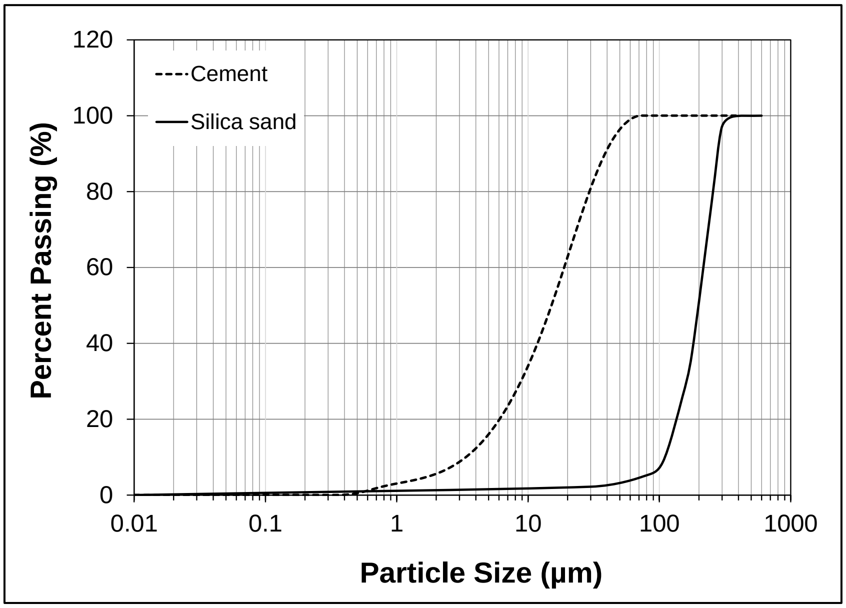

Figure 2.1: Detailed particle size distribution of cement and silica sand.

2.5.4. Recycled Concrete Aggregates

The major depletion of natural resources over the last 20 years directed interest toward using recycled concrete aggregates (RCA), which are collected from buildings demolishing or renovating. It is then separated from the existing concrete to be reused as a replacement of the natural or conventional aggregates. The recycling concrete aggregates was found to be advantageous since these recycled aggregates provide a cost-effective construction material and a remarkable saving of virgin natural aggregate resources and energy (ECCO, 1999). Additionally, the use of RCAs can significantly improve some concrete properties according to Huoth *et al.* (2014). The study found that concrete mixtures (w/c=0.40) with the use of RCA achieved a higher compressive strength than that of mixtures (w/c=0.49) having natural aggregates by nearly 26%, 24% and 17% at 7,14 and 28 days of age, respectively.

The incorporation of recycled aggregates in new concrete production provides similar or better durability, carbonation, permeability and freeze/thaw resistance. This could be due to the recycled aggregates generally having higher absorption and lower specific gravity properties than normal aggregates (Design and Control of Concrete Mixtures-EB001). However, distinguishing the aggregate types, contents and gradations, as in **Table 2.5** (which also shows the recycled stone aggregates' 19-38 mm size range used in the experimental part of this dissertation), is needed to advance in identifying the aggregates' influences on the concrete behaviors because coarse aggregates occupy almost one third of the concrete volume. In fact, the overall strength of high strength concrete, for instance, relies on its aggregates' strength and all over compatibility with the surrounding cementitious matrix (Kozul and Darwin, 1997). Therefore, careful selection of recycled coarse aggregates, according to ASTM C33 (Standard Specification for Concrete Aggregates), ensures its adequate quality. This is crucial in order to avoid issues that could cause an increase in fine particles due to the coarse aggregate breakage during mixing, which can result in a less workable concrete (Mahla and Mahla, 2015).

Table 2.5: Grading limits and sieve analysis for fine and coarse aggregates

Fine Aggregates					
Sieve Size		Cumulative Percentage Passing (%)			Reference
U.S Mesh	mm	Grading (1)	Grading (2)	Grading (3)	
No.4	4.75	----	100	----	(ACI 304.1,2005; ACI 304,2005)
No.8	2.36	100	90-100	----	
No.16	1.18	95-100	80-90	----	
No.30	0.60	55-80	55-70	----	
No.50	0.30	30-55	25-50	----	
No.100	0.15	10-30	05-30	----	
No.200	0.075	00-10	00-10	----	
Fineness Modulus		1.3-2.1	1.6-2.45		
Coarse Aggregates					
Sieve Size		Cumulative Percentage Passing (%)			Reference
U.S Mesh	mm	Grading (1)	Grading (2)	Grading (3)	
1½ inch	37.5	95-100	----	0.5	(ACI 304.1,2005; ACI 304,2005)
1	25.0	40-48	----	----	
¾ in	19.0	25-40	0-10	----	
½ in	12.5	0-10	0-02	----	
3/8 in	9.50	0-02	0-01	----	
6 in	150	100	----	----	(Neville and Brooks, 2010)
3 in	75.0	67	100	----	
1½ in	37.5	40	62	97	
¾ in	19.0	06	04	09	
½ in	12.5	01	01	01	

2.5.5. Superplasticizer Chemical Admixture

Concrete substructures and superstructures have suffered extreme damages that affected their physical and mechanical performance. These damages could be the reason behind the significant changes and improvements in the cement and concrete industry foyer the last 100 years (Zayed *et al.*, 2016). Concrete durability has drawn the attention of many concrete researchers in recent years (Kumar and Singh, 2015). As a result, chemical admixture development is critical, as the enhancement imparted by such supplementary chemical substances is a key factor in improving the quality of concrete and achieving modern structure standards (Kanitkar, 2013). These standards are initially designed to overcome the environmental challenges and the complexity of structural behaviors. Significant developments achieved with the inclusion of admixtures in the cementitious proportions include moderating the water content, accelerating concrete strength at early ages, and improving the mechanical strength and impact resistance (ACI 212.4R, 1998).

High-range water reducing admixtures (HRWRA), typically known as super-plasticizers, super-fluidizers and super-water reducers (Mihai and Bogdan, 2008), are classified in different Types according to ASTM C494 (Standard Specification for Chemical Admixtures for concrete). The chemical liquid admixture used in this dissertation is commonly identified in the chemical market industry as Master Glenium7700. HRWRA has provided such promising workable and flowable concrete features that ease concrete placement and pumpability in construction, so it is highly recommended to be part of concrete production for water retaining structures (Chan *et al*., 1999).

2.6. Tire Waste Effects on Concrete Durability and Strength Performance

2.6.1. Effects of Tire Rubber Waste

In recent years, several findings have illustrated the effects of tire waste materials, including rubber and steel cord particles, as partial substitute for natural aggregates on the durability and strength performance of concrete. Generally, whether shredded (2-20) mm, crumbed (4.75-0.425) mm or grounded (≤ 0.425) mm, tire rubber waste has influenced concrete properties differently. The methodology of incorporating tire waste, whether mixed with the cementitious materials or laid and distributed on coarse aggregates (as in preplaced or two-stage concrete technology), has also produced different concrete properties. In fact, the durability and strength of rubberized concrete mainly depends on the ability of its tire waste proportion to bond with the cementitious matrix. Usually, the finer the rubber particles are, the higher is the workability that concrete tends to achieve (Khaloo *et al*., 2008).

In terms of higher bonding criteria, rough particles tend to provide better bond with the cementitious matrix, which has a positive impact on the compressive strength of rubber concrete (Nehdi and Khan, 2001). Furthermore, rubberized concrete showed better durability (Mavroulidoum and Figueiredo, 2010), higher energy absorption capacity, and is considered to be tougher than conventional concrete. In terms of failure behavior, concrete utilizing rubber exhibited more brittle and plastic failures than that of normal concrete (El-Gammal *et al*., 2010). However, the motivation to implement rubberized concrete in structural engineering applications has not been considered, due to the non-suitable compressive strength that rubber concrete displayed (Balaha *et al*., 2007). This barrier limits the current rubber concrete applications in structures where high vibration, energy absorption, and impact load resistance are needed such as in-machinery and railway foundations (Fatuhi and Clark, 1996).

2.6.3. Effects of Tire Steel-Wires Cord Waste

Concrete’s toughness has attracted much concern due to recent significant development of engineering applications that highly require concrete structures with extraordinary toughness and ductility. Although the addition of rubber improved certain concrete properties, the soft characteristic of rubber particles concentrates the applied stress and causes rapid internal crack development in the cementitious matrix. Many studies have agreed that the addition of a high proportion of rubber in concrete results in a notable reduction of the compressive strength, but not as much of a decrease when concrete contains steel fibres. The Batayneh *et al*. (2007) study illustrates that a reduction in concrete compressive strength of nearly 50% occurred after increasing the proportion of rubber to 40%. However, the same study reported a remarkable effect after adding 2% and 4% of steel cords in concrete, showing that the compressive strength of concrete reinforced with tire steel waste gained an overall improvement. On the other hand, ductility behavior performance (stress-strain) was enhanced significantly by 15%. Hence, the major purpose of utilizing steel cord fibre components is to develop ductility and toughness (Bdour and Al-Khalayleh, 2010) that can highly resist crack growth, improve post-crack behavior, and gain high deformation capacity without complete failure. As a result, these properties support the possible implementation of tire waste concrete, reinforced with steel fibres, in various structural applications.

2.7. Preplaced Aggregate Concrete Technology

2.7.1. The Introduction of Preplaced Aggregate Concrete (PAC)

According to the ACI 304.1 (Guide for the Use of Preplaced Aggregate Concrete for Structural and Mass Concrete Applications), PAC technology was developed in the United States in 1937 by Lee Turzillo and Louis S. Werts. Its goal was to rehabilitate a Santa Fe railroad tunnel close to Martinez, California. The outcome of using this concrete technique was promising, as the consumption of grout was low due to the large spaces being filled with coarse aggregates and followed by grouting these aggregates. Even though the applications of preplaced concrete (PC) were limited to repairing bridges and tunnel linings, the use of preplaced concrete technology can be widely extended. In 1946, coarse aggregate was used as a back filler of 1.8-m precast concrete slabs attached in an upstream face of the 52m height during 10 days of grout pumping, as part of the resurfacing process of the Barker Dam (**Figure 2.2**) in Colorado, USA. In 1950, Japanese companies began owning the rights to use TSC in their projects. In Australia, PAC was used by "The Snow Mountains Authority" for turbine scroll cases and daft tubes' embedment in the Bull Shoals Dam powerhouse (**Figure 2.3**) as part of their hydroelectric power construction project (ACI 304.1, 2005). Further projects in which PAC technology was used are shown in **Table 2.6**.

Table 2.6: List of Projects where PAC technology was applied

Project	Date of Construction	Reference
Prefacing of Barker Dam at Nederland in Colorado	1946	(Davis et al.,1948)
Scroll case at Bull Dam Powerhouse	1951	(ACI 304.1,2005)
Piers of Mackinac Bridge	1954-1955	(Davis and Haltenhoff,1956)
Plugs in gold mine in South Africa	2001-2006	(Littlejohn and Swart,2006)
Auxiliary dam in China	2006	(Huang et al.,2008)

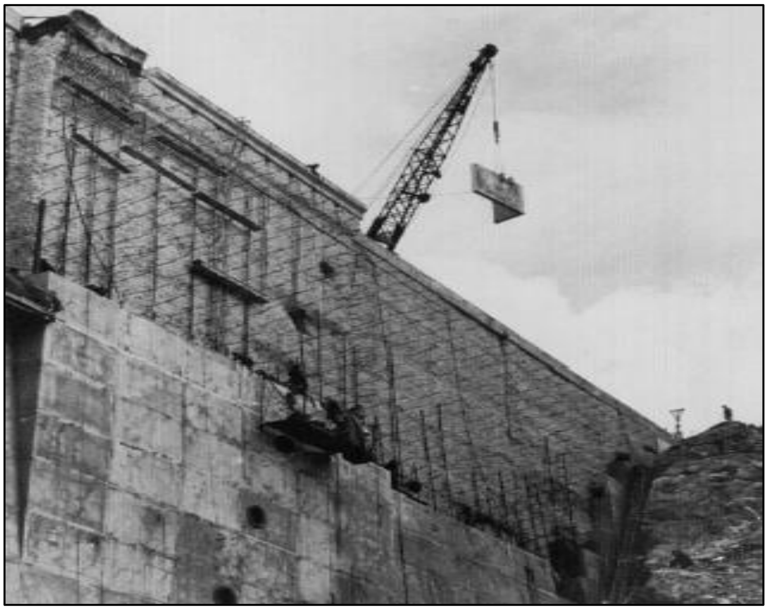

Figure 2.2: Barker Dam during refacing process in 1946 (ACI 304.1, 2005).

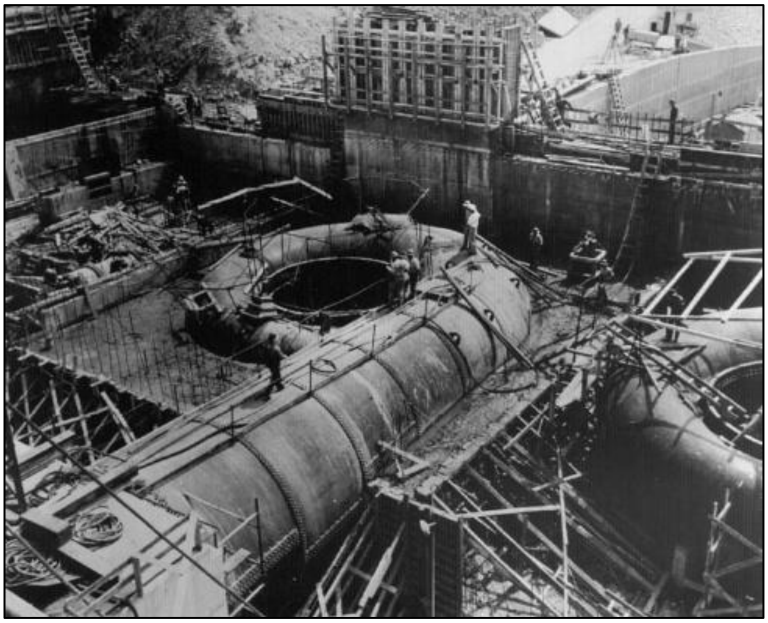

Figure 2.3: The use of Preplaced aggregate concrete in Bull Shoals Dam powerhouse in Australia (ACI 304.1, 2005).

2.7.2. PAC Characteristics

Preplaced aggregate concrete (PAC), commonly known as “two-stage concrete” (TSC), has been defined by the American Concrete Institute (ACI 116R) as a concrete product made by firstly placing coarse aggregate stages in a formwork, followed by injecting cementitious grout mixed with chemical admixtures to fill in the voids, as shown in **Figure 2.4**. In addition to the international definitions of the two-stage concrete listed in **Table 2.7**, ACI 304.1 also defined this type of concrete as Naturbeton, Arbeton, and injected aggregate concrete. PAC has been useful in both superstructures and substructures, such as underwater construction, spaced reinforcement, concrete and masonry repairs for stress distribution purposes, high lift monolithic sections, and where low-volume change is required. Significant transformations in concrete technology in utilizing tire waste materials have generated new methods of green concrete productions with different standards, properties and applications. In addition to rubber concrete, PAC has also shown notable and homogeneous characteristics with the inclusion of tire rubber waste. This technology differs from conventional concrete in which waste rubber is combined in the concrete mixture and then poured in the formwork. In preplaced concrete, the coarse aggregates are first placed in the formwork and then filled with a special cementitious grout (Najjar *et al*., 2014). Hence, PAC provides an exceptional concrete function that is almost 40% more cost-effective than normal concrete since it contains mostly prepacked coarse aggregates and the need of cement content is reduced by up to 30% in overall PAC production (Abdelgader, 1995).

Table 2.7: Different TSC historical definitions (Najjar et al.,2014)

TSC Definition	Reference
Preplaced concrete	Baumann, 1948; Abdul-Awal, 1984; Tang, 1977
Colcrete	Manohar, 1967; Abdelgader, 1996
Polcrete	Abdelgader, 1996; ACI 304.1, 2005
Grouted aggregate concrete	Champion and Davies, 1958; ACI 304.1,2005)
Naturbeton	ACI 304.1, 2005
Arbeton	
Preplaced aggregate concrete	
Injected aggregate concrete	
Rock filled concrete	Huang et al., 2008

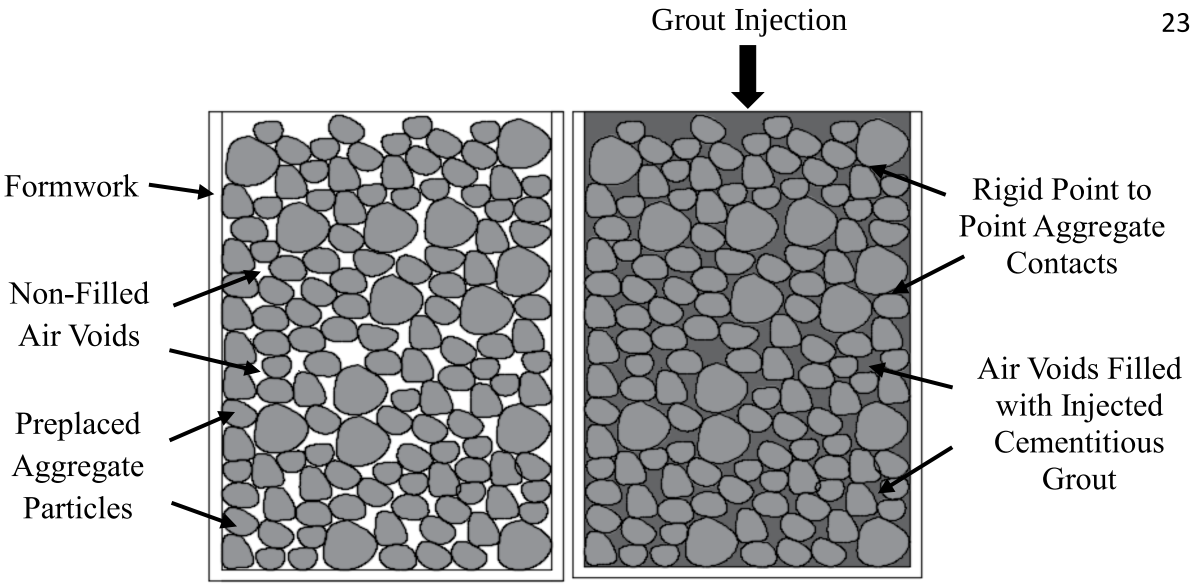

Figure 2.4: Schematic design of interior compositions of Preplaced aggregate concrete (PAC).

2.7.3. PAC Recent Research Interest Objectives

PAC technology was mainly applied for bridge repairing purposes owing to its high amount of different sizes of recycled stone coarse aggregates, which provides great filling ability in an existing damaged structure. However, there is need to advance the applications of PAC by improving its durability and strength in order to be better qualified for construction. In fact, the remarkable advancement in concrete technology over the years has not widely developed the applications of PAC, which is a reason behind the necessity to boost the discovery of this concrete technology. Therefore, enhancing studies on the quality and flowability of the injected cementitious grout, containing different types of sands and chemical admixtures in the preplaced coarse aggregates, should be highly considered, as grout constituents play a significant role in filling and reducing the voids efficiently among the coarse aggregate stages in the formwork. As a result, the injected grout produces durable and high strength PAC. Furthermore, studies agree that there is need to explore the effects of recycled stone aggregates and tire waste, including tire rubber and steel fibre waste, on PAC static and dynamic properties. The development of these properties can elevate the implementation of PAC and its applications and paves the path to generate more sustainable concrete methods.

2.7.4. PAC Implementation in Construction

2.7.4.1. PAC Utilization Effects in Construction

Concrete placement has always been considered a critical stage in construction due to its major impact on concrete quality (Neville, 1981; Neville and Brooks, 1987). The challenge of concrete placement varies upon the shape, complexity and position of formworks, for instance whether they are attached in a high-rise building, underwater tunnel, or artificial water channel. PAC technology was applied for various construction and repair purposes in tunnel lines, dams, bridge piers as well as underwater construction (Davis, 1960; Troxell *et al.*, 1969; Baumann,1948, Davis and Haltenhoff, 1956; ACI 304.1, 1997).

PAC has shown promising placement and repair compatibility with existing structures (Neville and Brooks, 1987; King, 1959; ACI 304, 1997), considering that the proportions of PAC technology differ from normal concrete when regarding the high amount of coarse aggregates typically ranging from 60% (Abdelgader, 1996) to up to 65%-70% (Ganaw, 2012) by volume of concrete. This high proportion of coarse aggregates does not compromise workability, even when recycled aggregates having high water absorption capacity are used, since aggregates are preplaced in the formwork. In addition, the high quantity of aggregates in PAC reduces the need to use high cement content; therefore, reducing shrinkage cracking and making concrete more cost effective and more eco-efficient. Additionally, the common segregation issue encountered in concrete is eliminated in PAC since the aggregates are first placed in the formwork, followed by the injection of mortar with no need for compaction due to the high homogeneity of the preplaced aggregates (Mehta, 1986; Neville, 1995). This technique was found to be more favorable than the traditional concrete casting and is particularly suitable for submerged and underwater concrete structures (Warner, 2004; and Neville, 1995) where high compressive strength, durability, flowability and self-compaction are required (Abdelgader *et al.*, 2009).

2.7.4.2. Recommended Placement Of PAC

In construction sites, the prepared formwork such as plywood formworks or steel sheet piling, should be strongly impermeable for underwater construction in order to prevent possible grout leakage and resist lateral pressure during pumping. After placing the coarse aggregates in the formwork, the aggregates should be saturated with the injected grout through inserted injection pipes. Additionally, the PAC technique can be applied through steel reinforcements where coarse aggregates fill the spacing between rebar. Prior to incorporating coarse aggregates and grouting, it is important to install 20 to 30 mm diameter grouting pipes (for normal structural concrete) or 40 mm diameter (for mass concrete) properly in the selected locations. The positions of pipes can be moved accordingly to provide enough space for the grout to flow. These pipes can be doubled for deep placements (Beeby, 1995), and can be placed 150 mm in the vertical direction from the bottom of the installed aggregates or in the horizontal direction for repair purposes. Grout should be injected at a very slow velocity (0.6-1.2) m/sec, as this low penetration of grouting prevents segregation and line blockage. However, in cold joints, the grout pumping should be stopped prior to reaching the upper surfaces of aggregate (i.e. 300mm under the aggregate surface). The hardened PAC should be properly cured to achieve the expected compressive strength (ACI 304.1, 2005; ACI 304, 2005). The relation between the grouting level and the spacing between the grouting pipes can be described through a typical propagation curve (**Figure 2.5**). The grout propagation slope (vertical: horizontal) is also reported as 1:4 ratio for dry conditions and 1:6 ratio for underwater placements (ACI 304.1, 2005). The propagation curve also describes the shape of grout flow among the preplaced coarse aggregate particles, and this shape can be affected by grout mixture proportions, intensity of mixing, and the shape and size of the coarse aggregates (Abdelgader, 1995). The equation of the propagation curve of grout in coarse aggregates can be illustrated as:

$$y = \frac{\boldsymbol{\alpha}}{(\boldsymbol{\beta} \mathbf{x}^2 + \mathbf{1})\sqrt{\frac{\boldsymbol{\gamma}}{\mathbf{t}} - \frac{\mathbf{1}}{\boldsymbol{\beta}} + \mathbf{1}}} \qquad \textbf{Eq. 2.1}$$

Where; y = grout mixture level in coarse aggregate (m), x = spacing between grout insert pipes (m), α = thickness of stone layer (m), t = time (min), β = ($a \times b \times f$), a = parameter dependent of the mixture fluidity, b = parameter dependent of stone: shape, size, type of grain, surface texture, and coarse aggregate fraction, f = parameter dependent of the environment of construction, γ = ($c \times d \times e$), c = parameter dependent of efficiency of flushing pipe (m^3/min), d = parameter dependent of perforation, e = parameter dependent of the type of excavation bottom.

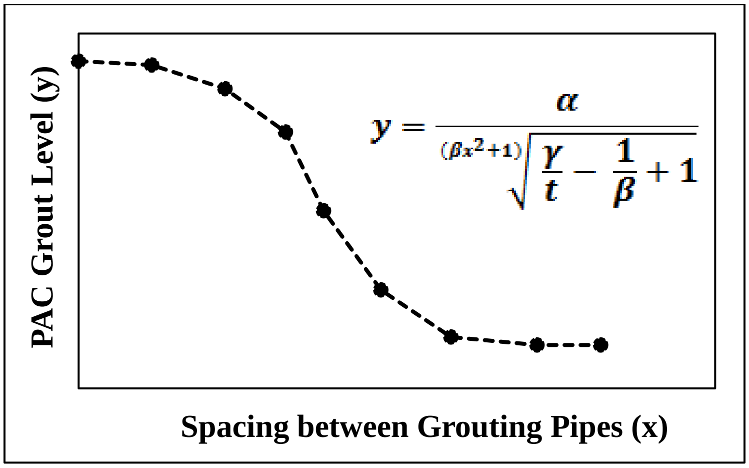

Figure 2.5: Propagation curve of PAC grout mixture in coarse aggregates (Abdelgader, 1995).

2.8. PAC Proportioning Elements Properties

The high amount of coarse aggregates and low content of cement in PAC have extended the investigations on the proportioning materials of this concrete technology. PAC requires a higher amount of coarse aggregates than that in normal concrete, which can result in higher strength properties when compared to conventional concrete. This can be explained by the fact that PAC properties rely mainly on the strength of skeleton structure of coarse aggregates. Furthermore, the strength of the injected cementitious grout affects the mechanical properties of PAC since it ensures the bond between the granular skeleton.

2.8.1. PAC Cementitious Grout Properties

Unlike normal concrete, coarse aggregates are preplaced in PAC and are not involved in the mixing process, which includes only the grout, thus providing energy savings and logistics advantages. The process escalates the need to ensure high quality of the injected grout, as it has a significant impact on the mechanical properties of PAC (Abdelgader, 1996; Abdelgader and Górski, 2002). Referring to ASTM C938 (Standard Practice for Proportioning Grout Mixtures for Preplaced Aggregate Concrete), the grout mixture proportions for PAC can be selected through flowability and bleeding measurements. The grout mixture proportions of PAC are varied based on the required applications and specifications. Additionally, careful consideration of the water/binder ratio (w/b) and sand/binder ratio (s/b) is important since these parameters play a crucial role in controlling the rheological and mechanical properties of the PAC grout (Najjar *et al*., 2014).

Grout ingredients including chemical admixtures are factors, which regulate the flowability and penetrability of the grout throughout the coarse aggregates' voids. The grout is penetrated depending on the gravity penetration concept recommended by Abdul-Awal (1984) to be used for a sectional depth of not more than 300mm, which is the same as cylindrical plastic molds' depth used in the experimental part of this thesis. Yet, grout could also be pumped through injection pipes in the formwork. PAC grout is prepared by mixing the cement, sand and water using a suitable mixer with the addition of chemical admixtures to enhance the grout flow properties as recommended by different studies and standards (Abdelgader, 1995; Neville, 1995; Newman and Choo, 2003; ASTM C937 and ASTM C938, 2002).

The cleanness and particle size and shape properties affect the grout flow through the voids between preplaced aggregates (ACI 304.1R, 1997). In engineering applications: a s/b ratio of 1.0 for beams, columns and thin concrete sections, 1.5 for massive concrete elements (ACI 304.1,2005), and 1-2 for underwater PAC applications is usually recommended (Orchard,1973). In addition, superplasticizer admixtures enhance the grout workability (Witte and Backstrom, 1954). They are also recommended to reduce the water requirement of the binder, thus improving the PAC compressive strength (Domone and Jefferis, 1994; ACI 304.1R, 1997).

2.8.2. Chemical Admixture Effects on PAC Properties

The incorporation of chemical fluidifier admixtures under ASTM C937 (Standard Specification for Grout fluidifier for Preplaced-Aggregate Concrete), with the physical requirements shown in **Table 2.8**, provides an essential property to the grout. The incorporation can aim to improve the grout flowability, reduce the water content, delay the setting time, and operate as a chemical moderator and expanding agent (ACI 304.1,2005; ASTM C937). The recommended fluidifier admixtures dosage in the grout is usually 1% by weight of the grout's cementitious materials according to ACI 304.1 (2005) but can vary depending on the type of admixture.

Integrating a superplasticizer with a viscosity-modifying admixture can enhance the flowability of the grout and its stability by resisting bleeding and segregation of the PAC grout (Christianto, 2004). For instance, adding 1% of aluminum powder by weight of the cement improved the PAC compressive strength by 46% (Abdul-Awal, 1984), while incorporating 2% of aluminum powder by weight of cement increased the compressive strength of PAC by only 20% (Abdelgader and Elgalhud, 2008), showing the negative impact of adding more than 1% of fluidifier admixture as reported in ACI 304.1. The benefit of including air entraining admixtures in the grout is enhancing the durability of the PAC to freeze/thaw cycles (ASTM C260, 2006). However, air voids decrease mechanical strength and moderating the dosage of air entraining admixtures can strike a compromise with mechanical strength of PAC (Najjar *et al*., 2014). In 1943, a study conducted by Menzel showed that adding an excessive quantity of aluminum powder admixture increased the PAC porosity. This caused reductions in compressive strength. Moreover, excessive dosage of a superplasticizer can result in bleeding and lead to possible sand segregation in the grout mixture (Tang, 1977).

Table 2.8: Recommended physical criteria of PAC grout chemical admixture (ASTM C937, 2002)

Physical Requirements	Limit
Min reduction in mixing water	3%
Expansion after 3 hrs. from mixing relative to cement alkali content:	
0.80 or more	7 to 14%
0.40 to 0.79	5 to 12%
0.39 or less	3 to 9%
Max bleeding after 3 h from mixing	2%
Min increase in water retentively	60%
Min initial setting time	4 hrs.
Max final setting time	24 hrs.

2.8.3. Recycled Stone Coarse Aggregates Effects On PAC

The fundamental difference between PAC and conventional concrete is the quantity, size and placement method of coarse aggregates, which represent the major proportional component of PAC. The coarse aggregate skeleton occupies the majority of the concrete volume (ACI 304.1, 1997; King and Wilson, 1988; Colle, 1992). Hence, the mechanical performance of PAC is directly affected by the properties of coarse aggregates (Nowek *et al*., 2007). In fact, coarse aggregates in PAC provide an exceptional feature due to the concentration of applied load on aggregates and transfer of stress via aggregate contact points. Consequently, the compressive strength and modulus of elasticity of PAC exhibited high values, compared to that of conventional concrete with similar water to binder ratio (Abdelgader and Górski, 2002; Abdul-Awal, 1988; Abdelgader and Górski, 2003). However, this mechanical performance depends on the strength of aggregates, size, particle gradation, stiffness, surface texture, mineralogy and cleanness (O'Malley and Abdelgader, 2009). Additionally, the extensive point-to-point contact through the aggregate skeleton is a factor that leads to lowering drying shrinkage in PAC compared to that in normal concrete.

Clean coarse aggregates with angular shapes and rough texture surfaces, under the ASTM C33 standard, are factors that highly boost PAC mechanical properties. The ease of movement of the cementitious grout through the aggregate skeleton is an indication of producing PAC with lower voids and better bond between the cementitious matrix and the coarse aggregates, leading to higher mechanical strength.

The recommended nominal selected coarse aggregate particle size in PAC should range between 10 mm (Orchard, 1973) and 38 mm (Champion and Davis, 1958) reduce air void cavities in the aggregate skeleton. This also helps lowering the consumption of grout and ensuring bonding points between the aggregates and the cementitious matrix. Fine aggregate with adequate properties (ACI 304.1) can be utilized as a supportive aggregate proportional filler to reduce air voids throughout coarse aggregates and help reducing segregation issues.

2.9. PAC Physical Properties

2.9.1. Shrinkage

Concrete shrinkage is a reduction of the concrete volume with time related to its physical loss of adsorbed water in the cement paste (Mehta and Monteiro, 2006). Concrete shrinkage can be classified into drying shrinkage, autogenous shrinkage and carbonation shrinkage (Nehdi and Soliman, 2011). Shrinkage in PAC is usually significantly lower than that in conventional concrete (ACI 304.1, 2005; Abdelgader and Elgalhud, 2008; Abdelgader and Ben-Zeitun, 2005). For instance, drying shrinkage of PAC and conventional concrete were found to be about 330 and 600 micro strains, respectively (Davis, 1960). Low shrinkage in PAC refers to its lower proportion of cement paste, and higher proportion of coarse aggregates compared to that in conventional concrete. The addition of a superplasticizer and/or expanding admixtures are also a factor in lowering PAC shrinkage (Abdul-Awal, 1984). However, PAC mixtures containing superplasticizer showed lower drying shrinkage than PAC with expanding admixtures since a superplasticizer generally reduces the water demand in PAC (Abdul-Awal, 1984). The drying shrinkage of concrete is represented for instance by Lyse (1959) as:

$$S_t = S_0\,(1 - e^{-S_t})\,\rho \qquad \textbf{Eq.2}$$

Where; S_t = shrinkage after time of drying (t), S_0 = final shrinkage in relation to the percentage of cement paste in the concrete, S = rate of shrinkage depending on the relative humidity of the ambient atmosphere, and ρ = percentage of cement paste in the concrete.

2.9.2. Heat of Hydration

The hydration process of cementitious materials leads to temperature rise, which is mainly dependent on the type of cement (i.e. cement composition and fineness), concrete mixture proportions (e.g. Cement dosage) (Chefdeville, 1963), the geometry of the concrete member, and the surrounding temperature. PAC technology is known to have been applied in massive concrete structures, such as dams, owing to its lower cement content. The low cement content leads to reducing both the heat of hydration and thermal cracking (Bayer, 2004). However, thermal cracking occurs when the exterior surface cools faster than the interior surface. This can lead to tensile strains and stresses in massive concrete specimens (ACI 207, 1996). To avoid the development of thermal cracking, it is recommended that the maximum temperature difference between the concrete core and its exterior surface not exceed 20°C (Portland Cement Association, 1997). Moreover, it is found that incorporating mineral admixtures (**Table 2.9**), such as rock powder, fly ash, and GGBFS as partial replacement for cement, significantly supports lowering the temperature differences between surface and core of PAC.

Table 2.9: PAC peak temperature differences incorporated with various mineral admixtures (Bayer, 2004)

Specimen No.	Mineral Admixture as Partial Replacement for Cement (%)	Peak Temperature Difference (°C)
1	20% Rock Powder	8.5
2	50% Rock Powder	8.0
3	25% Fly Ash and 25% Rock Powder	8.0
4	50% GGBFS	13.0
5	50% Fly Ash	9.5
6	50% Brick Powder	7.0
7	25% Brick Powder and 25% Fly Ash	9.5

2.9.3. Durability

Concrete durability refers to its ability to resist harmful mechanical and environmental loading effects during its service life. Concrete durability can be affected by some harmful substances including chloride and sulphate ions and carbon dioxide; their penetration rate mainly depends on the existence of porosity and micro-cracks in concrete (Mehta, 1988). PAC containing air entraining chemical admixtures showed remarkable durability against tough environmental weathering, which is similar to that of conventional concrete (ACI 304.1, 2005; Tynes and McDonald, 1968). In Australia, the PAC piles of the Tasman Bridge in Hobart were investigated to evaluate its condition after 48 years of service. It was found that PAC technology produced dense and durable concrete in a marine environment. The levels of chloride and sulphate ions in PAC piles were reported to be low (1.3% and 3.8% by weight of cement) considering that the PAC piles were placed in severe exposure marine conditions for long time (Berndt, 2012). However, such sulphate concentrations were still considered low

2.10. PAC Mechanical Strength

2.10.1. Compressive Strength

The high content of preplaced coarse aggregates in Ruiz's (1966) study produced PAC with high compressive strength, as the strategy of reducing the existing voids by incorporating aggregates density was found to be remarkably affect the compressive property. This is similar to the Carrasquillo *et al*. (1981) study, in which the compressive strength reached up to 62 MPa (9,000 psi). The characteristics of the coarse aggregates, preferably rough texture and angular aggregates, is one of the factors that regulate the bonding with the cementitious matrix and development of compressive strength.

Moreover, there is no disagreement regarding the critical influence of the water-to-cement (w/c) and sand-to-cement (s/c) ratios on the compressive strength of both conventional concrete and PAC. Studies have shown that increasing the s/c ratio negatively impacted the flowability of the PAC grout, causing partial complex binding and honeycombing due to difficult ability of grout penetration through the aggregate skeleton, leading to lower compressive property. Even though increasing the w/c enhances the grout workability, it can lead significant decrease in the overall mechanical strength of PAC. Therefore, the utilization of chemical admixtures, such as superplasticizers, helps reducing the water content and adapt the flowability of the grout.

The PAC compressive strength reported in the Davis *et al*. (1955) study was 22.30 MPa. The w/c and s/c of PAC were 0.44 and 1.50, respectively, without adding any chemical admixture, while a significant increase in the compressive strength by 28% (30.71Mpa) at 28-days was reported by Abdelgader (1996), who used similar w/c and s/c to that in Davis et al. (1955), but with added 2% of superplasticizer and 35% of the air entraining admixture. In addition, the 28-day compressive strength obtained by Abdelgader and El-Baden (2015) for PAC having w/c=0.55, s/c=1 and a 2% superplasticizer was increased by 43% compared to that of PAC with 0% of admixture and similar w/c and s/c ratios.

2.10.2. Splitting Tensile Strength

There is a general agreement that the correlation between the PAC compressive and tensile strength is that a high PAC compressive property exhibits a reasonable tensile strength (Abdul-Awal, 1984; Abdelgader and Ben-Zeitun, 2005). Accordingly, the high proportion of coarse aggregate creates interconnected coarse aggregate particles, resulting in a uniform aggregates shell structure, where the applied tensile stress is distributed and restricted until interfacial splitting occurs between the aggregates and the cementitious matrix.

Moreover, studies revealed the influence of increasing the w/c ratio with accordance to the tensile strength performance of PAC. For instance, in the Abdelgader and Elbaden (2014) study, the mean tensile strength at 28-days decreased by 15% after increasing the w/c from 0.45 to 0.55. However, adding a superplasticizer in the cementitious mixture of the PAC grout overcame the tensile strength reduction resulting from the w/c ratio increase. Remarkable improvements in the average tensile strength of PAC were displayed in various studies after utilizing chemical admixture, as shown in Abdelgader *et al*. (2015). The average tensile strength of the 28-day PAC specimens continued increasing by 18% due to the addition of superplasticizer, although the w/c was raised from 0.38 to 0.8 with the same s/c ratio of 1:1. Furthermore, the PAC tensile strength increased for specimens utilizing a superplasticizer with a w/c of 0.55 than that for specimens having a w/c of 0.45 by nearly 24.5% with the same c/s of 1:0.5 and a curing period of 28 days. This result indicates the notable effect the superplasticizer in improving the tensile strength of PAC, even with a high w/c ratio.

2.10.3. Modulus of Elasticity

The stiffness and elastic deformation functions of PAC have been investigated and compared with that of conventional concrete. The type of aggregates in these concretes play a key role in their stiffness (McNeil and Kang, 2013). Generally, for both types of concrete, the modulus of elasticity is related to the compressive strength. The stress-strain correlations of PAC and normal concrete appeared to be similar, according to various findings, such as those of Akatsuka and Moriguchi (1967), who revealed that the coarse aggregates in PAC can be the main factor for the increased modulus of elasticity. This is also supported by Neville (1995), who indicated the critical effect of the high coarse aggregates content on increasing the modulus of elasticity of PAC at almost all ages from 7 to 365 days. This is ascribed to be the physical contact among coarse aggregate particles in PAC. In addition, studies designated the major effect of decreasing the s/c ratio with accordance to the PAC modulus of elasticity. Abdelgader and Górski (2003) study indicate the important impact of keeping the s/c ratio high, which provides higher modulus of elasticity. Increasing the s/c ratio from 0.80 to 1.50 at a w/c ratio of 0.55, utilizing the same superplasticizer dosage of 2%, improved the overall 28-day PAC modulus of elasticity by 13%. Furthermore, the effect of keeping the s/c ratio as high as 1.50 prevented the occurrence of reduction in the PAC modulus of elasticity in the Abdul-Awal (1984) investigation. This indicates a remarkable impact of using a high s/c ratio and chemical admixture on enhancing the modulus of the elasticity of PAC.

2.11. PAC Failure Mechanisms

Certain factors affect the failure mechanisms of normal concrete and PAC. The high coarse aggregate content in PAC alters the failure behaviour of PAC. The failure characteristic of both types of concrete are commonly affected by the bond between the aggregates and cementitious matrix. The bond resists applied stresses until reaching the peak load, then severe interfacial cracks through the aggregates matrix occur (Carrasquillo *et al*., 1981). Moreover, Bayasi and Zhou (1993) demonstrated the crucial role of the high aggregates content with relation to the concrete mechanical strength, especially on the flexure strength performance and the aggregates function as a crack arrestor. As a result, the possibility of a sudden failure in PAC is less probable than it would be in normal concrete (Abdul-Awal, 1984, 1988a) due to the high content of aggregates in PAC, and the consideration of the effect the aggregates strength has on the overall flexure strength performance (Giaccio *et al*., 1992). Furthermore, the higher proportion of aggregates significantly delays the propagation of cracks by highly interlocking the aggregate matrix (Perdikaris and Romeo, 1995). This evidence is also supported by Abdelgader (1995), who verified that PAC failure occurs initially through the coarse aggregates and secondly by the failure of the cement matrix.

2.12. Conclusions

- This overview illustrates the potential of innovating green concrete production by taking advantage of tire stockpiles via the process of recycling tire waste in concrete along with replacing natural virgin aggregates with recycled aggregates.
- Studies describe the positive engineering, environmental and economical impacts of creating cost-effective projects by introducing a high coarse aggregates content concrete, such as PAC, as well as concrete incorporating recycled tire waste and recycled concrete aggregate.
- Studying the physical characteristics of tire rubber waste transformed to shredded, chipped, crumb, granulated or ground rubber particles, supports the understanding of its effects on the workability and strength of rubberized concrete.

- PAC or two-stage concrete is shown to be a very promising green concrete technology owing to its high coarse aggregates content and effective ability to be placed in hard placement sites, such as underwater applications.
- Even though the grout proportion in PAC is considered low, the injected cementitious grout which flows throughout the coarse aggregate skeleton plays an important role in controlling the PAC engineering properties.
- Proper formulation of the grout using chemical admixtures and adequate control of its rheology via the use of admixtures such as superplasticisers and viscosity-modifying admixtures can produce grout with effective flow properties and strong bond to preplaced aggregates.
- The dense coarse aggregate skeleton feature in PAC provides higher overall mechanical strength and stiffness, better deformation properties and lower shrinkage compared to that of conventional concrete owing to its high one-to-one aggregate contacts skeleton, which highly distributes stresses and resists applied loads. Its notable bonding with the cementitious matrix can results in durable and low shrinkage PAC characteristics.

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Chapter 3

3. ECO-EFFICIENT PREPLACED RECYCLED AGGREGATE CONCRETE INCORPORATING RECYCLED TIRE RUBBER GRANULES AND STEEL-WIRE

3.1. Introduction and Background

Millions of scrap tires are discarded or buried annually worldwide. This represents a stern environmental threat in view of its flammability, non-biodegradability and history of becoming breeding grounds for disease carrying mosquitoes. For instance, the United States dispose about 4.7 million tons of waste tires each year (Thomas and Gupta, 2016). An economically and ecologically viable solution for scrap tires is to recycle it in concrete mixtures towards greener construction.

The use of scrap tires in producing sustainable concrete has gained increased attention owing to its lightweight, elasticity, energy absorption, and heat and sound insulating properties. A typical tire consists of approximately 47% rubber, 22% carbon black, 17% steel cords, 5% fabrics, and additional minor additives (Sengul, 2016). In scrap tire recycling, steel-wires are usually pulled out where the rubber is then shredded. Scrap tire rubber is generally classified as chipped, crumb and ground, based on the size of the produced rubber particles, which in turn depends on the type of grinder used and temperature generated. While granulated tire rubber is commonly used in concrete mixtures as partial substitute for coarse and fine aggregates, steel-wires from scrap tires are rarely used for concrete reinforcement as a replacement for commercial steel fibers.

Rubberized concrete has been used in various applications, such as pavements, sidewalks and road barriers. Several studies (e.g. Turatsinze *et al*., 2005; Guneyisi, 2010; Torgal *et al*., 2012; Yung *et al*., 2013; Gesoglu *et al*., 2014; Thomas *et al*., 2014; Aslani, 2015) have reported that rubberized concrete mixtures exhibit increased resistance to freezing-thawing cycles, acid attack and chloride ions penetration. In addition, while ordinary concrete has a brittle behavior, rubber particles offer high-strain capacity inclusions in concrete. They can also act as crack arresters to control the initiation and propagation of cracks with ability to increase the overall ductility and toughness of concrete. It was also reported that various factors can affect the compressive, tensile and flexural strengths of rubberized concrete, including the size, proportion, and surface texture of the tire rubber particles. It was found that the workability, compressive and tensile strengths of concrete are negatively affected by the addition of rubber particles, especially at a high dosage. However, using adequate supplementary cementitious materials in the mixture can help minimize strength loss and enhance the abrasion resistance, as well as increasing the durability in acid, sulfate and chloride ions environments. Extensive literature review on the mechanical properties of rubberized concrete can be found in Siddique and Naik (2004), and Thomas and Gupta (2016).

Because of their lower cost when compared to that of commercial steel fibers, several studies have investigated the use of steel-wires recovered from scrap tires in concrete technology (e.g. Wang *et al.*, 2000; Neocleous *et al.*, 2006; Graeff *et al.*, 2012; Sengul, 2016). Such steel-wires generally have irregular undulations and inherent variance in its geometrical characteristics (diameter and length), unlike commercial steel fibers that are often manufactured with optimized and consistent shape. Tire steel-wire usually has circular cross-section and diameter ranging between 0.1 and 2 mm. Previous studies concluded that using scrap tire steel-wire fibres generally enhanced the mechanical properties of rubberized concrete as compared to that of a control rubberized fibreless concrete, owing to its crack-bridging effect. Some studies also compared the effects of the mechanical properties of concrete on steel-wires recovered from scrap tires and commercial steel fibers. For instance, Sengul (2016) reported that tire steel-wires did not affect the compressive strength, flexural strength and splitting tensile strength of concrete as much as commercial steel fibers did.

Preplaced aggregate concrete (PAC), also known as Two-Stage Concrete (TSC), is a special type of concrete distinguished by its higher coarse aggregate content and unique placement technique, whereby aggregates are first pre-placed in the formwork and then injected with a cementitious grout to fill intergranular voids. The rheological properties of the cementitious grout are a key factor in achieving the desired mechanical strength and durability. PAC has an additional 50% coarse aggregate content than that of conventional concrete (Abdelgader, 1999). Thus, it has a characteristic stress distribution mechanism whereby stresses are transferred through contact areas between aggregate particles. Such stresses can be responsible for the fracture and/or tearing of aggregate particles from the grout (Abdelgader and Gorski, 2003). Using recycled solid waste materials, such as recycled concrete aggregate, can further increase the sustainability of PAC while saving natural resources and providing a cost-effective alternative to virgin natural aggregates. Moreover, such concrete can have superior resistance to shrinkage and thermal cracking, considering its dense particle packing granular skeleton. Producing PAC with notable homogeneous inclusion of tire rubber waste materials has already been proven feasible (Najjar *et al*., 2014).

3.2. Research Significance and Objectives

While numerous studies have been conducted on concrete mixtures incorporating rubber and/or steel-wires recovered from scrap tires, there is an inadequacy of data on the combined use of these waste materials in the pre-placed aggregate concrete technology, particularly when recycled concrete aggregate is used as the basic granular skeleton. Recently, Nehdi *et al*. (2017) proposed the green PAC technology in utilizing tire rubber granules and recycled stone aggregate as a partial replacement for virgin coarse aggregates, along with scrap tire steel-wire as fibre reinforcement. They injected his granular system with sustainable grout, incorporating high-volume recycled supplementary cementitious materials. They reported the feasibility of producing durable and cost-effective concrete that could be suitable for sidewalks and pavements, offering ease of placement and superior sustainability features. However, the mechanical properties of PAC, prepared using 100% recycled concrete aggregate along with scrap tire rubber and steel-wire materials, still needs investigation and quantification of its engineering properties to open the door for full-scale construction implementation. Accordingly, the present study aims at filling this knowledge gap by exploring the effects of rubber and steel-wire content, recovered from scrap tires, has on the mechanical properties and post-cracking behavior of preplaced recycled aggregate concrete.

3.3. Experimental Program

Various eco-efficient, rubberized and steel-wire, reinforced, preplaced, recycled aggregate concrete mixtures were prepared. The properties of the ingredients used, the mixture proportions, specimen preparation, and mechanical testing procedures are described below.

3.3.1. Material Properties

Recycled concrete aggregate, having 19-38 mm in particle size, was used in this study as a full replacement for natural stone coarse aggregates. Its specific gravity and water absorption were 2.60 and 2.0%, respectively. Recycled granulated tire rubber with a particle size ranging from (6-12) mm, recycled tire steel-wires with length ranging from 20-35 mm, and a mean diameter of 0.2 mm and tensile strength of 2000 MPa (made from high strength steel) were used. The tire rubber and steel-wires were obtained from a scrap tire recycling plant in London, Ontario, Canada. Tire rubber was recovered using a shredding process of waste tires, with the separation of steel-wires via an electromagnetic process. The selected steel-wires had consistent, relatively geometrical properties and were free from rubber and textile inclusions. The density of the scrap tire rubber obtained, according to ASTM C127 (2007), was 0.97 g/cm^3. For the grout mixture, CSA A3001 GU (general use) cement with chemical properties, reported in Error! Reference source not found., was used. It has a specific gravity and surface area of 3.15 g/cm^3 and 371 m^2/kg, respectively. Uniformly graded standard Ottawa sand, with the commercial name of “Barco 49”, having round to sub-round particle shape was also used. The saturated surface dry specific gravity of the sand was 2.65 with a fineness modulus of 1.47, providing high strength and excellent permeability. It should be noted that sand used in pre-placed aggregate concrete grouts is finer than of that used in normal concrete, to ensure adequate flow and filling of inter-granular space. A poly-carboxylate based High Range Water Reducing Admixture (HRWRA) was used to adjust the flow-ability and stability of the grout, as per ACI 304.1 (2005) requirements (efflux time = 35-40 ± 2 s). It has a specific gravity of 1.06 and a solid content of 34%. **Figure 3.1** exhibits ingredients utilized in the experimental program of this study.

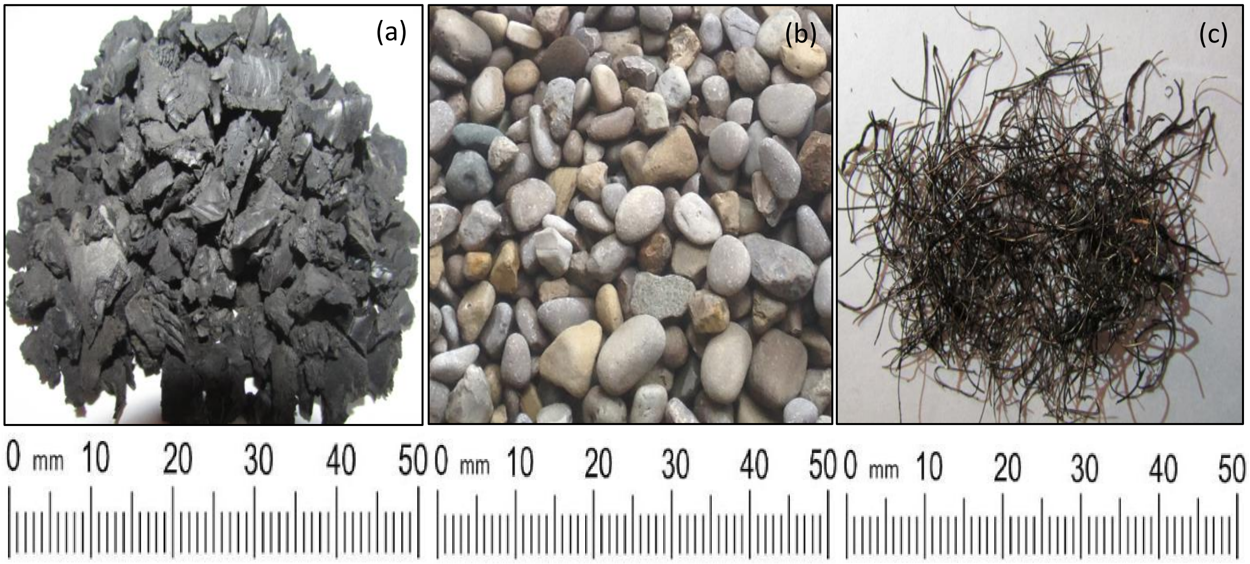

Figure 3.1: Illustration of ingredients used in producing various mixtures: (a) recycled rubber tire; (b) recycled stone aggregate (c) recycled steel-wires.

3.3.2. Mixture Proportions

An identical grout mixture for all eco-efficient, preplaced, recycled aggregate concrete mixtures was prepared with a water-to-binder ratio (w/b) of 0.45 and sand-to-binder ratio (s/b) of 1, using a 100% OPC without adding supplementary cementitious materials (SCMs). Exploring the effects of various SCMs will be explored in a subsequent study. For all mixtures, a superplasticizer dosage of 0.4% by the weight of cement was adequate to ensure the recommended efflux time. It should be noted that the flow cone method is the most commonly used for assessing the grout flow-ability for PAC. This flow cone test consists of measuring the time of efflux of 1725 ml of grout through a specific cone having a 12.7 mm discharge tube, according to ASTM C939 "Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete". Previous research has shown that grout with a time of efflux between 20 and 24 s is ideal for TSC (ACI 304.1, 2005; ASTM C939, 2010). However, grout with a time of efflux of 35 to 40 s was recommended to achieve higher mechanical strength (ACI 304.1, 2005). The grout mixture composition is outlined in **Table 3.1**. The recycled concrete aggregate was partially replaced by mass using 10%, 20%, 30%, 40%, and 50% of the recycled granulated tire rubber. The volume fraction of recycled tire steel-wire was 0%, 0.25%, 0.5%, and 1%. A total of 21 different mixtures were investigated. From each mixture, standard specimens were made to evaluate the compressive, tensile, and flexural strengths and modulus of elasticity. A summary of mixture proportions is provided in **Table 3.2**.

Table 3.1: Grout mixture proportions

Grout Mixture	OPC $(\mathrm{kg/m^3})$	Sand $(\mathrm{kg/m^3})$	Water $(\mathrm{kg/m^3})$	HRWRA Dosage (%)	(w/b)	(s/b)
Proportion	874	874	393	0.4	0.45	1.0
Specific gravity	3.15	2.65	1.0	1.064		

Table 3.2: Eco-efficient preplace recycled aggregate mixture proportions

Mixture ID	Coarse Aggregate (%)		Recycled Tire Steel-wires (% by Concrete Volume)
	Recycled Aggregate	Tire rubber Particles	
C-R0-W0	100	0	0
C-R10-W0	90	10	0
C-R10-W0.25	90	10	0.25
C-R10-W0.5	90	10	0.5
C-R10-W1.0	90	10	1.0
C-R20-W0	80	20	0
C-R20-W0.25	80	20	0.25
C-R20-W0.5	80	20	0.5
C-R20-W1.0	80	20	1.0
C-R30-W0	70	30	0
C-R30-W0.25	70	30	0.25
C-R30-W0.5	70	30	0.5
C-R30-W1.0	70	30	1.0
C-R40-W0	60	40	0
C-R40-W0.25	60	40	0.25
C-R40-W0.5	60	40	0.5
C-R40-W1.0	60	40	1.0
C-R50-W0	50	50	0
C-R50-W0.25	50	50	0.25
C-R50-W0.5	50	50	0.5
C-R50-W1.0	50	50	1.0

3.3.3. Specimen Preparation

Cylindrical specimens (150 mm x 300 mm) were prepared to evaluate the compressive strength, static modulus of elasticity, and splitting tensile strength for each mixture, while prismatic specimens (150 mm x 150 mm x 550 mm) were prepared to evaluate the flexural strength at 28 days. The recycled concrete aggregates were first washed and dried to remove fine particles from its surface. **Figure 3.2** illustrates a schematic diagram of the specimen preparation process where steel molds were filled in approximately three equal layers. Initially the recycled stone aggregates were preplaced in the bottom of the molds, and then covered with the specified amount of recycled tire rubbers and steel-wires as per each design mixture to form the first reinforced aggregate layer. The second and third layers were placed in a similar sequence. The final top layer consisting of recycled stone aggregate was then placed. This methodology prohibited higher rubber and steel-wire concentration at the top layer, which is a common problem in the preplaced aggregate, to prevent their upward movement and floating during the cement grout injection process.

The cement grout was mixed for 6 minutes using a high-speed mixer, according to ASTM C938 (standard practice for proportioning grout mixtures for preplaced aggregate concrete), and then injected to fill voids in the specimens. The mixing and flow-ability measurements were conducted at room temperature (23 ± 2^{o} C). The amount of accumulated bleeding water at the surface of the fresh grout was evaluated. To ensure proper consolidation, the molds were placed on a vibrating plate device. No problems were encountered during the injection process and self-compacting was achieved. **Figure 3.3** illustrates the casting process of cylindrical and prismatic specimens. After casting, the specimens were covered with wet burlap to prevent surface drying. At age of 24 hours, the specimens were demolded and cured in a moist room at a temperature of 25 ^{o}C with a relative humidity of 98% until testing. **Figure 3.4** illustrates the grouting process. The compressive strength of the grout was tested on 50 mm cubic specimens at ages of 7 and 28 days.

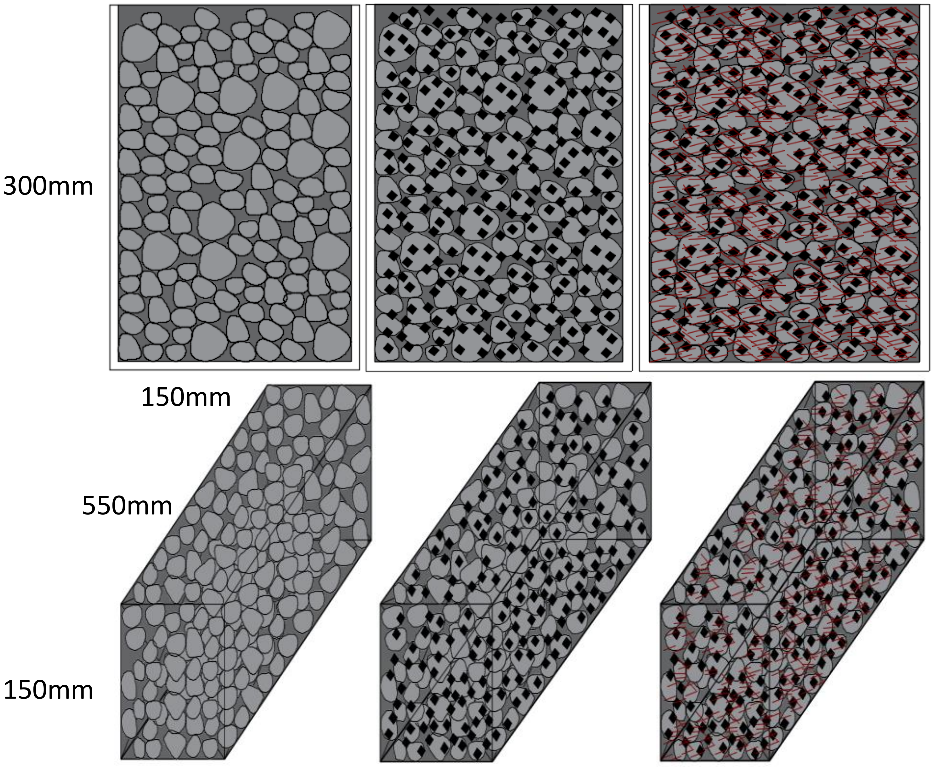

Figure 3.2: Schematic diagram of homogeneous distributions of recycled materials in prism and cylindrical formwork.

Figure 3.3: Preparation of cylindrical and beam specimens.

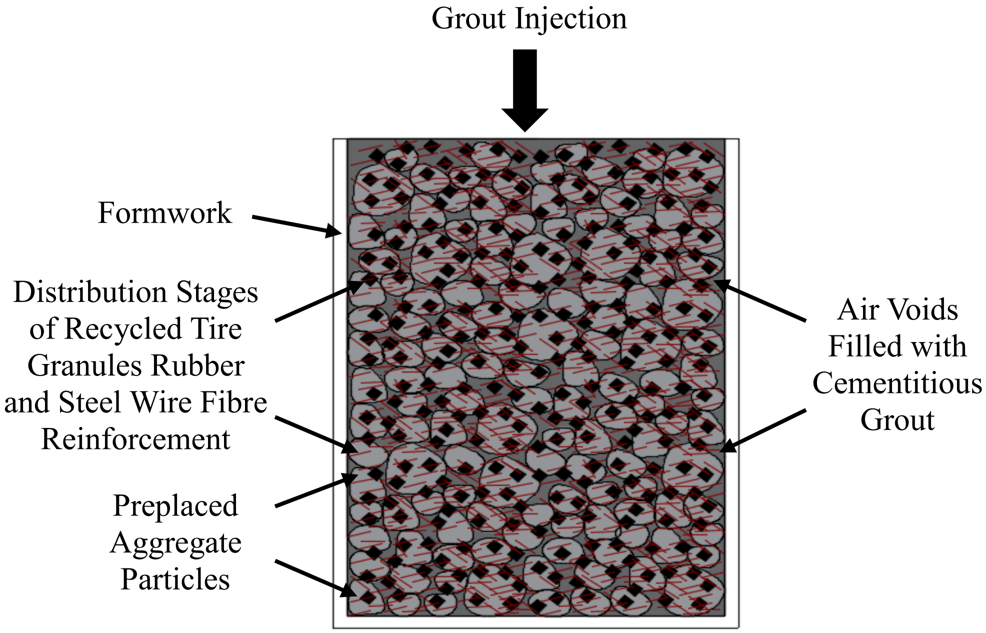

Figure 3.4: Schematic diagram of cementitious grouting process throughout the recycled stone aggregate and recycled tire waste stages.

3.3.4. Experimental Procedure

Figure 3.5 illustrates the test setup for the various tests. Compressive strength testing was conducted as per ASTM C943-2010 (Standard Practice Method for Making Test Cylinders and Prisms for Determining Strength and Density of Preplaced-Aggregate Concrete in the Laboratory). Tests were performed using an automated 2000 kN capacity testing machine. Splitting tensile strength testing was conducted in accordance with ASTM C496-2011 (Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens). The maximum load sustained by the specimen is divided by geometrical factors ($\pi l d/2$) to obtain the splitting tensile strength where *l* and *d* are the length and diameter of the specimen, respectively. The modulus of elasticity test was conducted in accordance to ASTM C469/C469M-2011 “Standard Test Method for Static Modulus of Elasticity of Concrete in Compression” using a Humboldt compressometer and a Forney calibrated load frame. The samples were tested to 40% of the ultimate compressive strength and the modulus was calculated as:

$$E = \frac{(S_2 - S_1)}{(\varepsilon_2 - 0.000050)} \qquad \textbf{Eq. 3.1}$$

where S_2 is the stress corresponding to 40% of the ultimate load of the concrete; $S_1$is the stress corresponding to a longitudinal strain of ε_1 at 50 millionths; and ε_2 is the longitudinal strain produced by S_2. The flexural strength was measured using the three-point bending method in accordance with ASTM C1609-2010 “Standard Test Method for Flexural Performance of Fibre Reinforced Concrete Using Beam with Third-Point Loading”. Results are calculated as the modulus of rupture:

$$R = \frac{PL}{bd^2} \qquad \textbf{Eq. 3.2}$$

where P is the maximum applied load; L is the span length; and b and d are the average width and depth of a specimen at fracture, respectively. For all tests above, three specimens from each mixture were tested at 28-day age and the average value was recorded.

Figure 3.5: Illustration of mechanical testing: (a) compressive strength; (b) splitting tensile strength; (c) modulus of elasticity; and (d) flexural strength.

3.4. Experimental Results

Table 3.3 summarizes the results of mechanical properties of eco-efficient, preplaced, recycled aggregate concrete mixtures investigated in this study. Experimental results are discussed below.

3.4.1. Compressive Strength

Figure 3.6 illustrates the average compressive strength of the 21 tested mixtures. The compressive strength decreased with the increasing level of waste tire rubber. The reduction rate varied between 9% and 28% depending on the replacement level. Incorporating waste steel-wires also decreased compressive strength likely due to the steel-wire obstructing the filling effect of the grout, leading to increased porosity. Interestingly, preplaced recycled aggregate concrete having a 25 MPa compressive strength could be achieved while incorporating up to 30% of tire rubber and 0.5% of tire steel-wire fibres, whereas a 20 MPa compressive strength could be achieved by incorporating up to 50% of tire rubber granules and 0.5% of steel-wires. This offers a highly eco-efficient option for the construction of multiple infrastructure works.

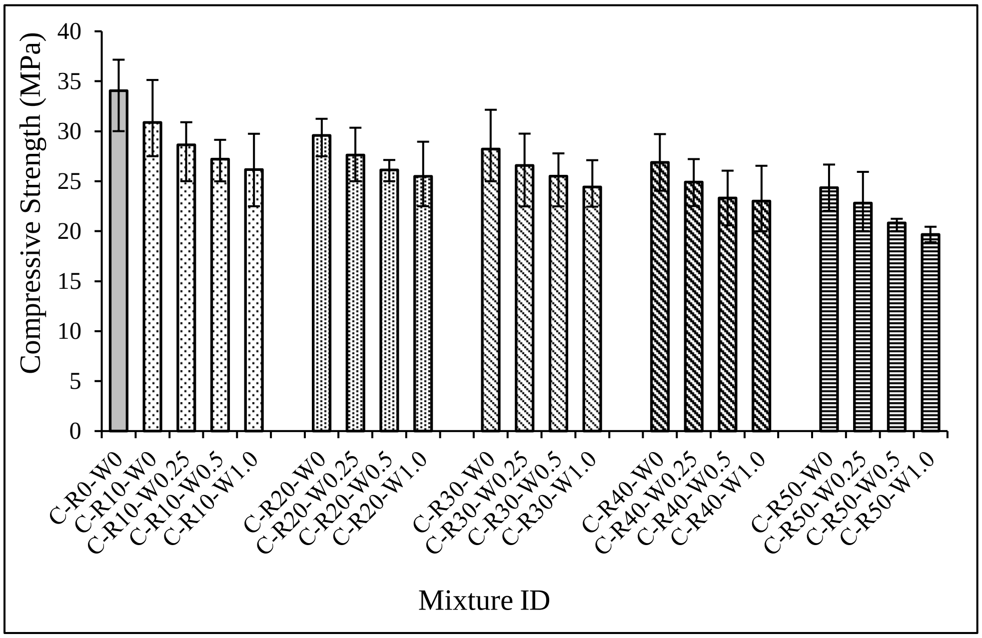

Figure 3.6: Average compressive strength for 21 cylindrical mixtures incorporating different percentages of recycled concrete aggregate, scrap tire rubber and steel-wire fibres.

3.4.2. Splitting Tensile Strength

Figure 3.7 illustrates the average tensile strength for the 21 tested mixtures. Splitting tensile strength also decreased with increasing percentages of waste tire rubber. The average splitting tensile strength of the control specimens was 5.12 MPa, and decreased to 4.75 MPa, 3.22 MPa, 2.94 MPa, 2.58 MPa, and 2.24 MPa when 10%, 20%, 30%, 40%, and 50% rubber tire was incorporated in the mixture, respectively. The corresponding reduction rate varied between 7% and 56%, which is approximately double the corresponding reduction rate of compressive strength at the same percentage of tire rubber. However, significant improvement in tensile strength was achieved when steel-wires were incorporated in the mixture. For instance, the average tensile strength of specimens with a 10% tire rubber increased from 4.75 MPa with 0% steel-wire fibres to 5.72 MPa with 1% steel-wire addition (increase of about 20%). A similar increase rate was observed for specimens made with 20% tire rubber, whereas specimens having 30%, 40%, and 50% tire rubber exhibited a rate of increase in tensile strength through a steel-wire addition of 25%, 38%, and 52%, respectively.

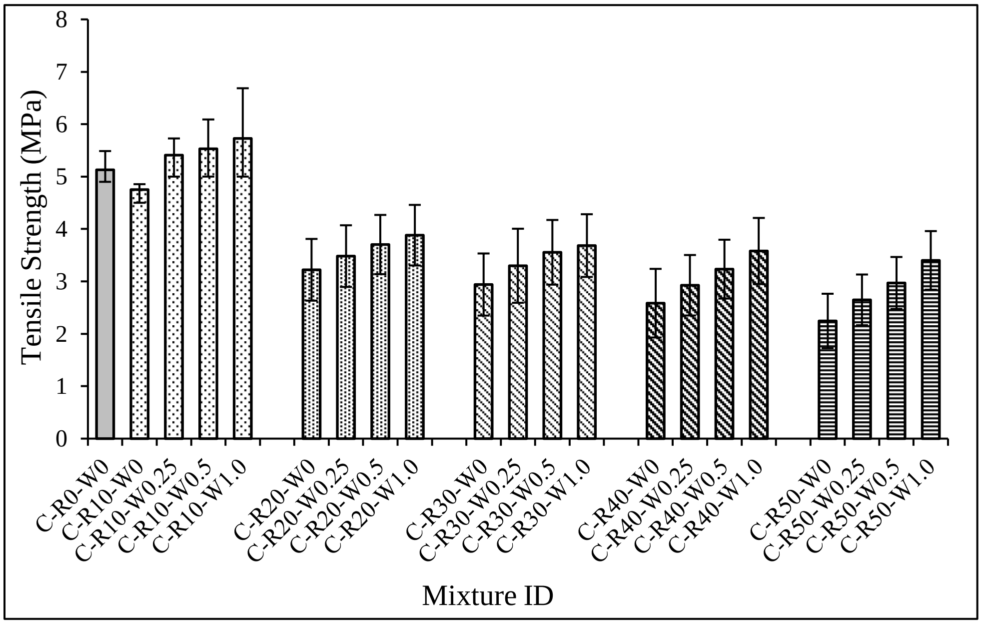

Figure 3.7: Average splitting tensile strength results for 21 cylindrical mixtures incorporating different percentages of recycled concrete aggregate, scrap tire rubber and steel-wire fibres.

3.4.3. Modulus of Elasticity

Since the modulus of elasticity is primarily affected by the concrete compressive strength and stiffness of aggregates, it has decreased with an increasing percentage of waste tire rubber as expected. The average modulus of elasticity of the control specimens was 41 GPa. This is a high modulus due to the fact that PAC has about an increased 50% coarse aggregate content than normal concrete. The modulus decreased by about 4% to 20% with an increased rubber content. The inclusion of waste steel-wire fibres also decreased the modulus due to the reduced compressive strength discussed earlier. **Figure 3.8** displays the average modulus of elasticity of the 21 tested mixtures. Preplaced recycled concrete aggregate with a 30 GPa modulus of elasticity could be produced while incorporating up to 50% of tire rubber and 0.25% of tire steel-wire fibres.

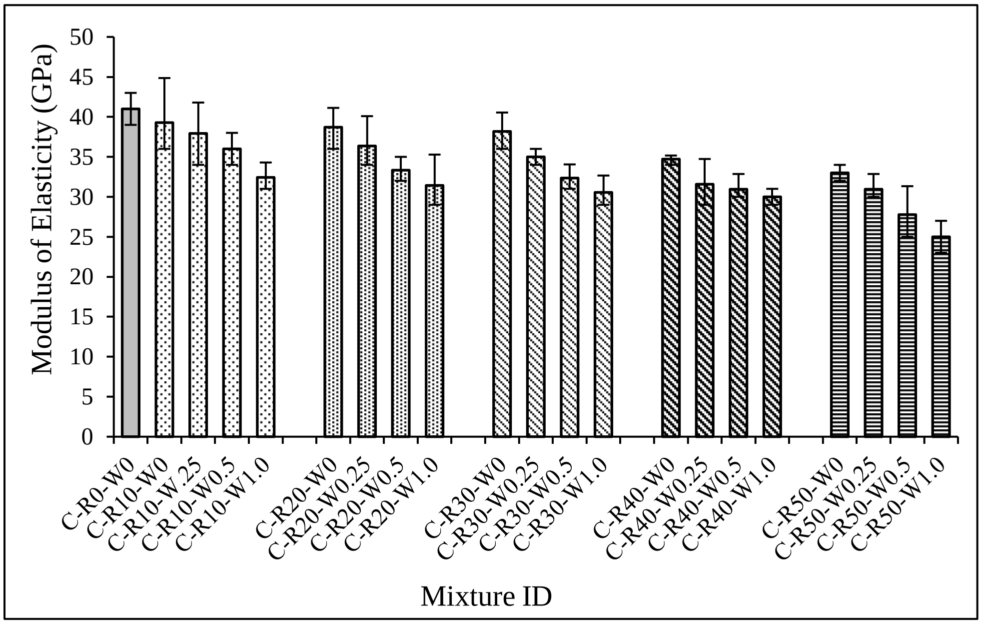

Figure 3.8: Average modulus of elasticity results for 21 cylindrical mixtures incorporating different percentages of recycled concrete aggregate, scrap tire rubber and steel-wire fibres.

3.4.4. Flexural Strength

The average flexural strength for the 21 tested mixtures is portrayed in **Figure 3.9**. The flexural strength decreased with an increasing percentage of waste tire rubber. The average flexural strength of the control specimens was 10.61 MPa, but decreased to 10.14 MPa, 7.75 MPa, 7.14 MPa, 6.32 MPa, and 4.46 MPa when 10%, 20%, 30%, 40%, and 50% of tire rubber tire was incorporated in the mixture, respectively, corresponding to a reduction of 4% to 58%. However, significant improvement in flexural strength was achieved when steel-wires were incorporated in the mixture. For instance, the average flexural strength of specimens with a 10% tire rubber content was increased from 10.14 MPa with 0% steel-wire fibres to 11.72 MPa with 1% steel-wire (about 16% increase). For specimens made with 20%, 30%, 40%, and 50% tire rubber, the flexural strength was increased by 21%, 23%, 17%, and 39%, respectively due to 1% steel-wire addition.

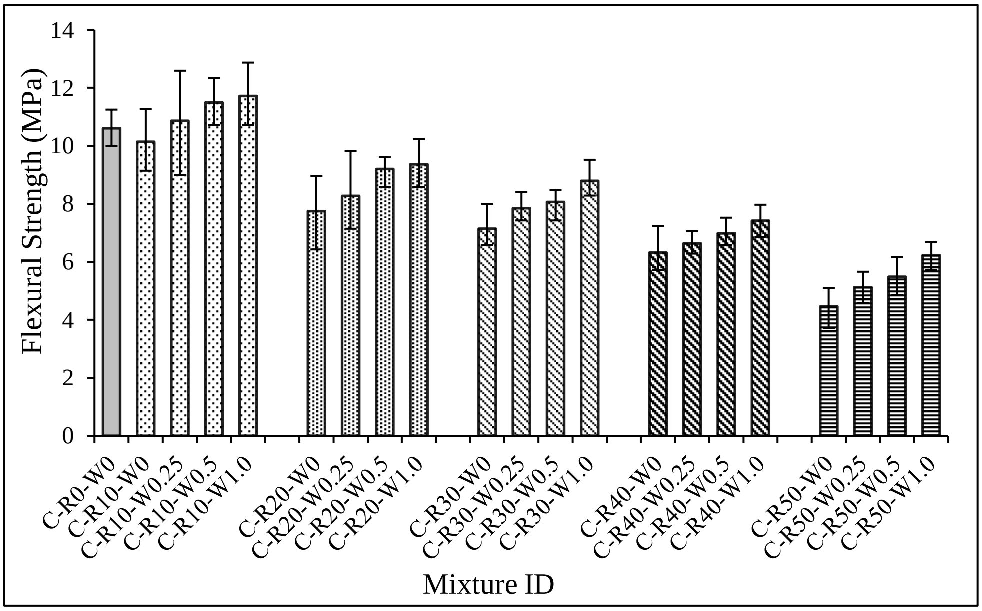

Figure 3.9: Average flexural strength results for 21 beam mixtures incorporating different percentages of recycled concrete aggregate, scrap tire rubber and steel-wire fibres.

Table 3.3: Mechanical properties of tested mixtures

Mixture ID	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Flexural Strength (MPa)
C-R0-W0	34.05	5.12	41.01	10.61
C-R10-W0	30.87	4.75	39.28	10.14
C-R10-W0.25	28.63	5.40	37.93	10.86
C-R10-W0.5	27.20	5.53	36.01	11.49
C-R10-W1.0	26.16	5.72	32.43	11.72
C-R20-W0	29.57	3.22	38.70	7.75
C-R20-W0.25	27.61	3.48	36.36	8.27
C-R20-W0.5	26.12	3.70	33.33	9.20
C-R20-W1.0	25.48	3.88	31.43	9.36
C-R30-W0	28.21	2.94	38.18	7.14
C-R30-W0.25	26.57	3.29	35.01	7.85
C-R30-W0.5	25.50	3.55	32.35	8.06
C-R30-W1.0	24.42	3.68	30.56	8.79
C-R40-W0	26.88	2.58	34.72	6.32
C-R40-W0.25	24.91	2.92	31.57	6.64
C-R40-W0.5	23.32	3.23	30.95	6.98
C-R40-W1.0	23.01	3.58	30.01	7.41
C-R50-W0	24.35	2.24	33.01	4.46
C-R50-W0.25	22.81	2.64	30.95	5.12
C-R50-W0.5	20.82	2.97	27.77	5.48
C-R50-W1.0	19.67	3.40	25.01	6.22

3.5. Discussion

Figure 3.10 synthetises the effects of the incorporation of rubber and steel-wire fibres from scrap tires on the compressive strength, splitting tensile strength, modulus of elasticity, and flexural strength of the preplaced, recycled aggregate concrete mixtures investigated in this study. The effect of tire rubber is presented with the value of the average results for mixtures incorporating 10%, 20%, 30%, 40%, and 50% tire rubber content without adding steel-wire fibres. The effect of incorporating steel-wire fibres is presented through the value of the average results for mixtures incorporating 0.25%, 0.5%, and 1% of steel-wire with different percentages of tire rubber.

The reduction in compressive strength, when tire rubber particles were added, can be attributed to the weak adhesion between rubber particles and the concrete matrix. It can also be attributed to the reduction of the load-carrying capacity due to the replacement of rigid recycled concrete aggregate by flexible granules. The elastic and thermal mismatch between the much softer rubber particles and the adjacent cementitious matrix enhances crack formation around the rubber particles, which induces premature failure (Nehdi and Khan, 2001; Zheng *et al*., 2008). Also, the high porosity and water absorption of the recycled concrete aggregate can enhance shrinkage stresses and decrease the effective water available for the cement hydration process. This consequently compromises the quality of the interfacial transition zone between aggregates and cement paste.

Using recycled tire wire as fibres reduced the compressive strength loss of the eco-efficient concrete mixtures, induced by rubber addition, owing to the role of recycled tire wires in resisting crack formation and propagation (e.g. Farnam *et al*., 2010; Graeff *et al*., 2012). However, fibres typically do not alter the compressive strength of fibre-reinforced concrete, unless fibre clustering and balling leads to reduce flow and increased porosity. In the present study, steel-wire fibres were preplaced and the only negative effect they could have is obstructing grout flow and filling. However, the mechanical strength of the eco-efficient concrete can be further increased using effective supplementary, cementitious materials, as a partial replacement for cement and chemical treatment of rubber particles, to alter its hydrophobic nature.

The negative effect of incorporating waste tire rubber in the cementitious matrix can be seen in the splitting tensile strength of the eco-efficient concrete that can be attributed to the weak bond between rubber particles and the cementitious matrix. This leads to the cracking and failure under the splitting tensile loading (Ganjian *et al*., 2009). However, the splitting tensile strength was significantly improved by incorporating steel-wires with some mixtures, exhibiting similar or higher tensile strength than that of the control mixture without rubber. The opening and propagation of micro-cracks can be controlled by steel-wire fibres along the fracture plane. Hence, energy absorption and toughness can be increased, making the eco-efficient concrete a strong contender for certain applications requiring high energy absorption (e.g. Graeff *et al*., 2012; Giedrius and Džigita, 2016).

As expected, implementing recycled tire rubber particles significantly reduced the modulus of elasticity as indicated in **Figure 3.10**. This is ascribed to be the very low elastic modulus of the added rubber particles (Turatsinze *et al.*, 2005; Onuaguluchi and Panesar, 2014; Ganjian *et al.*, 2009). In addition, the stiffness of the recycled concrete aggregate, which is typically lower than that of stiff natural stone aggregates, further influenced the modulus of elasticity. The use of steel-wire fibers reduced the drop in the modulus of elasticity imparted by rubber granules. As mentioned earlier, recycled tire wire fibres resist crack formation and arrest crack propagation, leading to improved stiffness.

The reduction in the flexural strength when tire rubber particles were added can be attributed to the weak interfacial transition zone between hydrophobic rubber particles and the grout matrix, leading to initiation and propagation of cracks around rubber particles (Najim and Hall, 2010; Xie *et al.*, 2015). In addition, relatively less angular recycled concrete aggregate has adverse effects on aggregate interlock, leading to weaker mechanical interlock. However, the addition of recycled tire steel-wires counterbalanced negative effects of tire rubber particles owing to their crack bridging mechanism. Thus, some mixtures exhibited similar to higher flexural strength than that of the control.

Figure 3.11 illustrates compressive stress strain curves at 28 days and represents the effect of waste tire rubber and waste steel-wires exhibiting the difference in ductility between specimens with no rubber or steel-wires and with those that are rubberized, and steel-wire reinforced. Control specimens had brittle failure. The addition of up to 20% rubber content did not alter such sudden and brittle failure, whereas higher rubber levels and steel-wire induced ductility changes the mode of failure from brittle to more ductile. Specimens with no rubber shattered into small pieces when it reached its peak load, while rubberized and steel-wire fibre-reinforced specimens were able to sustain loads beyond the peak load. When rubber particles offered with high-strain capacity inclusions are combined with the cross-crack stress bridging effect induced by steel-wires, they can increase ductility and toughness of concrete.

Figure 3.12 demonstrates the important role of incorporating waste tire rubber with steel-wires has on the failure mode of eco-efficient concrete specimens in compressive, tensile, modulus of elasticity, and flexural testing. Steel-wires increased the overall energy dissipation through arrested micro-cracks initiation and propagation. **Figure 3.13** illustrates displacement curves of specimens during flexural strength. Concrete specimens without rubber and steel-wires exhibited a sudden increase in deflection, accompanied by a reduction in load capacity after first crack. Conversely, rubberized and steel-wire reinforced specimens achieved a better post-crack flexural behaviour. Their enhanced load-deflection behaviour can be ascribed as rubber particles arresting cracks owing to its ability to sustain large elastic deformation, (Toutanji, 1996), and the crack bridging effect of steel-wire fibres can lead some mixtures to a strain hardening behaviour.

Toughness was evaluated for the tested mixtures, as the area under the load-deflection curves up to 3 mm as per ASTM C1609/C1609M-10. Flexural toughness index, which are defined as the ratio between the absorbed energy up to a given deflection to that at the first crack, were evaluated based on ASTM C1018 (Standard Test Method for Flexural Toughness and First-Crack Strength of Fibre-Reinforced Concrete-Using Beam with Third-Point Loading). The toughness chart (**Figure 3.14**) displays that incorporating recycled tire rubber particles and recycled tire wire improved toughness. Toughness results (**Table 3.4**) display that the overall toughness increased with an increasing steel-wire dosage. For example, the average toughness of specimens incorporating 30% rubber and 1% steel-wire was 16 times that of specimens made with 30% rubber and 0% steel-wire, and 22 times that of specimens made solely with 100% recycled concrete aggregates. The higher the flexural toughness indices, the higher is the ability of concrete to absorb energy (Zhang *et al.*, 2014). Generally, replacing recycled concrete aggregates with tire rubber particles enhanced energy absorption, owing to its elastic properties. The addition of recycled tire wire fibres further increased the required energy for crack growth, resulting in enhanced toughness (Graeff *et al.*, 2012).

Furthermore, the residual strength factor charts (**Figure 3.15**) show that specimens contained 0.5% and 1.0% steel-wire fibre achieved almost a higher residual strength. The residual strength values obtained from **Table 3.4** demonstrate the notable effect the specimens utilized with recycled tire waste obtained in the overall residual strength factors. For example, the R_{5-10} value increased significantly after adding 10% recycled tire rubber and 1.0% of recycled steel-wire content (C-R10-W1.0), which was found to be higher than that of the control specimen (C-R0-W0) by nearly 25.82%. The residual strength factor R_{10-20} in mixture 50% rubber and 1.0% steel wire (C-R50-

W1.0) achieved higher value than that of the mixture made with 10% rubber with the same steel content (1.0%) by 58.13%. By adding 1.0% recycled steel-wire in a 50% rubber mixture, the R_{20-30} factor has improved by 38.13%. This improvement ascribed to incorporating a higher percentage of steel-wire dosage absorbed higher energy. As a result, this exhibited higher residual strength due to the delay task in the early first crack (Yap *et al.*, 2014).

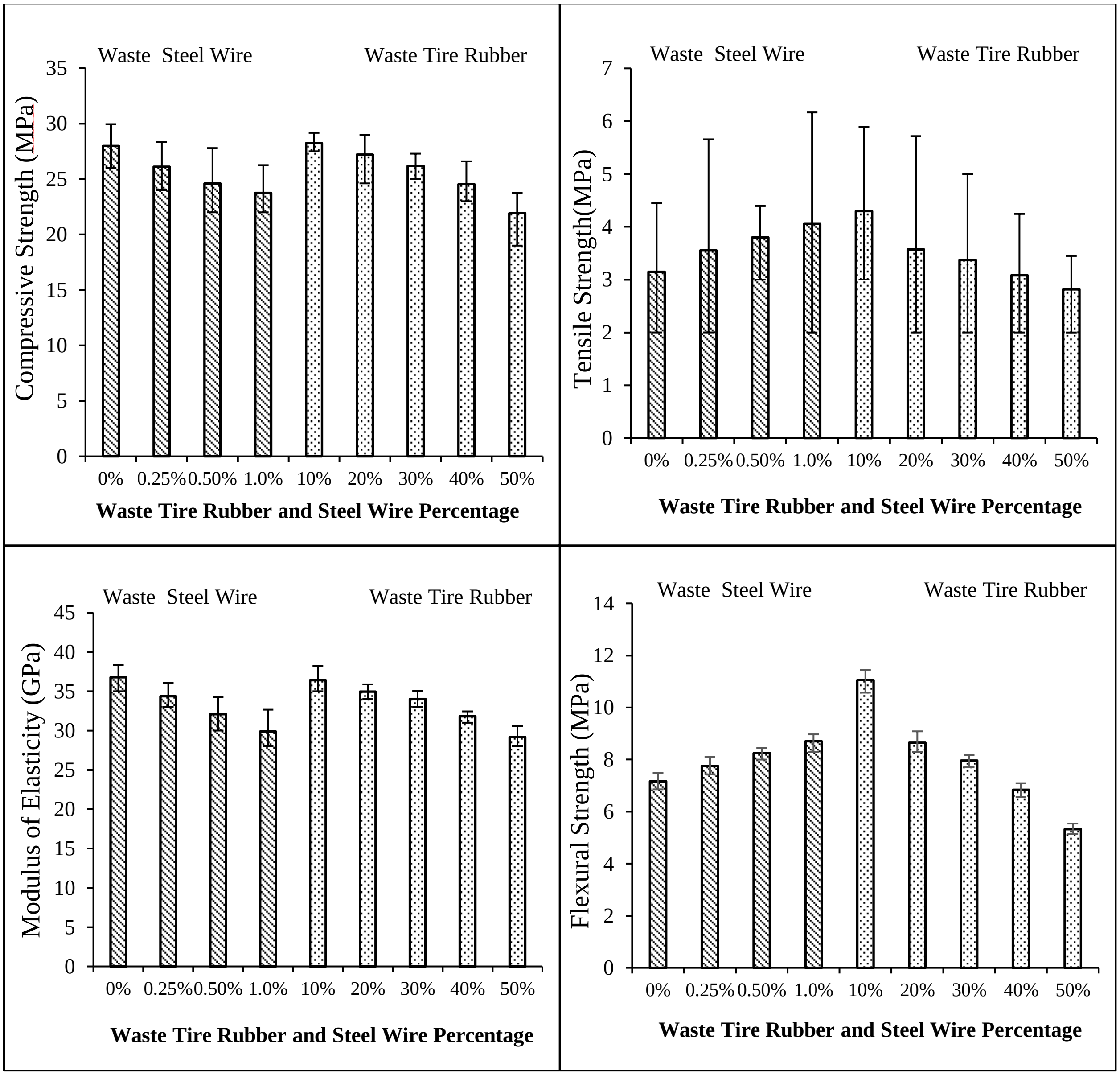

Figure 3.10: Effect of incorporating waste tire rubber and steel-wires on the mechanical properties of preplaced concrete mixtures using recycle concrete aggregate.

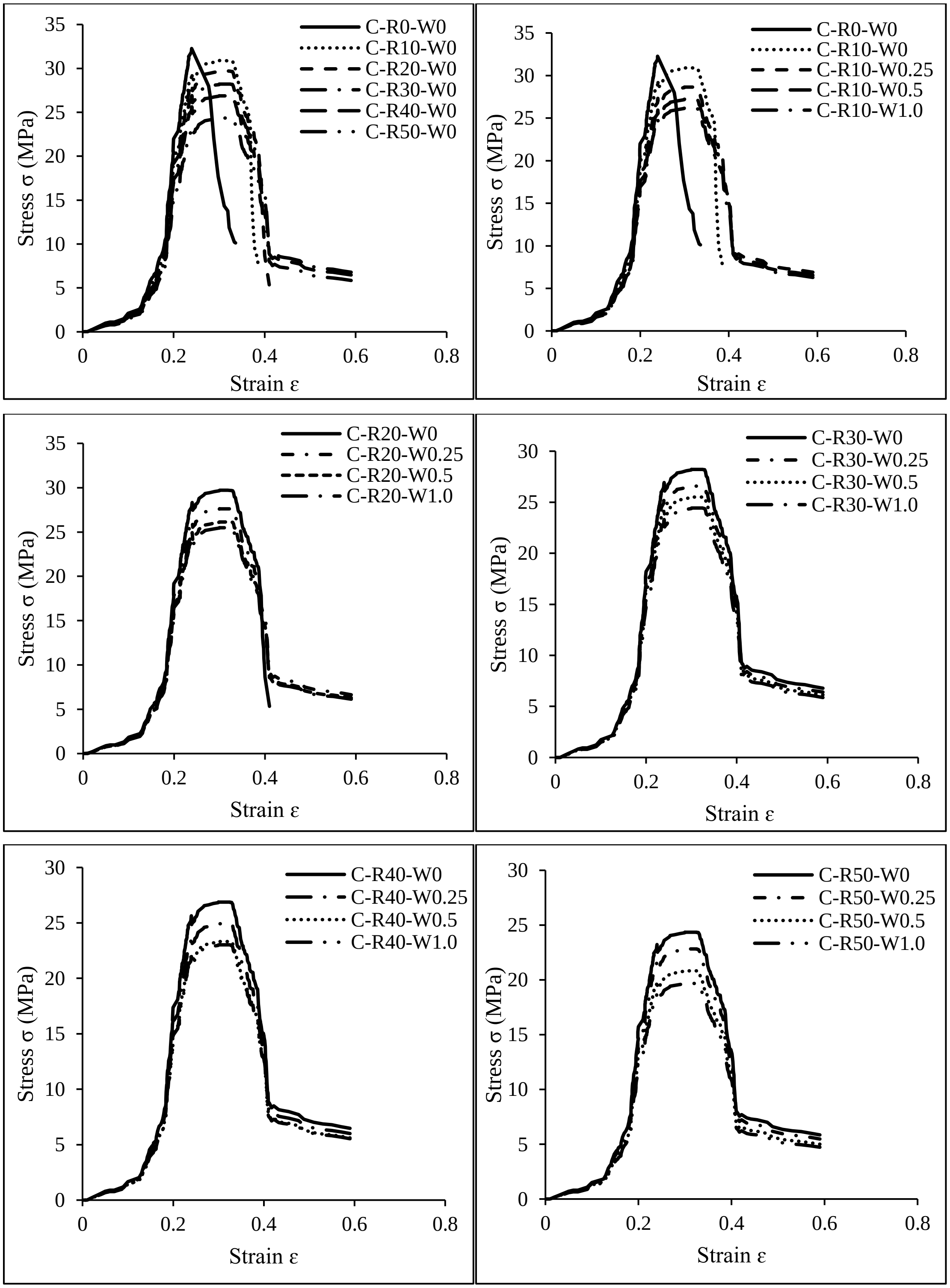

Figure 3.11: Stress-strain curves for cylindrical specimens incorporating different percentages of recycled concrete aggregate, scrap tire rubber and steel-wire fibres.

Figure 3.12: Failure mode of specimens with and without waste steel-wires in: (a) compressive testing; (b) modulus of elasticity testing; (c) splitting tensile testing; and (d) flexural testing.

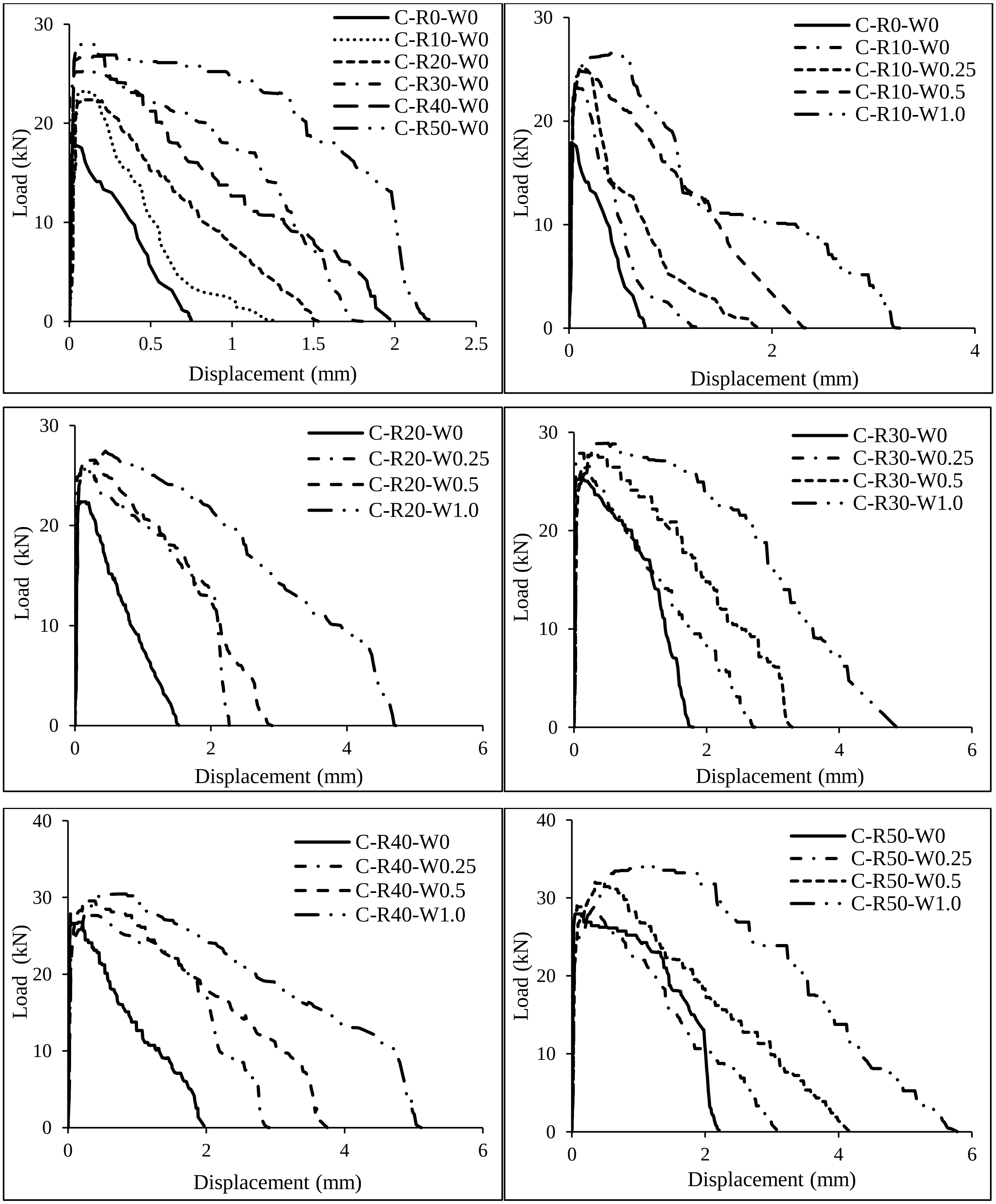

Figure 3.13: Load-deflection curves for beam specimens incorporating different percentages of recycled concrete aggregate, scrap tire rubber and steel-wire fibres.

Table 3.4: Toughness of tested beam mixtures

Mixture ID	First Crack Toughness (kN.mm)	Toughness Indices				Residual Strength Factors		
		I_5	I_{10}	I_{20}	I_{30}	R_{5-10}	R_{10-20}	R_{20-30}
C-R0-W0	1.302	5.594	9.783	12.884	16.090	83.787	31.008	32.054
C-R10-W0	2.489	6.740	10.042	14.118	17.218	66.046	40.758	31.001
C-R10-W0.25	3.999	7.777	11.378	15.892	18.580	72.035	45.135	26.878
C-R10-0.5	7.053	8.020	13.352	16.551	19.487	106.634	31.991	29.361
C-R10-W1.0	28.041	9.188	14.836	18.090	20.774	112.958	32.533	26.846
C-R20-W0	3.383	7.078	11.370	16.027	18.303	85.843	46.564	22.768
C-R20-0.25	1.421	8.198	12.604	16.821	19.149	88.117	42.164	23.287
C-R20-W0.5	8.468	9.011	14.117	18.393	20.206	102.121	42.763	18.126
C-R20-W1.0	25.854	10.098	15.637	19.579	21.831	110.768	39.424	22.519
C-R30-W0	1.789	9.692	13.585	16.824	19.965	77.852	32.394	31.406
C-R30-0.25	1.204	10.874	14.589	17.662	20.260	74.300	30.737	25.973
C-R30-W0.5	10.390	11.638	15.079	19.267	21.427	68.812	41.887	21.597
C-R30-W1.0	28.052	12.335	17.014	20.744	22.598	93.591	37.300	18.539
C-R40-W0	1.115	10.143	14.801	21.117	22.527	93.161	63.152	14.106
C-R40-0.25	1.425	11.890	15.524	21.621	24.138	72.669	60.969	25.176
C-R40-W0.5	10.284	12.743	17.326	23.302	25.083	91.665	59.759	17.808
C-R40-W1.0	26.398	14.607	18.482	23.972	28.729	77.499	54.896	47.578
C-R50-W0	1.232	10.757	15.654	24.740	27.330	97.956	90.853	25.902
C-R50-0.25	2.358	12.706	16.474	25.329	28.385	75.350	88.547	30.560
C-R50-W0.5	11.782	14.319	18.740	26.373	28.998	88.411	76.336	26.244
C-R50-W1.0	24.630	15.795	18.801	27.939	32.126	60.131	91.379	41.870

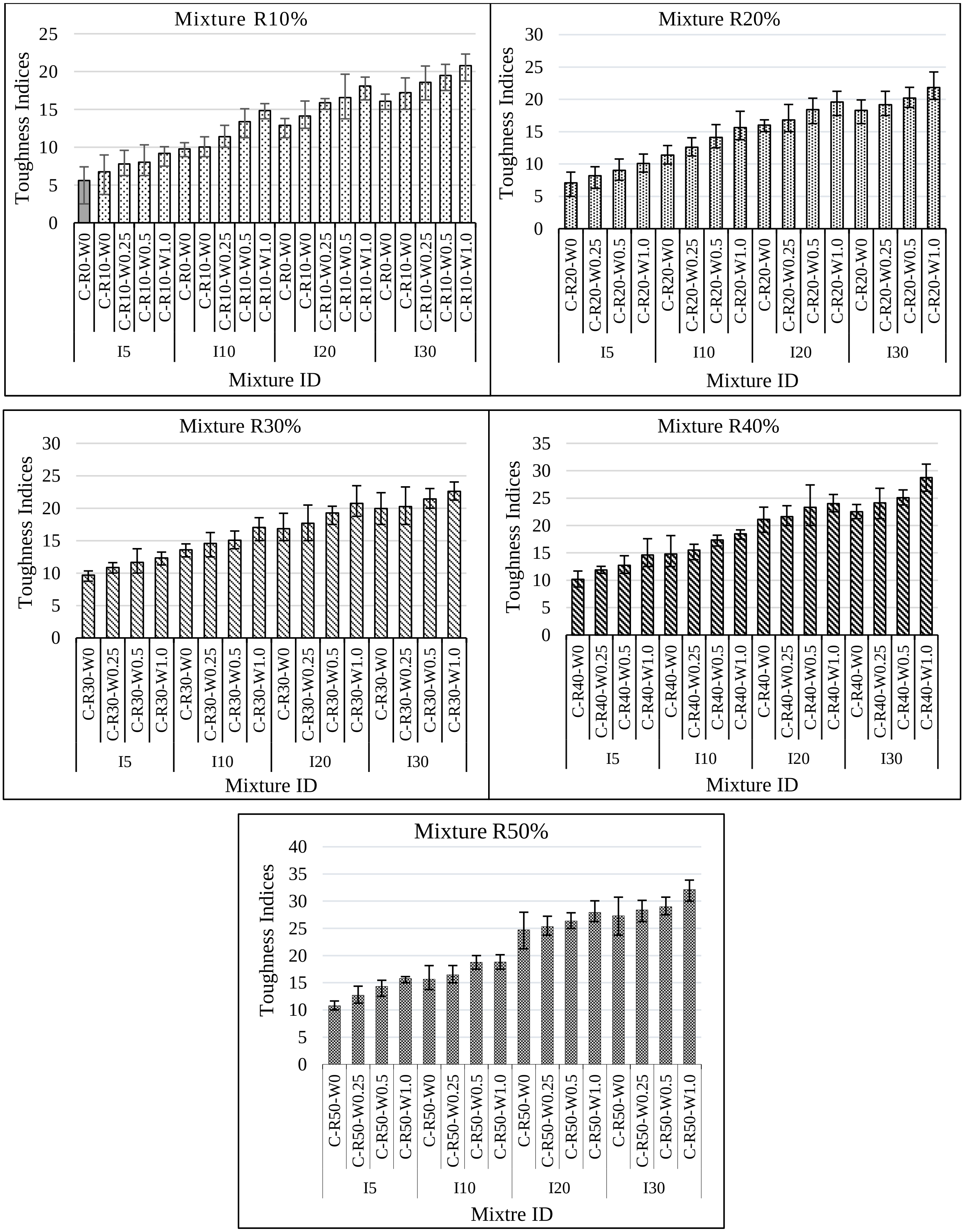

Figure 3.14: Toughness indices charts of tested beam mixtures.

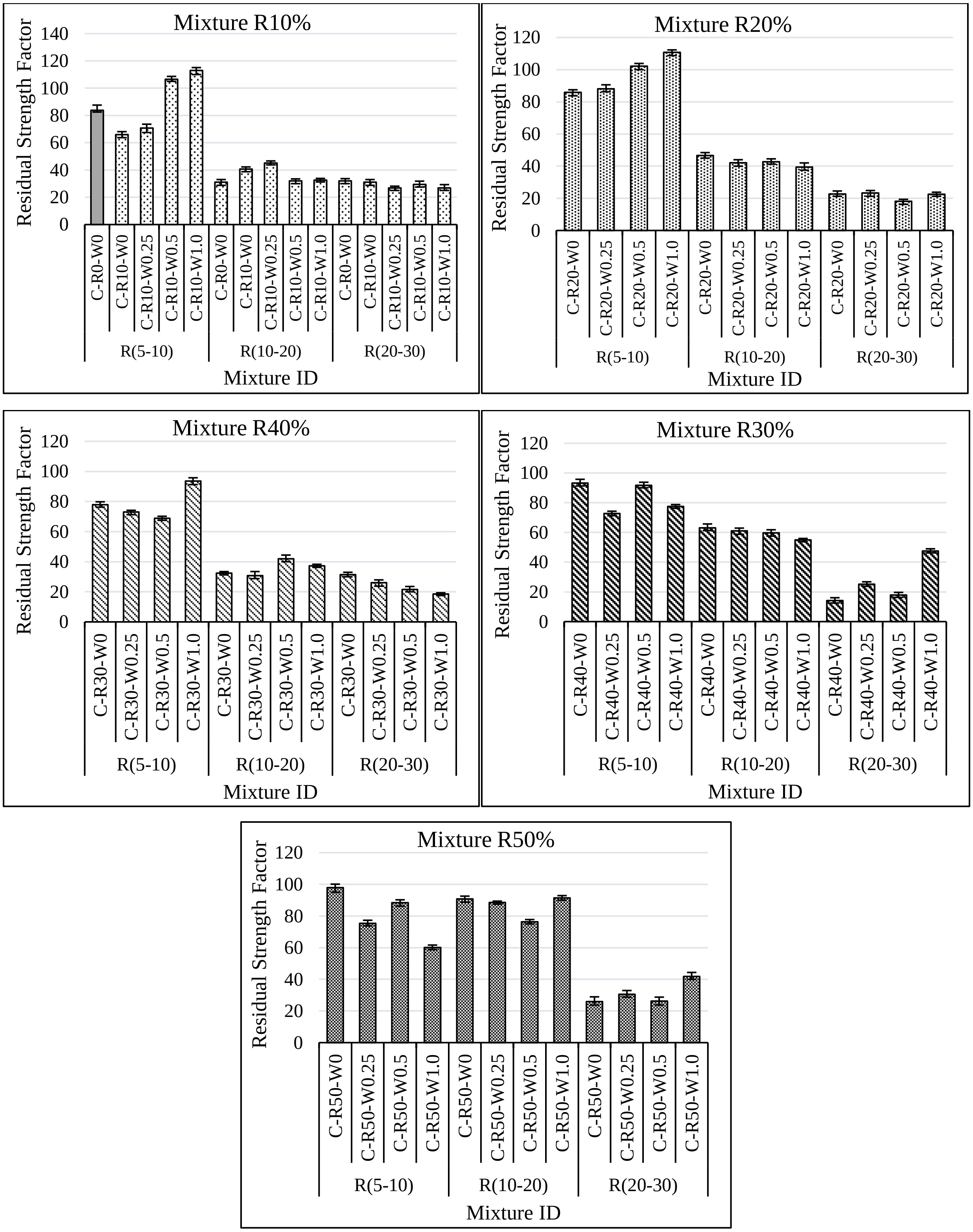

Figure 3.15: Residual strength factors charts of tested beam mixtures.

3.6. Concluding Observations

- This study explored the performance of eco-efficient, preplaced, recycled aggregate concrete incorporated with scrap tire rubber granules and tire steel-wire fibres. This material is intended to create ecological construction technology for sidewalks, pavements, crash barriers, building exteriors and partition walls that offer minimal material mixing and placement energy with a very high recycled content, minimal cementitious material dosage, and overall substantial labor and energy savings.
- Aggregates are preplaced and are not involved in materials mixing. The volume of preplaced aggregates is 50% higher than that in normal concrete, which reduces the need for cement, limiting green house gas emissions from cement production.
- The preplaced aggregate consists of recycled concrete aggregate and scarp tire granules, thus saving virgin aggregates. A self-leveling grout is injected with no need for mechanical vibration or compaction effort, which saves labour and energy.
- The preplacement technique eliminates the well-known negative effects of recycled concrete aggregate and tire rubber on the rheology and flow of concrete.
- Results indicate that incorporating tire rubber particles significantly decreased the mechanical properties as expected. The addition of steel-wire from scrap tires enhanced the tensile and flexural behaviour, limiting the drop in compressive strength and modulus of elasticity due to rubber inclusion, and improved the overall toughness and post-crack behaviour.
- Not only does this technology offer energy and cost savings, but also superior volume stability through high resistance to shrinkage and thermal cracking, owing to the dense skeleton of preplaced aggregates.
- Accordingly, the proposed eco-efficient technology can be implemented for making durable and sustainable concrete. Yet, there is still a need for further research to improve the strength of this eco-efficient concrete; for instance, through addition of effective cementitious materials.

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Chapter 4

4. EXPLORING BEHAVIOUR OF ECO-EFFICIENT PREPLACED AGGREGATE CONCRETE UNDER IMPACT LOADING

4.1. Introduction and Background

Concrete is the world's most widely used construction material. Over the past decades, reinforced concrete structures have been subjected to various extreme loading conditions, including impacts, explosions and earthquakes, which instigated several unexpected structural failures. This has escalated the impact load design requirements of concrete structures to mitigate such catastrophic failures (Adhikary *et al*.,2016; Alhadid *et al*.,2014; Remennikov and Kaewunruen,2006). Accordingly, the dynamic properties of concrete structural elements have to be investigated in order to acquire needed knowledge and data for structural safety specifications (Kennedy,1976; Li *et al*.,2005; Luccioni,2004).

The impact resistance of concrete is of utmost importance in infrastructure and underground design and construction (Murali *et al*.,2014). Concrete is naturally a brittle material that can be damaged by sudden impact, which could compromise the life span of concrete elements (Murnal and Chatorikar,2015). The brittle characteristic of concrete generally restricts its use in dynamic applications (Chen and May, 2009).

The concept of using fibers to reinforce brittle materials has been utilized for thousands of years. For instance, sunbaked straw-fiber-reinforced bricks were used to build the 57-m high hill of Aqar-Quf in Iraq (Hannant, 1995). Cement-based matrices have also been reinforced with asbestos and cellulose fibers over the past ninety years (Macvicar *et al*.,1999). Metallic, glass, and synthetic polymer fibers have also been used in reinforcing cementitious products for over seventy years (Hannant, 1995).

Many studies have demonstrated significant improvements in the impact resistance of concrete with the addition of metallic fibers (Ali *et al*.,2017). Fibre-reinforced concrete exhibited extraordinary advantages pertaining to impact resistance from the initial crack to final failure stages (Nili and Afroughsabet, 2010; Yildirim *et al*.,2010; Nia *et al*.,2012). Metallic fiber addition also enhanced fatigue, toughness and energy absorption capacity (Ali and Nehdi, 2017). Such benefits primarily emanate from the ability of fibers to arrest the initiation and propagation of cracks in cementitious matrices (Ali *et al*.,2017; Rao *et al*.,2012). Interest in the impact behaviour of fibre-reinforced concrete escalated rapidly, due to its increased ductile behaviour when compared to that of conventional concrete (Adhikary and Fujikake, 2015; Swamy and Jojagha, 1982). It is now well established that the process of concrete failure under stress depends on the fiber-matrix and aggregate-matrix bond, which control the crack pattern and mode of failure (Murali *et al*., 2014; Yew *et al*.,2011).

On the other hand, recycled rubber from scrap tires and other sources has provided promising properties to concrete under static and dynamic loading (Khalil *et al*., 2015). For instance, it was shown that rubberized concrete incorporating up to 20% of rubber content, as partial replacement for sand or cement, achieved adequate engineering properties (Al-Tayeb *et al*. 2012). It was also observed that incorporating 50 to 75% of crumb or chipped rubber, by volume of aggregate, enhanced the energy absorption properties in concrete (Reda-Taha *et al*., 2008).

Moreover, sources of natural aggregate have been depleting in many countries, and rock extraction has led to environmental damage worldwide (Vadivel *et al*., 2014). High demand of natural aggregate resources has contributed to the rise in cost of concrete construction (Abdullah *et al*., 2016). Hence, utilising recycled concrete aggregate and recycled rubber in concrete, as a full or partial replacement for natural aggregate, is an essential step towards the sustainability and eco-efficient management of by-products (Yehia *et al*., 2015).

Preplaced aggregate concrete (also known as two-stage concrete, referred to as TSC in the remainder of the text) has existed for several decades. Yet, its sustainability features have only been captured recently (Nehdi *et al*., 2017). TSC can be made by first placing the coarse aggregate, then injecting a cementitious grout to fill voids between aggregates. Recycled concrete aggregate and scrap tire rubber granules can be used as full or partial replacement for the coarse aggregate. This results in less mixing energy (only the grout is mixed), ease of placement and a minimal desire for pumping. Workability problems associated with the loss of slump due to the high absorption of recycled aggregate, buoyancy of lighter rubber granules, honeycombing and segregation are all prevented since the recycled aggregate and rubber granules are preplaced in the formwork. This results in a sustainable and low-cost construction (Nehdi et al., 2017).

Yet, there is still ongoing controversy regarding the efficiency of using recycled rubber granules in concrete production with regards to the associated drop in mechanical strength (Ismail and Ramli, 2016). Although various studies explored TSC in terms of its performance under static loading (Nehdi *et al*., 2017; Liu *et al*., 2012), there is a dearth of information on its performance under impact loads. Hence, in the present study, the impact resistance of sustainable TSC mixtures incorporating high recycled content (recycled concrete aggregate, scrap tire rubber granules and steel fibers from scrap tires) have been investigated. The main thrust of this study is to define sustainable concrete, not only in terms of its composition, but its eco-efficient placement technique as a green, minimal cost. Superior resistance to impact loading with a focus on developing novel alternative construction for pavements, road barriers, and other pertinent civil infrastructure is just one of the many features sustainable concrete can offer.

4.2. Experimental Program

4.2.1. Materials and Mixture Proportions

Type I Portland cement (OPC) with a surface area and specific gravity of 371 m^2/kg and 3.15 g/cm^3, respectively, in accordance to ASTM C150 (Standard Specification for Portland Cement), was used in the production of TSC. The chemical composition of the cement is given in Error! Reference source not found.. Micro-silica sand (SS) with maximum particle size and specific gravity of 200 µm and 2.65 g/cm^3, respectively, was also utilized. The laser diffraction particle size distribution curves for the OPC and SS are displayed in Error! Reference source not found.. Recycled concrete aggregate having 19-38 mm particle size with specific gravity measured as 2.60 g/cm^3 and water absorption of 2.0% was also used. Recycled granulated tire rubber was also utilized with a particle size ranging from (0.6-1.2) mm. Different TSC mixtures were prepared using the recycled granulated tire rubber with different percentages of 0%, 10%, 15%, and 20% by volume fraction. The different TSC mixtures were reinforced with recycled tire steel-wires having 20-45 mm in length and a mean diameter of 0.2 mm. The volume fraction of the utilized recycled tire steel-wires was 0%, 0.5%, 1%, and 1.5%. A poly-carboxylate high-range water reducing admixture (HRWRA) as per specifications of ASTM C494 (Standard Specification for Chemical Admixtures for Concrete) was added by the percentage of cement weight to control the workability of the different TSC mixtures. **Table 4.1** displays the proportions of the tested TSC mixtures with a target of 28-days compressive strength of 25 MPa. The first number in the mixture abbreviation relates to the recycled granulated tire rubber content, while the second shows the recycled tire steel-wire content. For example, TSC20-0.5 refers to a preplaced aggregate (two-stage) concrete incorporating 20% of recycled granulated tire rubber and 0.5% recycled tire steel-wires by volume fraction.

Table 4.1: Mixture proportions of TSC cylindrical mixtures

Mixture	Cement	Silica sand	w/cm	HRWRA	Tire rubber (%V_f)	Steel-wires (%V_f)
TSC0-0	1.00	1.00	0.45	0.0004	0.00	0.00
TSC0-0.5	1.00	1.00	0.45	0.0004	0.00	0.50
TSC0-1	1.00	1.00	0.45	0.0004	0.00	1.00
TSC0-1.5	1.00	1.00	0.45	0.0004	0.00	1.50
TSC10-0	1.00	1.00	0.45	0.0004	10.00	0.00
TSC15-0	1.00	1.00	0.45	0.0004	15.00	0.00
TSC20-0	1.00	1.00	0.45	0.0004	20.00	0.00
TSC10-0.5	1.00	1.00	0.45	0.0004	10.00	0.50
TSC15-0.5	1.00	1.00	0.45	0.0004	15.00	0.50
TSC20-0.5	1.00	1.00	0.45	0.0004	20.00	0.50
TSC10-1	1.00	1.00	0.45	0.0004	10.00	1.00
TSC15-1	1.00	1.00	0.45	0.0004	15.00	1.00
TSC20-1	1.00	1.00	0.45	0.0004	20.00	1.00
TSC10-1.5	1.00	1.00	0.45	0.0004	10.00	1.50
TSC15-1.5	1.00	1.00	0.45	0.0004	15.00	1.50
TSC20-1.5	1.00	1.00	0.45	0.0004	20.00	1.50

4.2.2. Mixture and Specimen Preparation

Premixed recycled concrete aggregate, recycled tire rubber and tire steel-wires were first placed at the bottom of the 150 mm x 300 mm cylinders as displayed in **Figure 4.1** and **Figure 4.2**. An electric cement mixer was used to dry mix grout solid ingredients including cement and silica sand for one minute. The mixing water and HRWRA were gradually added to the dry mixture over three minutes of mixing until a homogeneous mixture was achieved. Finally, the cementitious grout was injected into the forms and vibrated in order to fill gaps between granules. All specimens were demolded after 24 h and then placed in a 20 ± 2 °C curing room with a relative humidity of 95% for 28 days. All reported test results represent average values obtained on identical triplicate specimens.

Figure 4.1: TSC specimen preparation.

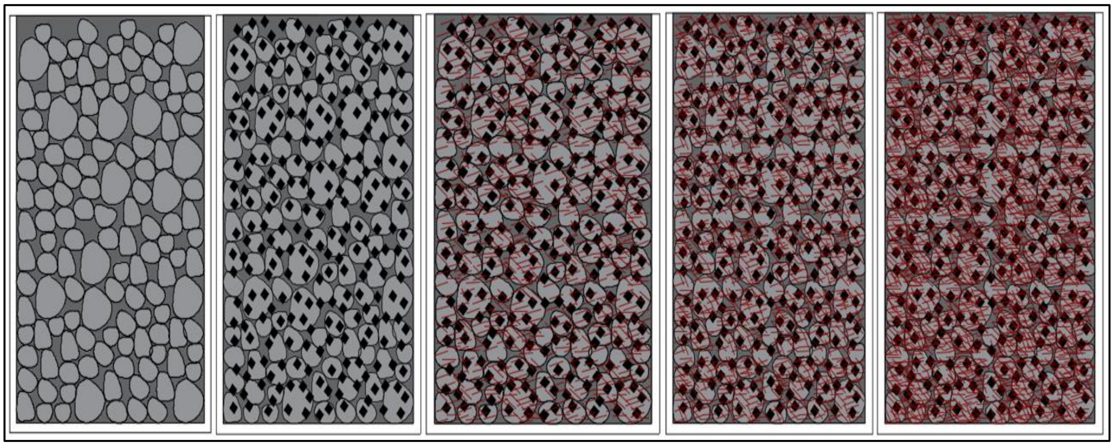

Figure 4.2: Overview of preplaced recycled concrete aggregate with scrap tire rubber granules and steel-wire TSC.

4.2.3. Test Procedures

For each TSC mixture, three 150 mm diameter by 300 mm in height cylindrical specimens were tested at the age of 28 days to determine the compressive strength, as per ASTM C39 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens), using a standard MTS compression testing machine with a capacity of 2000 kN. Similarly, three cylindrical specimens of 150 mm x 300 mm from each TSC mixture were tested at 28 days in order to evaluate the elastic modulus, according to ASTM C469 (Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression). The elastic modulus for all TSC mixtures was calculated using:

$$E = \frac{(Q_2 - Q_1)}{(\varepsilon_2 - 0.000050)} \qquad \textbf{Eq. 4.1}$$

Where E is the elastic modulus in GPa, Q_2 and Q_1 are stresses in MPa corresponding to 40% of the ultimate compressive load and a longitudinal strain of 50 millionths, respectively. $\mathcal{E}_2$, is the longitudinal strain produced by stress Q_2. Furthermore, three cylindrical specimens of 150 mm x 300 mm from each TSC mixture were tested at 28 days to obtain the splitting tensile strength, as per ASTM C496 (Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens). The splitting tensile strength was calculated as follows:

$$T = \frac{2*P}{\pi*l*d}$$ **Eq. 4.2**

Where T is the splitting tensile strength in MPa, P is the maximum applied load in Newton, l and d are the length and diameter of the cylinder in mm, respectively.

Drop weight impact testing was applied in compliance with guidelines of the American Concrete Institute (ACI) Committee 544. Each test specimen was adjusted in the testing setup and subjected to an impact loading in a 28-day period induced by a 4.5-kg impactor, dropped from a height of 457 mm above the cylindrical TSC specimen. This produced an impact energy of 20.167 J per hit, as shown in **Figure 4.3**. The number of applied impacts load to induce a first visible crack (N1) and failure (N2), respectively were recorded. The impact energy for each TSC specimen was evaluated according to ASTM D5628 (Standard Test Method for Impact Resistance of Flat, Rigid Plastic Specimens by Means of a Falling Dart) guidelines in the following equation:

$$IE = N_i.h.w.f$$ **Eq. 4.3**

Where IE is the sustained impact energy in Joule, Ni is the number of blows, h is the falling height of the steel mass in mm, w is the mass of the steel hammer in kg, and f is a constant with a value of 9.806×10^{-3}.

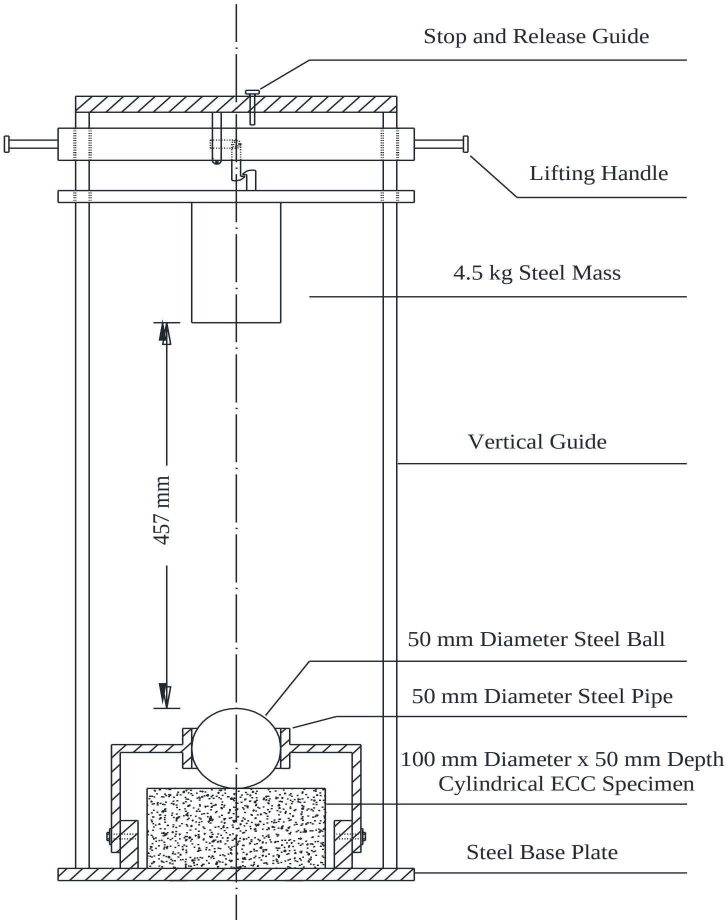

Figure 4.3: Schematic diagram of drop weight impact testing system.

4.3. Results and Discussion

4.3.1. Compressive Strength

Figure 4.4 a, **b** and **c** exhibit the variation in compressive strength for the different TSC mixtures at 28 days, which ranged from 25 to 34 MPa. Generally, steel fiber addition induced a slight decrease in the TSC's compressive strength due to a decreased efficiency of grout filling by fibre obstruction. For instance, the compressive strength of TSC0-0.5, TSC0-1, and TSC0-1.5 decreased by 5.1%, 6%, and 6.4%, respectively, as compared to that of the control TSC0-0 specimen. Likewise, recycled tire rubber addition decreased the compressive strength of the different TSC specimens. For example, the compressive strength of TSC10-0, TSC15-0, and TSC20-0 decreased by 10.4%, 12.5%, and 14.1%, respectively, when compared to that of the control TSC0-0. This can be attributed to the deformability of rubber granules. Incorporating a combination of recycled tire rubber and steel fibers in the TSC mixtures also induced reduction in the compressive strength observed in **Figure 4.4**.

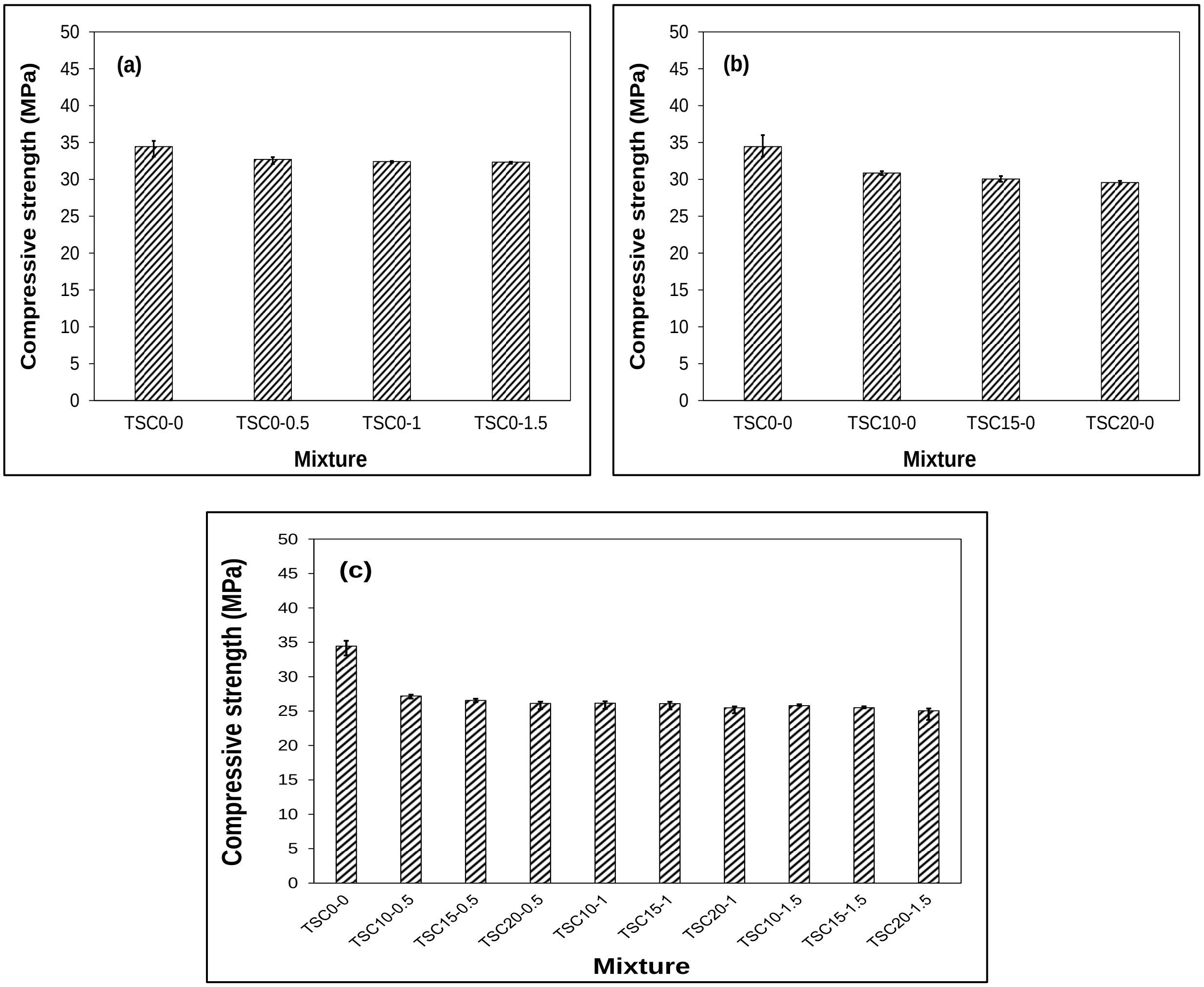

Figure 4.4: Compressive strength of different TSC specimens: a) steel-wires b) tire rubber, and c) steel-wire and tire rubber.

4.3.2. Elastic Modulus

The elastic modulus test results of TSC mixtures at 28 days are displayed in **Figure 4.5 a**, **b** and **c**. As expected, incorporating recycled tire rubber in TSC mixtures led to a significant reduction in elastic modulus when compared to that of the control TSC0-0 mixture. A similar trend was observed due to the combined rubber granules and steel fiber addition. For instance, the elastic modulus of TSC10-0.5, TSC15-0.5, TSC20-0.5, TSC10-1, TSC15-1, TSC20-1, TSC10-1.5, TSC15-1.5, and TSC20-1.5 specimens was reportedly lower than that of the control TSC0-0 specimens by about 21%, 23%, 24.5%, 24.2%, 24.5%, 26%, 25.1%, 26%, and 27.4%, respectively. The overall reduction in the elastic modulus of the TSC mixtures is ascribed to the low stiffness of rubber, and the reduced compressive strength is caused by increased porosity due to fiber addition.

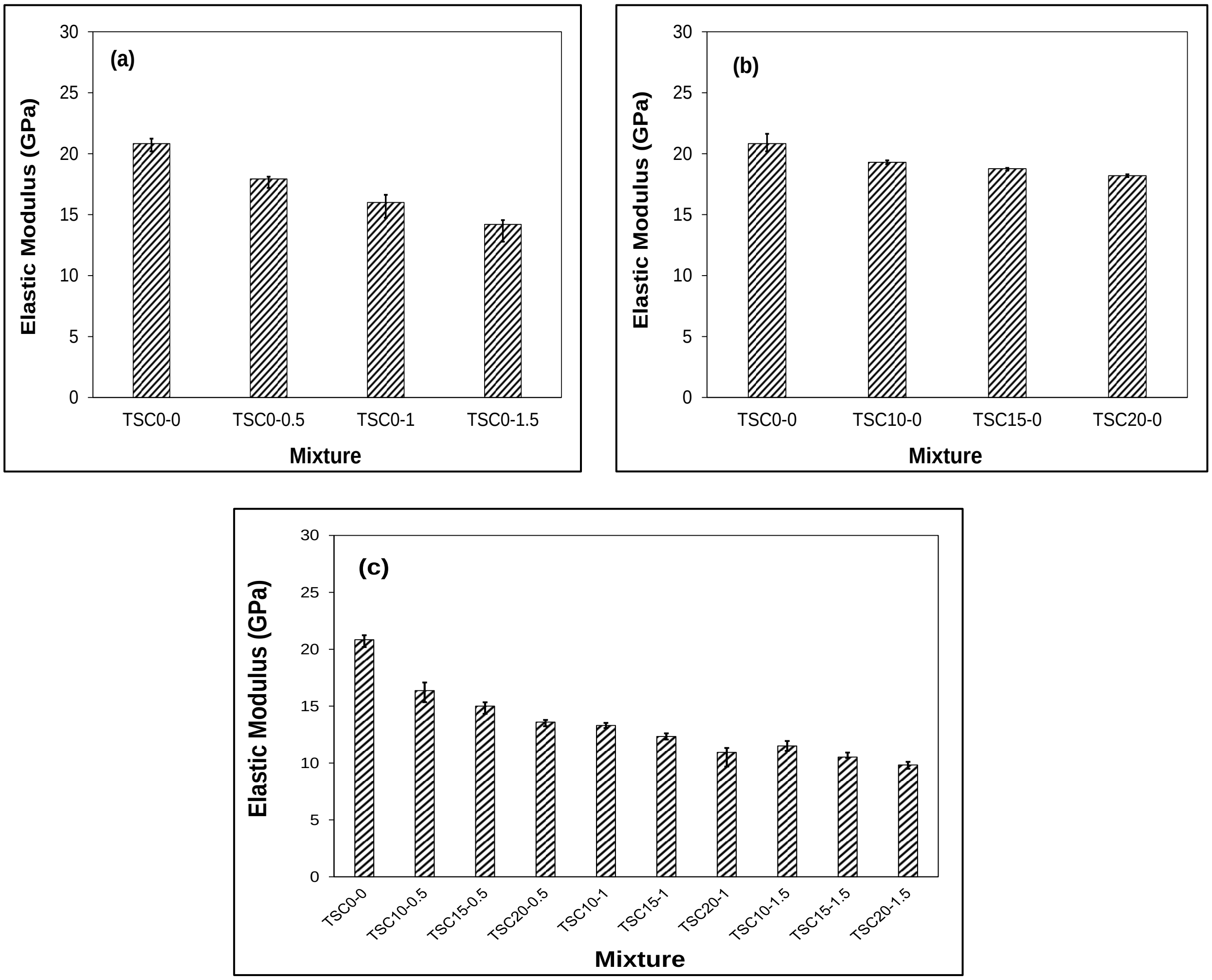

Figure 4.5: Elastic modulus of different TSC specimens: a) steel-wires b) tire rubber, and c) steel-wire and tire rubber.

4.3.3. Splitting Tensile Strength

Variation in the 28-day splitting tensile strength of the different TSC specimens are displayed in **Figure 4.6 a**, **b** and **c**. It ranged from 3.8 to 6 MPa, depending on the fiber type and dosage. It can be observed that the tensile capacity of the TSC specimens was enhanced due to scrap tire steel-wire fiber addition. For instance, the tensile capacity of the mixtures incorporating 0.5%, 1%, and 1.5% of steel fibre content increased by 44.7%, 50.8% and 60.5%, respectively, when compared to that of the control TSC0-0 mixture. This enhancement in tensile capacity is ascribed to the fiber-matrix interfacial bond, which enhanced the load transfer across cracks with increasing fiber content, thus improving the overall tensile load carrying capacity.

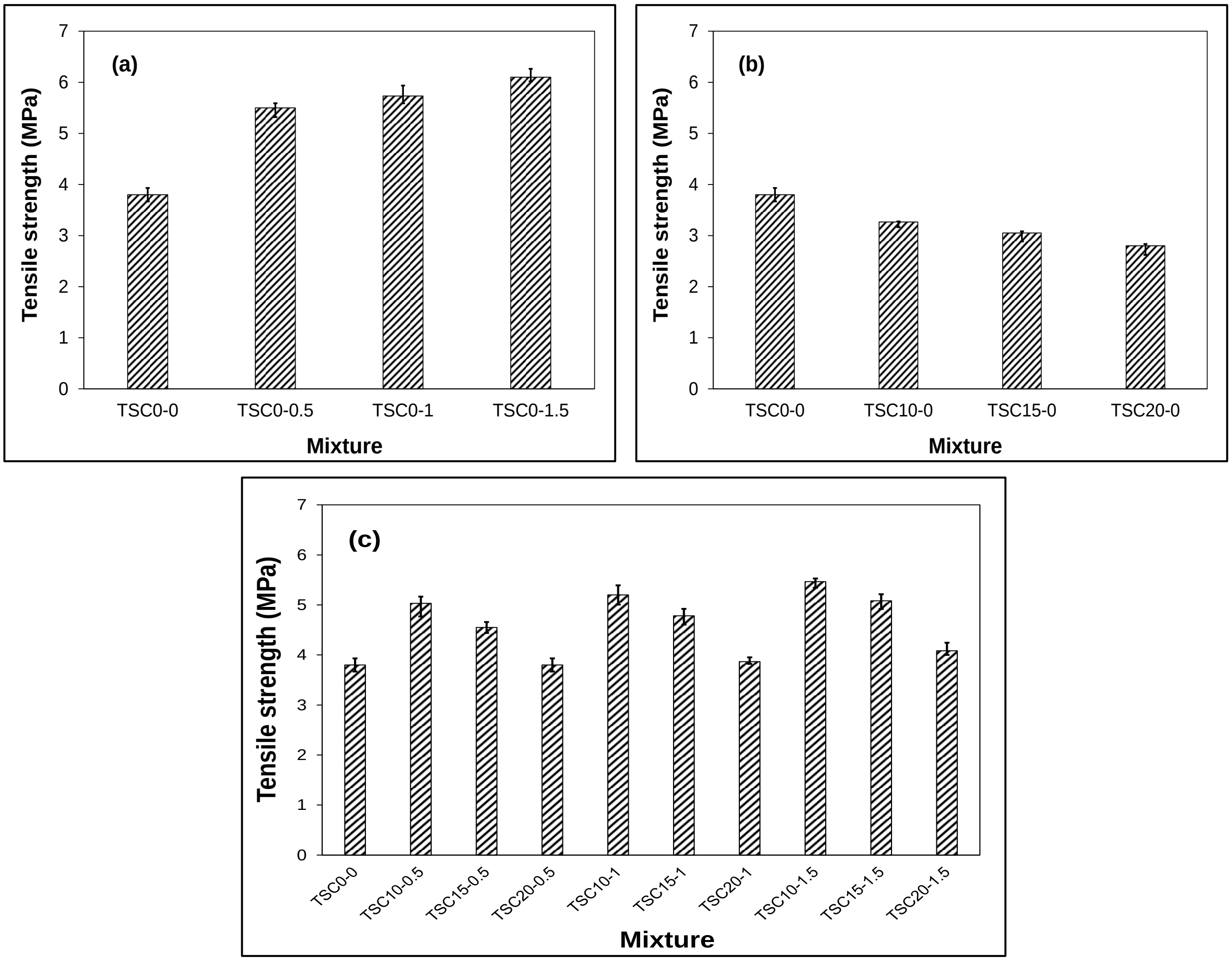

Figure 4.6: Tensile strength of different TSC specimens: a) steel-wires b) tire rubber, and c) steel-wire and tire rubber.

Conversely, recycled tire rubber addition induced reduction in splitting the tensile capacity of TSC specimens. For example, the tensile capacity of TSC10-0, TSC15-0, and TSC20-0 specimens decreased by 14%, 19.7%, and 26.3% as compared to that of TSC0-0, respectively. Yet, TSC specimens which incorporated a combination of recycled tire rubber and steel fiber exhibited superior tensile capacity when compared to that of TSC control specimen. For instance, the tensile capacity of TSC10-0.5, TSC15-0.5, TSC20-0.5, TSC10-1, TSC15-1, TSC20-1, TSC10-1.5, TSC15-1.5, and TSC20-1.5 specimens increased by about 32.5%, 19.7%, 3.7%, 36.8%, 25.8%, 5.7%, 43.9%, 33.7%, and 7.5% when compared to that of the control specimens, respectively.

4.3.4. Impact Behaviour

The behaviour of TSC specimens under impact load was determined through evaluating its resistance to a drop weight impact with accordance to ACI 544 guidelines. The impact energy sustained by the different TSC specimens up to first crack and up to failure is illustrated in **Figure 4.7**. Specimens from the fibreless control mixture (TSC0-0) failed after only one hit by the drop weight and split into multiple fragments, which reflects its brittle nature under impact loading. Similarly, TSC specimens, which incorporate tire rubber alone, followed a similar trend under impact loading, as shown in **Figure 4.7 b**. Conversely, steel fiber addition significantly enhanced the TSC's behaviour under impact loading by up to 40 times as compared to that of the fibreless and tire rubber TSC specimens. For instance, incorporating 0.5%, 1%, and 1.5% steel fiber in TSC specimens increased its impact resistance to reach first crack and failure by about 3, 4 and 5 in TSC0-0.5, TSC0-1 and TSC0-1.5 and 22,25 and 40 times than that of the fibreless TSC specimens TSC10-0, TSC15- and TSC20-0, respectively (**Figure 4.7 a**).This is attributed to the ability of steel fibers to restrain crack propagation in TSC specimens under impact loading, thus altering the mode of failure from brittle to more ductile. Furthermore, incorporating a combination of recycled tire rubber and scrap tire steel-wire fiber in TSC production only led to a slight increase in impact resistance up to first crack as compared to that of the fibreless TSC specimens (**Figure 4.7 c)**.

However, significant improvement in the failure impact energy of TSC specimens was achieved owing to the incorporation of tire rubber granules and scrap tire steel-wire fiber. For instance, the energy sustained up to the failure of TSC10-0.5, TSC15-0.5, TSC20-0.5, TSC10-1, TSC15-1, TSC20-1, TSC10-1.5, TSC15-1.5, and TSC20-1.5 specimens was improved by about 600%, 600%, 500%, 1000%, 700%, 700%, 1100%, 900%, and 800%, compared to that of the TSC control specimen, respectively (**Figure 4.7 c)**.

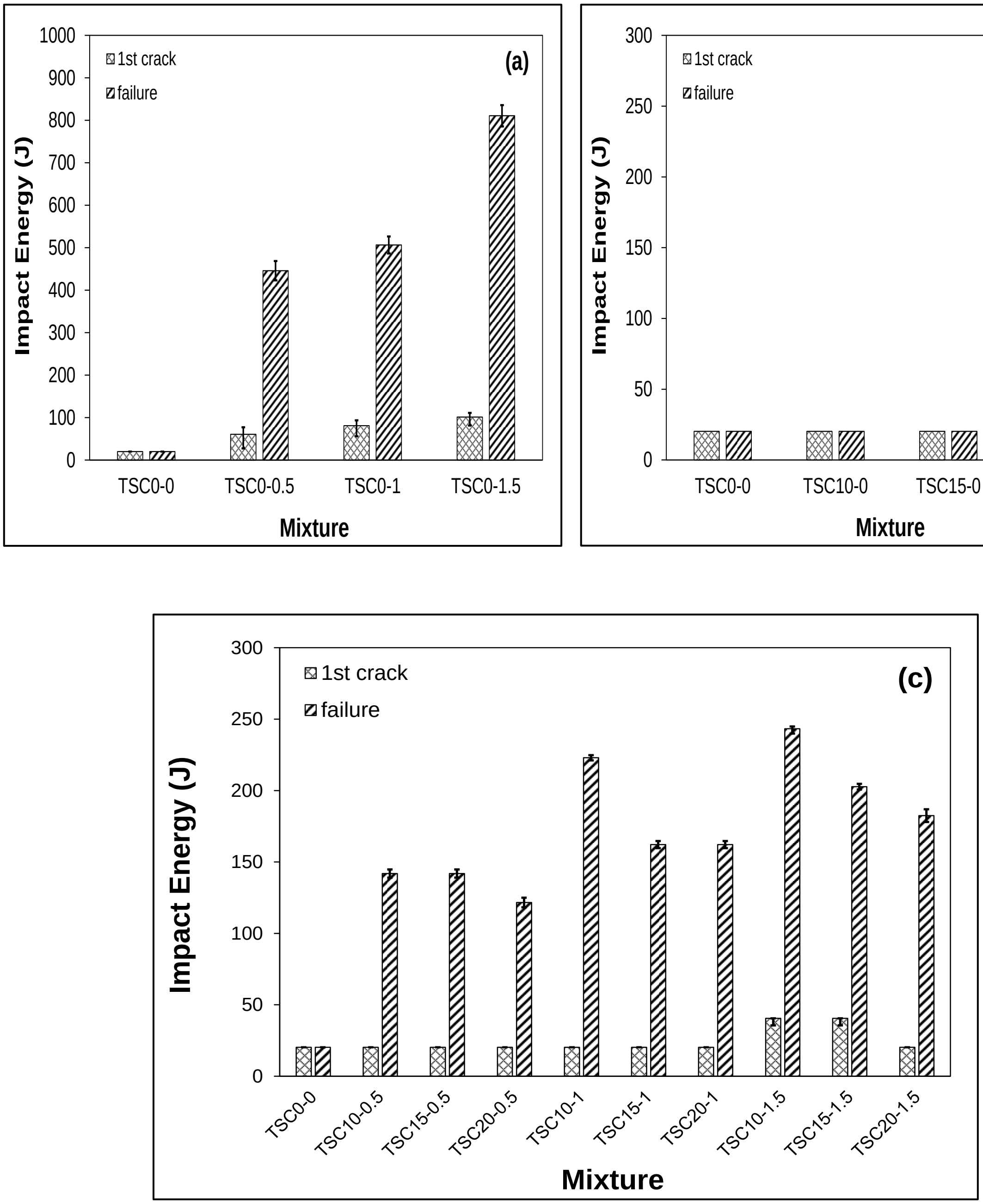

Figure 4.7: Impact energy sustained by different TSC cylindrical specimens: a) steel-wires, b) tire rubber, and c) combined steel-wire and tire rubber.

Generally, the tested specimens under impact loading suffered different failure patterns as displayed in Error! Reference source not found.. For instance, fibreless TSC control specimens exhibited brittle and sudden failure under a single impact. Incorporating tire rubber in TSC specimens led to a similar trend. Conversely, scrap tire steel-wire addition changed the mode of failure from brittle, characterised by a single crack, to ductile failure with the appearance of multiple cracking, as shown in **Figure 4.8 b**, **c**, and **d**. The number of cracks increased with an increasing steel-wire volume fraction within the mixture. This can be attributed to the crack arresting capability of steel-wires, which enhanced the ductile behavior of the TSC specimens under impact loading.

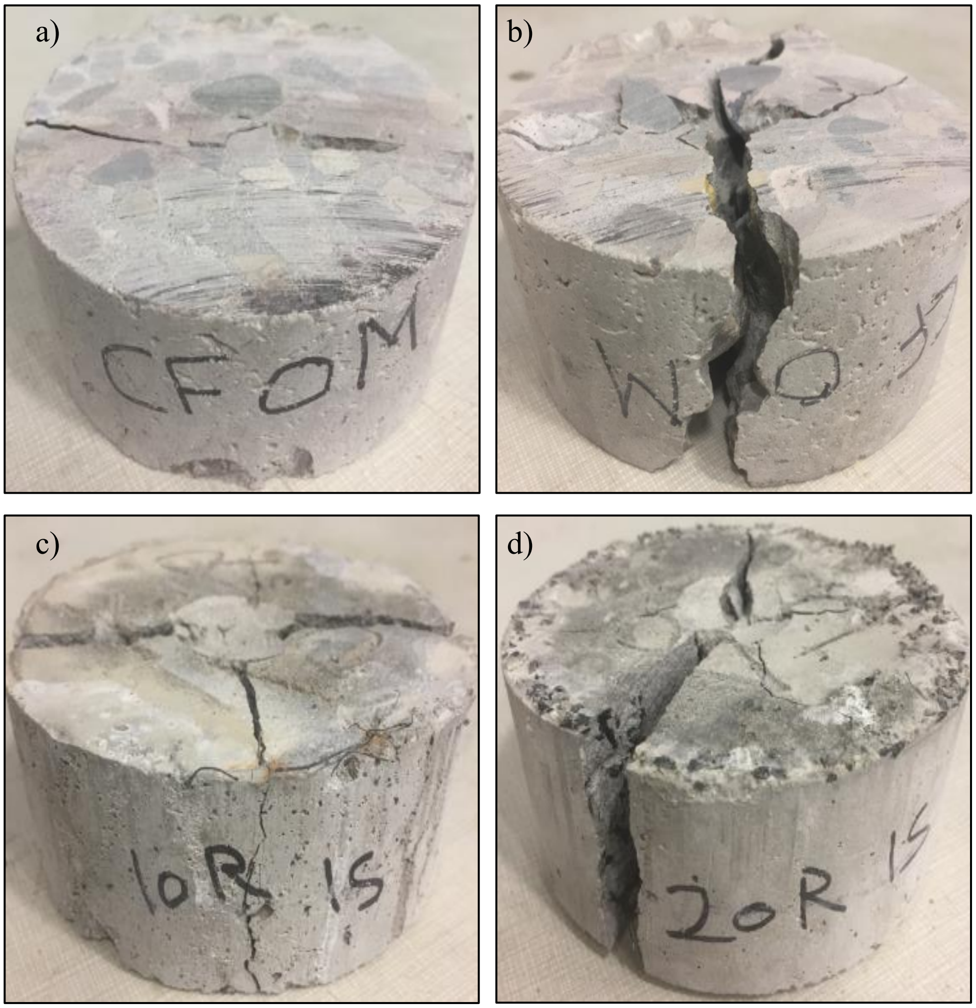

Figure 4.8: Failure pattern of TSC cylindrical specimens under impact loading: a) control, b) 0.5% steel-wire, c) 1% steel-wire, and d) 1.5% steel-wire.

4.4. Statistical Analysis

4.4.1. Analysis of Variance of Test Results

Experimental test results of concrete have been widely analyzed using different probabilistic models. Specifically, the analysis of variance (ANOVA) has been widely utilized (Ali *et al.*,2017; Ahmad and Alghamdi, 2014; Soliman and Nehdi, 2012). According to ANOVA, in order to investigate whether an experimental variable, such as steel fiber addition, is statistically significant, an F_o value is estimated and compared to a standard F value of an F-distribution density function, obtained from statistical tables based on the significance level (α_1), and the degrees of freedom of error, determined from an experiment using the number of variables and observations. Exceeding the critical value of an F-distribution density function indicates that the tested variable significantly affects the mean of the results (D.C. Montgomery, 2012). The F_o value can be calculated after estimating the sum of the squares of test results as follows:

$$SS_T = [\sum_{i=1}^{a} \sum_{i=1}^{n} y_{ij}^2] - [\frac{y_n^2}{N}] \qquad \textbf{Eq. 4.4}$$

$$SS_{Treatments} = [\frac{1}{n} \sum_{i=1}^{a} y_i^2] - [\frac{y_n^2}{N}] \qquad \textbf{Eq. 4.5}$$

$$SS_E = SS_T - SS_{Treatments} \qquad \textbf{Eq. 4.6}$$

Where SS_T is the total corrected sum of squares, $SS_{Treatments}$ is the sum of squares due to reinforcing the specimens (e.g. different steel fiber reinforcement ratios), SS_E is the sum of squares due to error (using replicates rather than testing only one specimen), a is the number of treatments (variables), n is the number of observations (specimens), y_{ij} is the jth observation taken under factor level of treatment i, and N is the total number of observations. The mean square of test data can be calculated as follows:

$$MS_{Treatments} = \frac{SS_{Treatments}}{a-1} \qquad \textbf{Eq. 4.7}$$

$$MS_E = \frac{SS_E}{N-a}$$ **Eq. 4.8**

Where $MS_{Treatment}$ and MS_E are the mean square due to treatments and error, respectively. The F_o value can be determined as the ratio of the mean square due to treatments to that obtained due to error as follows:

$$F_o = \frac{MS_{Treatments}}{MS_E}$$ **Eq. 4.9**

ANOVA at a significance level $\alpha_1 = 0.05$ indicated that the variation in the dosage of recycled steel-wire fiber had an insignificant effect on the mean value of the compressive strength of the TSC concrete. The obtained F_o value for the compressive strength results was 3.96, which is lower than that of the corresponding critical F value of 4.46 ($F_{0.05,2,8}$). Conversely, variation in the addition level of steel-wire fiber showed a significant effect on the splitting tensile strength and impact resistance of the TSC concrete. The determined F_o values for the splitting tensile strength and impact resistance were 31.87 and 117.6, respectively. On the other hand, incorporating tire rubber granules in TSC specimens indicated an insignificant effect on the mean value of the compressive strengths, splitting tensile strengths and the impact resistance of the TSC specimens with corresponding F_o values of 1.52, 2.1 and 2, respectively, which is lower than the corresponding critical $F_{0.05,2,8}$ value.

4.4.2. Weibull Distribution

Different probabilistic models have been utilized to statistically analyze the impact test data of concrete materials, among which the two-parameter Weibull distribution was widely utilized by many researchers for estimating the impact performance of concrete (Li et al., 2007; Sakin and Ay,2008; Bedi and Chandra, 2009). The Weibull distribution function is determined by a probability density function *f* (n) as follows:

$$f(n) = \frac{\alpha}{u}\left(\frac{n}{u}\right)^{\alpha-1} e^{-\left(\frac{n}{u}\right)^{\alpha}}$$ **Eq. 4.10**

Where α is the shape parameter (i.e. Weibull slope), u describes the scale parameter, and n is the specific value of the random variable N (i.e. N_1 and N_2 in this study). By integrating **Eq. 4.10, Eq. 4.11** can be determined as:

$$F_N(n) = 1 - e^{-\left(\frac{n}{u}\right)^{\alpha}} \qquad \textbf{Eq. 4.11}$$

Where $F_N\ (n)$ describes the cumulative distribution function. The probability of survivorship function is estimated using **Eq. 4.12** according to Saghafi *et al*. (2009):

$$L_N = 1 - F_N(n) = e^{-\left(\frac{n}{u}\right)^{\alpha}} \qquad \textbf{Eq. 4.12}$$

Equation 4.12 can be rewritten by taking the natural logarithm twice on both sides as follows:

$$ln\left[ln\left(\frac{1}{L_N}\right)\right] = \alpha ln(n) - \alpha ln(u) \qquad \textbf{Eq. 4.13}$$

In order to graphically estimate **Eq. 4.13**, the empirical survivorship function, L_N, for impact test data is determined from the following relation (Bedi and Chandra, 2009):

$$L_N = 1 - \frac{i-0.3}{k+0.4} \qquad \textbf{Eq. 4.14}$$

Where i is the failure order number, and k represents the number of data points. According to **Figure 4.9** and **Figure 4.10**, a linear regression analysis was applied to the *ln [ln (1/*L_N*)]* and *ln (impact energy)* values. The linear trend is established by drawing the best fit line between data points using the method of least squares. The slope of the line provides an estimate of the shape parameter (α) and the scale parameter (u), which can be determined by calculating the value at which the line intersects the *ln [ln (1/*L_N*)]* axis. The shape parameter (α), scale parameter (u) and the coefficient of determination (R^2) for the TSC specimens are presented in **Table 4.2**.

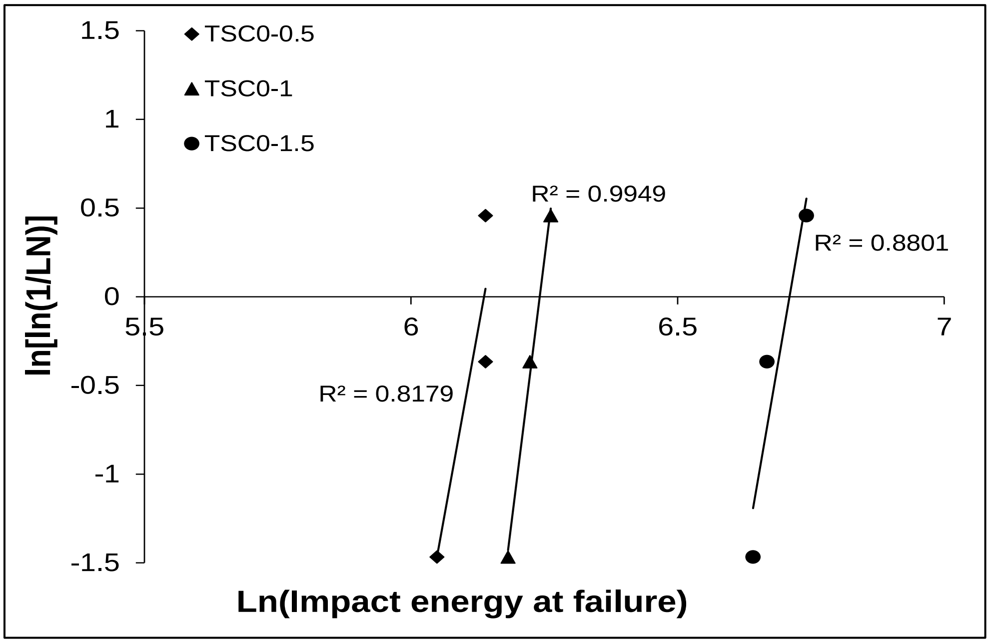

Figure 4.9: Weibull distribution of steel-wires for TSC cylindrical specimens.

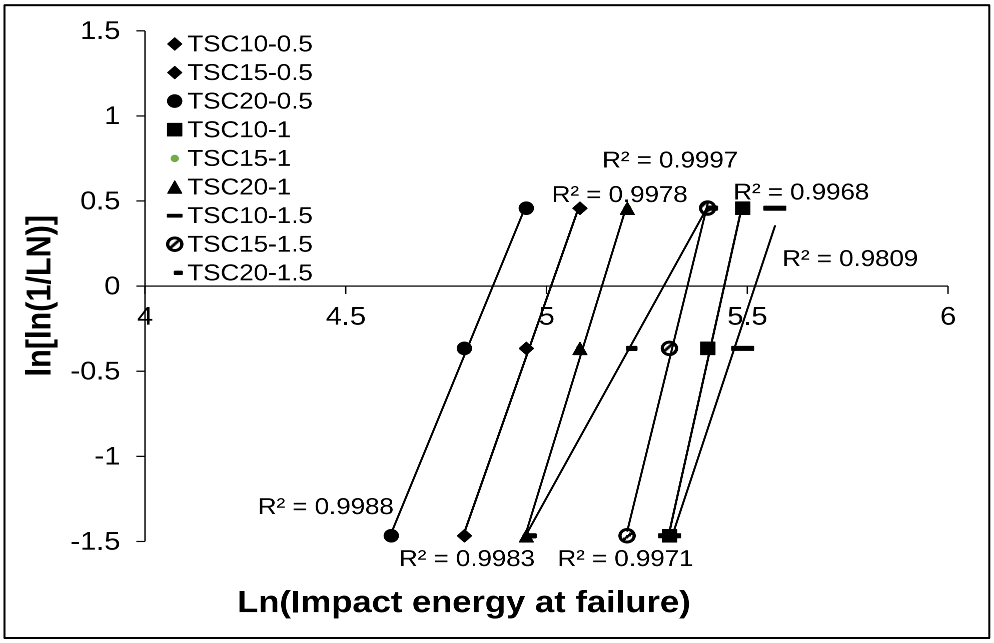

Figure 4.10: Weibull distribution of steel-wires and tire rubber for TSC cylindrical specimens.

Table 4.2: Shape, scale parameters and coefficient of determination of TSC specimens

Specimen ID	α	u	R^2
TSC0-0.5	16.632	-102.06	0.8179
TSC0-1	24.071	-150.2	0.9949
TSC0-1.5	17.447	-117.1	0.8801
TSC10-0.5	6.7033	-33.594	0.9983
TSC15-0.5	6.7033	-33.594	0.9983
TSC20-0.5	5.731	-27.89	0.9988
TSC10-1	10.575	-57.553	0.9968
TSC15-1	7.6731	-39.425	0.9978
TSC20-1	7.6731	-39.425	0.9978
TSC10-1.5	7.1142	-39.266	0.9809
TSC15-1.5	9.6084	-51.415	0.9971
TSC20-1.5	4.6243	-22.566	0.9997

The estimated impact energy values for TSC specimens at the failure stage are displayed in **Table 4.3** and **Table 4.4** based on reliability analysis. The first crack impact energy of TSC0-0.5, TSC0-1, and TSC0-1.5 specimens was approximately equal to or higher than 68.633, 89.147, and 109.544 J with R^2 of 0.9998, 0.9999, and 0.9994, respectively. Furthermore, the impact energy at failure of TSC0-0.5, TSC0-1, and TSC0-1.5 was approximately equal to or higher than 462.36, 513.64, and 820.585 J with R^2 of 0.8179, 0.9949, and 0.8801, respectively. As indicated by others (Rahmani *et al*., 2012; Chen *et al*.,2011), a coefficient of determination R^2 of 0.7 or higher is sufficient for a reasonable reliability model. Since all impact test data had R^2 equal to or higher than 0.8179, a two-parameter Weibull distribution can be used to estimate the statistical distribution of impact test results for TSC concrete. In addition, the developed reliability curves provide a useful tool to determine the impact resistance of TSC at first cracking and failure, without the need for costly and time-consuming additional impact testing.

Table 4.3: Weibull distribution for impact energy of steel-wires reinforced TSC specimens

Reliability Level	TSC0-0.5	TSC0-1	TSC0-1.5
0.99	350.647	424.295	630.411
0.90	403.857	467.803	721.298
0.80	422.496	482.616	753
0.70	434.579	492.112	773.516
0.60	444.067	499.511	789.607
0.50	452.292	505.885	803.542
0.40	459.945	511.784	816.499
0.30	467.558	517.623	829.378
0.20	475.79	523.902	843.291
0.10	486.146	531.756	860.781
0.01	506.835	547.291	895.667

Table 4.4: Weibull distribution for impact energy (J) of various TSC specimens

Reliability Level	TSC0-0.5	TSC10-0.5	TSC20-0.5	TSC0-0.5	TSC10-0.5	TSC20-0.5	TSC0-0.5	TSC10-0.5	TSC20-0.5
0.99	75.5889	75.5889	58.1972	149.5097	93.5563	93.5563	130.682	130.619	48.6716
0.90	107.324	107.324	87.6937	186.7112	127.078	127.078	181.828	166.807	80.9016
0.80	120.037	120.037	99.9621	200.4421	140.134	140.134	202.056	180.357	95.1556
0.70	128.736	128.736	108.487	209.5320	148.967	148.967	215.826	189.379	105.313
0.60	135.823	135.823	115.504	216.7714	156.106	156.106	227.003	196.593	113.819
0.50	142.15	142.15	121.822	223.1190	162.441	162.441	236.954	202.938	121.585
0.40	148.194	148.194	127.902	229.0859	168.458	168.458	246.434	208.919	129.149
0.30	154.355	154.355	134.143	235.0780	174.561	174.561	256.076	214.942	137.005
0.20	161.185	161.185	141.112	241.6197	181.29	181.29	266.74	221.534	145.88
0.10	170.031	170.031	150.212	249.9428	189.953	189.953	280.513	229.947	157.627
0.01	188.554	188.554	169.524	266.8744	207.911	207.911	309.219	247.148	183.117

4.5. Concluding Remarks

An experimental research was carried out to investigate the behaviour of sustainable preplaced aggregate concrete (TSC) under static and impact loading. The TSC concrete was made with recycled concrete aggregate and 0%, 10%, 15%, and 20% of recycled tire rubber granules, along with 0%, 0.5%, 1% and 1.5% (by volume fraction) of recycled steel-wire fibers from scrap tires. The Weibull distribution function was used to develop a reliability-based model for predicting the impact behaviour of the sustainable TSC. The conclusions below can be drawn:

- As expected, the compressive strength of TSC specimens decreased due to tire rubber addition. Steel-wire fiber addition did not have a significant effect on compressive strength.

- Generally, the tensile strength of the sustainable TSC specimens was significantly enhanced, owing to the recycled steel-wire fiber addition. ANOVA confirmed that incorporating steel fiber in the TSC mixtures had a significant positive effect on the tensile capacity of the TSC. Among all tested specimens, TSC incorporating no tire rubber and 1.5% of steel fibre content achieved highest tensile capacity.

- The behavior of TSC specimens subjected to impact loading was enhanced by 22 to 40 times compared to that of the fibreless TSC specimens owing to the addition of steel fiber. However, incorporating tire rubber granules in TSC decreased its impact performance.

- The Weibull distribution function achieved an adequate capability of representing the impact test data of TSC with a linear correlation between the numbers of impacts, which initiated ultimate failure for all TSC specimens.

- The behavior of sustainable TSC under impact loading demonstrates the need for further research to develop sustainable concrete with superior tensile properties and impact resistance for the protection of infrastructures in the event of unexpected severe loading conditions.

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Chapter 5

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1. Summary and Conclusions

In view of the growing global demand for sustainable construction materials and "green" concrete structures, this study introduces preplaced, recycled aggregate concrete (PAC), also known as two-stage concrete (TSC), a type of concrete made primarily of recycled concrete aggregate and tire waste materials. This dissertation explores the engineering properties of PAC with a view of determining opportunities of full-scale implementation.

In **Chapter 2**, a review of recent developments of PAC has been provided, along with a discussion of scrap tire recycling practice. Interest in green concrete technology has recently escalated simultaneously with the need for recycling tire wastes worldwide. The main thrust is to contribute to reducing the colossal quantity of disposed tires, to preserve natural aggregate resources, and to attain impactful outcomes of utilizing waste materials in concrete production. Reusing recycled concrete aggregate has been highlighted in this chapter. Recycled concrete aggregate from demolished structures has gained noteworthy attention in recent years as a potential replacement for natural virgin aggregates to produce eco-efficient concrete. Indeed, recycled concrete aggregate and recycled tire wastes have shown great potential to produce PAC, which can be achieved by selecting adequate cementitious grout proportions.

In **Chapter 3**, the experimental implementation of the vision identified in Chapter 2 has been first pursued by presenting the production procedure of 189 (150 ×300) mm cylindrical specimens and 63 (150 × 150 × 550) mm prismatic beams of PAC containing recycled concrete aggregate (19-38 mm in size) to meet the sustainability goals in this dissertation. The recycled aggregate was provided by a recycling firm which specializes in beneficiating construction materials from demolished or renovated landscapes and buildings. Moreover, recycled tire granulated rubber particles (size: 6-12 mm) were used in PAC at dosages of 10%, 20%, 30%, 40% and 50% by volume of coarse aggregate, along with recycled tire steel-wire cord as fibre reinforcement with dosage of 0.25%, 0.5% and 1.0% (wire fibre length: 20-45 mm, diameter: 0.2mm) by volume fraction. A high flow-ability cementitious grout was developed and injected in the PAC formwork.

It incorporates ASTM C150 Type I ordinary portland cement (OPC), micro-silica sand, and a high-range water-reducing admixture (HRWRA) added to the mixing water to adapt the flow and workability. The sand to binder ratio (s/b) and water to binder ratio (w/b) were 1.0 and 0.45, respectively. The selected and injected cementitious grout proportions boosted flow-ability and effectively filled voids within the aggregate skeleton with the presence of high percentage of tire waste materials.

The effects of recycled tire wastes on the mechanical behaviour of the eco-efficient concrete under static load were discussed in **Chapter 3**, including compressive strength, splitting tensile strength, modulus of elasticity and four-point bending flexural strength tests, stress-strain, load-deflection, toughness and failure mechanisms. The control specimens achieved highest average compressive strength of 34 MPa, reflecting grout properties and stiffness of the recycled concrete aggregate. By increasing the recycled rubber percentage from 0% to 50%, the reduction in the overall compressive strength reached 21%. The inclusion of recycled steel-wire fibres lowered this strength reduction effect caused by the rubber addition. Increasing the steel fibres from 0% to 1.0%, rubberized PAC specimens showed lower reduction in their compressive strength, which ranged between 13.4% and 19.2%. These findings indicate that balancing rubber and steel-wire addition can lead to producing PC with adequate compressive strength.

Also, increasing the rubber content up to 50% caused significant reduction in the splitting tensile strength of rubberized PAC specimens by up to 52.8%. This decline in strength was mitigated notably by the incorporation of 1.0% recycled tire steel-wire by volume fraction. In this case the splitting tensile strength of the 10%, 20%, 30%, 40% and 50% rubberized PAC specimens had decreased the splitting tensile strength by only 16.95%, 17%, 20.10%, 27.93% and 34.11%, respectively. The decrease in splitting tensile strength reflects the weak bonding characteristic between hydrophobic rubber particles and the cementitious matrix.

The static modulus of elasticity of the tested PAC specimens exhibited gradual decrease due to rubber addition. The control PAC specimens without rubber achieved highest modulus of 41MPa. This reflects the much higher aggregate content in PAC when compared to that of normal concrete, and the stiffer nature of recycled aggregate concrete compared to rubber. The modulus of elasticity decreased by 19.5% due to the inclusion of 50% of rubber. When recycled steel tire wire fibre reinforcement of up to 1.0% was used, the mean modulus reduction of the 10% to 50% rubberized PAC specimens dropped by around 17.5% to 24.2%. Although rubber addition in the examined PAC caused modulus reductions, the modulus values remained in the acceptable range compared to normal concrete due to the dense granular skeleton.

Incorporating recycled tire rubber and steel-wire fibres affected considerably the stress-strain behaviour of PAC in compression. The stress-strain curves reveal that the control PAC and PAC containing 20% rubber granules had brittle behaviour. However, this changed after increasing the rubber content beyond this threshold to 30%, 40% and 50% with addition of 0.25%, 0.50% and 1.0% of tire steel-wire fibres. Rubberized and steel-wire fibre reinforced cylinders incorporating rubber levels beyond 20% acquired a more ductile behaviour, as they displayed larger deformation and elastic capacity. Rubber and steel-wire fibre helped in crack arresting and enhanced energy absorption capacity (area under stress-strain curve).

Moreover, rubberized PAC beam specimens exhibited decreased flexural strength with rubber addition compared to that of the control PAC without rubber by up to 56%. However, this changed by incorporating recycled steel-wire fibres. The average flexural strength decline in the 10% to 40% rubberized PAC beams reinforced with 1.0% steel fibre was nearly 16%. The effect of steel fibre addition was more notable in 50% rubberized specimens, in which the flexure strength increased by 28.29%. Furthermore, unlike the case of compression and modulus of elasticity results in which the mean reductions rate among 10% to 50% rubberized cylinders were exacerbated when steel-wire fibre inclusion was used, as the fibres mitigated the drop in flexural strength. This shows the well-known positive effects of fibres in delaying crack growth and enhancing the overall toughness via fibre pull out across growing cracks.

The load-deflection curves revealed the effects of recycled waste tire components on PAC toughness and ductility, indicating more ductility and higher toughness compared to that of control specimens. The brittle failure for the control PAC was gradually transformed to ductile behaviour with increased rubber and steel-wire fibre dosage. Observed failures were rather gradual than sudden and rubberized specimens gained larger elastic and post-peak deformation compared to that of control rubber-less specimens. In addition, specimens reinforced with a high percentage of steel-wire fibre content exhibited multiple micro-cracks instead of a single crack with a lower crack width than that in the control beam specimens. Accordingly, the areas under load-deflection curves (toughness) displayed the characteristics of increased energy absorption mechanisms. The overall flexure energy absorption capacity and toughness were determined from evaluating standard test toughness indices, by estimating the total area under the load-deflection curves. Both first crack deflection and toughness were greatly enhanced with the increase of steel-wire dosage, and has gradually enhanced with increased rubber content. Also, the residual strength factors (post-peak behaviour) displayed numerous improvements when recycled tire rubber and steel-wire were incorporated.

In **Chapter 4**, the steel-wire effect was further explored by increasing its volume fraction up to 1.5, considering the behaviour of rubberized and steel-wire reinforced PAC under impact loading. Drop weight impact resistance testing was conducted to investigate the dynamic behavior of PAC specimens. Control specimens of PAC without rubber failed in a splitting manner within one drop weight hit. Rubberized PAC specimens showed somewhat similar behaviour. However, by reinforcing PAC with 1.5% steel-wires, the first crack and failure impact resistance were improved by nearly 40 times compared to that of the control specimens. The efficiency of steel-wire and rubber addition in terms of its enhanced dynamic load behaviour of PAC was assessed statistically using analysis of variance (ANOVA) and was found to be significant. The impact performance of PAC was also assessed statistically using the Weibull distribution to statistically estimate the impact performance and reduce the need for laborious and costly tests. The obtained reliability curves support the efficiency of determining PAC impact resistance at first crack and failure using the Weibull distribution.

5.2. Recommendations for Future Study

- There is need to develop new strategies regarding the replacement of natural virgin aggregates with recycled concrete aggregate and recycled tire rubber. This would create sustainable methods for promoting value engineering and sustainability.
- Due to the limited utilization of rubberized concrete to the non-structural low strength applications, conducting more experimental research using high strength grout to produce higher strength PAC needs to be explored.
- The present study did not investigate the sustainability of the grout. It is possible to produce entirely recycled PAC using a geo-polymer grout based on alkali-activated fly ash, along with recycled concrete aggregate, tire rubber and tire steel-wire fibre. This needs further study.
- The applications of the eco-efficient PAC proposed in this study are non- structural and non-reinforced. If PAC is to be reinforced, then the study on permeability to chloride ions, corrosion, freeze-thaw and other durability performance criteria needs to be explored.

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