Properties of Concretes Produced with Recycled Concrete Aggregates

Kani Akhavan Kazemi

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Prof. Dr. Elvan Yılmaz
Director

I certify that this thesis satisfies the requirements as a thesis for the degree of Master of Science in Civil Engineering.

Assist. Prof. Dr. Mürüde Çelikağ
Chair, Department of Civil Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Civil Engineering.

Assoc. Prof. Dr. Özgür Eren
Co-Supervisor

Asst. Prof. Dr. Alireza Rezaei
Supervisor

Examining Committee

1. Assoc. Prof. Dr. Özgür Eren
2. Asst. Prof. Dr. Alireza Rezaei
3. Asst. Prof. Dr. Giray Ozay
4. Asst. Prof. Dr. Mehmet Metin Kunt
5. Asst. Prof. Dr. Serhan Şensoy

ABSTRACT

The usage of concrete dates back to 19^{th} century after discovery of cement. Normally, concrete making materials are cement, aggregates, water and mineral or chemical admixtures. On the other hand, usage of natural aggregates from seashore, river beds or other sources can damage our earth seriously if it is not done according to environmental regulations. Therefore, scientists are trying to improve recycled materials to be used as aggregates. One solution for this need is recycled concrete aggregates. There are already many old buildings which are demolished due to their economic life.

Cyprus is also a candidate for using recycled aggregates in concrete. Nowadays, aggregates from Beşparmak mountains are being used as crushed limestone aggregates (both fine and coarse).

From the literature, it is known that usage of recycled concrete as aggregates has some limitations for strength and freeze-thaw resistance. This study aims to perform experimental studies to investigate the properties of concretes produced with recycled aggregates obtained from concrete samples at waste yard of Materials of Construction Laboratory, EMU in North Cyprus. Various experiments such as compressive strength, splitting tensile strength, nondestructive tests, density and freeze-thaw resistance for two different concrete classes (C20/25, C30/37) were done.

Keywords: Environmental impact, Recycled concrete aggregates, Natural aggregates, Concrete strength.

ÖZ

Beton kullanımı 19.cu yüzyılda çimentonun keşfi ile başlamış olur. Normalde ise betonu oluşturan malzemeler çimento, agregalar, su, mineral veya kimyasal katkılardır. Diğer taraftan ise özellikle doğal agregaların betonda kullanımına çevreye verilen zarardan dolayı gün geçtikçe sınırlamalar getirilmektedir. Bundan dolayı bilim adamları doğal agrega yerine agrega olarak kullanılabilecek geridönüşümlü yeni malzemeler için çalışmalar yapmaktadırlar. Bu malzemelerden birisi de eski betonlardır. Mevcut eski yapıların ekonomik hayatlarını tamamlamasında dolayı yılıklması ile ortaya çıkan büyük miktarlarda betonlar vardır.

Kıbrıs adası da geridönüşümlü malzemelerin agrega olarak kullanılabileceği aday ülkelerden birisi olabilecek durumdadır. Günümüzde Beşparmak dağlarında elde edilen agregalar kullanılmasına rağmen çevreye verilen zarardan dolayı bu agregaların kullanımının çok uzun süremeyeceği bir gerçektir.

Öte yandan ise, geridönüşümlü betonun agrega olarak kullanılmasının mukavemet ve donma-çözünme dayanımı bakımından bazı sakıncaları veya dezavantajları olduğu bilinmektedir.

Bu çalışmanın amacı ise geridönüşümlü agrega ve normal agrega ile üretine betonların özelliklerinin karşılaştırılmasıdır. DAÜ Malzeme Laboratuvarında üretilen ve deneyleri tamamlandıktan sonra çoplük bölümünde biriktirilen betonlar kırma makinelerinde kırılarak belli oranlarda beton yapımında kullanılmıştır. Üretine beto sınıfları ise C20/25 ve C30/37 olarak iki sınıf olarak tasarlanıp üretilmiştir.

Anahtar kelimeler: Çevre, Geridönüşümlü agrega, Doğal agrega, Beton mukavemeti

This thesis is dedicated to my family

Thank you for your unconditional support with my studies. I am honoured to have you as my parents. Thank you for giving me a chance to prove and imporove myself through all my walks of life. Please do not ever chang. I love you

تقدیم به پدر و مادر عزیزم که هر چه دارم از آنهاست . دوستتون دارم.

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LIST OF ABBREVIATIONS

C & D..Construction and Demolition

ISWM..Integrated Solid Waste Management

TSMA...Two Stage Mixing Approach

RAC..Recycled Aggregates Concrete

NA...Natural aggregates

NAC...Natural Aggregates Concrete

BRE...Building Research Establishment

SSD...Saturated Surface Dry

PUNDIT...Ultrasonic Pulse Velocity Test

MPa..Mega Pascal

D10..Aggregates with nominal diameter of 10 mm

D13.. Aggregates with nominal diameter of 13 mm

D14.. Aggregates with nominal diameter of 14 mm

D20.. Aggregates with nominal diameter of 20 mm

D23.. Aggregates with nominal diameter of 23 mm

LIST OF SYMBOLS

$K_d = \frac{G_0 - G_1}{G_0} \times 100$ ……………………………………………………...……….. Eq. 1

$K_{dt} = 0.5 \times K_{d1} + 0.3 \times K_{d2} + 0.2 \times K_{d3}$ ………………………...……………Eq. 2

Chapter 1

INTRODUCTION

1.1 Background

Waste management is an industry which revolves around the collection, storage and waste disposal. A waste management system is a particular method to treat waste materials consisting collection, recycling, and disposal or waste processing.

Recycling, reuse, combustion and landfill methods reduce construction and demolition waste.

Landfilling method is cheaper and easier than recycled in order to reduce construction waste, but human meets nowadays problems to find the landfills. Thus, the natural resource protection is one of the important parts of environmental issues. Recycling will help to conserve natural resources for next generations.

North Cyprus is an island that has problem with finding landfills; therefore, construction waste recycling is the best method for reducing construction and demolition waste.

1.2 Objectives of the Study

The first and main scope of this study is to save natural aggregates. For reaching this aim, environmental management plays an important role in protecting natural resources.

The following process is necessary for making recycled concrete. First, concrete should be crushed in several nominal sizes. Second, the crushed concrete will be used as aggregates in recycled concrete. Finally, recycled concrete should be produced from different mix designs.

Contractors must spend more money for these processes that cause natural resources to be protected. So, natural resource management is more beneficial for human beings.

1.3 Works Undertaken

The following steps were conducted and the particular conclusions were obtained from the experimental works:

1. The literature review about waste management and recycled aggregate concrete (RAC) were done.
2. Structural concrete was crushed and sieve analyses were done for both group of aggregates (normal aggregates and recycled aggregates).
3. Water absorption test and specific gravity of normal and recycled aggregates were performed.
4. According to two different mix designs, materials were mixed; concrete was made and poured into forms and compacted; and the hardened concrete samples were cured.
5. Hardened density, compressive strength, splitting tensile strength, PUNDIT, rebound (Schmidt) hammer and freeze-thaw resistance of each sample was determined.
6. According to the test results, comparison between normal concrete and recycled aggregate concrete were performed.

1.4 Thesis outline

This thesis consists of five chapters. The previous researches on waste management issues and recycled aggregate concrete will be mentioned in chapter 2.

Experimental works such as tests on aggregates, tests on fresh concrete, destructive tests (compressive strength, splitting tensile and freeze-thaw resistance) and non-destructive tests (PUNDIT, rebound hammer and density) will be discussed in chapter 3.

The results, analysis, and discussions on the achievements are included and graphs are drawn in chapter 4.

The constructions of the research are mentioned in chapter 5.

Chapter 2

LITERATURE REVIEW AND BACKGROUND

2.1 Introduction

Researchers have conducted some researches from 10 years ago, related to recycled aggregates to be used in concrete roads, pavements, bridges, etc. however, they have not applied recycled aggregates for structural concrete. The purpose of this research is to use recycled aggregate for structural concrete in North Cyprus. The reason of selecting North Cyprus for this study is environmental conditions that make it a special region. This chapter focuses on previous research studies about environmental issues, waste management and Recycled Aggregate Concrete (RAC).

2.2 Environmental Management

Environmental rules and regulations are made to improve the environment in order to create suitable condition (healthful water, air, land, etc.) for human and organisms as well as to fix the problems of polluted sites. Protecting from further degradation, preserving the present situation, and enhancing the environment are the main tasks of environmental engineering. There are several divisions in the environmental rules including environmental impact assessment and mitigation, waste-water conveyance and treatment, contaminated land management and site remediation, solid waste management, etc. (Wagner, 2007).

Generally, environmental management has processes including planning, implementation, monitoring, measurement and management review (Tam et al., 2006).

2.3 Waste Management

In the past, the volume of waste generated by human beings was not very important because of the low people densities, coupled with the fact that there was very little utilization of natural resources. During the early ages, common wastes were mostly ashes and human & biodegradable wastes, and these were liberate rear into the ground locally, with minimum environmental effect.

With the arrival of manufacturing rebellion, waste management became a pivotal topic due to increasing in the population and the enormous relocation of people to industrial towns and cities from countryside through the 18th century. Thus, a resultant raise in manufacturing and household wastes caused human health and environment to be threatened.

Waste management industry involves the compilation, storage, and waste disposal which are ranging from usual house waste to the generated waste at nuclear power plants. The increase of efficient waste management strategies is critical to all nations, as many forms of waste can be changed into a main problem when they are not managed properly. Several firms supply various types of waste management services, and governments also control the waste management industry for security and effectiveness.

In the past, the waste has been buried under the ground; therefore, it has become more and more problematic because of the limited area, contamination, and another concern that utilizable materials may not be involved in recycling process. Waste has also been incinerated to produce the electricity, and some other inventive approaches to waste management contain simply dumping. Overall, these disturbing approaches make waste management problems for the future generations. Totally, there are four types of waste consisting human waste, industrial waste, hazardous waste, and biodegradable waste.

2.4 Waste management in Construction Industry

Nowadays, environmental sustainability plays a significant role in construction industry. A lot of project practitioners meet demanding situations so as to find an efficient method to stop contamination and reduce wastes by creating the greatest use of fright natural resources. However, the majority of these efforts is related to planning and design strategies. As a result, contractors have not been completely successful in covering up the environmental issues according to the construction implementation stage (Hee et al., 2009).

One of the solid waste types is construction and demolition waste (C&D). Integrated Solid Waste Management (ISWM) is an inclusive waste prevention, recycling, composting, and disposal program. A useful ISWM system considers how to prevent, recycled, and manages solid waste in ways that keep human and the environment healthy. ISWM considers evaluating local requirements and situation, and then selecting and combining the most suitable waste management actions for those situations. The major ISWM actions require cautious planning, financing, collection, and transport (U.S. Environmental Protection Agency, 2012).

Construction and demolition waste is produced in each step of any construction/demolition activity, like building roads, bridges, fly over, subway, remodeling, etc. It includes inert and non-biodegradable materials such as concrete, plaster, metal, wood and plastics (Sunil, 2005).

2.5 Waste management in Building Construction

It was easier and cheaper to transfer demolished building materials and construction waste to landfills than to make an attempt to recycled (Winkler, 2009), but some landfills will be closed in the near future and limited place for landfill will exist. Indeed, there were roughly the recycling markets for many demolition materials even 10 years ago. So, recycling materials have some benefits such as financial savings and reduction in the use of original materials like woods products, stone ores, water and energy (Seattle, 2009).

Figure 1 shows a diagram of recycling organization for aggregate replacing technique.

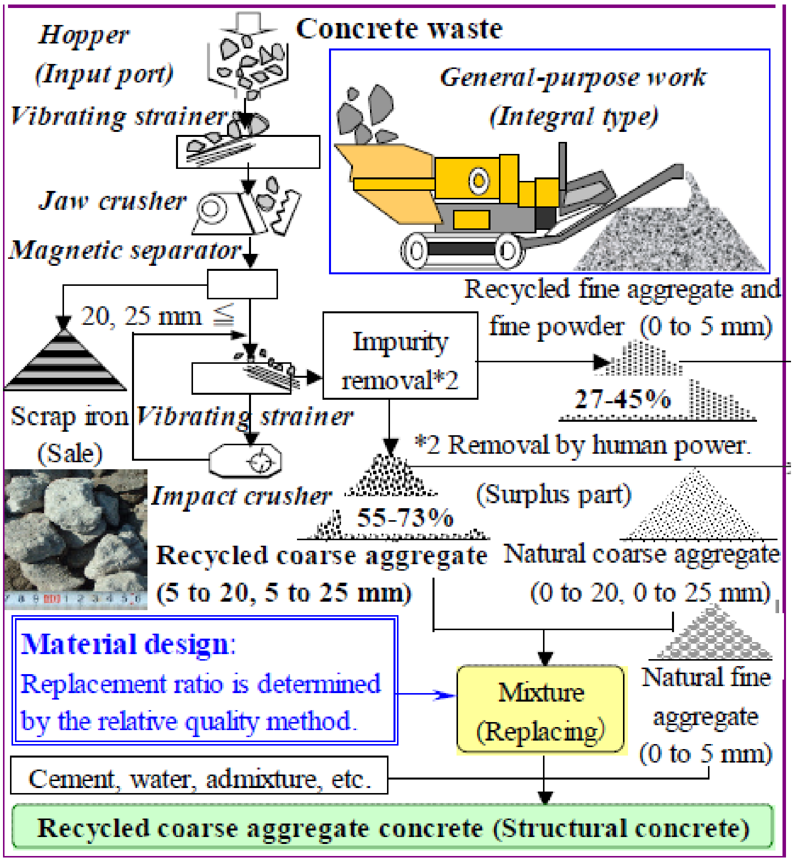

Figure 1: Recycled system for concrete waste (Dosho, 2007).

The recycling process for different waste materials can be conducted (Illinois Environmental Protection Agency, 2012) in which concrete and masonry waste can be recycled by sorting, crushing and sieving into recycled aggregates that can be used to make concrete for road construction and building material.

Literature shows a growing interest on concrete recycling among academicians and practitioners in different regions such as UK, USA, Canada, Japan, India, Nigeria, and New Zealand.

Movasagh (2006) used concrete from back-fill or road sub-base materials in pavements as recycled aggregates. The maximum coarse aggregate was 16 mm. He compared reinforced concrete with natural aggregates and with recycled aggregates. His results showed that compressive strength of concrete with natural aggregates was 35% higher than compressive strength of concrete with recycled aggregates.

In a study by Dosho (2007) in Japan, it was found that construction industry produced 83 million tons construction waste per year of which, 35 million tons was related to concrete waste. He replaced 30% and 50% of recycled coarse aggregates from building with 30 years age. He obtained 32.6-35.8 MPa compressive strength after 28 days with standard curing condition.

Butler et al. (2011) focused on characterizing two recycled concrete aggregate (RCA) sources in Ontario and producing novel concrete utilizing RCA as coarse aggregate (RCA concrete). Three aggregate types were investigated, one control virgin aggregate source and two RCAs produced from the crushing of hardened concrete.

First of all, they resolute the quantities of adhered mortar in two recycled concrete aggregates (3 methods). Then, they obtained abrasion resistance and absorption capacity and density of fine and coarse aggregates and after that, they obtained the aggregate crushing value.

They found that “the recycled aggregates had lower densities and higher absorption capacities than the natural aggregates”. The thermal treatment is the most effective method in order to remove the adhered mortar from both types of RCA in comparison with the acid dissolution or freeze-thaw chemical attack methods. In the 30 MPa and the 50 MPa direct replacement mixtures, comparison of both the RCA-1 and RCA-2 concrete with the natural aggregate concrete depicted that RCA type concretes had lower slump values. In the 30 MPa direct replacement mixtures, both types of RCA concretes had higher compressive strength values than the natural aggregate concrete (Butler et al., 2011).

Limbachiya et al. (2004) used samples of four diverse sources including laboratory cast concrete, airport pavement, discarded structural precast part and demolished concrete structure to manufacture the coarse RCA that were clean and free from detrimental effects of chemical materials. RCA samples were made of aggregate size between 5 mm and 20 mm using commercial plant for the manufacture of crushed-rock aggregate, comprising firstly jaw and secondary cone crushers and screens. The maximum size of natural aggregates (NA) used were 20 mm. Generally, RCAs were used to be coarser, more permeable and rougher compared with NA.

The use of four different sources for comparing the physical parameters of RCA represented that the density of RCA was 3% to 10% less than NA and the water absorption of RCA was 3 to 5 times more than NA in the saturated surface dry state, returning to the porosity of mortar around the RCA.

Based on their research, the results also represented that "there was no significant variation in strength of concrete at a given RCA content; in addition, the RCA concrete mixes were found to possess bulk engineering and durability properties similar to the corresponding natural aggregate concretes" to provide the equal strength.

Arum (2011) investigated that the workability of virgin concrete is higher than the recycled concrete, when the water/cement ratio is same. The compressive strength of recycled concrete is to some extent less than virgin concrete, when the water/cement ratio is low. Moreover, at higher ratios, the compressive strength of recycled concrete is similar to the virgin concrete.

Jeong (2011) used concrete structures of Chicago O'Hare airport for recycled coarse aggregate. He stated that Two Stage Mixing Approach (TSMA) is an effective technique for increasing strength of a given RAC mixture. Initial moisture states of RCA are one of the most important variables that impact on strength and shrinkage. The RCA with using 74% initial moisture states of recycled coarse aggregates reached almost the same compressive strength of normal concrete when using TSMA. Restrained stress under drying conditions developed slowly in RAC specimens; thus, cracking in ring specimens did not occur. When greater volume of recycled fine aggregates and fly ash was used, free shrinkage of the specimens was reduced.

The crushing and hardening process of concrete as recycled aggregate was investigated by Chisholm (2011) in new concrete; in addition, secondary recycled material was used as aggregate in new concrete as well.

Table 1 shows an uneven evaluation of construction and demolition (C&D) waste generated in countries using the majority percentage of recycled concrete as aggregates (Lauritzen, 2004; Kasai, 2004; Gomez-Soberon, 2002; Poon et al., 2004; Shayan and Xu, 2003; Salem et al., 2003).

Table 1: Global consumption of construction and demolition wastes as aggregates

Country	C&D waste (million	Percentage of C&D waste Recycling %	Recycled concrete (million tones/year)
United State	650	20 - 30	150
Europe	200	28	50
Japan	85	85	35
Hong Kong	14	50	3.5
Canada	11	21	2.3
Australia	3	50	1.5

According to Table 1, the lack of natural resources and landfill capacities leads to increasing the amount of construction and demolition waste recycling in Japan and Hong Kong (around 85% and 50%); whereas, recycled waste construction materials are largely used for backfilling and as pavement materials in some countries (such as Canada) because of not having plenty resources of the high-quality natural sand and rock.

Tables 2 and 3 show waste delivered to Dikmen disposal site by private companies and military in North Cyprus at 2006 and 2007, respectively.

Table 2: Waste delivered to Dikmen disposal site by private companies and military, tone in 2006 (Adopted from Afshar Ghotli.A, 2009).

Months of 2006	Private companies	Military
January	2,483 90	294.30
February	4,492.50	227.40
March	5,392.00	410.40
April	5,193.80	439.60
May	4,832.90	483.90
June	5,503.20	228.40
July	4,193.70	230.00
August	4,394.70	359.40

Table 3: Waste delivered to Dikmen disposal site by private companies and military, tone in 2007 (Adopted from Afshar Ghotli.A, 2009)

Months of 2007	Private companies	Military
January	2,730.90	312.70
February	4,804.90	213.30
March	6,011.80	496.20
April	5,282.60	501.60
May	276.80	791.30
June	6,862.00	298.90
July	4,425.00	381.00
August	5,096.60	415.10

Table 4 shows the annual waste generation in North Cyprus.

Table 4: Evaluated annual waste generation in Northern part of Cyprus(Afshar Ghotli.A, 2009)

Waste type	Waste Generation, thousand tons per year
Household waste	73.30
Commercial waste	33.90
Municipal waste	107.20
Construction/demolition waste	129.10
Green waste	14.90
Industrial waste	39.50
Total waste generation	290.80

There is a lack of study on using recycled concrete aggregates as a construction material for reuse in structural concrete in Cyprus. Therefore, normal concrete made of normal aggregates were compared with recycled aggregate concrete in this study. To do so, some samples and experimental work were necessary to perform the study.

Chapter 3

EXPERIMENTAL WORK

3.1 Introduction

The main aim of this study is to perform experimental study to investigate the properties of concretes produced with recycled aggregates in North Cyprus and comparison of them with normal concrete. During the experimental work, different concrete samples with various concrete mix designs were investigated by different ages.

For casting normal concrete samples, cement with class of 32.5 was used. Aggregates from Beşparmak mountains were used as crushed limestone aggregates (both fine and coarse). Drinkable water was used as mixing water.

For casting recycled concrete samples, same cement of class of 32.5 was used. Recycled concretes with different strength levels (20-30 MPa) were crushed by jaw crusher and were separated according to their size distributions. Figures 2 and 3 show jaw crusher which was used for crushing concrete.

Figure 2: Overlooking of jaw crusher

Figure 3: Entrance place of jaw crusher

Two different concrete samples were cast. Cubic samples with the sizes of 150 mm and cylinder samples with the size of 100×200 mm were chosen for compressive strength, non-destructive tests, freeze-thaw resistance, and splitting tensile strength, respectively. The natural curing condition was performed for the samples. Compressive strength and splitting tensile test were conducted at 7 days, 14 days and 28 days. Non-destructive tests were done at 14 and 28 days and freeze-thaw resistance tests were done at 28 days.

3.2 Materials

3.2.1 Aggregates

3.2.1.1 Natural Aggregates

In this study, both coarse and fine aggregates of this type were provided with the crushed limestone. Crushed limestone aggregates were used as natural aggregates. Totally, four different nominal sizes of natural aggregates were selected as 5 mm, 10 mm, 14 mm and 20 mm. Moreover, sieve analysis test was conducted on the mentioned aggregates (Table 5 to Table 8).

Table 5: Sieve analysis results of normal aggregate with maximum size of 20 mm

Sieve (mm)	Weight (kg)	Retained %	Cumulative Retained %	Cumulative Passing %
28	0.00	0.00	0.00	100.00
20	0.23	12.71	12.71	87.28
14	1.15	62.68	75.39	24.60
10	0.28	15.64	91.03	8.96
6.3	0.15	8.31	99.34	0.56
5	0.00	0.21	99.56	0.43
3.35	0.00	0.05	99.61	0.38
Pan	0.00	0.38	100.00	0.00
Total	1.81	-	-	-

Table 6: Sieve analysis results of normal aggregate with maximum size of 14 mm

Sieve (mm)	Weight (kg)	Retained %	Cumulative Retained %	Cumulative Passing %
28	0.00	0.00	0.00	100.00
20	0.00	0.00	0.00	100.00
14	0.95	46.04	46.04	53.95
10	0.70	33.97	89.02	19.97
6.3	0.40	19.48	99.51	0.48
5	0.00	0.09	99.61	0.38
3.35	0.00	0.04	99.66	0.33
Pan	0.00	0.33	100.00	0.00
Total	2.05	-	-	-

Table 7: Sieve analysis results of normal aggregate with maximum size of 10 mm

Sieve (mm)	Weight (kg)	Retained %	Cumulative Retained %	Cumulative Passing %
28	0.00	0.00	0.00	100.00
20	0.00	0.00	0.00	100.00
14	0.00	0.00	0.00	100.00
10	0.00	0.00	0.00	100.00
6.3	0.80	54.51	54.50	45.49
5	0.34	23.66	78.16	21.83
3.35	0.27	18.50	96.67	3.32
2.36	0.02	1.55	98.23	1.76
Pan	0.02	1.76	100.00	0.00
Total	1.45	-	-	-

Table 8: Sieve analysis results of normal aggregate with maximum size of 5 mm

Sieve (mm)	Weight (kg)	Retained %	Cumulative Retained %	Cumulative Passing %
4.75	0.00	0.00	0.00	100.00
2.36	0.17	17.84	17.84	82.15
1.18	0.32	32.20	50.04	49.95
0.6	0.21	21.33	71.38	28.61
0.425	0.06	6.18	77.56	22.43
0.3	0.04	4.58	82.13	17.84
0.18	0.04	3.98	86.14	13.85
0.15	0.02	2.29	88.43	11.56
0.075	0.02	2.39	90.82	9.17
Pan	0.09	9.17	100.00	0.00
Total	0.97	-	-	-

Figure 4 shows the grading curves for natural aggregates.

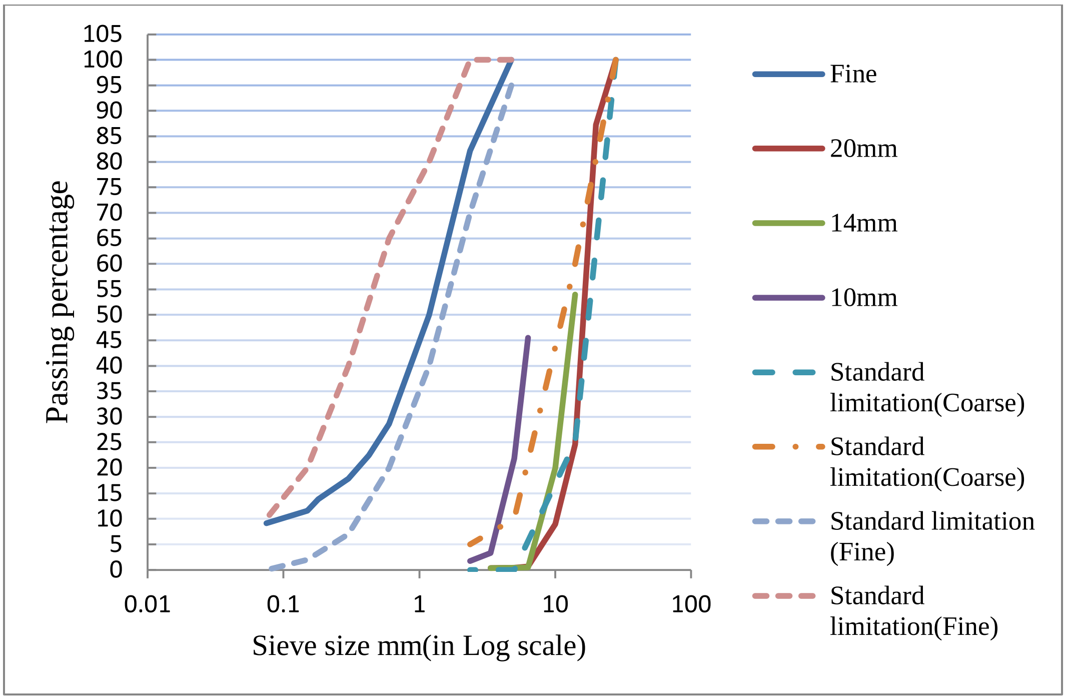

Figure 4: Grading curves for natural aggregates

3.2.1.1 Recycled aggregates

Totally three different nominal sizes of recycled aggregates were chosen including 5 mm, 13 mm, and 23 mm. Recycled aggregates were prepared with jaw crusher. Concretes loaded from laboratory waste yard were transferred to crushing area put into the jaw crusher to produce them with pre-determined sizes (Table 9 to Table 11).

Table 9: Sieve analysis results of recycled aggregate with maximum size of 23 mm

Sieve (mm)	Weight (kg)	Retained %	Cumulative Retained %	Cumulative Passing %
28	0.00	0.00	0.00	100.00
20	0.05	5.80	5.80	94.20
14	0.57	57.60	63.40	36.60
10	0.34	34.80	98.20	1.80
6.3	0.01	1.30	99.50	0.50
5	0.00	0.10	99.60	0.40
3.35	0.00	0.00	99.60	0.40
Pan	0.00	0.40	100.00	0.00
Total	0.97	-	-	-

Table 10: Sieve analysis results of recycled aggregate with maximum size of 13 mm

Sieve (mm)	Weight (kg)	Retained %	Cumulative Retained %	Cumulative Passing %
28	0.00	0.00	0.00	100.00
20	0.00	0.00	0.00	100.00
14	0.00	0.00	0.00	100.00
10	0.10	10.38	10.38	89.61
6.3	0.55	55.54	65.93	34.06
5	0.30	29.97	95.90	4.09
3.35	0.02	2.79	98.70	1.29
Pan	0.01	1.29	100.00	0.00
Total	0.98	-	-	-

Table 11: Sieve analysis results of recycled aggregate with maximum size of 5 mm

Sieve (mm)	Weight (kg)	Retained %	Cumulative Retained %	Cumulative Passing %
4.75	0.00	0.09	0.09	99.90
2.36	0.12	12.08	12.18	87.81
1.18	0.24	23.97	36.16	63.83
0.6	0.24	24.17	60.33	39.66
0.425	0.08	8.39	68.73	31.26
0.3	0.06	6.89	75.62	24.37
0.18	0.06	6.09	81.71	18.28
0.15	0.04	3.99	85.71	14.28
0.075	0.03	3.79	89.51	10.48
Pan	0.10	10.48	100.00	0.00
Total	0.97	-	-	-

The grading curves for recycled aggregates are shown in Figure 5.

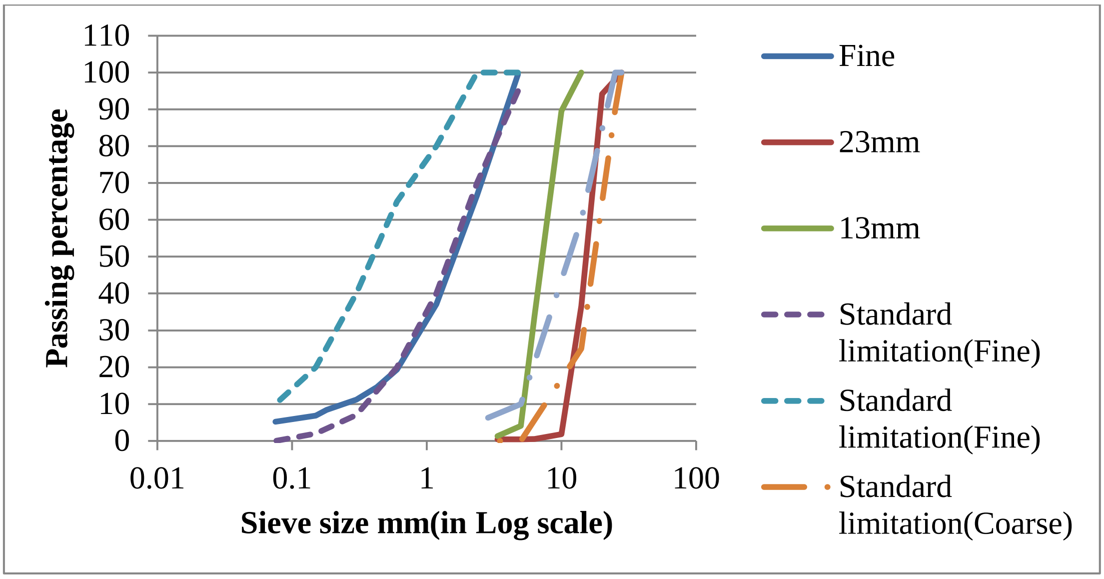

Figure 5: Sieve analysis curve for recycled aggregates

3.2.2 Cement

Cement with the class 32.5 was used for making both normal concretes and recycled aggregate concretes. Tables 12 and 13 depict the chemical composition and the physical properties of the cement.

Table 12: Chemical compositions of cement

Chemical composition (%)							Insoluble residue (%)	Heat at hydration (%)
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Cl		
16.12	6.97	3.13	56.52	2.09	2.16	0.02	0.16	13.17

Table 13: Physical properties of cement

Specific gravity (g/cm^3)	Specific surface (cm^2/g)	Retained on 90 µm sieve (%)	Retained on 45 µm sieve (%)	Water/Cement ratio (%)
2.95	4355	0.50	7.80	27

3.2.3. Water

Drinkable tap water within the laboratory was used for casting all samples.

3.3 Mix Design

This study compared normal concrete with recycled concrete in two classes (C20/25, C30/37). Concrete mixes were designed with regard to BRE for normal concrete (Teychenné, 1997). The variety of mix designs was determined according to various cement contents and water/cement ratios. Each concrete mix was designed by the proportions of materials shown in Table 14.

Table 14: Mix designs properties

Mix Designs	Cement (kg/m³)	Water (kg/m³)	W/C	D5 (kg/m³)	Coarse aggregates(kg/m³)				
					D10	D13	D14	D20	D23
Mix A	350	225	0.65	876	237	-	380	332	-
Mix B	450	225	0.46	828	224	-	359	314	-
Mix C	350	316.25	0.9	876	-	474.50	-	-	474.50
Mix D	450	311.25	0.68	828	-	448.50	-	-	448.50

3.4 Tests on Aggregates

3.4.1 Water Absorption

Table 15 represents the water absorption of the normal and recycled aggregates.

Table 15: Water absorption of normal and recycled aggregates (Based on SSD)

Type of	Aggregates	Water Absorption %
Normal	Fine	2.06
	D10	0.47
	D14	0.76
	D20	1.50
Recycled	Fine	5.49
	D13	5.22
	D23	5.18

Absorption capacity of recycled aggregates was 5 times more than absorption capacity of normal aggregates; therefore in mix design, 5% of the total amount of aggregates was added to the recycled samples.

3.4.2 Specific Gravity

Table 16 shows the specific gravity for normal and recycled aggregates.

Table 16: Specific gravity results for normal and recycled aggregates

Type of Aggregate	Aggregates	Bulk specific gravity SSD	Apparent specific
Normal	Fine	2.74	2.84
	D10	2.70	2.72
	D14	2.68	2.72
	D20	2.65	2.72
Recycled	Fine	2.48	2.71
	D13	2.47	2.68
	D23	2.47	2.68

3.4.3 Crushing Value

The crushing strength of aggregate cannot be tested with any direct test. Some indirect tests exist to determine the crushing strength of aggregate. Crushing value for normal aggregates and recycled aggregates was obtained to be 23.42% and 27.13%, respectively.

3.4.4 Aggregate Impact Value

Impact value of aggregates measures the toughness of particles by impact. Impact value for normal aggregates and recycled aggregates was obtained to be 16.52% 31.60%, respectively based on BS 812-112:1990.

3.5 Methodology

Two different concrete mix designs were determined based on BRE in order to design normal concrete (Teychenné, 1997) and two different concrete mix designs were established to design recycled concrete. Subsequently, based on the method of weight batching, test mixes were designed, casted and after some replications, mix designs A, B, C and D were confirmed (Table 14).

3.5.1 Casting Concrete

According to British Standards, the process of batching, weighting and mixing of required materials were performed. First, aggregates and cement were mixed with mixer for 30 seconds, and then water was added and mixed for almost 3 minutes. For slump test, sample was taken from fresh concrete, test was conducted and then, sample of fresh concrete was poured back to the mixer for remaining mixing and finally moulds were filled (BS 1881: Part 125:1986, 2009).

3.5.2 Compacting and Curing

For vibration and compaction of the filled concrete in the moulds, vibration table shown in Figure 6 was used.

After casting and compacting concrete samples, the samples were placed to curing room with more than 90% moisture and 21°C temperature for 24 hours. Then, samples were put into the water tank and kept until testing ages of 7, 14 and 28 days.

Figure 6: Vibrating table

3.6 Test on Fresh Concrete

3.6.1 Workability Test

Slump test was the only test accomplished on fresh concrete. According to BS EN 12350-2: 2009, this test was performed.

3.7 Tests on Hardened Concrete

Two groups of tests were applied to hardened concrete: Non-destructive tests and destructive tests. Non-destructive tests were conducted namely PUNDIT, rebound hammer, and density; and destructive tests namely compressive strength, splitting tensile strength, and freeze-thaw resistance.

3.7.1 Compressive Strength

BS EN 12390-3:2009 was considered for evaluation of compressive strength of cubes. Loading speed was adapted to be 0.6 ± 0.2 MPa/s (BS EN 12390-3:2009). This test was performed on samples at the ages of 7, 14 and 28 days

3.7.2 Splitting Tensile Strength

Splitting tensile strength test was performed on cylinder samples at the ages of 7, 14 and 28 days. Figure 7 shows one cylinder sample while conducting the test by the machine.

Figure 7: Cylinder specimen failed under splitting tensile test

3.7.3 Determination of Concrete Density

BS EN 12390-7:2009 was used for evaluation of concrete density samples.

3.7.4 Ultrasonic Pulse Velocity Test (PUNDIT)

This test is one of the non-destructive tests performed on cubic samples at the ages of 14 and 28 days. Porosity of samples was determined with this experiment (BS 1881: Part 201, 2009).

Before the test, related equipment had to be calibrated. Then, certain points of two opposite sides of each sample were marked. Center points and the equipment’s probe were coated with grease, and then the probes were put on every side’s centers. The number (duration of the pulse in microseconds) was then represented.

Figure 8: PUNDIT test

3.7.5 Rebound (Schmidt) Hammer Test

Rebound (Schmidt) hammer test is classified as surface hardness test. This test is one of non-destructive tests performed for evaluating concrete sample's compressive strength. During the process of compressive strength test, 10 times were exerted on one side of the sample (BS 1881: Part 201, 2009). Figure 9 shows the rebound hammer test process.

Figure 9: Rebound hammer test on cubic sample

3.7.6 Accelerated Freeze-Thaw Resistance

This test has established the accelerated freeze-thaw resistance exerted on concrete with using sodium sulfate solution according to TS 699 (1987). First, samples were broken with a hammer. Broken samples were put into the oven at the temperature of 110ºC and then separated with regard to Table 17. The sample sizes were between 37.5 mm-25.4 mm sieve, 25.4 mm-20 mm sieve, 20 mm-10 mm sieve and 10 mm-5 mm sieve that put into different receptacle, and finally sodium sulfate solution was added. Samples were kept immersed in the solution for 16-18 hours, then were removed from the solution and were put into the oven at the temperature of 110ºC ± 5 for 4 hours. Samples were taken out from the oven and allowed to attain room temperature. This procedure was repeated for 5 times. After finishing 5 cycles, samples were taken out from the oven. The samples were kept in water for 16-18 hours and washed to be removed from sodium sulfate solution completely in order to control whether samples were cleaned from sodium sulfate solution or not as well as HCl and $BaCl_2$ solution were added to water used for washing the samples. If water's color was white it meant that the sulfate sodium solution was still remained in the samples. Otherwise, the samples were put into the oven for at least 24 hours at a temperature of 110ºC. Afterwards, the samples were sieved by sieve sizes of 20, 10 and 5 mm, successively. Mass retained on the sieve was measured (G_1).

Table 17: Size fractions and the mass of samples

Sieve size (mm)	Mass of the sample (gr)
37.5 – 28	1000
28 – 20	1000
20 – 10	500
10 – 5	100

Accelerated freeze-thaw resistance of concrete was calculated by the equation 1.

$$\mathbf{K_d = \frac{G_0 - G_1}{G_0} \times 100} \qquad \text{(Eq. 1)}$$

Where;

K_d = Accelerated freeze-thaw resistance of concrete (%)

G_0 = Initial mass of test sample (gr)

G_1 = Mass of the retained sample on the sieve after test (gr)

This formula used for each group and total accelerated freeze-thaw resistance was calculated by the equation 2.

$$\mathbf{K_{dt} = 0.5 \times K_{d1} + 0.3 \times K_{d2} + 0.2 \times K_{d3}} \qquad \text{(Eq. 2)}$$

Where;

K_{dt} = Total accelerated freeze-thaw resistance of concrete (%)

K_{d1} = Accelerated freeze-thaw resistance of sample between 37.5mm–20mm sieve (%)

K_{d2} = Accelerated freeze-thaw resistance of sample between 20mm–10mm sieve (%)

K_{d3} = Accelerated freeze-thaw resistance of sample between 10mm–5mm sieve (%).

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this section, the results of experimental works and graphs will be represented and then, the results will be analyzed.

The experiments performed were consisted of slump, hardened density, ultrasonic pulse velocity test (PUNDIT), rebound hammer test, compressive strength, splitting tensile test, and freeze-thaw resistance.

4.2 Tests on Fresh Concrete

4.2.1 Slump Test

Slump test was conducted for each mix design. Table 18 shows the results of slump test.

Table 18: Slump test results

Mix Design	Slump(cm)
A	15
B	14
C	14
D	13

According to the obtained results, slump was decreased by increasing amount of water.

The main reasons for mix design A having high slump was low water/cement ratio (0.65). Three types of coarse aggregates were used in mix design A.

In mix design C, the water/cement ratio was increased to 0.9 because of using two types of coarse aggregates.

4.3 Experiments on Hardened Concrete (Non-Destructive Tests)

4.3.1 Compressive Strength

This test was performed on the cubic samples at the ages of 7, 14 and 28 days. The results are shown in Table 19.

Table 19: Compressive strength test results for the cubic samples (150 mm)

Days	Samples	Mix Design A	Mix Design B	Mix Design C	Mix Design D
7 Days	No. 1	17.40	25.30	11.74	15.60
	No. 2	17.30	24.00	11.95	15.60
	No. 3	17.00	24.50	11.20	14.50
	No. 4	17.20	26.50	11.34	15.40
	No. 5	17.60	25.80	11.63	15.60
	Average	17.30	25.22	11.57	15.34
14 Days	No. 1	22.70	30.20	14.40	22.50
	No. 2	22.80	31.00	14.90	22.60
	No. 3	32.00	29.10	17.30	22.80
	No. 4	22.20	33.20	17.10	22.80
	No. 5	23.20	31.00	16.70	22.80
	Average	24.58	30.90	16.08	22.70
28 Days	No. 1	31.90	38.60	21.40	25.70
	No. 2	27.80	40.80	21.70	26.60
	No. 3	28.00	38.30	21.10	26.10
	No. 4	27.50	38.30	21.10	26.30
	No. 5	27.80	37.70	20.80	26.50
	Average	28.60	38.74	21.22	26.24

4.3.1.1 Compressive strength of normal concrete versus compressive strength of recycled concrete

One of the main purposes of this research is to bring compressive strength of recycled concrete into a level close to compressive strength of normal concrete. Thus, compressive strength of normal concrete was compared with recycled concrete.

Average of compressive strength results at ages 7, 14 and 28 days are shown in Table 19. In addition, Figures 10 to 15 depict a comparison of recycled concretes' compressive strength results with normal concrete compressive strength results.

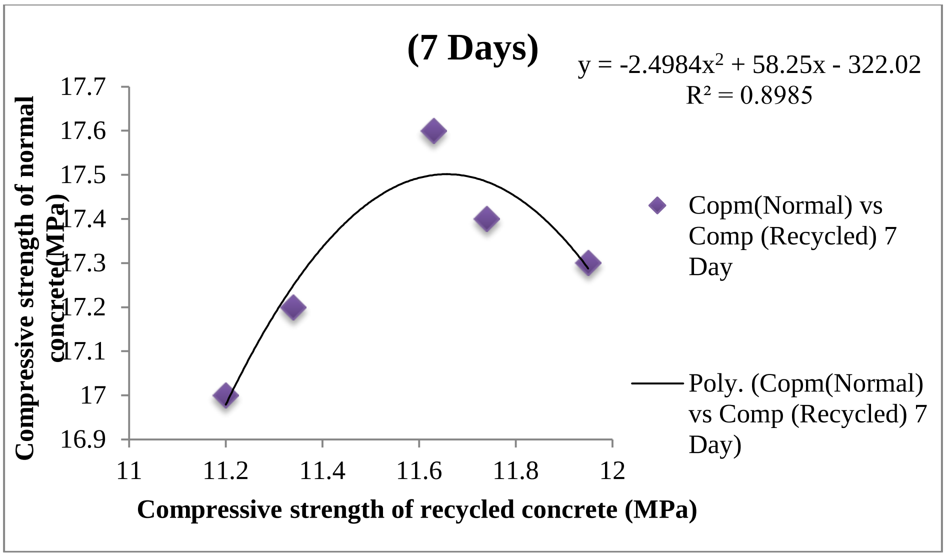

Figure 10: Compressive strength of normal concrete versus compressive strength of recycled concrete at 7 Days (Mix design A and Mix design C)

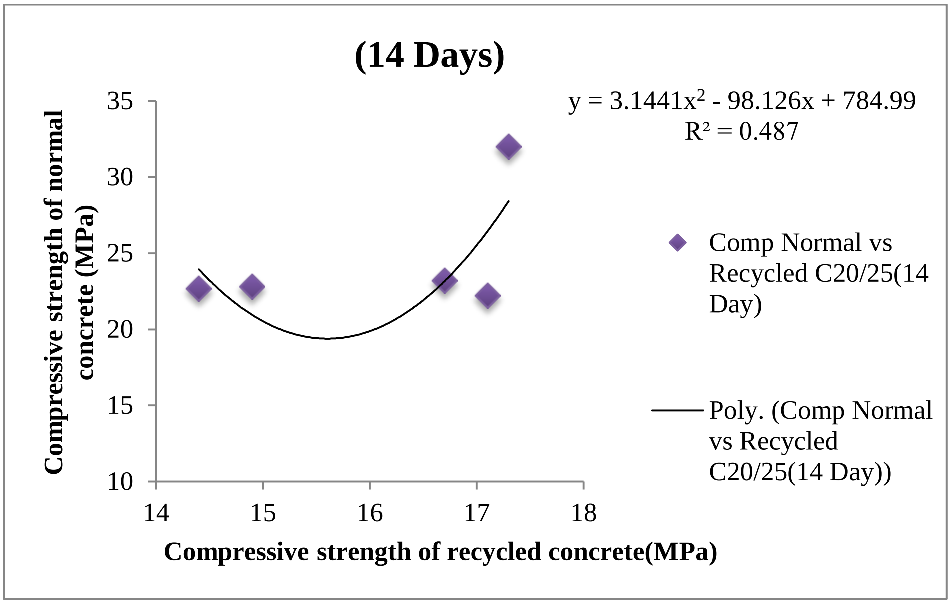

Figure 11: Compressive strength of normal concrete versus compressive strength of recycled concrete at 14 Days (Mix design A and Mix design C)

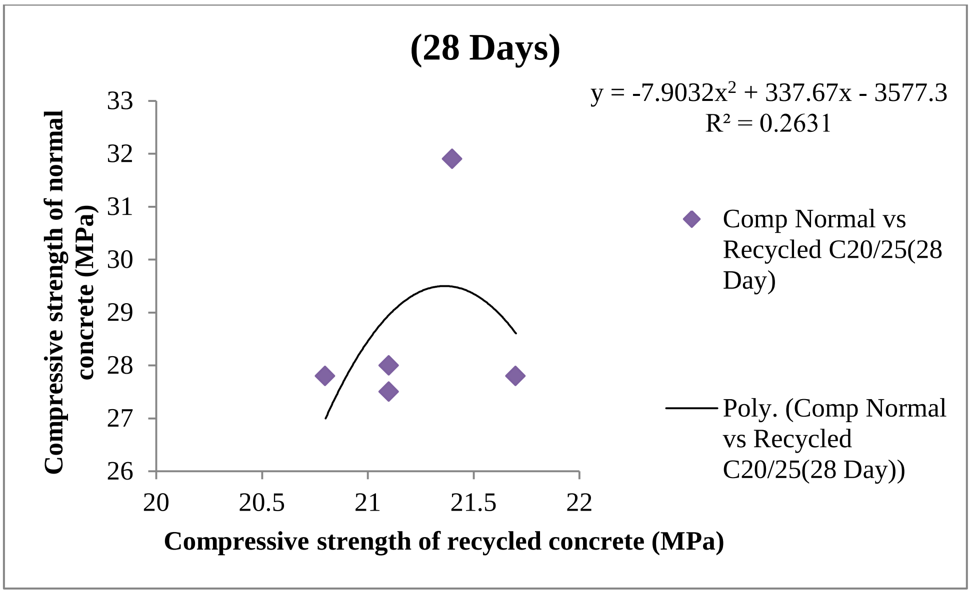

Figure 12: Compressive strength of normal concrete versus compressive strength of recycled concrete at 28 Days (Mix design A and Mix design C)

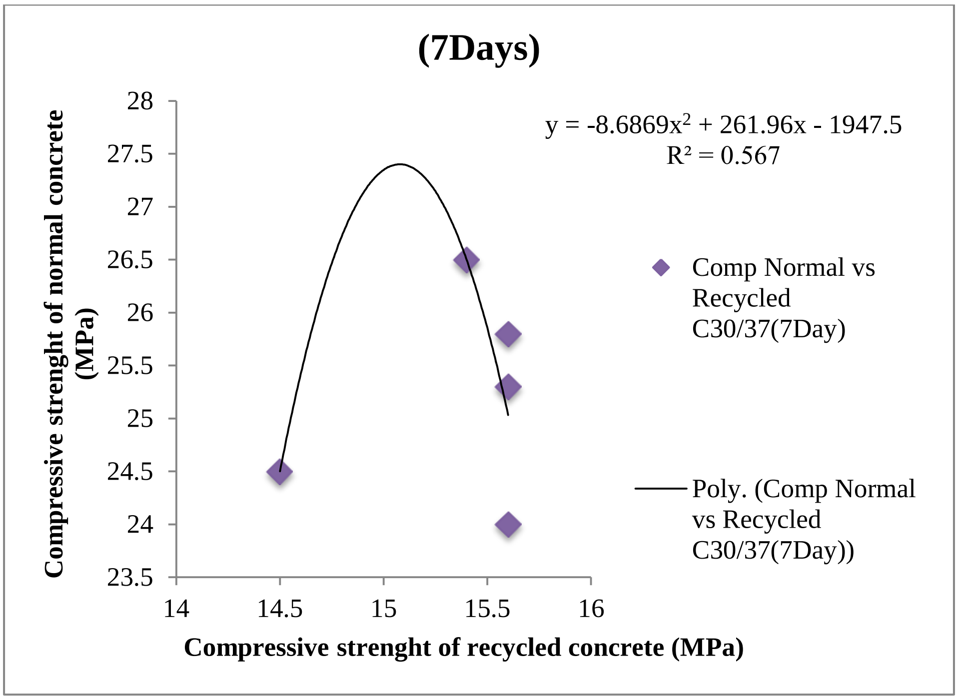

Figure 13: Compressive strength of normal concrete versus compressive strength of recycled concrete at 7 Days (Mix design B and Mix design D)

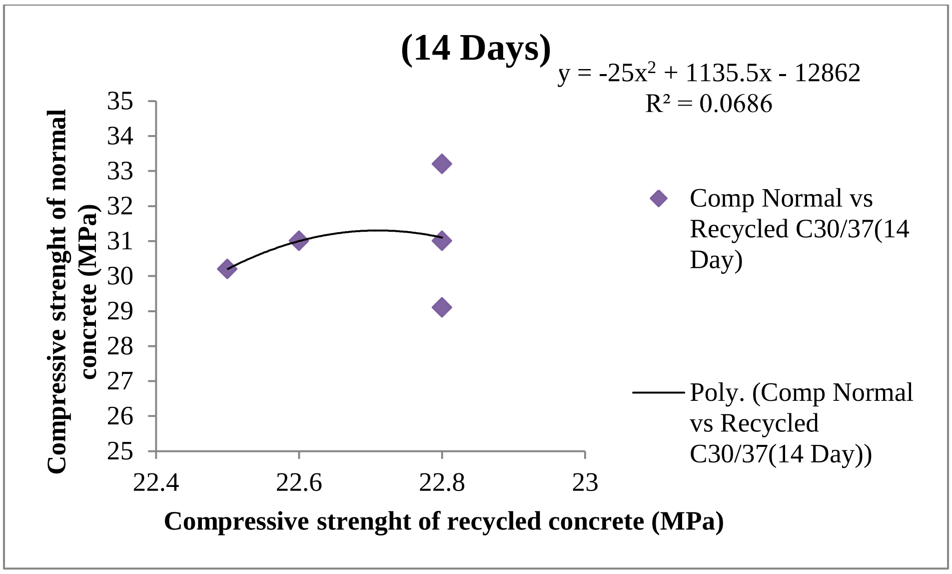

Figure 14: Compressive strength of normal concrete versus compressive strength of recycled concrete at 14 Days (Mix design B and Mix design D)

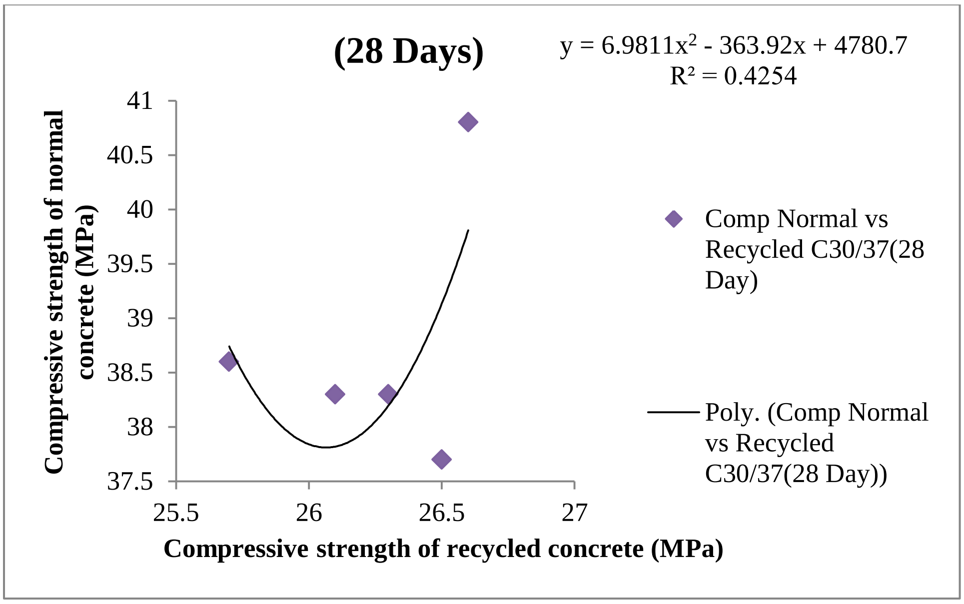

Figure 15: Compressive strength of normal concrete versus compressive strength of recycled concrete at 28 Days (Mix design B and Mix design D)

Because of replacing 100% recycled coarse aggregate and with increasing the amount of water/cement ratio in recycled concrete moreover recycled aggregates were not washed compressive strength of recycled concrete in both types of concrete (C20/25 and C30/37) was less than compressive strength of normal concrete (approximately 30%) (Lin, Y et al. 2003). Meanwhile, Yamato et Al. (1998) investigated that with replacement of 30%, 50% and 100% coarse aggregate, the compressive strength was decreased 20%, 30% and 45%, respectively.

4.3.1.2 Compressive strength versus splitting tensile

Tables 19 and 20 show the average of compressive strength and splitting tensile strength results for all mix designs at ages of 7, 14 and 28 days.

Table 20: Average of splitting tensile results for cylinder samples (100×200)

Days	Samples	Mix Design A	Mix Design B	Mix Design C	Mix Design D
7 Days	No. 1	1.85	3.04	1.64	2.09
	No. 2	1.75	2.94	1.88	2.40
	No. 3	1.79	2.75	2.02	2.71
	Average	1.80	2.91	1.84	2.40
14 Days	No. 1	2.82	3.08	2.38	2.81
	No. 2	2.55	3.15	2.54	2.73
	No. 3	2.60	3.26	2.72	2.68
	Average	2.66	3.16	2.55	2.74
28 Days	No. 1	2.87	3.13	3.06	2.97
	No. 2	3.17	3.33	3.05	2.89
	No. 3	2.73	3.67	2.94	3.07
	Average	2.92	3.38	3.02	2.98

Figures 16 to 21 represent comparison between compressive strength and splitting tensile in three different ages (7, 14 and 28 days).

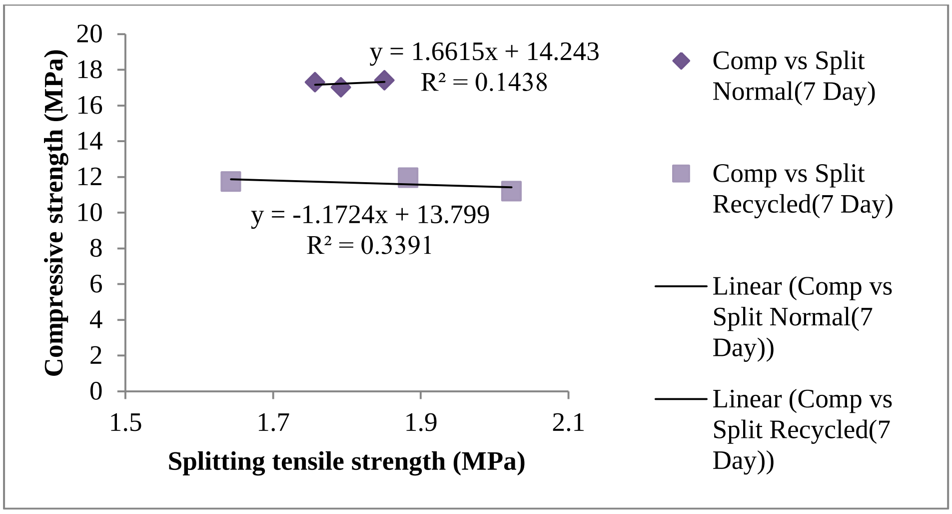

Figure 16: Compressive strength versus splitting tensile strength for age of 7 days (Mix design A and Mix design C)

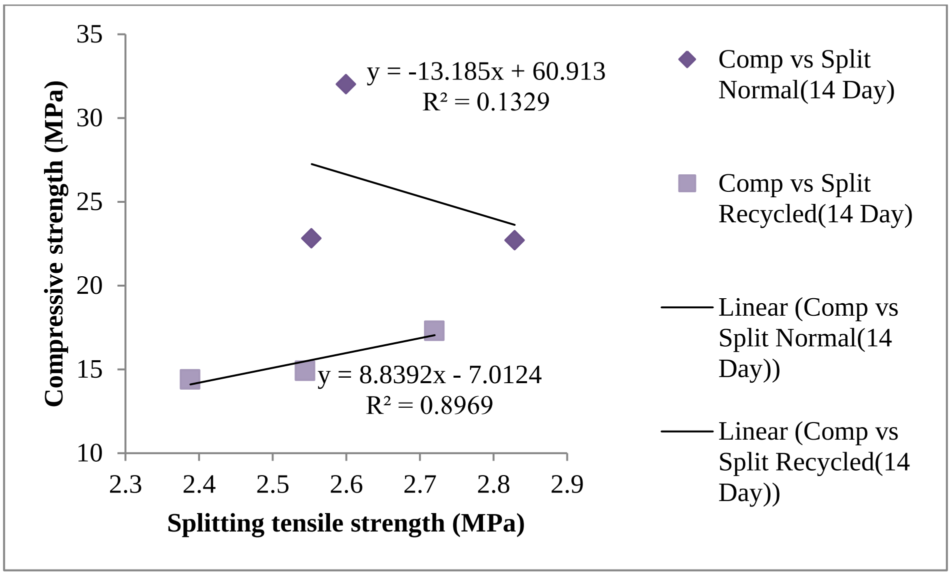

Figure 17: Compressive strength versus splitting tensile strength for age of 14 days (Mix design A and Mix design C)

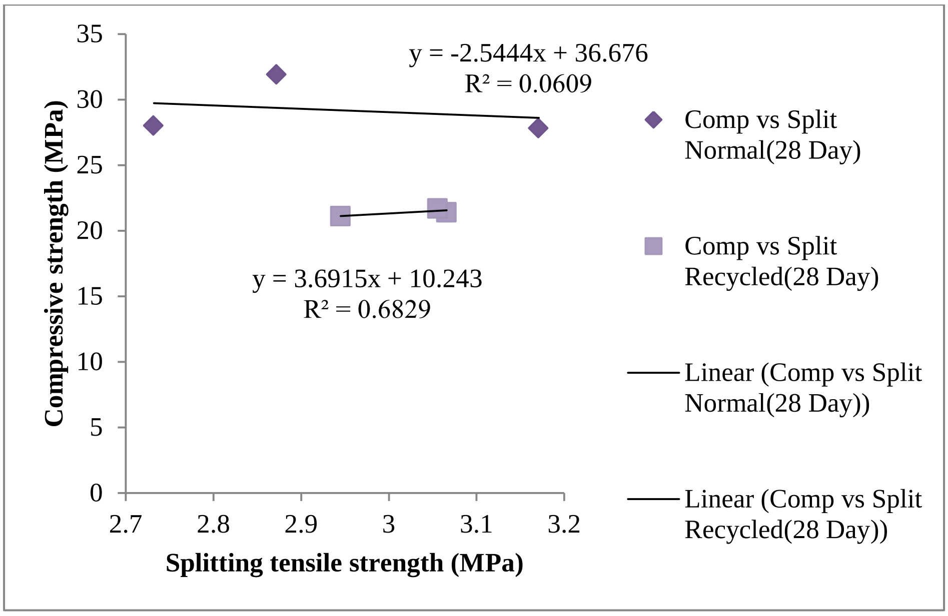

Figure 18: Compressive strength versus splitting tensile strength for age of 28 days (Mix design A and Mix design C)

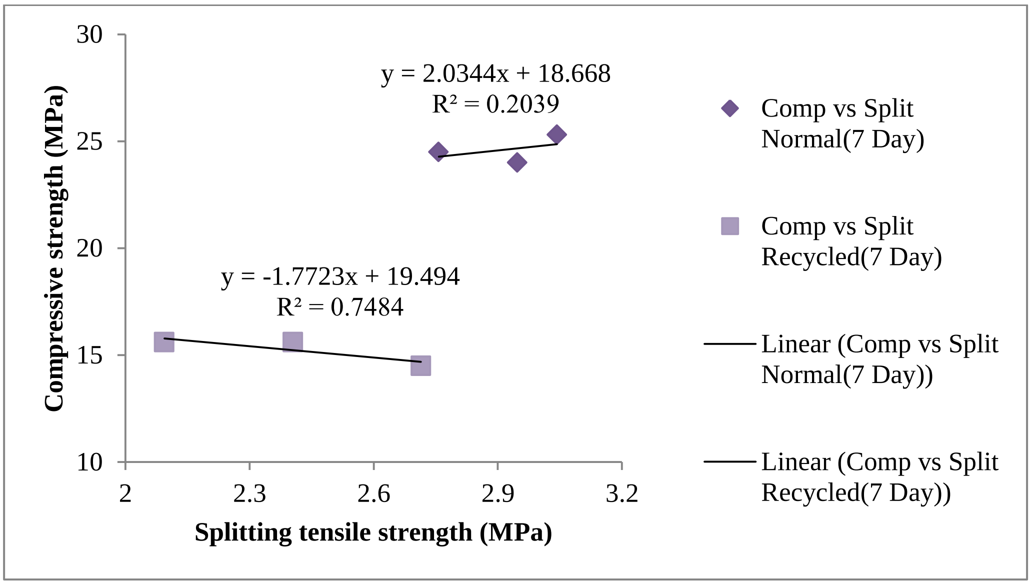

Figure 19: Compressive strength versus splitting tensile strength for age of 7 days (Mix design B and Mix design D)

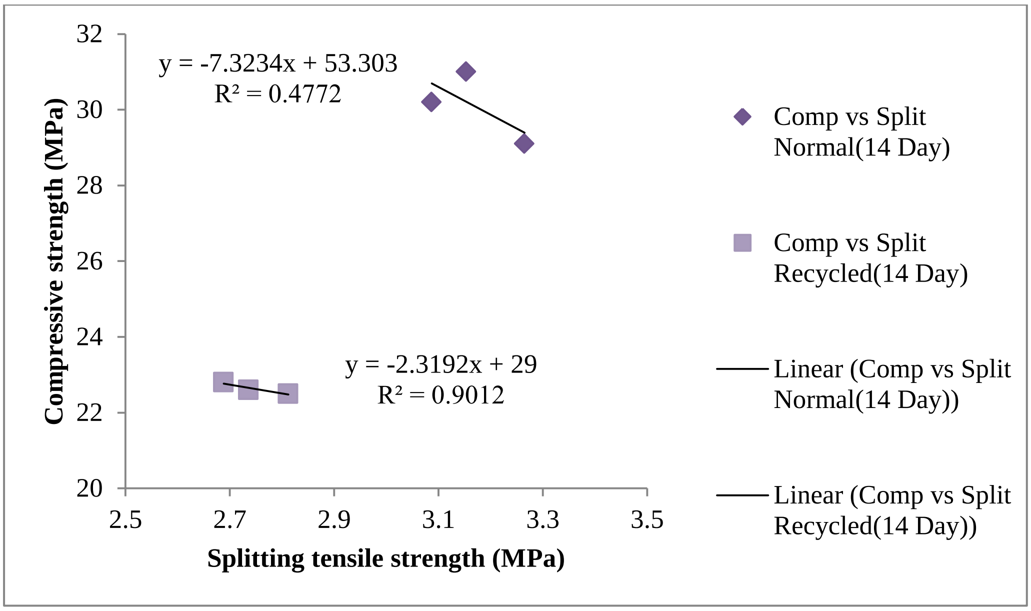

Figure 20: Compressive strength versus splitting tensile strength for age of 14 days (Mix design B and Mix design D)

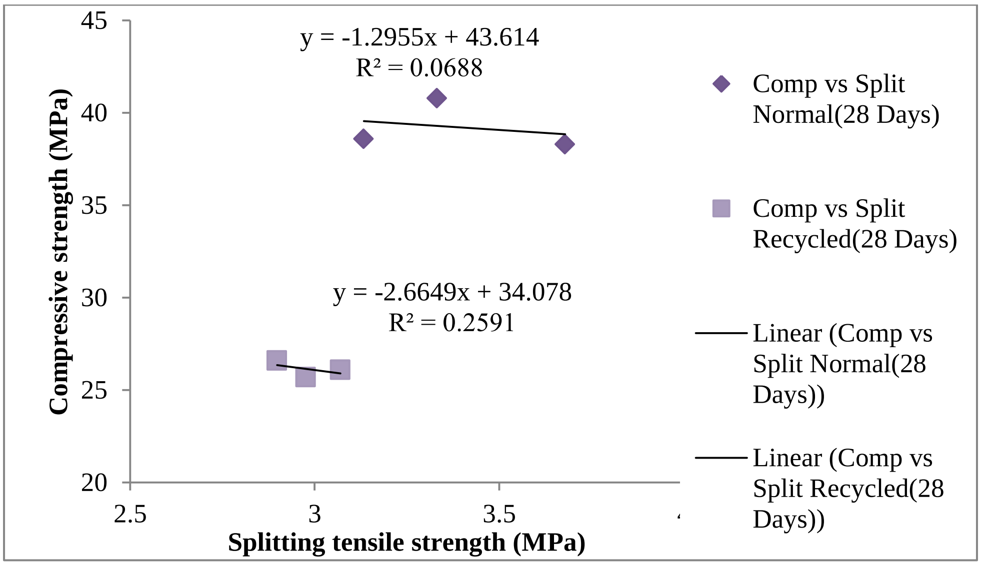

Figure 21: Compressive strength versus splitting tensile strength for age of 28 days (Mix design B and Mix design D)

As shown in graphs, compressive strength in both types of concretes (normal and recycled) has linear relation with splitting tensile strength. With increasing the amount of cement splitting tensile strength was increased. On the other hand compressive strength was increased with increasing the amount of cement. So compressive strength and splitting tensile strength has linear relation (Sagoe-Crentsile, 2001).

4.3.1.3 Compressive strength versus rebound (Schmidt) hammer test

Rebound (Schmidt) hammer test was performed on cubic specimens at the ages of 14 and 28 days.

The results of rebound (Schmidt) hammer are shown in Table 21 and results of difference between compressive strength and rebound hammer shows in Table 22.

Table 21: Rebound hammer results for cubic samples

Days	Samples	Mix Design A	Mix Design B	Mix Design C	Mix Design D
14 Days	No. 1	19.60	26.30	19.70	26.10
	No. 2	19.60	26.70	20.40	25.80
	No. 3	23.20	25.10	23.10	25.50
	No. 4	19.70	29.50	21.30	25.20
	No. 5	21.40	27.20	21.60	25.80
	Average	20.70	26.96	21.22	25.68
28 Days	No. 1	29.00	30.70	24.00	24.40
	No. 2	25.40	34.70	21.70	23.30
	No. 3	27.00	29.70	23.30	25.00
	No. 4	26.50	26.40	20.60	24.40
	No. 5	26.60	32.10	22.50	24.10
	Average	26.90	30.72	22.42	24.24

Table 22: Difference between compressive strength and rebound hammer result

Days	Samples	Mix Design A	Mix Design B	Mix Design C	Mix Design D
14 Days	No.1	+13.65%	+12.91%	-26.90%	-13.79%
	No. 2	+14.03%	+13.87%	-26.96%	-12.40%
	No. 3	+27.50%	+13.74%	-25.10%	-10.58%
	No. 4	+11.26%	+11.14%	-19.71%	-9.52%
	No. 5	+7.75%	+12.25%	-22.68%	-11.62%
28 Days	No. 1	+9.09%	+20.46%	-10.83%	+5.05%
	No. 2	+8.63%	+14.95%	0.00%	+12.40%
	No. 3	+3.57%	+22.45%	-9.44%	+4.21%
	No. 4	+3.63%	+31.07%	-2.36%	+7.22%
	No. 5	+4.31%	+14.85%	-7.55%	+9.05%

Figures 22 to 25 show the comparison between compressive strength and rebound hammer at ages of 14 and 28 days.

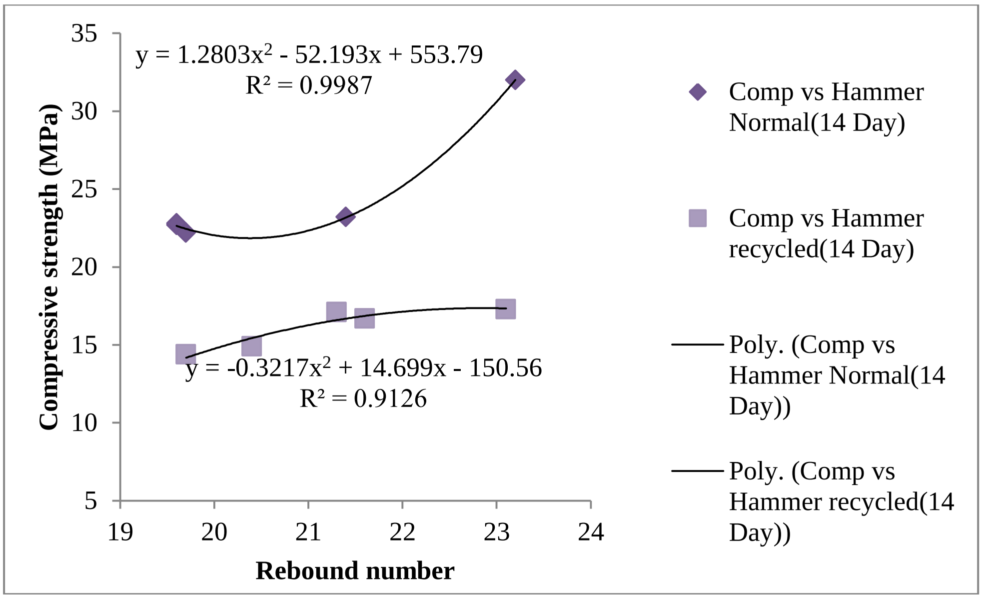

Figure 22: Compressive strength versus rebound hammer for age of 14 days (Mix design A and Mix design C)

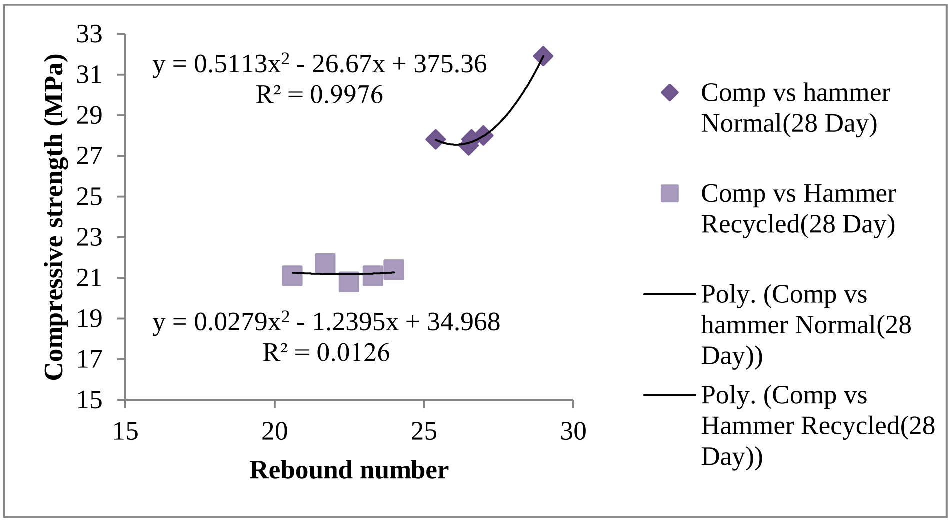

Figure 23: Compressive strength versus rebound hammer for age of 28 days (Mix design A and Mix design C)

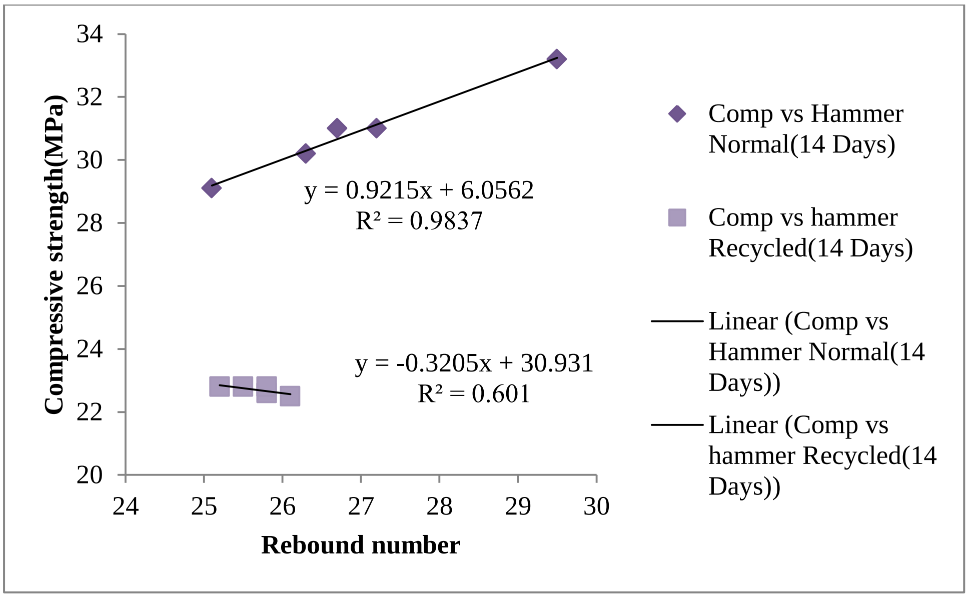

Figure 24: Compressive strength versus rebound hammer for age of 14 days (Mix design B and Mix design D)

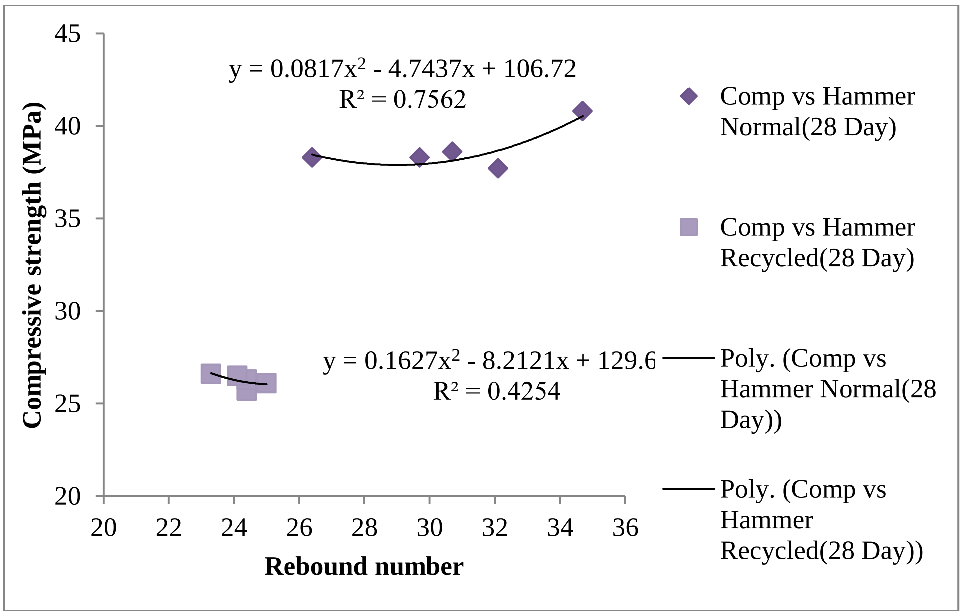

Figure 25: Compressive strength versus rebound hammer for age of 28 days (Mix design B and Mix design D)

As shown in above figures, rebound hammer was increased by increasing of compressive strength amount.

With regard to the results mentioned in Tables 19 and 21, Mix design B has highest average of compressive strength and hammer among four mix designs at 14 and 28 days.

The particular results of rebound hammer can be related to the aggregates category. In conformity with BS 1881: Part 201 (2009), rebound hammer test was affected to surface related to surface-density. Sago and Brown (1998) investigated that recycled concrete aggregates have lower density in comparison with natural aggregates since the porous and less dense residual mortal lumps is adhering to the surface. The percentage of residual mortal volume is increased by the increase of particle size. By increasing maximum size of coarse aggregates in both groups- C20/25 and C30/37- including normal and recycled aggregate from 20 mm to 23mm, the amount of adhered mortal volume is increased. Thus, the percentage of density is decreased in each group (16.6% decreased in C20/25 and 21% decreased in C30/37).

4.3.1.4 Compressive strength versus PUNDIT test

Ultrasonic Pulse Velocity Test (PUNDIT) was performed on cubic samples at ages of 14 and 28 days. Table 23 shows the results of pulse velocity.

Table 23: PUNDIT results for cubic samples

Days	Samples	Mix Design A	Mix Design B	Mix Design C	Mix Design D
14 Days	No. 1	3.16	3.16	3.81	3.61
	No. 2	3.48	3.15	3.82	3.74
	No. 3	3.36	3.21	3.80	3.68
	No. 4	3.31	3.25	3.88	3.73
	No. 5	3.46	3.20	3.80	3.67
	Average	3.35	3.19	3.82	3.68
28 Days	No. 1	3.34	3.15	3.77	3.63
	No. 2	3.15	3.25	3.80	3.74
	No. 3	3.19	3.13	3.79	3.80
	No. 4	3.27	3.16	3.82	3.79
	No. 5	3.25	3.19	3.75	3.77
	Average	3.24	3.17	3.78	3.74

Figures 26 to 29 show comparison between compressive strength and PUNDIT at two different ages (14 and 28 days).

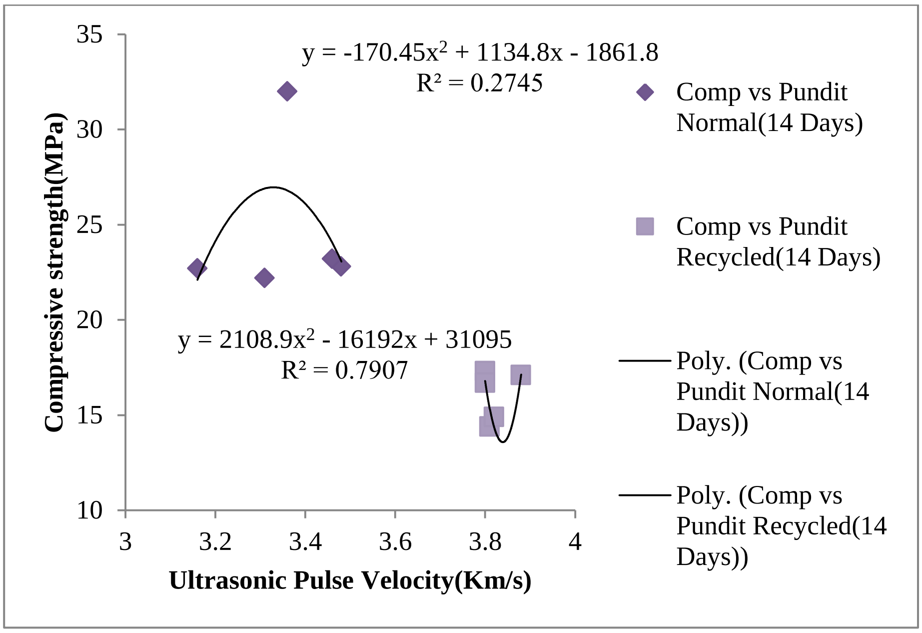

Figure 26: Compressive strength versus PUNDIT at age of 14 days (Mix design A and Mix design C)

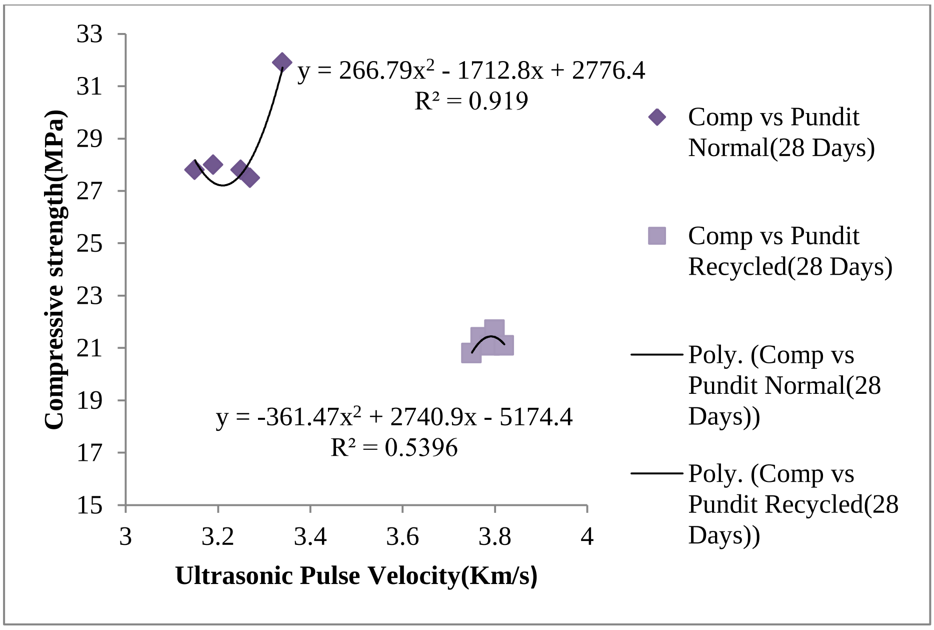

Figure 27: Compressive strength versus PUNDIT at age of 28 days (Mix design A and Mix design C)

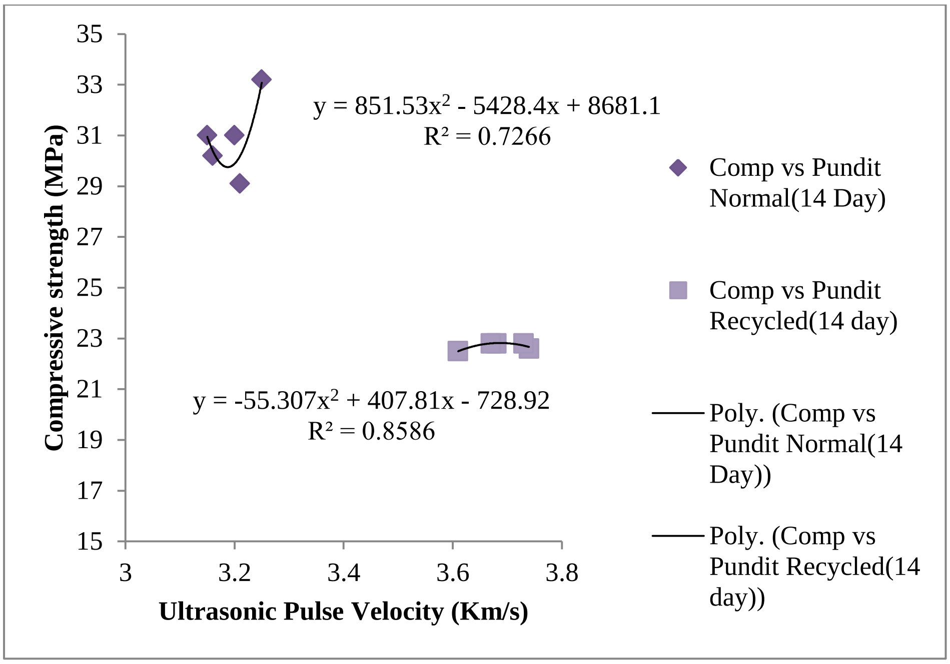

Figure 28: Compressive strength versus PUNDIT at age of 14 days (Mix design B and Mix design D)

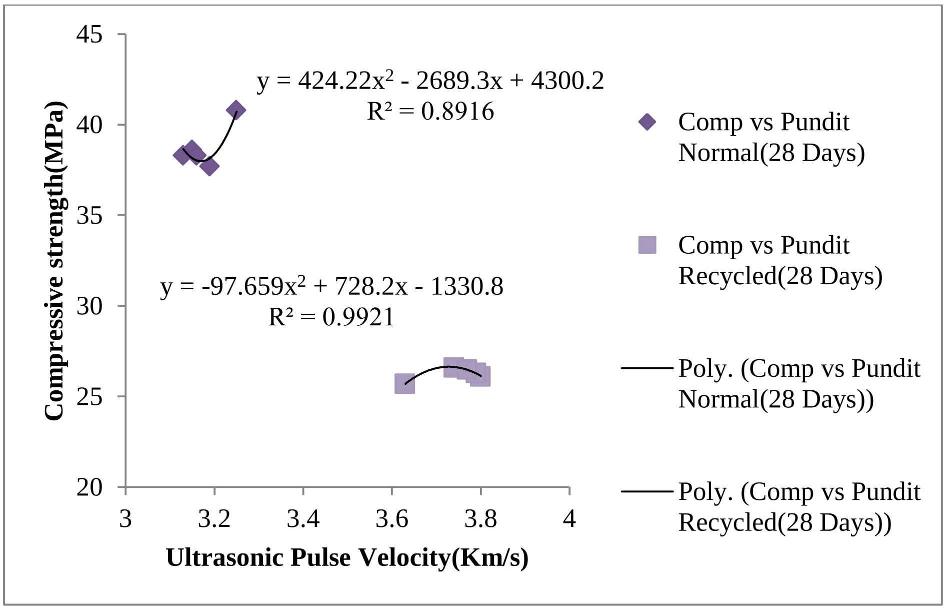

Figure 29: Compressive strength versus PUNDIT at age of 28 days (Mix design B and Mix design D)

The aim of PUNDIT test is to determine the porosity of concrete. Angulo et al. (2009) stated that with reducing compressive strength approximately 65%, the amount of porosity was increased from 0% to 40%. In this research, when the compressive strength was decreased 25.8% and 32.26%, concrete porosity was increased 14.28% and 15.24% in C20/25 and C30/37, respectively. Consequently, the amount of pulse velocity was decreased by increasing of compressive strength with regard to these graphs. Trtnik et al. (2008) investigated that with increasing the amount of water the amount of pulse velocity was increased and the amount of compressive strength was decreased.

4.3.2 Splitting tensile strength

Splitting tensile strength test was conducted on cylinder samples (100×200mm) at the ages of 7, 14 and 28 days. The results of this test are shown in Table 20.

4.3.2.1 Splitting tensile of normal concrete versus splitting tensile of recycled concrete

Figures 30 to 35 represent comparison between splitting tensile strengths of normal concrete and recycled concrete.

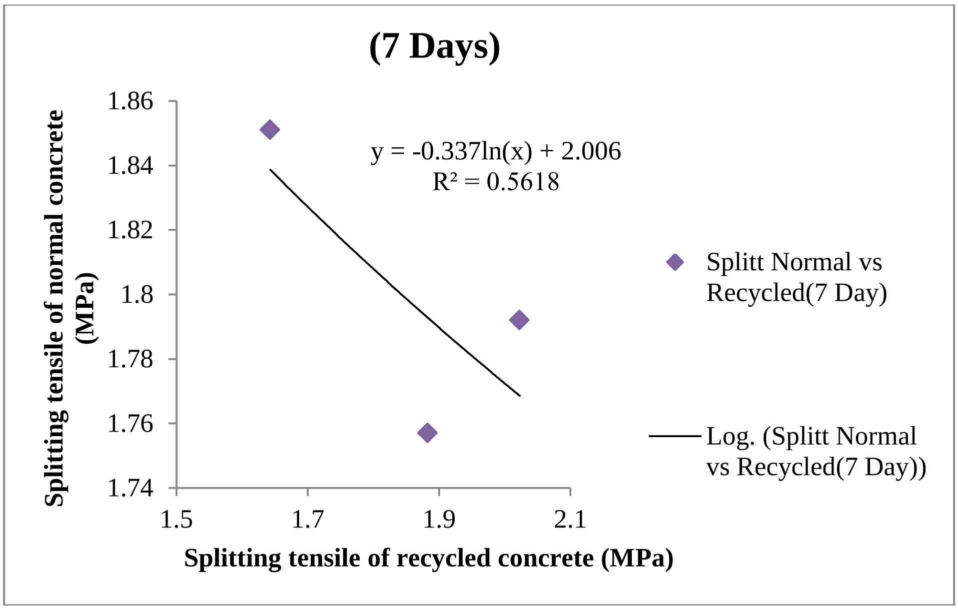

Figure 30: Splitting tensile strength of normal concrete versus splitting tensile strength of recycled concrete at age of 7 days (Mix design A and Mix design C)

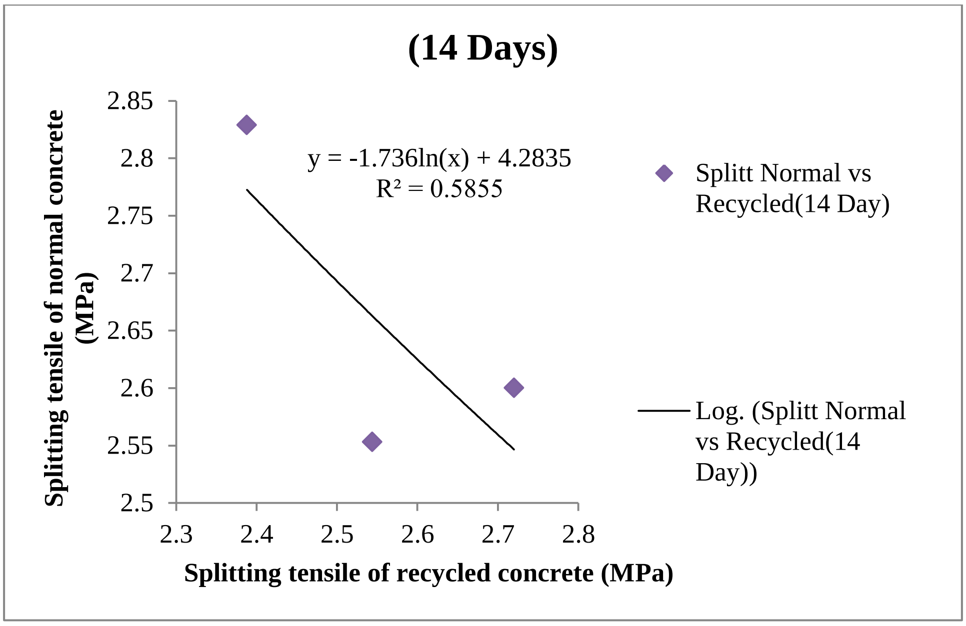

Figure 31: Splitting tensile strength of normal concrete versus splitting tensile strength of recycled concrete at age of 14 days (Mix design A and Mix design C)

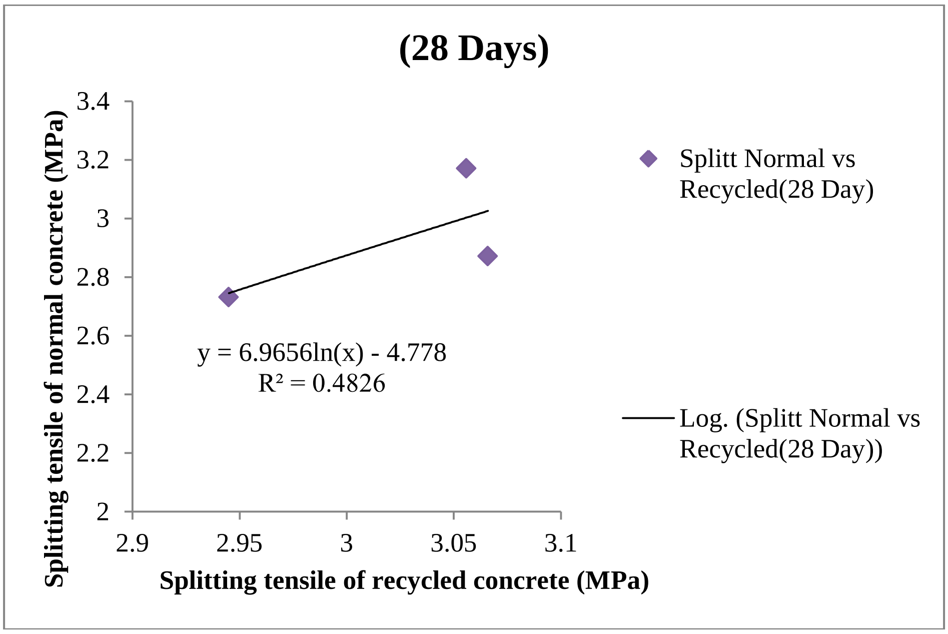

Figure 32: Splitting tensile strength of normal concrete versus splitting tensile strength of recycled concrete at age of 28 days (Mix design A and Mix design C)

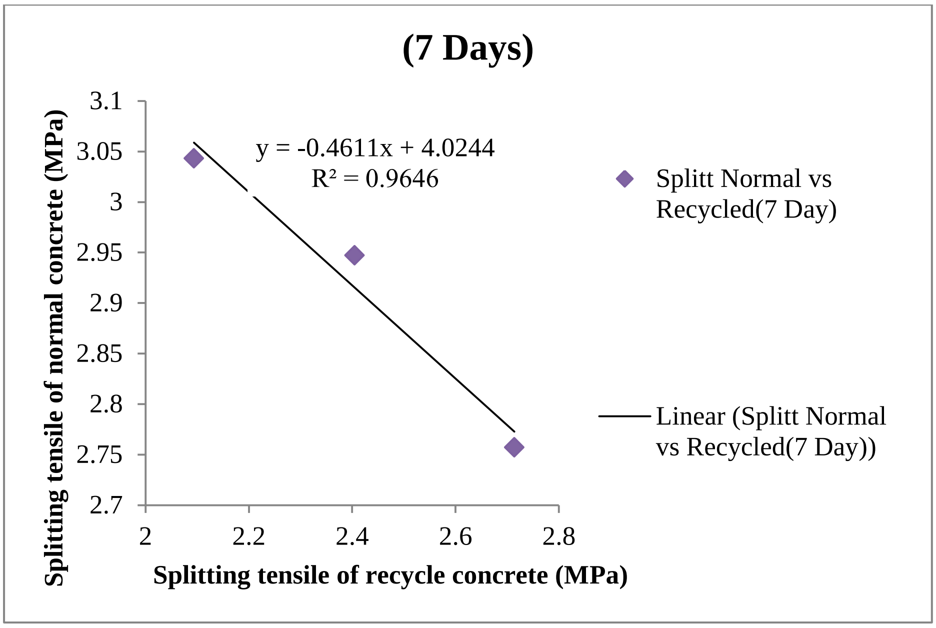

Figure 33: Splitting tensile strength of normal concrete versus splitting tensile strength of recycled concrete at age of 7 days (Mix design B and Mix design D)

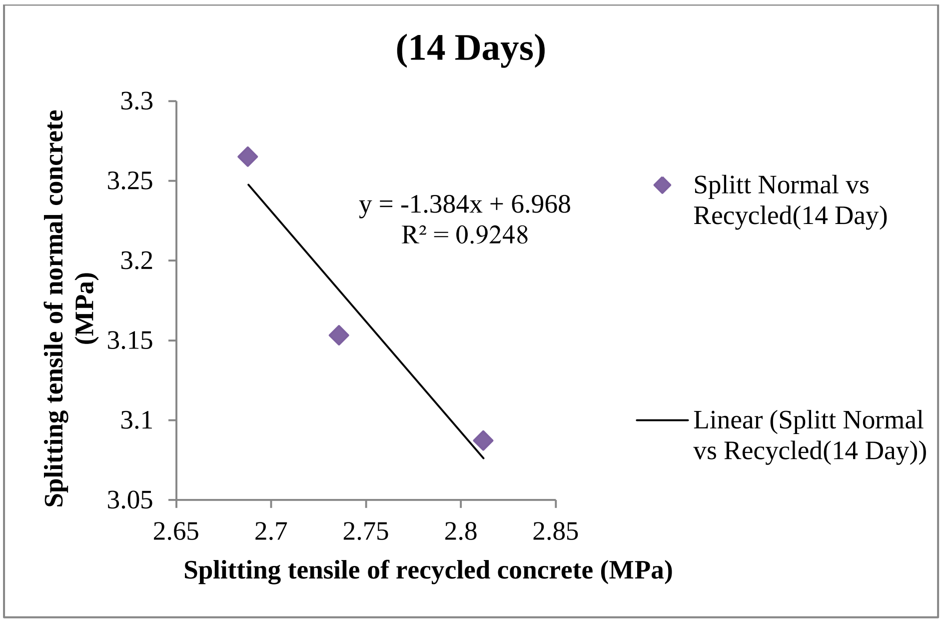

Figure 34: Splitting tensile strength of normal concrete versus splitting tensile strength of recycled concrete at age of 14 days (Mix design B and Mix design D)

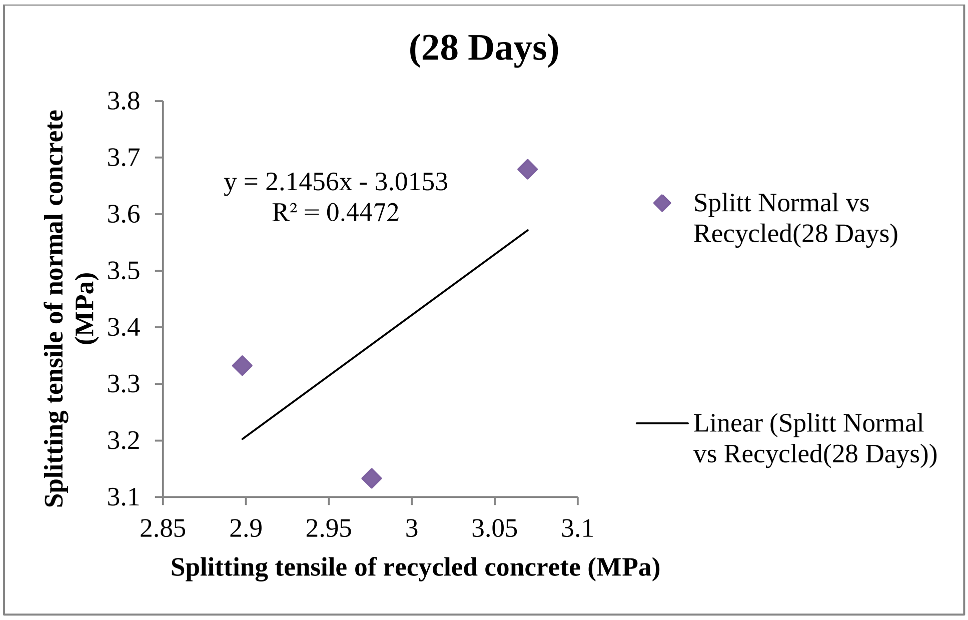

Figure 35: Splitting tensile strength of normal concrete versus splitting tensile strength of recycled concrete at age of 14 days (Mix design B and Mix design D)

By increasing water/cement ratio in C20/25 (0.64 to 0.9), the amount of splitting tensile strength was decreased (3.4%) and by increasing water/cement ratio in C30/37 (0.5 to 0.69), the amount of splitting tensile strength was decreased (12%).

According to these graphs, there was a liner relation between splitting tensile in normal and recycled concrete.

4.3.2.2 Splitting tensile strength versus rebound test

The results of these tests are shown in Tables 20 and 21.

The relation between splitting tensile strength and rebound hammer test are depicted in Figures 36 to 39.

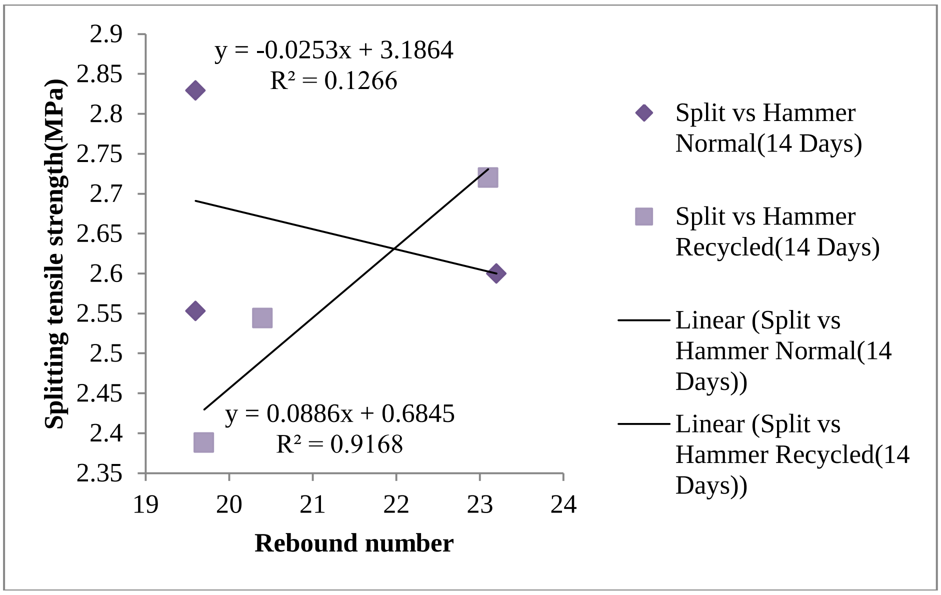

Figure 36: Splitting tensile strength versus rebound number at age of 14 days (Mix design A and Mix design C)

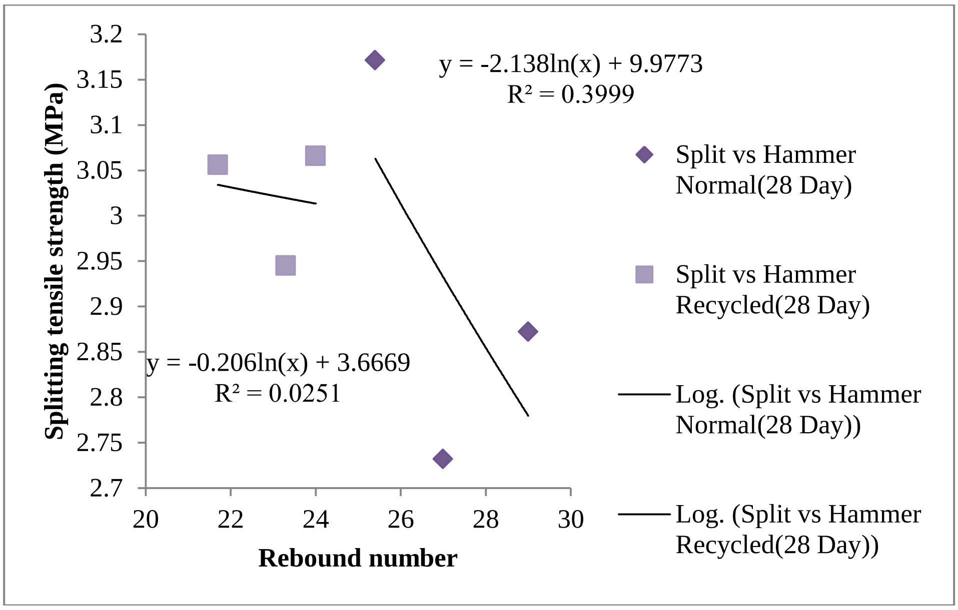

Figure 37: Splitting tensile strength versus rebound number at age of 28 days (Mix design A and Mix design C)

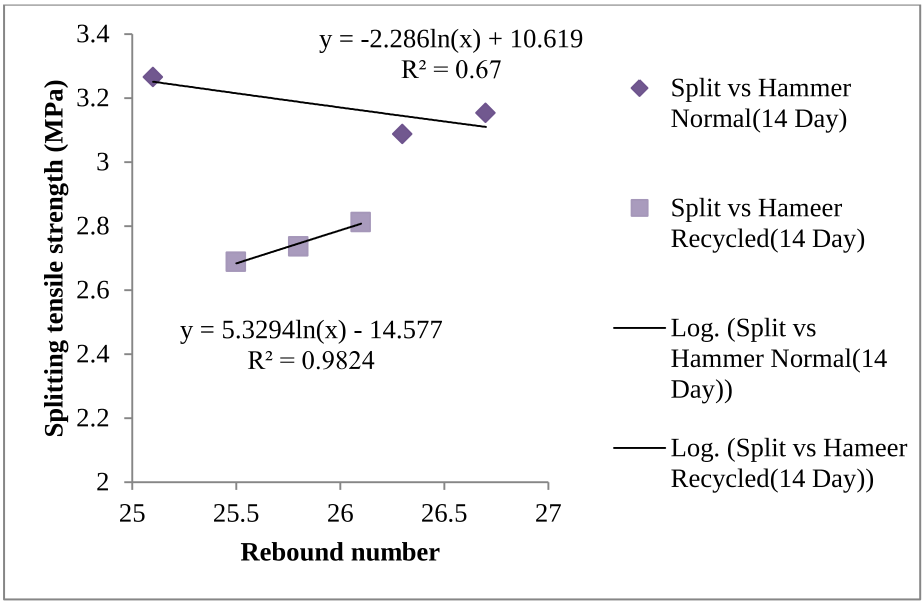

Figure 38: Splitting tensile strength versus rebound number at 14 days (Mix design B and Mix design D)

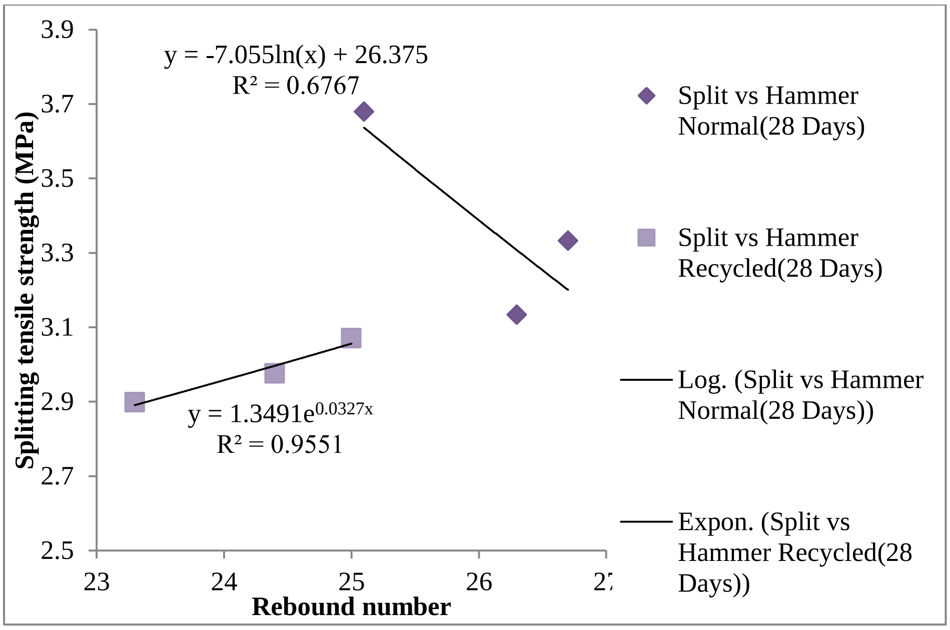

Figure 39: Splitting tensile strength versus rebound number at 28 days (Mix design B and Mix design D)

Because splitting tensile strength is a destructive test and rebound hammer is a non-destructive and unreliable test, so there is an opposite relation between splitting tensile strength and rebound hammer.

4.3.2.3 Splitting tensile strength versus PUNDIT test

According to Tables 20 and 23, Figures 40 to 43 are shown as comparison between splitting tensile strength and PUNDIT.

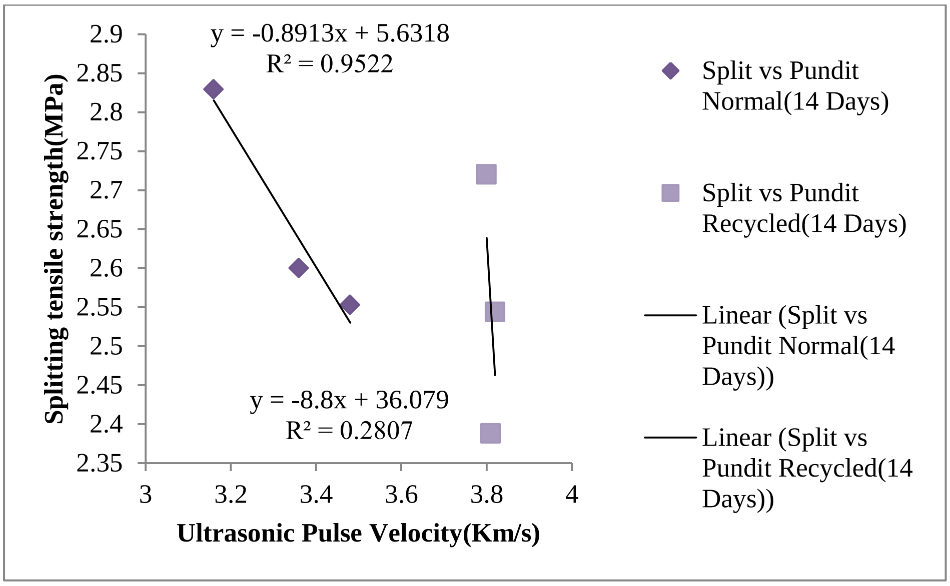

Figure 40: Splitting tensile strength versus PUNDIT at age of 14 days (Mix design A and Mix design C)

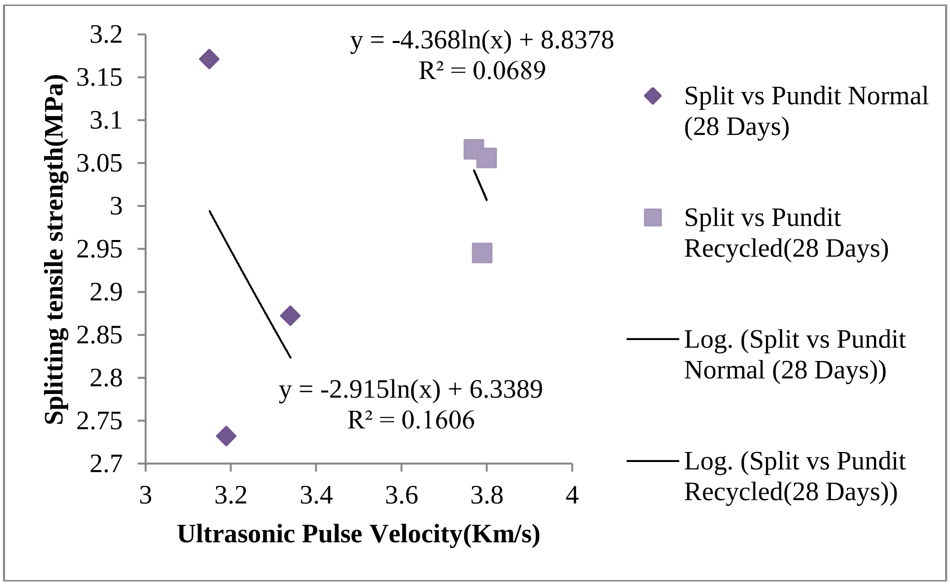

Figure 41: Splitting tensile strength versus PUNDIT at age of 28 days (Mix design A and Mix design C)

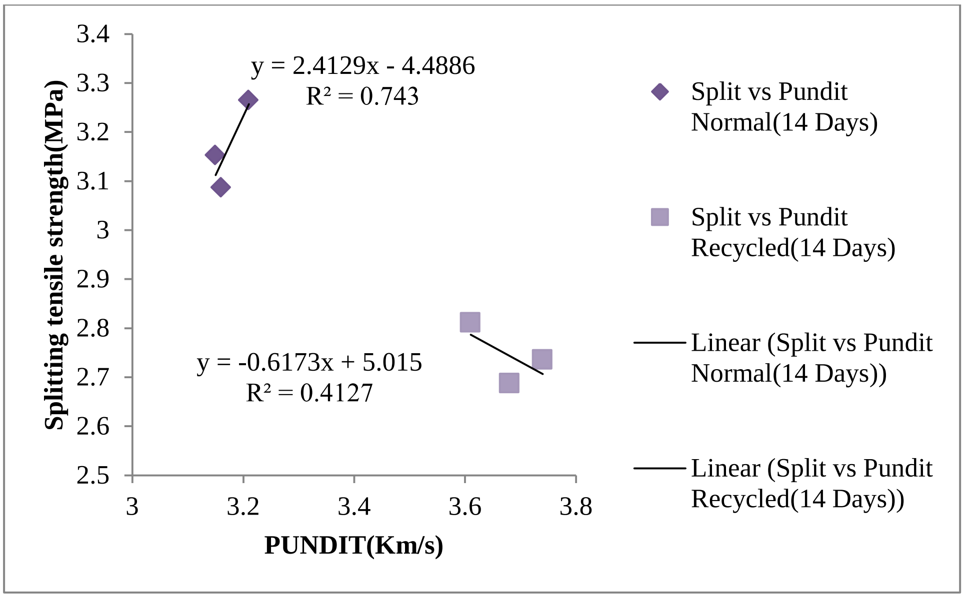

Figure 42: Splitting tensile strength versus PUNDIT at age of 14 days (Mix design B and Mix design D)

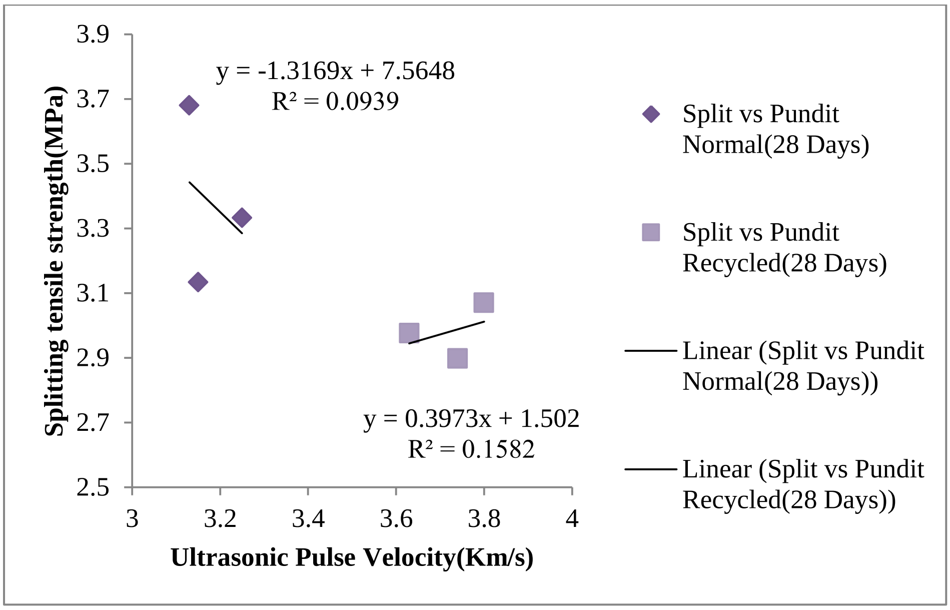

Figure 43: Splitting tensile strength versus PUNDIT at age of 28 days (Mix design B and Mix design D)

4.3.3 Ultrasonic Pulse Velocity Test (PUNDIT)

This test was performed on cubic samples (150×150×150) at 14 and 28 days. By increasing maximum size of coarse aggregates in both groups- C20/25 and C30/37- including normal and recycled aggregates from 20 mm to 23mm, the percentage of concrete porosity was increased to 13.29% and 14.28% in C20/25 and C30/37, respectively.

4.3.4.1 PUNDIT versus Rebound (Schmidt) hammer test

Graphs of these tests are shown in Figures 44 to 47. By reducing aggregate fraction and increasing maximum aggregate size in recycled and normal concretes, the surface hardness values of recycled concrete obtained from Schmidt hammer test were less than normal concrete.

Based on hammer test results, when surface hardness values were increased in recycled and normal concretes, the porosity values obtained from PUNDIT test were decreased. The average of hammer and PUNDIT test results were mentioned in Tables 21 and 23.

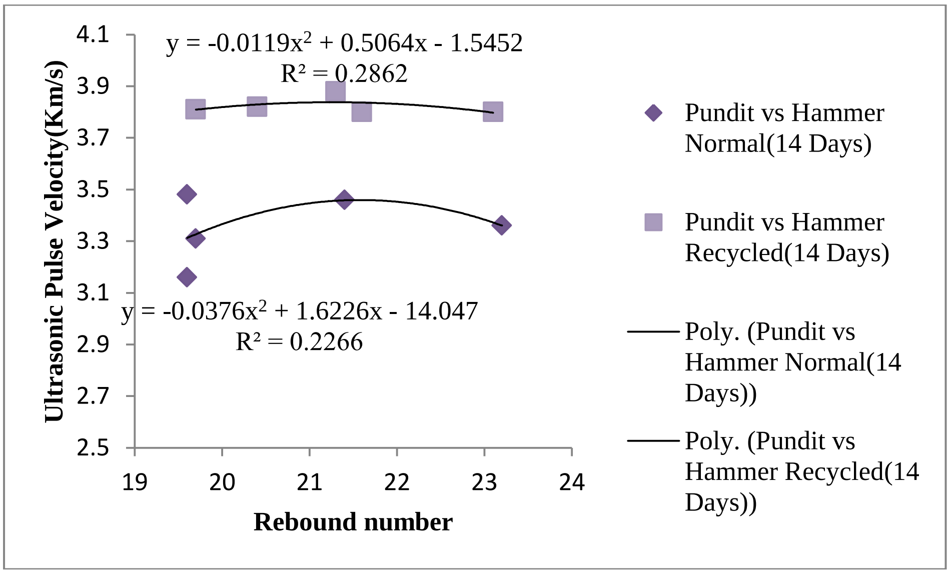

Figure 44: PUNDIT versus rebound number at age of 14 days (Mix design A and Mix design C)

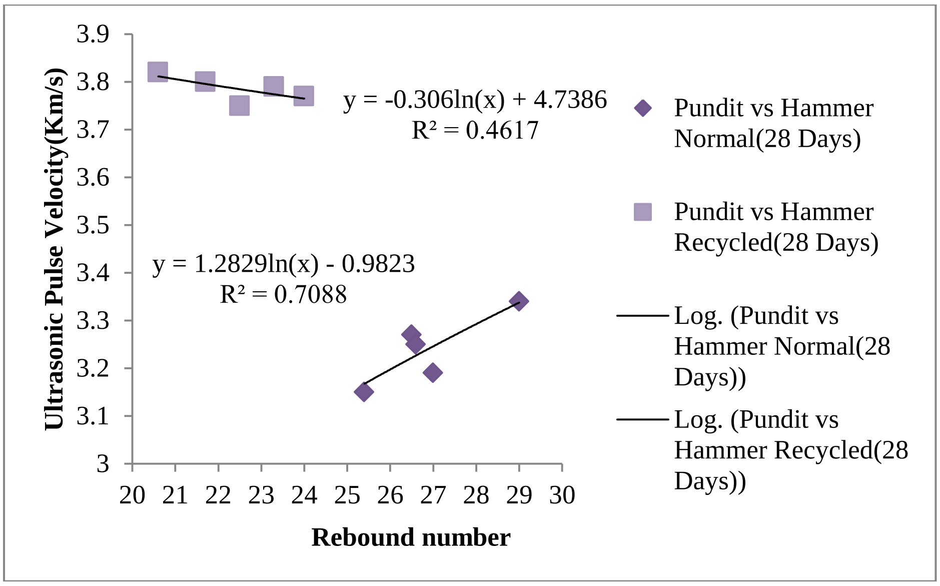

Figure 45: PUNDIT versus rebound number at age of 28 days (Mix design A and Mix design C)

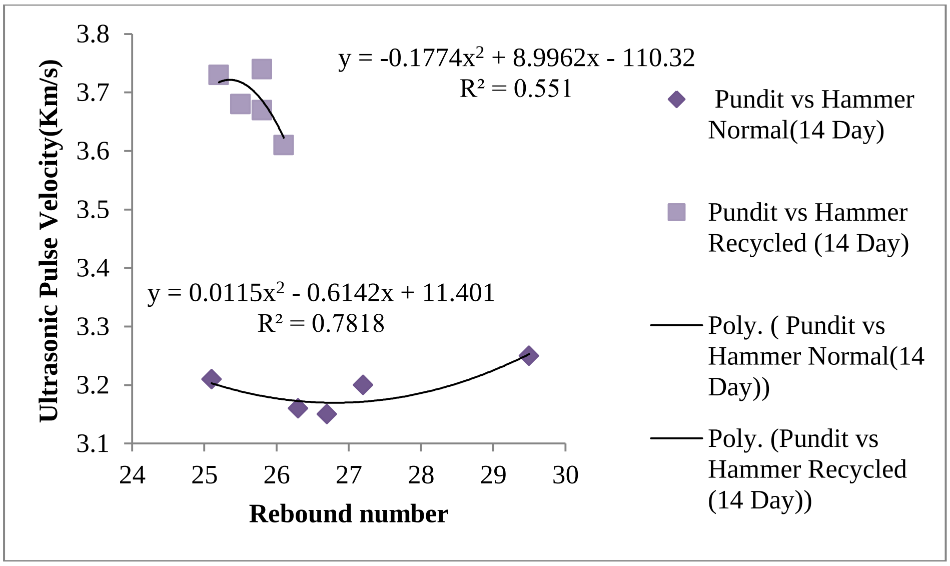

Figure 46: PUNDIT versus rebound number at age of 14 days (Mix design B and Mix design D)

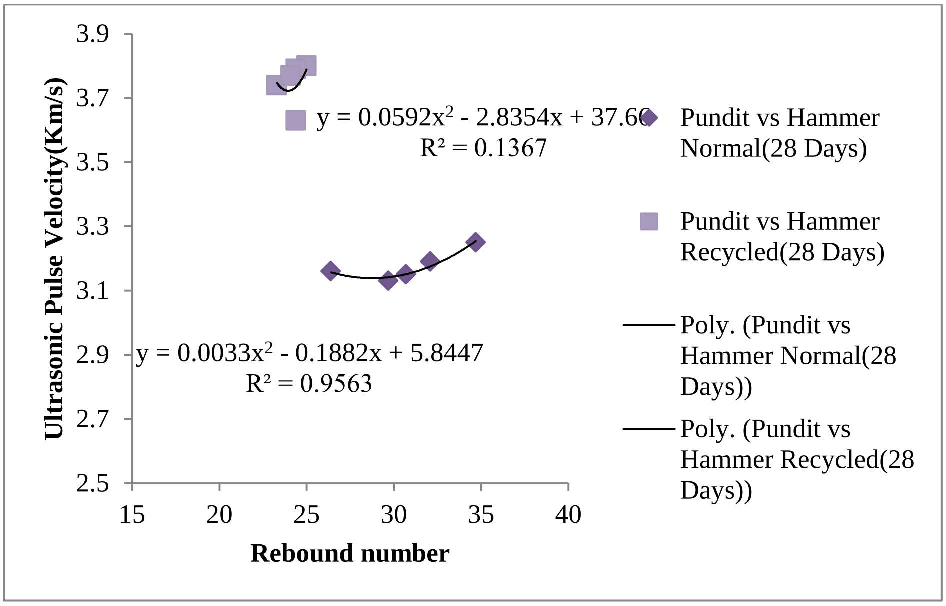

Figure 47: PUNDIT versus rebound number at age of 28 days (Mix design B and Mix design D)

4.3.4 Hardened Density of Concrete

Based on BS EN 12390-7 (2009) for each mix design, hardened concrete density was conducted. Table 24 shows weight of cubic samples and Table 25 shows results of hardened density for each mix design at three different ages. Curing condition for this test was water curing.

Table 24: Weight of cubic samples

Days	Samples	Mix Design A	Mix Design B	Mix Design C	Mix Design D
7 Days	No. 1	7.90	7.99	7.46	7.25
	No. 2	7.84	7.65	7.44	7.24
	No. 3	7.99	7.87	7.36	7.30
	No. 4	8.02	7.87	7.32	7.24
	No. 5	7.96	8.03	7.42	7.20
	Average	7.94	7.88	7.40	7.24
14 Days	No. 1	8.12	7.93	7.49	7.28
	No. 2	8.14	7.96	7.48	7.19
	No. 3	7.94	8.10	7.41	7.14
	No. 4	8.17	7.76	7.14	7.30
	No. 5	7.97	7.87	7.49	7.21
	Average	8.06	7.92	7.40	7.22
28 Days	No. 1	7.83	8.00	7.40	7.13
	No. 2	8.12	7.87	7.39	7.22
	No. 3	8.07	8.22	7.35	7.03
	No. 4	8.11	7.85	7.39	7.41
	No. 5	8.02	7.79	7.46	7.24
	Average	8.03	7.94	7.39	7.20

Table 25: Test results of hardened density

Days	Samples	Mix Design A	Mix Design B	Mix Design C	Mix Design D
7 Days	No. 1	2340.74	2367.40	2210.37	2148.14
	No. 2	2331.85	2266.66	2204.44	2145.18
	No. 3	2367.40	2331.85	2180.74	2162.96
	No. 4	2376.29	2331.85	2168.88	2145.18
	No. 5	2358.51	2379.25	2198.51	2133.33
	Average	2355.16	2335.40	2192.58	2146.95
14 Days	No. 1	2405.92	2349.62	2219.25	2157.03
	No. 2	2411.85	2358.51	2216.29	2130.37
	No. 3	2352.59	2400.00	2195.55	2115.55
	No. 4	2420.74	2299.25	2115.55	2162.96
	No. 5	2361.48	2331.85	2219.25	2136.29
	Average	2390.51	2347.84	2193.17	2140.44
28 Days	No. 1	2320.00	2370.37	2192.59	2112.59
	No. 2	2405.92	2331.85	2185.62	2139.25
	No. 3	2391.11	2435.55	2177.77	2082.96
	No. 4	2400.00	2325.92	2185.62	2195.55
	No. 5	2376.29	2308.14	2210.37	2145.18
	Average	2378.66	2354.36	2190.39	2135.10

Table 26: Average density for each mix design

Mix Design	*Average of Density (Kg/m^3)
A	2374.77
B	2345.86
C	2192.04
D	2140.83

*Average density of 45 samples with the same mix design.

Density was increased by increasing water/cement ratio for different mix designs. The hardened density of mix design B was a little lower than density of mix design A and density of mix design D was lower than mix design C.

4.3.5 Freeze-Thaw Resistance Test

This test was conducted on broken concrete samples at 28 days. The results of this test are shown in Table 27.

Table 27: Results of freeze-thaw resistance test

Mix design	$K_{d1 (\%)}$	$K_{d2 (\%)}$	$K_{d3 (\%)}$	$K_{dt (\%)}$
A	64.75	52.40	35.00	55.09
B	86.55	71.20	67.00	78.03
C	56.65	50.40	52.00	53.84
D	61.05	49.60	52.00	55.80

Figure 48 shows the percentage of weight loss for each concrete type.

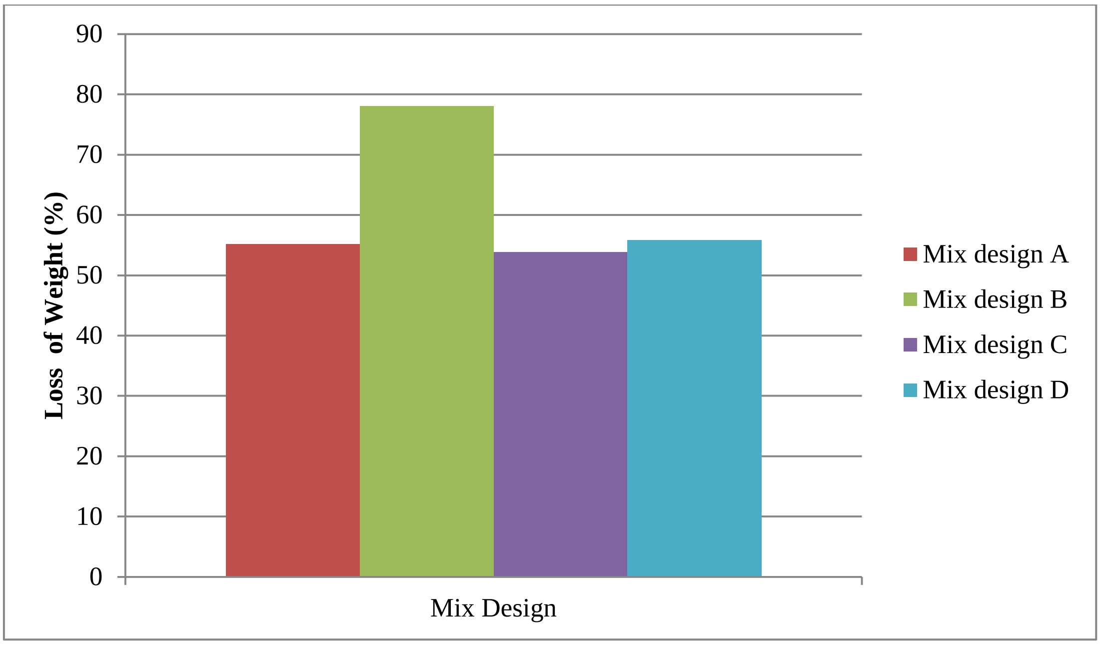

Figure 48: Loss of weight after freeze-thaw test for various concrete types

In this bar chart, one can see that mix design B lost more weight than other mix designs since this type of concrete had more cement. The percentage of weight loss for mix design B was approximately 80%.

Table 28 shows overall comparison between recycled concrete aggregate and normal concrete aggregate.

Table 28: Comparison between properties of normal concrete and recycled concrete

Applied tests	Comparison of test results between recycled and normal concrete
Slump control	Higher water demand in RCA
Compressive strength	RAC < NAC (35%)
Strength development to 7 days	RCA comparable with NAC
Splitting tensile strength	RAC < NAC (15%)
Hammer	RAC < NAC (18%)
PUNDIT	RAC > NAC (15%)
Density	RAC < NAC (8%)
Loss weight	RAC > NAC (20%)

Sagoe-Crentsil et al. (1996) compared NAC with RAC shown in Table 29.

Table 29: Comparison between properties of normal concrete and recycled concrete (Sagoe et al., 1996)

Concrete property	RAC concrete compared to normal
Slump control	Higher water demand in RCA
Compressive strength at equal w/c	RAC < NAC (90%)
Strength development to 7 days	RAC comparable with NAC
Flexural strength	RAC comparable to NAC
Modulus of elasticity	RAC < NAC
Drying shrinkage	RAC > NAC
Expansion	RAC comparable with NAC

With regard to Tables 28 and 29, recycled concrete needed more water than normal concrete. Moreover, Sagoe-Crentsil et al. (1996) has obtained low compressive strength in comparison with this study.

Chapter 5

CONCLUSIONS AND RECOMENDATIONS

Recycled aggregate concrete was the focus of this study. Concrete samples from Materials of Construction Laboratory of Civil Engineering Department in Eastern Mediterranean University were crushed. After sieving the crushed concretes, different mixes with natural aggregates and crushed aggregates were designed. Normal concrete and recycled aggregate concrete samples were cast, cured, and tested. Different tests were done on the samples including compressive strength, splitting tensile strength, PUNDIT, rebound hammer, and freeze-thaw resistance.

Based on the obtained results of physical and chemical tests and the influence of normal and recycled aggregates on strength, porosity, and density, the following conclusions and suggestions were mentioned.

1- The numerical value of RCA slump was less than NAC slump due to high water absorption percentage.

2- Compressive strength of recycled aggregate concrete was 35% less than normal aggregate in which the volume of cement was held constant.

3- Splitting tensile strength of recycled aggregate concrete was 15% less than normal aggregate with the same cement volume.

4- The rebound hammer test results of recycled aggregate concrete was 18% less than normal aggregate concrete because the maximum size of recycled aggregate and normal aggregate was 23(mm) and 20(mm), respectively.

5- The pundit test results of recycled aggregate concrete was 15% more than normal aggregate concrete since three different sizes of aggregates were used in recycled aggregate in comparison with four different sizes of aggregates used in natural aggregate.

6- Density of recycled aggregate concrete was 8% less than normal aggregate concrete.

7- The lost weight of recycled aggregate concrete was 20% more than normal aggregate concrete because of having cement mortar.

8- Bring compressive strength of recycled aggregate concrete to the level of normal concrete by adding the minimum amount of cement.

9- The environmental impacts and financial issues of using recycled aggregates.

10- Various initial moisture contents for aggregates should be studied in concrete mixes in order to see the effects on mechanical properties.

REFERENCES

Afshar Ghotli, A.(2009), *Sustainability and Steel Housing in North Cyprus and Mediterranean Region*, Ms Thesis, Civil Engineering Department, Eastern Mediterranean University, Magusa, North Cyprus.

Arum, C. (2011).“ Recycling of Construction and Demolition Concrete for Sustainable Buildings”, *European Journal of Scientific Research*, 25(2), pp.265-270.

BS 812 - 112 (1990) *Testing aggregates. Method for determination of aggregate impact value*. British Standards Institution

BS 1881 : Part 125: 1986. (2009). *Methods for mixing and sampling fresh concrete in the laboratory* . British Standards Institution.

BS 1881 : Part 201. (2009). *Guide to the use of nondestructive methods of test for hardened concrete*. British Standards Institution.

BS EN 12390-3:2009. (2009). *Compressive strength of test specimens*. British Standards Institution.

BS EN 12390-7:2009. (2009). *Density of hardened concrete*. British Standards Institution.

BS EN 12350-2:2009. (2009). *Testing fresh concrete- Slump test*. British Standards Institution.

Butler, L., West, J.S. and Tighe, S.L. (2011). " Quantification of Recycled Concrete Aggregate (RCA) Properties for Usage in Bridges and Pavements: An Ontario Case Study", Paper prepared for presentation at the Innovative Developments in Sustainable Pavements Session of the 2011 Annual Conference of the Transportation Association of Canada, Edmonton, Alberta

Chisholm, D. (2011). "Best Practice Guide for the use of Recycled Aggregates in New Concrete" *Paper of Cement & Concrete Association of New Zealand*, ISSN: 1171-4204.

Dosho, Y. (2007). "Development of a Sustainable Concrete Waste Recycling System _ Application of Recycled Aggregate Concrete Produced by Aggregate Replacing Method", *Journal of Advanced Concrete Technology*, 1, pp. 27-42.

Gomez-Soberon, J.M.V. (2002). "Porosity of recycled concrete with substitution of recycled concrete aggregate", *Cement and Concrete research,* 32, pp. 1301-1311

Hee, S., Jeehye, K. and Ju-Yeoun, H. (2009). "Identifying and assessing influence factors on improving Waste Management performance for building construction projects." *Construction Engineering and Management,* 7, pp. 647-656.

Jeong, H. (2011). “Processing and properties of recycled aggregate concrete”, Master of thesis in civil engineering in the graduate College of the University of Illinois at Urbana-Champaign.

Kasai, Y. (2004) “Recent trends in recycling of concrete waste and use of recycled aggregate concrete”, Recycling concrete and other materials for sustainable development, ACI text, SP-219-2, Farmington Hills, Michigan, pp.11-34.

Lauritzen, E.K. (2004). “Recycling concrete-an overview of challenges and opportunities”, Recycling concrete and other materials for sustainable development, ACI text, SP-219-1, Farmington Hills, Michigan, pp. 1-10.

Limbachiya, M.C., Koulouris, A., Roberts, J.J. and Fried, A.N. (2004). “Performance of recycled aggregate concrete”, RILEM International Symposium on Environment-Conscious Materials and Systems for Sustainable Development, (2004), pp. 127-136.

Lin, Y. (2003). “An assessment of optimal mixture for concrete made with recycled concrete aggregates” *Cement and Concrete Research,* vol. 34, pp. 1373–1380

Movasagh, R. (2006). “Durability of Reinforced Concrete Incorporating Recycled Concrete as Aggregate (RCA)” MS Thesis, University of Waterloo.

Poon, C.S., Shi, Z.H. and Lam, L. (2004). “Effect of Microstructure of ITZ on CS of concrete prepared with recycled aggregate.” *Construction and Building Materials*, vol. 18, no. 6, pp. 461-468.

Sagoe-Crentsil, K.K., Brown, T. and Taylor, AH. (2001).“Performance of concrete made with commercially produced coarse recycled concrete aggregate”. *Cem Concr Res*, 31:707–12

Salem, M.R., Burdette, E.G. and Jackson, M.N. (2003). “Resistance to freezing and thawing of recycled concrete”, *ACI Materials Journal*, vol.100, no.3, pp. 216-221.

Seattle, (2009). Construction Waste Management. . *QUICK GUIDE. TO GREEN TI. Sustainable Tenant Improvements city green building* .2011. from http://www.seattle.gov

Shayan, A. and Xu, A. (2003). “Performance and properties of structural concrete made with recycled concrete aggregate”, *ACI Materials Journal*, vol.100, no.5, pp. 371-380.

Sunil. (2005). Construction and demolition waste. *Minister of State for Urban Development of India*.2011.from http://www.waste-management-world.com

Tam, V., Tam, C., Yiu, K. and Cheung, S. (2006). “Critical factors for environmental performance assessment (EPA) in the Hong Kong construction industry.” *Construction. Management. Economic*., 24, pp. 1113-1123.

Teychenné, F.E. (1997). *Design of normal concrete mixes.* Construction Research Communications Ltd.

Trtnik, G., Kavcic, F. and Turk, G. (2008). “Prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks” *Ultrasonics,* 49, pp. 53–60.

T S 699. (1987) *Accelerated Freeze – Thaw.* Turkish Standards.

United.States. Environmental Protection Agency, (2012).What Is Integrated Solid Waste Management. 2011. from . http://www.epa.gov

Yamato, T., Emoto, Y., and Soeda, M. (1998).“Mechanical properties, drying shrinkage and resistance to freezing and thawing of concrete using recycled aggregate”,. *ACI Special Publication SP 179-7. Farmington Hills, MI, USA: American Concrete Institute,* . pp. 105–121.