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AUSTRALIA

Faculty of Health, Engineering and Sciences

INVESTIGATION ON MECHANICAL AND DURABILITY PROPERTIES OF RECYCLED CONCRETE

A dissertation submitted by

Milasari Brady

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Abstract

Population growth and the increasing infrastructure and construction development has led to significant demand for natural aggregates resources. As the primary consumer of natural resources, construction industry has contributed to the deterioration of the environment, by depleting natural aggregates resources and generating a large amount of construction and demolition waste (C&D). These wastes are ineffectively disposed of in the landfills at significant cost and over the years, could lead to a depletion of landfill spaces (OZbakkaloglu et al. 2017). Thus, the broader use of recycled aggregate needs to be explored to promote more sustainable practice in the construction industry.

This research provides thorough theoretical investigation on the mechanical and durability properties of recycled concrete, which is based on the previous published experimental data reports. A total of 28 experimental data reports were collected and summarised into Microsoft Excel spreadsheet for further analysis. Data which were presented in figures or non-tabular form, were extracted by using an online application tool, i.e. WebPlotDigitizer. This software was found to be significantly faster, reducing time for data extraction process and provided better accuracy and higher reliability than manual estimation.

The strength characteristics of recycled concrete such as compressive strength, slump, tensile strength, flexural strength, modulus of elasticity and water absorption was analysed by incorporating two main parameters such as water/cement ratio and recycled aggregate percentage replacement. This analysis was performed by using Matlab and the results were presented in contour plots to show the relationship between the three variables. This method was shown to improve understanding on how much the strength characteristics of concrete decrease when these parameters' proportions increase in a concrete structure.

Correlation between mechanical properties of recycled concrete were also evaluated and compared with the conventional concrete's properties by using Microsoft Excel. The proposed relationship equation of the experimental data was developed by using statistical linear regression line method. Additionally, the 95% confidence and prediction interval were also calculated and plotted together for each linear regression lines. The result of this analysis was used to validate the relationship between the published experimental data reports with the majority of the conventional concrete design codes and standards. It is anticipated that this research will present a significant knowledge of recycled concrete's properties and can be used as a fundamental resource in designing higher strength characteristics for recycled concrete.

University of Southern Queensland

Faculty of Health, Engineering & Sciences

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Limitations of Use

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own efforts, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Milasari Brady

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I would like to express my sincere appreciation to my supervisors, Dr Weena Lokuge for her continuous support and invaluable guidance in carrying out this research project.

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Chapter 1

Introduction

1.1 Introduction

Construction and demolition (C&D) waste, which is largely disposed of in landfills each year, has become a major concern due to environmental issues. Concrete as the main waste materials generated from C&D, contributes to the largest portion of the total debris in the landfill spaces (Kou et al. 2012). Thus, recycling this waste as coarse and fine aggregates will not only reduce the accumulated waste in landfills but also minimise the depletion of natural resources in concrete production. Many researchers have already recognised the importance of employing recycled concrete as a substitution for natural aggregate. They investigated the strength characteristics of recycled concrete aggregate (RCA) through various experimental studies. However, the use of RCA for new concrete structures still requires thorough research, so that a standard guideline for recycled concrete production can be developed and accepted by the international code and design standards.

1.2 Background/problem statement

The use of recycled concrete as coarse aggregates has been well researched to pursue a sustainable future in civil engineering. As the main consumer in natural resources, construction industries, particularly building sectors, are responsible for about 49 per cent of raw materials used, 25 per cent of virgin wood and 16 per cent of water consumed (Dixit et al. 2010). The increasing infrastructure and construction development lead to significant demand for natural aggregates which will inevitably cause serious damage to the ecological environment.

Meanwhile, the increasing rate of the demolition of old structures has generated a significant amount of construction and demolition (C&D) waste. According to the National Waste Report 2010, around 166, 000,000 tonnes from C&D waste stream was generated in Australia in 2006-2007. Recent studies by Tangchirapat et al. (2009) and Ho et al. (2013) also show that C&D waste as the mainstream of solid waste was ineffectively disposed of in landfills at a substantial cost and resulted in depletion of landfill spaces. Thus, the wider use of recycled aggregate needs to be explored to promote more sustainable construction practices in the construction industry.

This research project provides collective summaries of a total 28 published international experimental data that deal with recycled concrete as coarse aggregate. The study will be emphasising the mechanical and durability properties of recycled concrete by incorporating parameters such as water/cement ratio (w/c) and recycled coarse aggregate substitutions (RA%). The mechanical properties relationship of RCA such as compressive strength, tensile strength, flexural strength and modulus of elasticity will also be compared to the conventional concrete (CC) design standards, such as the Australian Standard (AS 3600: 2009), the American Concrete Institute (ACI 318: 2011) and Eurocode (BSI 2004). The methodology will be carried out mainly by using the Microsoft Excel and Matlab program to analyse the behaviour of recycled concrete structure. An online application tool such as WebPlotDigitizer will also be used to extract the data from the research papers, particularly the data which are presented in graphs or in non-tabular forms.

1.3 Project aims and objectives

This project aims to investigate the mechanical and durability properties of recycled concrete (RC) and comparing these properties with that of conventional concrete. The project will help to validate the relationship between the published experimental data reports with the majority of the conventional concrete design codes and standards. It also intends to provide a better understanding and good estimation on the recycled concrete properties, which can be used as a guideline in designing recycled concrete mix.

To ensure these aims are achieved, the following objectives are programmed for this project:

- Literature review of the general properties of recycled concrete as coarse aggregates.
- To collect the experimental data of RC and establish a comprehensive data summary according to the designated range parameters.
- To compare the mechanical and durability properties of recycled concrete with the conventional concrete properties.
- To develop a mathematical relationship between recycled concrete's properties and conventional concrete.
- To undertake analysis results and recommendation for further research area.

The scope of this project is limited to recycled concrete properties as coarse aggregates. It is intended that the mechanical properties such as slump, compressive strength, flexural strength, modulus of elasticity, tensile strength and the durability properties such as shrinkage, creep, water absorption and Alkali silica reaction will be investigated as part of this project. The result of this study can also be employed to predict the mechanical properties of RC properties, such as tensile strength, flexural strength and modulus of elasticity as a function of its compressive strength based on the statistical trend lines given from the data sets.

Chapter 2

Literature review

2.1 Recycled concrete aggregate general background

Previous research works have indicated that recycled aggregate from concrete waste (RCA) could be used as a replacement of natural aggregates for construction materials, meeting performance requirements of normal concrete structure (Behera et.al 2014). Nowadays, RCA is commonly being used for both structural and non-structural applications such as road's sub-base or surface materials, backfill materials, hydraulically bound materials and for new concrete production (De Brito et al. 2013). The process and benefits of recycling concrete from construction and demolition waste is shown schematically in figure 2.1 and figure 2.2 below.

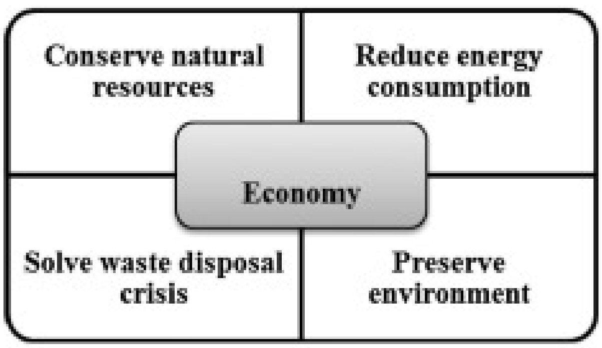

Figure 2. 1 Benefits of using RCA (Behera et.al 2014)

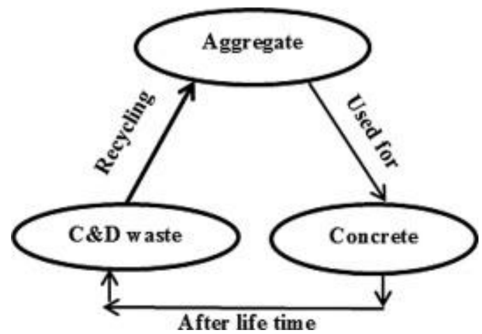

Figure 2. 2 Process of RCA recycling technique (Behera et.al 2014)

RCAs are extracted through the processing of the demolition debris, which are crushed by several different types of crushers. Moreover, each type of crusher has a different effectiveness of the crushing process and produces different outcomes on the physical and mechanical properties of RCAs (Matias et al.2013). Studies show that Impact type crushers produce a better recycled aggregate quality with less adhered mortar content (Etxeberria et al. 2007).

Guoliang et al. (2020) evaluated that the presence of adhering old mortar, water absorption and recycled concrete's shape and size are the key parameters that control the recycled aggregate's quality. Duan et al (2014) reported that the higher presence of adhering mortar results in the higher water absorption, crushing index, and Los Angeles abrasion value (LA) which resulted in the weaker performance of recycled concrete (RC) compared to that of natural concrete (NC). Furthermore, Gómez-Soberón (2002) investigated that this high-water absorbency of RA is due to the pore structure of mortar bonded. It showed that porosity increases when recycled concrete aggregate are used in the concrete mix design. The increase in porosity leads to the reduction of RAC workability, and adversely affects the mechanical strength and durability properties of recycled concrete.

2.2 Mechanical properties of recycled concrete

2.2.1 Slump

Slump test is commonly used to evaluate the workability of the fresh concrete batch. Generally, the slump of RCA decreases as recycled aggregate replacement ratio increases. Ozbakkaloglue et al. (2017) studied the effect of recycled concrete as coarse aggregates to the mechanical and durability properties of the concrete. The slump tests of their experimental results are shown on the table 2.1 The letter N is labelled for Normal strength concrete mixes and H is for High strength concrete mixes. Based on this data, the higher ratio of RCAs replacement leads to the decrease in effective water binder ratio, resulting in lower slumps of these concrete mixes.

Table 2. 1 Mix properties of concrete (González-Fonteboa et.al 2018)

	Normal-strength concrete									High-strength concrete				
Proportions	NC-0-T	NC-25-T	NC-50-T	NC-100-T	NC-100-N	NF-0-T	NF-50-T	NF-100-T	NF-100-N	HC-0-T	HC-25-T	HC-50-T	HC-100-T	HC-100-N
RCA%	0%	25%	50%	100%	100%	0%	50%	100%	100%	0%	25%	50%	100%	100%
Cement (kg/m^3)	380	380	380	380	380	380	380	380	380	506	506	506	506	506
Silica fume (kg/m^3)	0	0	0	0	0	0	0	0	0	44	44	44	44	44
Sand (kg/m^3)	710	710	710	710	710	710	710	710	710	710	710	710	710	710
Natural aggregate (kg/m^3)	1,065	799	533	0	0	1,012	506	0	0	1,065	799	533	0	0
Recycled aggregate (kg/m^3)	0	204	408	816	816	0	394	787	787	0	204	408	816	816
Water-effective (kg/m^3)	209	201	194	179	179	201	186	171	171	167	159	152	137	137
Water-total (kg/m^3)	237	236	236	235	235	227	218	209	209	195	194	193	193	193
Superplasticizer (kg/m^3)	0	0	0	0	0	0	0	0	0	7	7	7	10	10
Effective w/b ratio[a]	0.55	0.53	0.51	0.47	0.47	0.53	0.49	0.45	0.45	0.31	0.30	0.29	0.26	0.26
Total w/b ratio[a]	0.62	0.62	0.62	0.62	0.62	0.60	0.57	0.55	0.55	0.36	0.36	0.36	0.36	0.36
Slump (mm)	220	180	125	115	105	235	155	125	110	180	170	130	100	85
Hardened density (kg/m^3)	2,347	2,289	2,236	2,199	2,138	2,287	2,174	2,147	2,115	2,518	2,486	2,425	2,403	2,378

[a]Including the water coming from the superplasticizer (i.e., 70% water by weight).

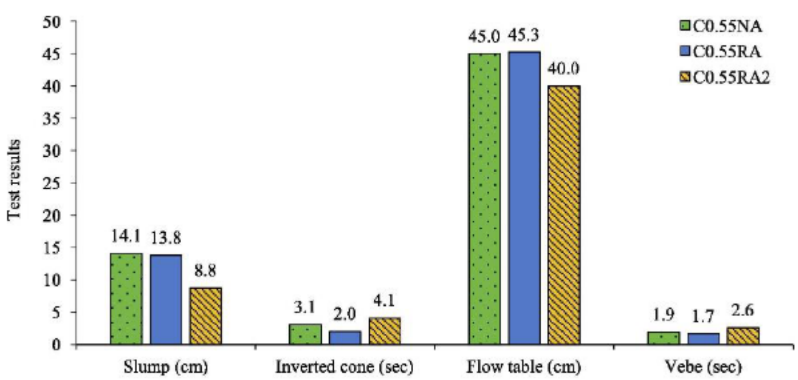

Figure 2. 3 Fresh properties of recycled concrete with w/c 0.55 (Lavado et al. 2020)

Figure 2.3 above shows the fresh state behaviour of different types of aggregates with the same water/cement ratio. Lavado et al. (2020) reported that slump in natural aggregate (NA) was slightly higher than in recycled aggregates (RA), which has 3.3% lower fresh density than NA. Additionally, it was found that the slump in RA with more irregular shape and rougher texture was 38% lower than that of natural aggregate concrete.

Sami et al. (2009) also investigated that recycled aggregates from concrete waste require more water than natural concrete to maintain the same without additional admixtures. Tam and Tam (2007) founded that this is due to the high-water absorption from the old cement mortar attached to the RA. To compensate

this issue, the authors developed the Two-Stage Mixing Approach (TSMA) for improving the strength characteristics of RCA.

The procedures of TSM methods shows in the figure 2.4 below.

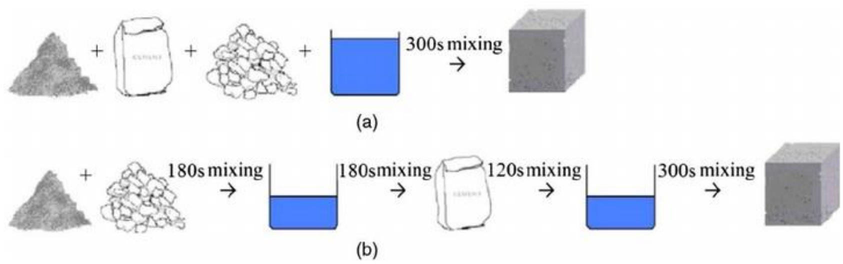

Figure 2.4 Mixing procedures (a) NMA; (b) TSMA (Tam et.al 2005)

It was shown from their experimental result that the slump values prepared by using TSMA approaches were higher than the Normal Mixing Approach (NMA). The TSMA mixing method also improve the concrete strength for up to 21.19% for 20% RA replacements. Ozbakkaloglu et al. (2017) in their study also confirms a similar result and concluded that TSMA mixing methods provides more free water to interact with the binder. This method can lower the water absorption of recycled aggregate by filling up the old cracks and pores on the recycled aggregates.

A few alternative methods have also been proposed by many researchers to improve the slump of recycled concrete. Zhang et al. (2007) investigated that pre-soaking the RCAs for a fixed time can reduce the high-water absorption in RC. The workability of the RC also can be controlled by using a significant amount of superplasticizer without adding extra water in the concrete mixes (A. Katz 2004, Sami et al. 2009).

2.2.2 Compressive strength

It has been established in the previous studies that recycled concrete's compressive strength is lower than the conventional concrete made with natural aggregate. The compressive strength decreases as the replacement of RC and water-cement ratio increases (Belén et al. 2011; A.Khan 1984). The degree of this decrease mainly depends on the recycled aggregate's content such as type, size, origin (A. Khan 1984) and the concrete production method (Silva et al. 2015). In addition, the increase of water absorption rate and the poor quality of the interfacial transition zone (ITZ) generated on the recycled aggregate could lead to higher of the strength loss (M. Etxeberria et al. 2007; J.S. Ryu 2002).

González-Fonteboa et al. (2018) reviewed the relationship of recycled concrete's compressive strength (fc, RC) vs conventional concrete's compressive strength (fc, CC) based on the previous studies' report. The experimental data are collected from the coarse recycled concrete aggregates (RCA) ratio with 229 mixes of 100% RCA replacements, 80 mixes of 50% RCA replacements and 75 mixes of 20% RCA replacements and the result is present in figure 2.6.

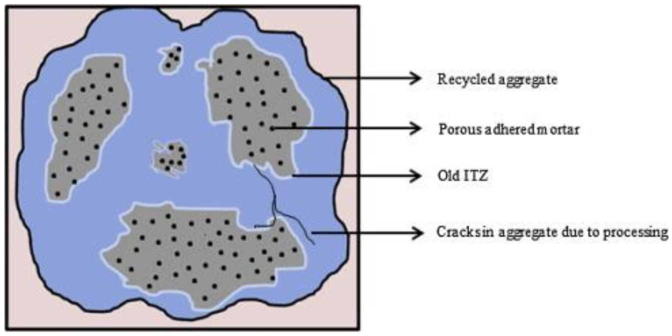

Figure 2.5 Physical characteristics of recycled aggregates (Behera et al. 2014)

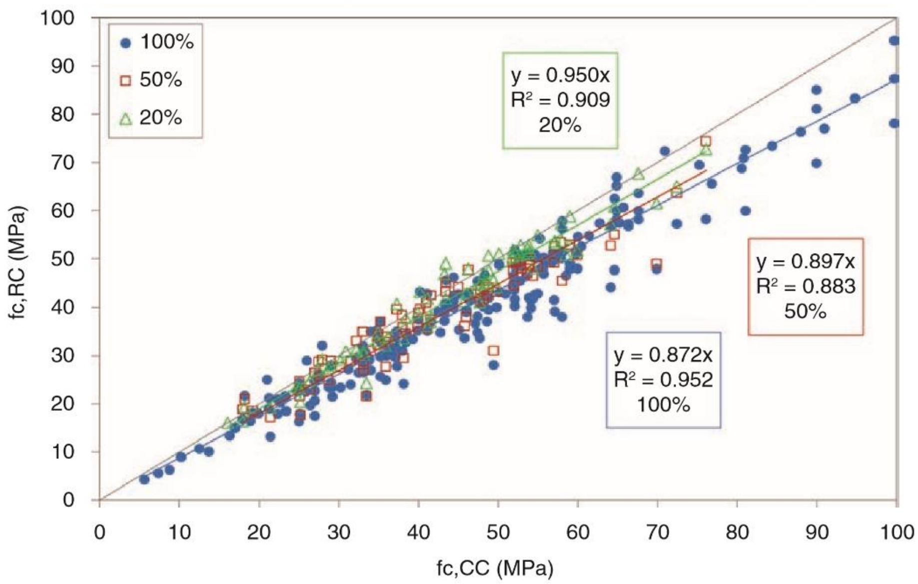

Figure 2.6 RC's compressive strength Vs CC's compressive strength (González-Fonteboa et.al 2018)

The figure confirms that the higher recycled aggregate replacements ratio is, the higher compressive strength loss will be. The square of coefficient determination (R^2) value is between 0.9 and 1 which means that there is a very strong correlation in the data. Based on the figure, the average reductions for 20%, 50% and 100% recycled aggregates replacement were 5%, 10% and 13% respectively.

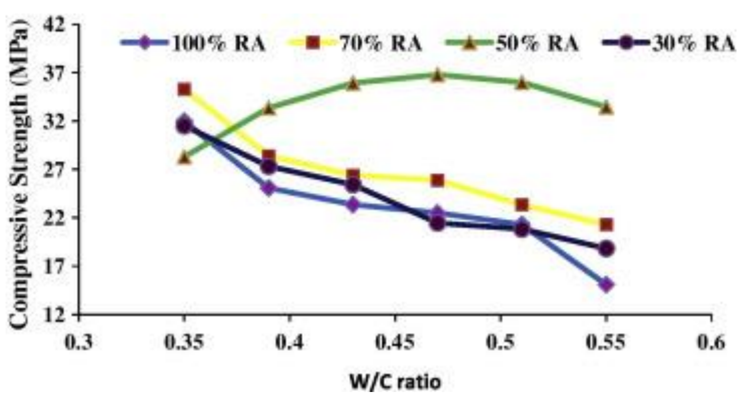

Figure 2.7 compressive strength Vs w/c ratio with variation of RCA content (Xiao et al. 2012)

Behera et al. (2014) reported that the compressive strength also decreased as w/c ratio increase despite of variation in RCA replacement level. However non-linearity between the strength and w/c ratio can be seen in figure 2.7 for concrete with 50% RA replacement. This is possibly due to new approaches tried by the researcher during concrete production, which lead to higher value of compressive strength test results.

Many researchers have investigated how to improve the compressive strength of recycled concrete. Khan (1984) investigated that to achieve the similar compressive strength to NAC, the water-cement ratio of RC should be 0.05-0.1 less than NA. Furthermore, Laserna et al. (2016) concluded that when rounded or crushed natural aggregates are used to produce RC, the compressive strength of recycled concrete could be increase for up to 15%.

The concrete production method also has an important role in the quality of RC. Brown et. al (2001) found that the recycled concrete aggregates which process commercially, produces smoother round particles than those produced in the laboratory, thus improving RC workability. In conclusion, it has been observed in various studies that by reducing the water-cement ratio, increasing the maximum of recycled concrete aggregates (RCA) size, using smooth, round or spherical RCA shapes, considering the higher quality of parent concrete strength, and the use of minerals and chemicals including the use of silica fume and plasticizer, can improve compressive strength to a great extent (Padmini et al. 2009, Bui et al. 2017).

2.2.3 The tensile strength

Many researchers agree that recycled concrete generally also has lower tensile strength than natural aggregates concrete when RCA replacements ratio increases (Exteberria et al. 2007, Kou et al. 2012, Fonseca et al. 2011, Ozbakkaloglu et al. 2017, Bairagi et al. 1993). This observation is due to the reduced bond strength of the interfacial transition zone (ITZ) and the reduction of particle interlocking between the old and new mortar content (Kumar and Dhinakaran 2011). Furthermore, the tensile strength also is influenced by the coarse aggregates' sizes and water cement ratio used in the concrete mixes. Ozbakkaloglu et al. (2017) reported that the smaller coarse aggregates exhibited a slightly higher tensile strength than larger coarse aggregates due to the lower mortar strength in larger RC aggregates. In addition, Berredjem et al. 2020 cited that a high-water cement ratio induces higher porosity in RCA which may result in lower matrix strength and poor ITZ which subsequently reduced tensile strength of the RC.

Due to these strength characteristic differences, many researchers (Xiao et al. 2006, Li 2008 and Katz 2003) suggested that the equations proposed by codes and standards for natural aggregate concrete are not suitable to predict splitting tensile strength for recycled concrete properties. Based on their extensive research and experimental investigations, they have adjusted the equation and proposed expression to estimate the splitting tensile strength as function of compressive (Table 2.2).

Table 2.2: Author's equation – Tensile strength (f_{sp}) (González-Taboada et al. 2016)

Reference	Equation
Li et al. (2008) (46)	$f_t = (0.24 - 0.06 \cdot r) \cdot f_{cu}^{2/3}$
Xiao et al. (2006) (44)	$f_{sp} = 0.24 \cdot f_{cu}^{0.65}$
Katz (2003) (45)	$f_{sp} = 0.59 \cdot \sqrt{f_c}$

In contrast, many literatures show that RCA has the same or even higher tensile strength than the conventional concrete (Fonseca et al. 2011, Dilbas et al. 2014, Exteberria et al. 2007). Table 2.3 below is the mechanical properties data of cubic test specimens at 28 days of curing extracted from Exteberria et al. 2007.

Table 2.3. Mechanical properties of cube test specimen at 28 days of curing (Exteberria et.al 2007)

	Density (kg/dm^3)	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (MPa)
CC	2.42	29	2.49	32,561.7
RC25	2.40	28	2.97	31,300.4
RC50	2.39	29	2.70	28,591.7
RC100	2.34	28	2.72	27,764.0

As shown on the data above, the tensile strength of RC is higher than conventional concrete when the replacement ratio of RA as high as 25%. Salem et al. (1998) and Sague-Crentsil et al. (2001) investigated that this is due to the water absorption capacity of the adhered mortar and the effectiveness of the new ITZ of the RC. The tensile strength of RC has a good bond characteristic between aggregate and the mortar matrix which lead to the higher tensile strength than using natural aggregate.

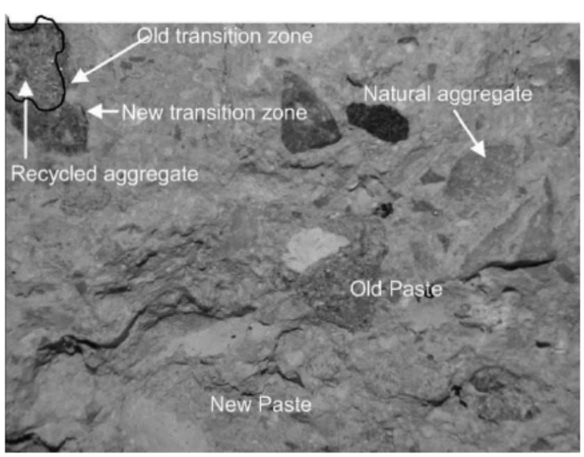

Figure 2.8. The recycled concrete interfacial transition zones (ITZ) (González-Taboada et.al 2016)

Regarding the equation to predict the tensile strength of conventional concrete, the Australian Standard AS 3600 (AS 2009) and American Concrete Institute code ACI 363 R (ACI 1992) provide models to describe the relationship between the splitting tensile as a function of its compressive strength

Table 2.4 Tensile strength for conventional concrete

Reference	Equation
AS 3600 Section 3.1.1.3 (AS 2009)	$f'_{ct.sp} = 0.4\sqrt{f'_c}\ MPa$
ACI 318 Section 8.5.2.3 (ACI 2008)	$f'_{sp} = 0.59\sqrt{f'_c}\ MPa$
Eurocode2 (BSI 2004)	$f_{ctk} = 0.7 \times f_{cm}\ (5\%\ fractile)$ $f_{ctk} = 1.3 \times f_{cm}\ (95\%\ fractile)$

Where; $f'_{ct.sp}$, f_{ctk} and f'_{sp} is tensile strength

f'_c and f_{cm} is the characteristic compressive strength

2.2.4 The Flexural Strength

Some researchers reported the flexural strength of RC has similar behaviour to its compressive strength and tensile strength property. Several past investigations showed that the flexural strength of RC also decreases with increase in the proportion of recycled aggregate replacement and water binder ratio (Katz 2003, Padmini et al. 2009). This reaction was due to low bonding quality between the attached old mortar and the new cement paste (Bai et al. 2020).

The relationship between the replacement ratio of RCA and relative flexural strength is shown in the figure 2.9 below.

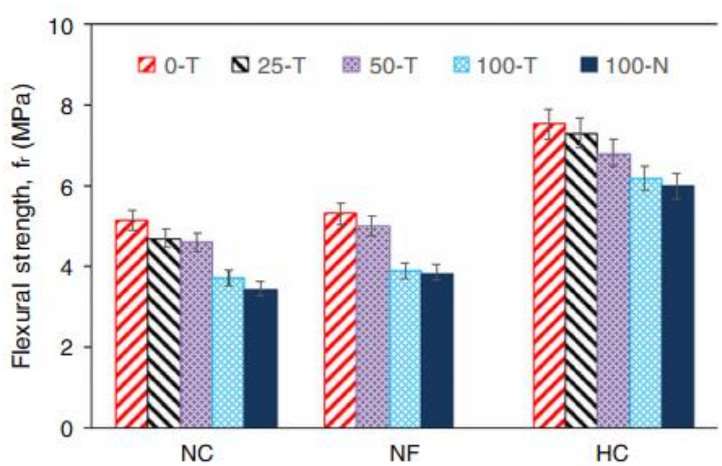

Figure 2.9 Flexural strength of concrete at 28 days of curing (Ozbakkaloglu et.al 2017)

Ozbakkaloglu et al. (2017) summarised that for both normal grade concrete (NC) with 40MPa and high-grade concrete (HC) with 80MPa, their flexural strength decreases with the increase in recycled concrete aggregate replacement. Figure 2.9 also shows that concrete mixes with finer aggregates better perform than coarse aggregates due to higher effective water binder ratio in larger RC aggregate's size.

Additionally, Bairagi et al. (1993) reported that RC has similar behavior as conventional concrete properties in terms of its flexural strength. This strength characteristics gradually decreases as water/cement ratio increase.

However, Ravindrajah et al. (1985) suggested that there was no substantial difference between flexural strength of RC and conventional concrete. The flexural strength or deflection of conventional concrete can be estimated by using equation from the codes and standards (Australia and America) in the table below.

Table 2.5 Flexural strength for conventional concrete

Reference	Equation
AS 3600 Section 3.1.1.3 (AS 2009)	$f'_{ct.f} = 0.6\sqrt{f'_c}\, MPa$
ACI 318 Section 8.5.2.3 (ACI 2008)	$f'_r = 0.62\sqrt{f'_c}\ MPa$

Where; $f'_{ct.f}$ *and* f'_r is flexural strength

f'_c is the characteristic compressive strength

2.2.5 Modulus of elasticity

Modulus of elasticity is related to the aggregates and the rigidity of the cement paste (González-Taboada et al. 2016). As shown on the previous studies, the Modulus of elasticity of recycled concrete is also lower than the conventional concrete. González-Taboada et al. (2016) cited that the old adhered mortar present in the recycled aggregates caused the weakness of the new interfacial transition zone (ITZ) which can lead to cracking and affecting the concrete deformability.

Ozbakkaloglu et al. (2017) investigated that modulus of elasticity of RC decreases with an increase in RCAs replacement level as shown on table 2.7. They concluded that the behaviour of modulus elasticity of RC is highly correlated with its compressive strength. Table 2.7 also explained that fine coarse aggregate attributed to a slight decrease in RC's modulus of elasticity. Xiao et al. (2013) concluded that fine RCA increases the overall surface area of its concrete mixes, thus leading to an increased volume fraction of ITZ which has adversely affected its modulus of elasticity.

The Australian Standard (AS 3600), American Concrete Institute Code (ACI 318) and the British standard, Eurocode2 (BSI 2004) provide equations for estimating normal concrete's modulus of elasticity as a function of its compressive strength and these equations are presented in table 2.6.

Table 2.6 Modulus of elasticity for conventional concrete

Reference	Equation
AS 3600 Section 3.1.1.3 (AS 2009)	$E_c = 0.043p^{1.5}\sqrt{f_{cmi}}\ when\ f_{cmi} \leq 40MPa$ $E_c = p^{1.5}\left(0.024\sqrt{f_{cmi}} + 0.12\right) when\ f_{cmi} \geq 40MPa$
ACI 318 Section 8.5.2.3 (ACI 2008)	$E_c = 4{,}733\sqrt{f'_c}\ MPa$
Eurocode2 (BSI 2004)	$E_c = 22{,}000\left(\frac{f_c}{10}\right)^{0.3}$

Where; E_c is Modulus of elasticity

f_{cmi} and f_c is the compressive strength

p is the density of concrete

Table 2.7 Axial Compression Tests results (Ozbakkaloglu et al. 2017)

Concrete series	f_{cm} (7-day) (MPa)	f_{cm} (28-day) (MPa)	E_c (28-day) (GPa)
N-C-0-T	29.4 (0.06)	40.9 (0.10)	29.3 (0.28)
N-C-25-T	29.9 (0.15)	41.0 (0.25)	29.0 (0.24)
N-C-50-T	29.0 (0.15)	40.5 (0.25)	28.2 (0.22)
N-C-100-T	29.3 (0.30)	40.3 (0.30)	27.2 (0.21)
N-C-100-N	26.7 (0.22)	38.0 (0.19)	26.7 (0.16)
N-F-0-T	28.8 (0.15)	40.1 (0.20)	28.1 (0.22)
N-F-50-T	29.8 (0.18)	41.2 (0.30)	27.9 (0.25)
N-F-100-T	30.2 (0.13)	40.8 (0.21)	25.7 (0.22)
N-F-100-N	28.3 (0.24)	39.2 (0.23)	25.1 (0.24)
H-C-0-T	69.0 (0.18)	82.6 (0.30)	36.5 (0.28)
H-C-25-T	68.6 (0.19)	83.5 (0.29)	34.8 (0.27)
H-C-50-T	68.7 (0.16)	84.1 (0.19)	32.7 (0.21)
H-C-100-T	67.9 (0.20)	82.4 (0.12)	31.3 (0.16)
H-C-100-N	68.5 (0.24)	79.3 (0.19)	30.8 (0.23)

However, based on the experimental results, RC generally has lower modulus of elasticity than conventional concrete, therefore, these expressions are also not suitable when RCAs are used in the concrete production. To achieve better estimation, many authors have proposed different equations according to their investigation results. Their experimental data was also compared with another researchers' data report and their results' analysis are presented in table 2.8 below.

Table 2.8: Modulus of elasticity equation (Ec) (González-Fonteboa et.al 2018)

Reference	Equation
Bairagi et al. (1993) (51)	$E_c = (5780 - 1340 \cdot r) \cdot f^{0.5}$
KaziKazi et al. (1988) (61)	$E_c = 1.9 \cdot 10^5 \cdot \left(\frac{\rho}{2300}\right)^{1.5} \cdot \left(\frac{f_c}{2000}\right)^{0.5}$
Ravindrarajah et al. (1987) (62)	$E_c = 3480 \cdot f_c^{0.5} + 13050$
Ravindrarajah and Tam (1985) (63) a	$E_c = 7770 \cdot f_c^{0.33}$
Ravindrarajah and Tam (1985) (63) b	$E_c = 4630 \cdot f_c^{0.5}$
Dillman (1998) (64)	$E_c = 634.43 \cdot f_c + 3057.6$
González-Fonteboa et al. (2011) (43)	$E_c = (1 - 0.0020 \cdot r) \cdot 22000 \cdot \left(\frac{f_m}{10}\right)^{0.3}$
Corinaldesi (2010) (56) a	$E_c = 18800 \cdot \sqrt[3]{\frac{0.83 \cdot f_{cu}}{10}}$
Katz (2003) (45)	$E_c = 0.043 \cdot \rho^{1.5} \cdot f_c^{0.5}$
Zilch and Roos (2001) (58)	$E_c = 9100 \cdot (f_c + 8)^{1/3} \cdot \left(\frac{\rho}{2400}\right)^2$
Dhir et al. (1999) (59)	$E_c = 370 \cdot f_c + 13100$
Mellmann (1999) (60)	$E_c = 378 \cdot f_c + 8242$

Note: *E_c = Modulus of elasticity (MPa); f_c or f_{cu} Compresstive strength (MPa) ρ = Density (kg/m^3); r = Replacement ratio ($0 \leq r \leq 1$); WA = water absorption (%)*

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2.3 Durability properties of recycled concrete

2.3.1 Shrinkage

Shrinkage deformation is caused by the reduction of concrete volume due to its loss of internal moisture (Bai et al. 2020). It has been well investigated by many researchers that the shrinkage deformation of RC increases with the increase in replacement ratio of RCA. This was mainly due to its higher water absorption and its lower stiffness than natural aggregates (González-Fonteboa et al. 2018, Ozbakkaloglu et al. 2017, Gómez-Soberón 2002, Tam and Tam 2007). González-Fonteboa et al. (2018) collected data from 10 different authors and analysed the relationship between the recycled concrete's shrinkage with 20% to 100% RA replacements with the conventional concrete (100% natural aggregate concrete). The study result is shown in figure 2.10 below.

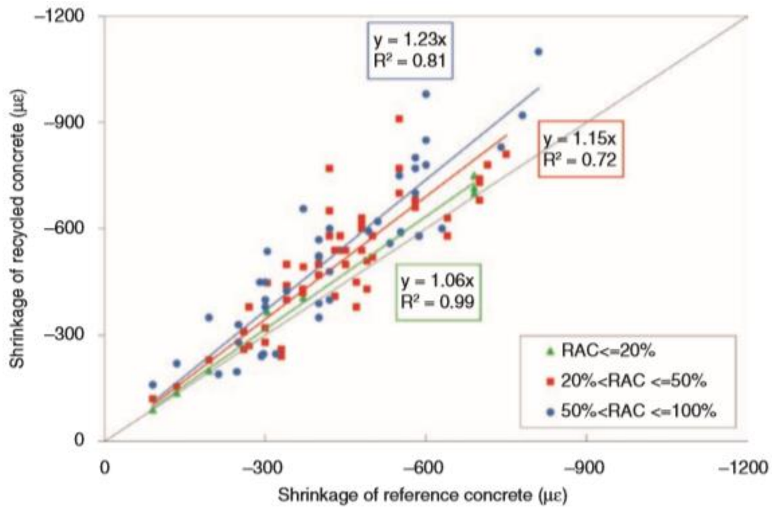


Figure 2.10 Shrinkage of recycled concrete Vs Shrinkage of control concrete (González-Fonteboa et.al 2018)

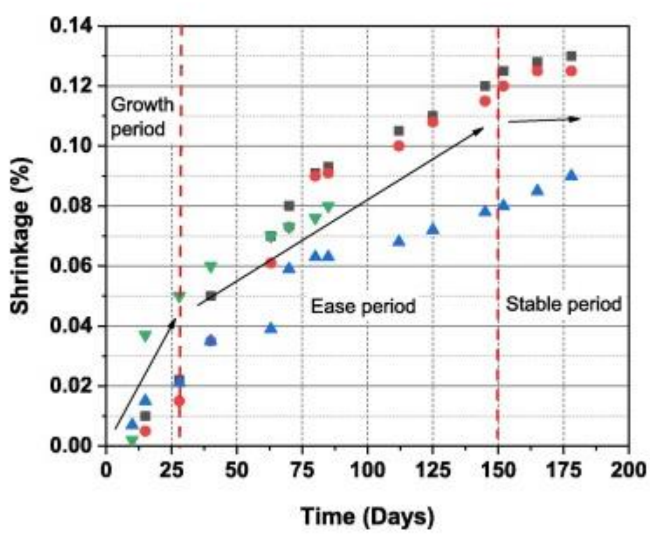


Figure 2.11 Shrinkage rate of recycled concrete Vs Time (Bai et.al 2020)

It is obvious that the RCA replacement ratio has substantial effect in the shrinkage deformation properties. A few studies also found that the concrete deformity is highly related to the water/cement ratio used in the concrete mixtures. Unlike conventional concrete, lower w/c ratio tends to weaken RC durability properties, due to higher water absorption caused by the attached old adhered mortar in RCA.

However, Eckert and Oliveira (2017) investigated that concrete shrinkage can be reduced using different mixing approaches such as internal curing, two-stage mixing approach (Tam and Tam 2007) and adding admixture to RCA (Kou and Poon 2012). Generally, the variation of shrinkage deformation of RC (for up to 20% replacement ratio) has a similar pattern to the natural concrete with respect to time (refer to figure 2.11). According to Bai et al. (2020) and González-Fonteboa et al. (2018), the concrete deformation mainly occurs during the first year and tends to stabilize over time.

2.3.2 Creep

Creep coefficient is an essential parameter to determine the long-term deformations of concrete under sustained load. Many researchers investigated that concrete creep is influenced by the RCAs replacements and water/cement ratio. As expected, the old adhered mortar present in the RCA generates higher water absorption which weakens ITZ, thus leading to the higher creep strain deformability of RC (Xiao et al. 2014, Tam et al. 2015). Table 2.9 is obtained from González-Fonteboa et al. (2018) data which is done by reviewing the creep increments relationship between the recycled concrete and conventional concrete based on the various research papers.

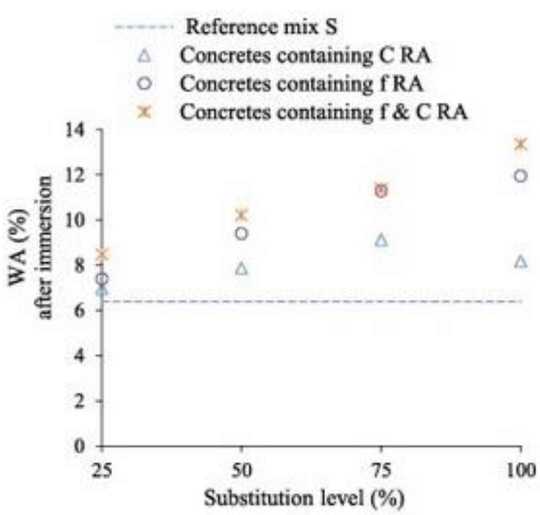
Table 2.9 Recycled concrete increment of creep (%) (González-Fonteboa et.al 2018)

Author	w/c	Absorption (%)	Recycled aggregate (%)	Increment of creep (%)
Seara et al. (2016) (2)	0.5	5.4	20	18
	0.5		50	19
	0.5		100	84
	0.65		20	9
	0.65		50	20
	0.65		100	51
Manzi et al. (2013) (6)	0.48	7	27	-17 (specific)
		9	63.5	17 (specific)
Fathifazl et al. (2011) (69)	0.45	5.4	100	32
Domingo et al. (2009) (78)	0.5	5.19	20	35
			50	42
			100	51
Yang et al. (2008) (95)	0.55	--	50	23
Masato et al. (2006) (94)	0.40	4.8	100	44 (specific)
	0.60	5.4		31 (specific)
	0.40			56 (specific)
	0.60			25 (specific)
Ajdukiewicz et al. (2002) (49)	0.41	--	100	-20
Gómez Soberon. (2002) (90)	--	--	15	5
			30	16
			60	32
			100	45
Limbachiya et al. (2000) (96)	--	--	30	2
			50	22
			100	65
Nishibayashi and Yamura (1988) (93)	--	--	100	30 (c=250 kg/m^3)
				50 (c=350-450 kg/m^3)

It can be observed that the creep increment of recycled concrete with a 100% substitution percentage was found to be 51% higher than that of the RC with 20% substitution percentage. This lower performance also significantly related to the lower modulus of elasticity of the RC which results in the increase of its creep deformation (González-Fonteboa et al. 2018).

2.3.3 Water absorption

Generally, water absorption of recycled concrete increases with the increasing in proportion of recycled concrete aggregates (Grdic et al. 2010, Ozbakkaloglu et al. 2018). As expected, from the previous discussion, this increasing water absorption is due to the attached old mortar in the RCA which leads to the higher porosity in the RCA. According to Sasanipour and Aslani (2020) from their experimental results as shown on figure 2.12, the water absorption increased by 6.4% when substitution of RCA was 25% and the amount of water absorb increase as the replacement ratio increase. It also can be seen that the concrete containing finer size RCA also has higher water absorption than concrete with coarse RCA. Santos et al. (2018) investigated that this is due to the specific surface area of fine RCAs being higher than the coarse RCA, thus eventually increasing the water absorption in the RC.



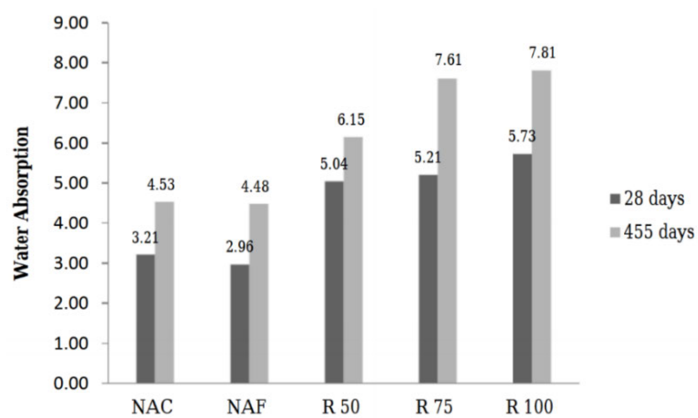


Figure 2.12. Water absorption test of recycled concrete aggregate
(Sasanipour and Aslani 2020), (Maruthupandian et.al 2014)

2.3.4 Alkali silica reaction

Alkali-silica reactions are a leading cause of concrete deterioration due to excessive expansion which occurs between an alkali and silica minerals in concrete (Adams et al. 2013, González-Fonteboa et al. 2018). In recycled concrete, the main source of alkalinity in the concrete mixture comes from the cement and the adhered mortar from the parent concrete, where the reactive silica presents in the aggregates themselves.

Few authors suggested that recycled concrete has very small risks attributed to the Alkali-silica reaction. According to the experimental tests, the expansions values in the specimens containing different types of coarse RCA was under 0.1% and had not reached limit values for expansion to exert a tensile force capacity which can cause cracking in RC, (Dhir et al. 2005, Desmyter and Blockmans 2000). Additionally, Adams et al. (2003) observed that the general trend expansions of the mortar bars increase as their RCA replacement levels increase (from 20 to 100%). This possible Alkali-silica reactivity of RCA was most likely due to the higher residual mortar contents in the coarse aggregates and the silica sand present in the old adhered mortar during initial crushing of the old concrete (Etxeberria et al. 2007).

Table 2.10 Expansion average of finer RCA (Adams et al. 2013)

RCA Replacement Level and Aggregate Type	Number of Samples(Bars)	Average Expansion (%)	Coefficient of Variation (%)	Precisio n Boundary Limits (43% A bove or Belo w Mean Expansion)		
				Lower Expansion Boundar y (%)	Upper Expansion Boundar y (%)	Number of Outliers
25% Alberta	24	0. 20	11.5	0.12	0.29	0
50% Alberta	24	0. 28	11.5	0.16	0.40	0
100% Alberta	12	0.31	5.8	0.18	0.45	0
25% Bernier	12	0.08	22.8	0.04	0.11	0
50% Bernier	24	0.09	8.5	0.05	0.13	0
100% Bernier	12	0.11	17.5	0.06	0.16	0
25% Potsd am	12	0.05	27.5	0. 03	0.07	0
50% Potsd am	12	0.06	7.3	0.04	0.09	0
100% Potsd am	12	0. 07	10.4	0.04	0.10	0
25% Spring hill	12	0.20	16.5	0.11	0.28	0
50% Spring hill	12	0.29	7.9	0.16	0.41	0
100% Springh ill	36	0.32	20.2	0.18	0.46	0

2.4 Data extraction tool

Data extraction is a crucial task in completing project research, particularly in analytical approach-based projects where numerous data are required for analysis or investigation. Some researchers present their experimental data in their publications as images or graphs, which make data collection processes become more challenging and time consuming. In this project, WebPlotDigitizer online tool is used to extract the data which presented only in graphs or non-tabular forms. It is a free web-based tool, easy to use and it provides higher data estimation accuracy or reliability. According to Kadic et al. (2016), using software for data extraction was significantly faster compare to manual estimation. It can reduce time for extraction for up to 47%.

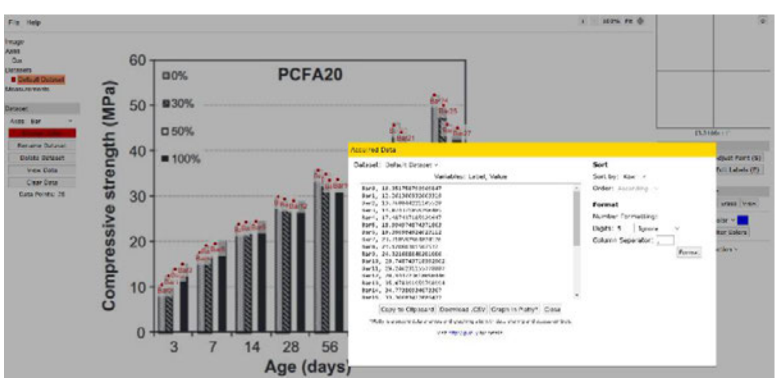


Figure 2.13 WebPlotDigitizer data extraction tool (WebPlotDigitizer.com)

2.5 Techniques for improving RAC properties

Many researchers have been exploring various techniques to improve the strength characteristics of RC. They aimed to eliminate the negative effects of RCA substitution by trying different ingredients and modifying the mix proportions in the concrete production. Behera et al. (2014) reviewed numbers of proposed methodology by various researchers and their investigation results are summarised in the table 2.11

Table 2.11 Proposed Methodology to improve RC properties (Behera et.al 2014)

Authors	Proposed methodology	Significance
Otsuki et al. 2003	Double mixing method	• Compressive strength increased up to 12.6% than normal mixing • Chloride penetration depth reduced to 22.7% • Carbonation depth was up to 12.3%
Tam et al. 2005	Two stage mixing approach	• 28-Days Compressive strength increased up to 21.19% at different percentage replacement • Developed a stronger ITZ by filling the cracks and pores in RA
Corinaldesi et al. 2009	Additions of fly ash or silica fume into concrete to replace fine aggregate	• Improvement of pore structure by reducing the volume of pores • As a result mechanical performance such as compressive strength, tensile and bond strength could be improved
Limbachiya et al. 2012	10% silica fume was used as a partial replacement of Portland cement	• Enhanced compressive strength and compactness • Target strength could be achieved with 100% RA • Showed less resistance towards carbonation. Causes pore refinement, as a result lower chloride ion ingression

Kou et al. 2012	Incorporation of 25-35% class F fly ash as well as partial replacement of cement	• Strength gain was more in between 28–90 days • Increase in strength was up to 19.4%, 36.1% and 47.6% from 28 to 90 days for concrete containing 0, 25, 35% fly ash respectively for 100% RA • Drying shrinkage, creep and chloride ion penetration reduced to a certain extent • Replacement of cement caused reduction in strength
Elhakam et al. 2012	Self-healing of RA,Modified two stage mixing method Addition of 10% silica fume as cement	• Unhydrated cement particles on RA got hydrated by self healing method thus enhanced its properties • Two stage mixing approach showed better split tensile strength, bond strength and enhanced porosity of RAC • Addition of silica fume improved the porosity of RAC
Kong et al. 2010	Surface coating of RA by pozzolanic substances. A novel triple mixing method	• A thin layer of pozzolanic particles formed around the aggregate which helped in improving the ITZ through filler effect and pozzolanic reactive effect • Improved compressive strength and chloride ion penetration resistance
Katz 2004	Pre-treating of RA with silica fume solution (10 wt%)	• Compressive strength increased up to 30% and 15% at ages of 7 days and 28 days respectively • ITZ between RA and matrix could be improved
Ann et al. 2011	Use of 35% pulverized fuel ash (PFA) and 65% ground granulated blast furnace slag (GGBS)	• Showed equivalent performance with conventional concrete for long term compressive strength (180 days), ion penetrability in terms of chloride ion and corrosion resistance (corrosion free life)

Kou et al. 2013	Incorporated different mineral admixtures such as fly ash (FA) (35%), silica fume (10%), meta kaolin (15%), GGBS (55%)	• Silica fume and GGBS contributes to both short term and long term properties • FA and GGBS showed their beneficial effect on long term properties • Contributions of mineral admixtures to the performance improvement of RAC are higher than that to natural aggregate concrete
Zhihui et al. 2013	Pre coating of RA surface with thin cement paste	• 28 days compressive strength of concrete increased up to 16% • With the use of pre coated recycled fine aggregate with sulpho aluminate cement, the compressive strength of mortar increased by 34.8% and with sodium silicate increased by 32.4%
Somna et al. 2012	Ground fly ash was used by 20, 35 and 50% by weight of cement to replace cement and to improve properties of RAC	• Result showed that it slightly improved the compressive strength only at 20% use of fly ash in RAC than concrete without fly ash • For all replacement% of fly ash compressive strength was less than conventional concrete • Did not show any effect on modulus of elasticity at all% replacement • Ground fly ash had significant influence on reducing the water permeability coefficient

Chapter 3

Methodology

As widely discussed in chapter 1, this research project focuses on investigating the mechanical and durability properties of recycled concrete (RC). It aims to give a better understanding on the performance of RC structure when recycled concrete aggregates are used in the concrete mix design, by incorporating water/cement ratio (w/c) and RCA substitution.

To achieve the project's aims and objectives, a database has been developed from various international experimental data research, which related to recycled concrete aggregate as natural coarse aggregate replacement. With this database and using MATLAB and Microsoft Excel program, the results of the analysis can be used to define the strength characteristics of recycled concrete and its relationship to the conventional concrete's code and design standard.

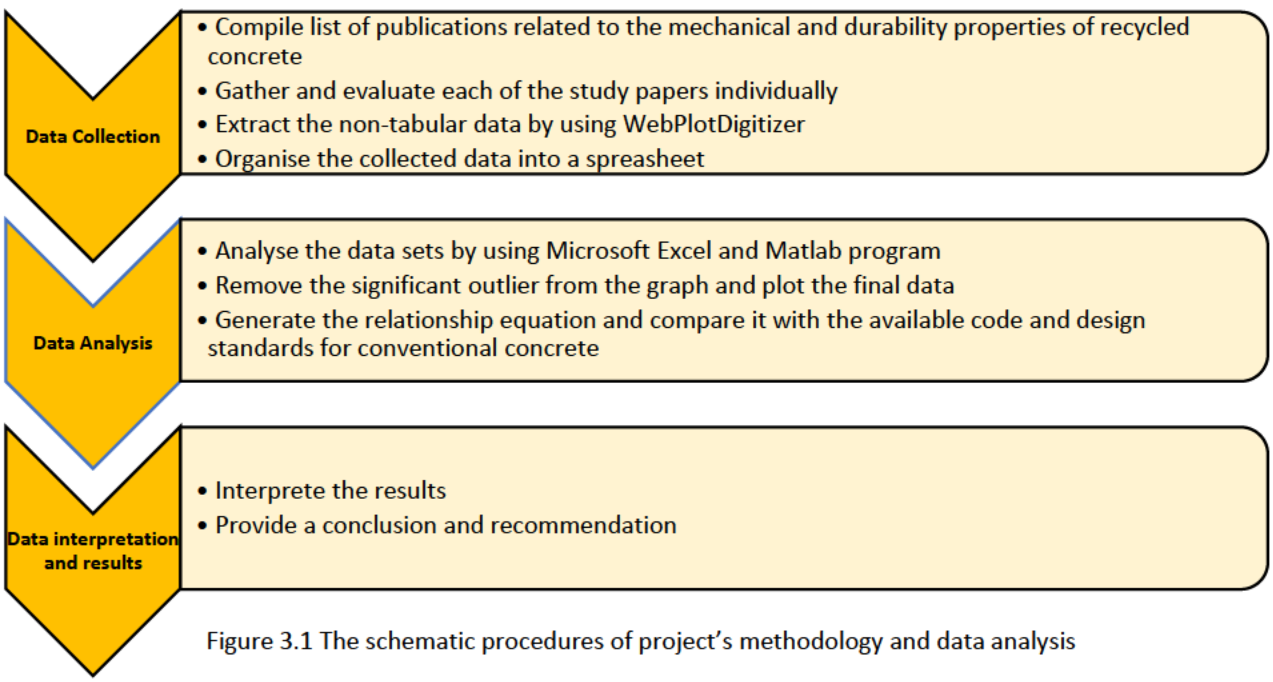


Figure 3.1 The schematic procedures of project's methodology and data analysis

3.1 Collection of data

Data collection is a major aspect of this research study. This phase involves selecting and gathering experimental data and compiling it into a spreadsheet. As largely described in section 2, the strength characteristics of RC are highly variable. It depends on various parameters such as recycled concrete's shape and size, the moisture state of RA, the crushing process and original grade of demolished concrete, concrete mixing approach, water/cement ratio and RCA% replacement used during RC production (Guoliang et al. 2020, Tam and Tam 2007, C. Zhou et al.2017). Data extraction is one of the main key activities in the data collection process. This activity is further described in the following section.

3.1.1 Data extraction

As mentioned earlier in section 2.4, an online application tool such as WebPlotDigitizer is used to extract the data from figures or images in this research project. According to Kadic et al. (2016), data extraction by using software is significantly faster, providing higher reliability and reducing time for extraction by 47%.

The data extraction process for this research project is outlined in the following procedures;

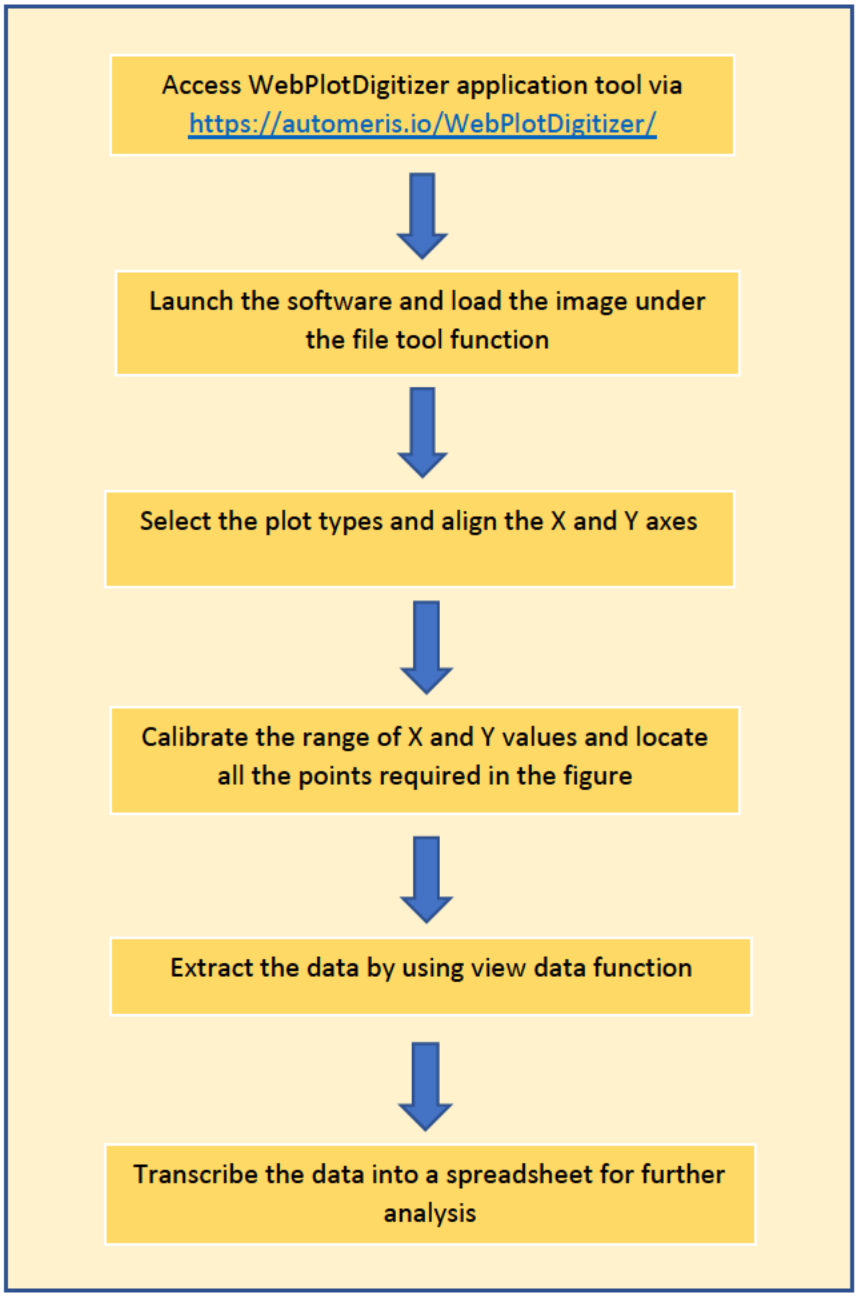


Figure 3.1 WebPlotDigitizer data extraction process

3.1.2 Data collection highlighted on recycled concrete's properties

Several interesting studies on RC's properties are highlighted and discussed in the section below.

Zhou et al. (2017) conducted an experimental study on the mechanical properties of RC with two different types of coarse recycled aggregates, i.e. crushed rock aggregate (CRA) and pebbles aggregate (PA). Unlike many other studies, the results show that the compressive strength and flexural strength of RC are similar or even higher than the conventional concrete's properties. They concluded that higher water absorption of RC improves bonding strength between recycled aggregate and cement paste in the compaction process. RC containing recycled pebble aggregate also presents a higher relative strength and elastic modulus than that containing crushed rock aggregate.

Table 3.2 Mix Proportions of recycled crushed rock concrete (RCRC) (Zhou et al. 2017)

Mix	RP (%)	Water-cement ratio	Cement	Water	Sand	CRA	RCRA
RCRC-0	0	0.49	398	195.0	614	1193	0
RCRC-10	10	0.49	398	196.6	614	1074	119
RCRC-20	20	0.49	398	198.2	614	954	239
RCRC-30	30	0.49	398	199.8	614	835	358
RCRC-40	40	0.49	398	201.4	614	716	477
RCRC-50	50	0.49	398	203.0	614	597	597
RCRC-60	60	0.49	398	204.6	614	477	716
RCRC-70	70	0.49	398	206.2	614	358	835
RCRC-80	80	0.49	398	207.8	614	239	954
RCRC-90	90	0.49	398	209.4	614	119	1074
RCRC-100	100	0.49	398	211.0	614	0	1193

Table 3.3 Mix Proportions of recycled pebble concrete (RPC) (Zhou et al. 2017)

Mix	RP (%)	Water-cement ratio	Cement	Water	Sand	PA	RPA
RPC-0	0	0.47	404	208.4	614	1228	0
RPC-10	10	0.47	404	208.9	614	1105	123
RPC-20	20	0.47	404	209.3	614	982	245
RPC-30	30	0.47	404	209.7	614	860	368
RPC-40	40	0.47	404	210.1	614	737	491
RPC-50	50	0.47	404	210.6	614	614	614
RPC-60	60	0.47	404	211.0	614	491	737
RPC-70	70	0.47	404	211.4	614	368	860
RPC-80	80	0.47	404	211.8	614	245	982
RPC-90	90	0.47	404	212.3	614	123	1105
RPC-100	100	0.47	404	212.7	614	0	1228

Table 3.4 Mechanical properties test result (Zhou et al. 2017)

RP (%)	f_{cu} (MPa)		f_c (MPa)		f_r (MPa)		Elastic modulus (GPa)		Poisson's ratio	
	RCRC	RPC	RCRC	RPC	RCRC	RPC	RCRC	RPC	RCRC	RPC
0	41.71	29.88	37.01	26.82	4.30	5.20	46.40	44.39	0.21	0.22
10	37.50	27.95	29.66	25.80	4.31	4.87	44.66	39.33	0.21	0.22
20	43.48	29.72	39.54	28.86	4.20	5.52	39.74	39.36	0.21	0.22
30	42.03	34.86	38.33	28.59	3.96	5.80	38.53	39.59	0.22	0.23
40	44.01	32.60	33.82	27.08	4.80	5.85	38.29	36.50	0.21	0.22
50	42.40	29.84	42.20	29.09	5.11	5.48	39.50	41.00	0.21	0.22
60	42.33	32.39	42.33	30.68	4.31	5.54	40.87	35.77	0.21	0.22
70	43.94	37.02	40.70	32.67	5.19	6.29	40.43	36.46	0.21	0.22
80	50.50	40.11	44.31	35.22	6.28	6.39	40.78	38.24	0.21	0.22
90	43.73	31.85	42.32	26.00	4.27	5.11	41.27	34.18	0.22	0.23
100	44.26	41.16	43.57	35.27	5.07	6.30	40.80	36.33	0.21	0.22

Note: f_{cu} is cube compressive strength; f_c is axial compressive strength; f_r is flexural compressive strength.

Berredjem et al. (2020) also investigated the influence of different sizes compositions (recycled coarse and fine aggregate) on the mechanical and durability properties of RC. The recycled aggregate materials for RC were prepared in saturated-surface-dry (SSD) condition, while natural aggregates were maintained in normal dry state. The specimens were then conserved in different types of water baths, i.e. fresh tap water, deionized water, and saltwater for 360 days of curing. The report shows that, in general, conventional concrete has a higher strength characteristic than RC. The study also shows that there was not much improvement in terms of durability properties of RC despite conserving different types of baths before testing. The experimental data from this research paper are extracted for concrete which conserved in the fresh mains water bath for 28 days of curing.

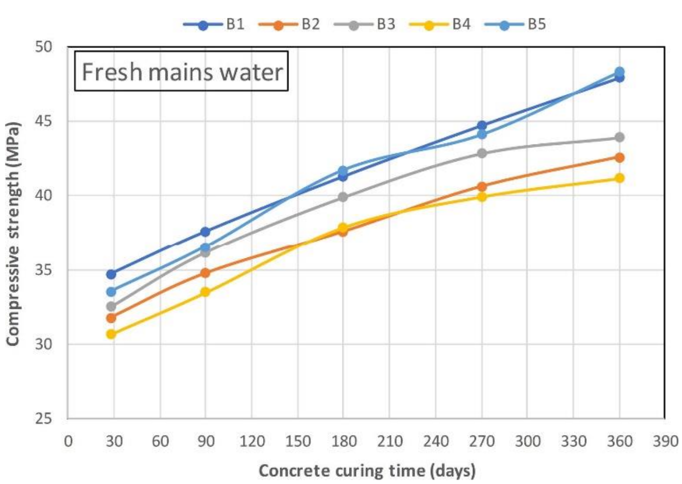


Figure 3.2 Compressive strength test result (Berredjem et al. 2020)

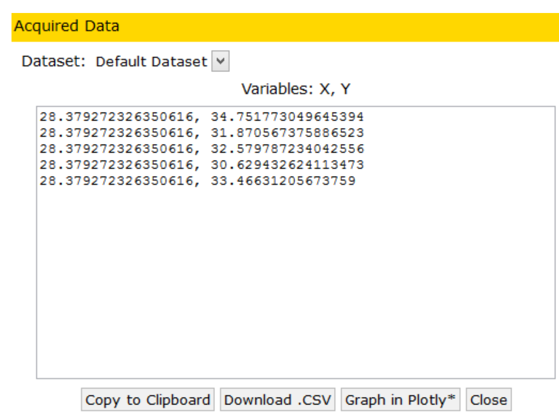


Figure 3.2a Compressive strength data extraction (WebPlotDigitizer.com)

Table 3.5 Concrete mix proportions (Berredjem et al. 2020)

		Proportions (kg/m³)				
		B1	B2	B3	B4	B5
Cement		400	400	400	400	400
CLS		578		578		578
RFA			571		571	
NCA 3/8 mm		185	168			139
NCA 8/16 mm		928	928			696
RCA 3/8 mm				176	160	44
RCA 8/16 mm				874	874	219
Mixing water (in liters)	Effective water	187	187	187	194	187
	Added water	0	51	39	71	21
	Total added water	187	238	226	265	208
Water/Cement ratio (W/C)		0.47	0.59	0.56	0.66	0.52
Slump (cm)		6.50	7.50	7.00	7.50	6.50
Fresh density (kg/m³)	real	2321	2296	2277	2207	2300
	calculated	2278	2305	2254	2270	2284

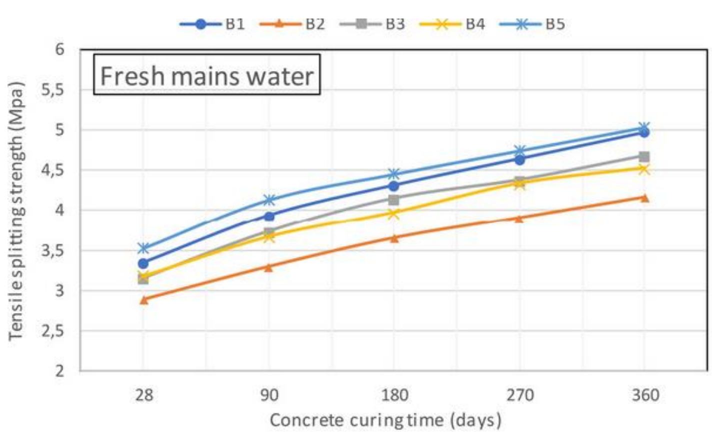


Figure 3.3 Tensile strength test result (Berredjem et al. 2020)

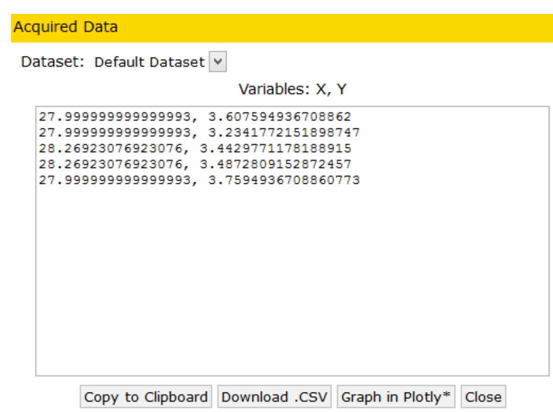
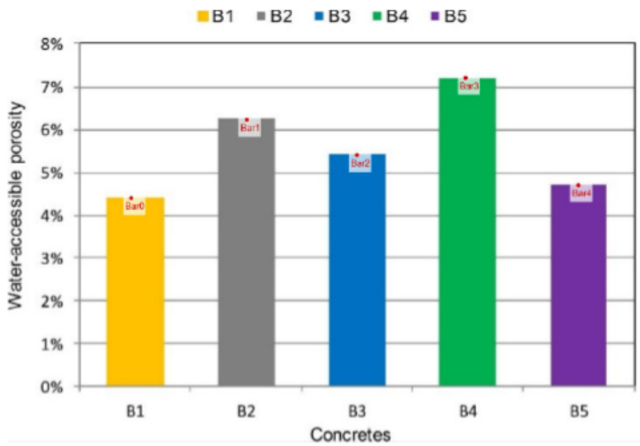


Figure 3.3a Tensile strength data extraction (WebPlotDigitizer.com)



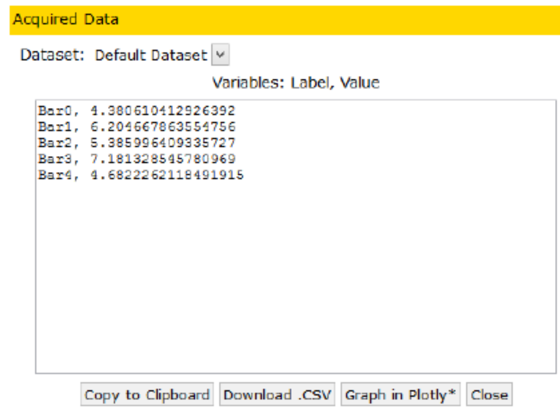


Figure 3.4 Water absorption test result (Berredjem et al. 2020)

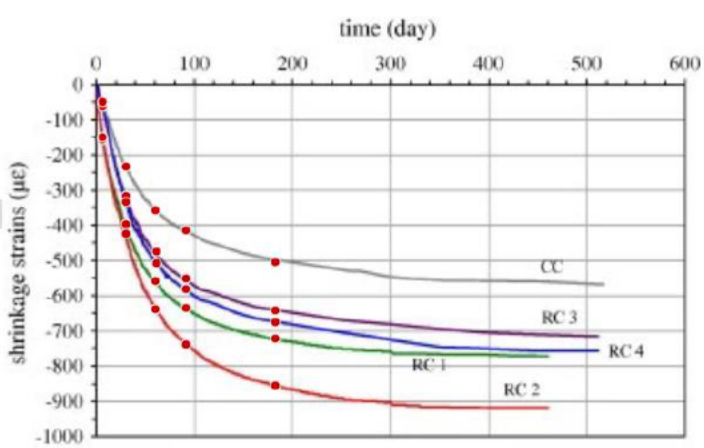
Figure 3.4a Water absorption data extraction (WebPlotDigitizer.com)

Manzi et al. (2013) investigated the effects of both fine and coarse recycled aggregates on the mechanical and durability properties of new concrete structure. They concluded that concrete workability is significantly influenced by the shape, texture and grain size distribution of the recycled aggregate itself rather than by their total amount in the concrete mixture. The use of RCA negatively affected the concrete shrinkage strain, whereas the creep results showed that recycled concrete with 27% coarse RA replacement has even better performance than the natural concrete.

Table 3.6 Mechanical properties of test data (Manzi et al. 2013)

Physical and mechanical properties of the investigated concrete mixes (D = bulk density; w_a = water absorption; f_{cm}@7d and f_{cm}@28d = compressive strength at 7 and 28 days of curing; E = secant elastic modulus; f_{ct} = tensile splitting strength; f_{cf} = three-point flexural strength).

Mix	D (g/cm^3)	w_a (%)	f_{cm}@7d (MPa)	f_{cm}@28d (MPa)	E (GPa)	f_{ct} (MPa)	f_{cf} (MPa)
CC	2.38	6.1	36.7	41.3	31.4	3.8	6.4
RC1	2.32	6.2	44.9	51.4	30.3	3.2	5.8
RC2	2.20	9.3	39.5	45.6	24.9	3.0	4.9
RC3	2.27	9.0	34.5	44.7	26.9	4.1	4.8
RC4	2.30	7.8	36.1	41.9	30.6	3.3	5.7



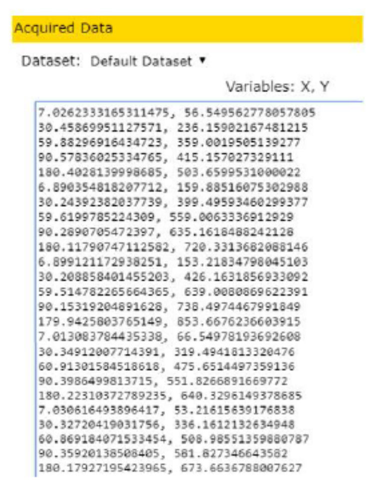


Figure 3.5 Shrinkage test data (Manzi et al. 2013)

Figure 3.5a Shrinkage data extraction (WebPlotDigitizer.com)

Yang et al. (2011) investigated the mechanical properties of recycled concrete with high levels of RCA and crushed clay bricks (CCB) replacement in the concrete mix production. The results showed that the aggregate absorptivity increases with increase in CCB content. A good quality concrete still can be produced with addition of RA and CCB for up to 50%.

Table 3.7 Workability of concrete mix (Yang et al. 2011)

Specimen	Substitution ratio (%)	Water/cement ratio	Slump (mm)
NA-100	RCA 0%	0.47	33
RCB-80	CCB 20%/RCA 80%	0.47	20
RCB-50	CCB 50%/RCA 50%	0.47	10
RC-100	RCA 100%	0.47	24

Table 3.8 Tensile strength test data (Yang et al. 2011)

Mixtures	Specimen age (day)	Tensile splitting strength (N/mm^2)			Relative strength reduction (%)
		Cylinder 1	Cylinder2	Average	
NA-100 (control)	7	3.07	3.29	3.18	0
	28	4.29	4.09	4.19	0
RCB-80	7	3.09	2.66	2.87	9.8
	28	2.67	3.13	2.9	30.8
RCB-50	7	2.64	2.83	2.73	14.2
	28	2.67	2.86	2.77	33.9
RC-100	7	3.28	2.61	2.94	7.5
	28	3.44	3.79	3.61	13.8

Table 3.9 Compressive strength test data (Yang et al. 2011)

Mixtures	Specimen age (day)	Compressive strength (N/mm^2)			Relative strength reduction (%)
		Cube 1	Cube 2	Average	
NA-100 (control)	7	41.9	41.2	41.55	0
	28	54.7	54.6	54.65	0
RCB-80	7	38.1	38.3	38.2	8.1
	28	49.3	48.3	48.8	10.7
RCB-50	7	35.5	35.8	35.65	14.2
	28	44.3	43.4	43.85	19.8
RC-100	7	38.8	38.7	38.75	6.7
	28	51.2	51.9	51.55	5.7

Table 3.10 Flexural strength test data (Yang et al. 2011)

Mixtures	Specimen age (day)	Modulus of rupture (N/mm^2)			Relative strength reduction (%)
		Prism 1	Prism 2	Average	
NA-100 (control)	7	3.18	3.6	3.39	0
	28	4.14	4.06	4.10	0
RCB-80	7	3.95	3.61	3.78	−11.5
	28	3.94	4.30	4.12	−0.4
RCB-50	7	3.13	3.44	3.28	4.1
	28	3.7	4.02	3.86	5.9
RC-100	7	3.42	3.08	3.25	3.2
	28	3.45	3.99	3.72	9.3

Kou and Poon (2012) studied the effects of fly ash addition in the concrete mix design to compensate the lower quality of recycled concrete aggregates. The report concluded that the durability properties of RC can be improved by using 25%-35% of fly ash as a partial replacement or as an addition to cement.

Table 3.11 Compressive strength test data (Kou and Poon 2012)

Notation	Fly ash (%)	Recycled aggregate (%)	Compressive strength (MPa)				
			1 day	4 days	7 days	28 days	90 days
R0	0	0	12.8	23.3	30.2	48.6	52.7
R20	0	20	11.9	22.4	29.1	45.3	50.8
R50	0	50	11.6	21.8	27.6	42.5	49.5
R100	0	100	10.2	18.6	24.4	38.1	45.5
r-R0F25	25	0	12.1	22.8	28.6	43.6	57.9
r-R20F25	25	20	11.5	24.3	32.8	42.8	57.3
r-R50F25	25	50	11.1	22.9	30.4	41.7	53.4
r-R100F25	25	100	9.4	19.1	25.1	36.8	50.1
r-R0F35	35	0	7.7	16.6	22.5	40.7	47.8
r-R20F35	35	20	6.6	14.6	20.9	41.0	46.6
r-R50F35	35	50	5.9	15.2	20.4	37.1	43.2
r-R100F35	35	100	4.8	14.6	19.4	25.2	37.4

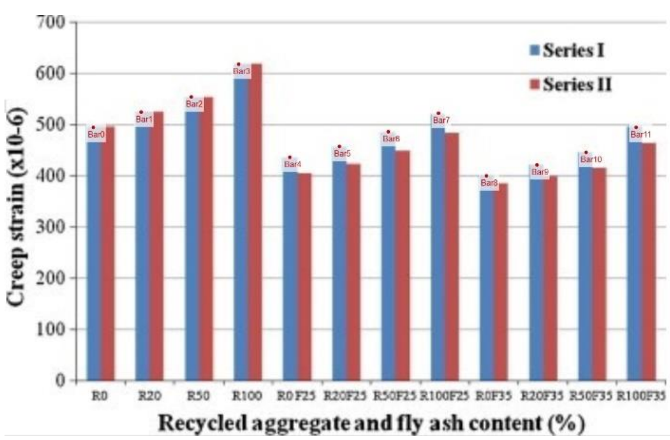


Figure 3.6 Creep test data (Kou and Poon 2012)

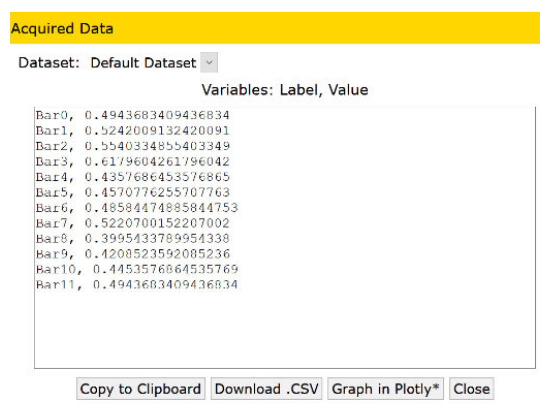


Figure 3.6a Creep test data extraction (WebPlotDigitizer.com)

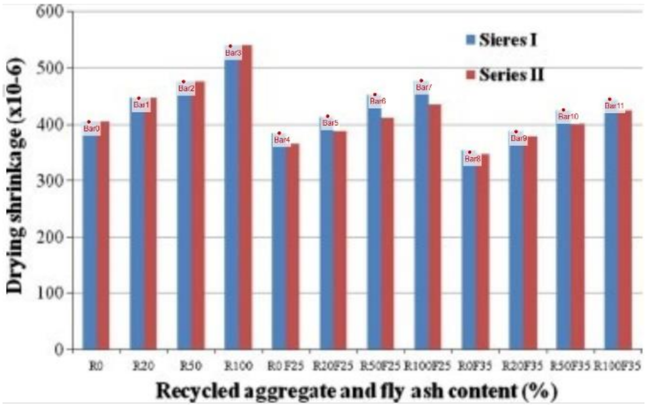


Figure 3.7 Shrinkage test data (Kou and Poon 2012)

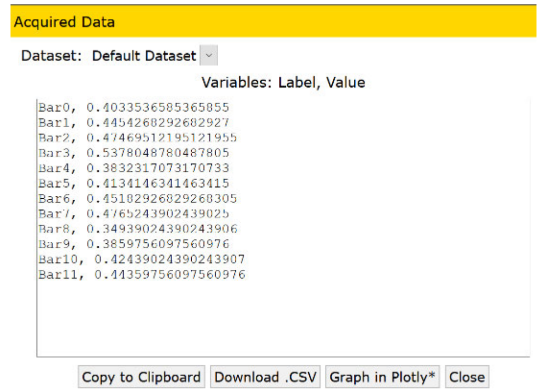


Figure 3.7a Shrinkage test data extraction (WebPlotDigitizer.com)

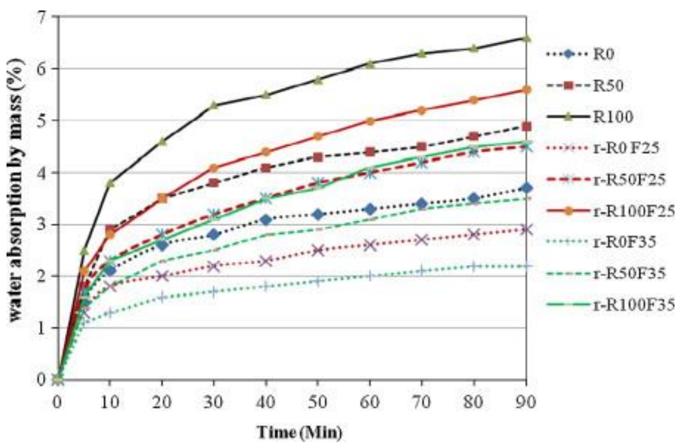


Figure 3.8 Water absorption test data (Kou and Poon 2012)

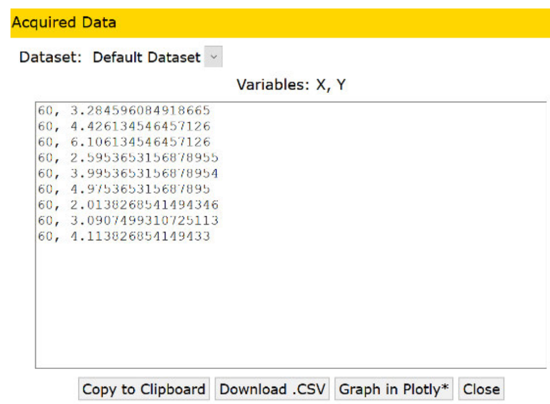


Figure 3.8a Water absorption data extraction (WebPlotDigitizer.com)

Chapter 4

Data Analysis and Results

The data analysis of this research project is carried out in the following phases:

Table 4.1 Schematic plan of data analysis phases

Phase 1	**Organise the data into a spreadsheet and find the significant outliers in the data series.** *Note: This stage is essential to achieve a good coefficient determination (r2) value between the data sets so that the generated equation from the graph can deliver more accurate function that fits the observed data*
Phase 2	**Remove the outlier from the data and create a new data set**
Phase 3	**Import the new data into Matlab and graph it into contour plots w.r.t x, y, z values.** *Note: The graph will show the relationship between the strength characteristics of RC ('z' as target) as a function of RA% content (as input 'x') and w/c ratio (as input 'y')*
Phase 4	**Generate the linear model regression equation from the graph and determine the 95% confidence and prediction interval for each regression lines.**
Phase 5	**Interpret the results and compare the recycled concrete properties to the available conventional concrete's code and design standards.**

4.1 Data collection summaries

The scope of this project is focused on the behaviour of RC strength characteristics by incorporating %RA replacement and water/cement ratio in the concrete mix design. Based on the collected experimental data researches, recycled concrete as coarse aggregates are very variable to its mechanical and durability properties. To achieve a good estimation from data analysis between RC and normal concrete, a range of parameters is developed to remove data irregularities and produce better data uniformity. A database has been established based on the following parameters:

a. The mechanical properties' data such as compressive strength, tensile strength, flexural strength and modulus of elasticity is collected and analysed for their mean value at 28 days of curing

b. Data are collected by focusing on the recycled concrete as coarse aggregates and manufactured with ordinary concrete mixing methods preferably without pre-treatments, special curing and using special admixture such as superplasticizer.

c. All recycled aggregates are generated from the real construction or demolition waste i.e. not produced from the laboratory

d. The durability properties of RC such as shrinkage and creep are analysed in mm/m, thus, all the specifics values (specific creep and shrinkage) data are converted into these units by dividing it with the applied load for each individual specimen.

Table 4.2 Mechanical and Durability Properties of Recycled Concrete Data

	MECHANICAL PROPERTIES OF RECYCLED CONCRETE																DURABILITY PROPERTIES OF RECYCLED CONCRETE							
	Authors	RCA Used	Fly ash (%)	RCA content		NA content		%RCA replaceme	w/c ratio		w/c	Compressive Strength (Mpa)	Tensile Strength (Mpa)	Flexural Strength (Mpa)	Modulus of Elasticity (Gpa)	Slump (mm)	Shrinkage (mm/m) (Days of exposure)					Water absorption	Creep (mm/m)	Alkali-S lica Reaction
No				Fine (Kg)	Coarse (Kg)	Fine (Kg)	Coarse (Kg)	%	water (Kg)	cement (Kg)							7	30	60	90	180	(%)	28	n/d
1	Corinaldesi 2010	RCA	0	0	0	553	556	0	140	350	0.4	58.6	n/d	n/d	37.3	n/d	0.09	0.26	0.34	0.4	0.44	n/d	n/d	
			0	0	0	547	549	0	153	340	0.45	56.1			36.9		0.11	0.3	0.37	0.4	0.48			
			0	0	0	541	543	0	65	330	0.5	51.2			35.6		0.19	0.27	0.43	0.45	0.5			
			0	0	0	535	537	0	176	320	0.55	47.1					0.18	0.33	0.47	0.49	0.64			
			0	0	0	531	533	0	86	310	0.6	43.9			33.9		0.24	0.34	0.48	0.58	0.7			
			0	519	0	0	556	30	140	350	0.4	43.3			28.6		0.05	0.26	0.4	0.5	0.54			
			0	512	0	0	549	30	153	340	0.45	39.6			28.6		0.06	0.28	0.42	0.47	0.54			
			0	507	0	0	543	30	65	330	0.5	38.1			27.2		0.05	0.27	0.41	0.5	0.52			
			0	502	0	0	537	30	176	320	0.55	34.5			26.7		0.1	0.24	0.45	0.51	0.58			
			0	497	0	0	533	30	86	310	0.6	31.6			26.4		0.19	0.44	0.63	0.68	0.73			
			0	0	523	553	0	30	140	350	0.4	46.1			32.7		0.11	0.31	0.5	0.5	0.58			
			0	0	517	547	0	30	153	340	0.45	45.8			33.3		0.12	0.32	0.43	0.47	0.6			
			0	0	511	541	0	30	65	330	0.5	39.9			27.7		0.14	0.38	0.54	0.54	0.58			
			0	0	506	535	0	30	176	320	0.55	36.3			24		0.17	0.26	0.38	0.43	0.63			
			0	0	501	531	0	30	86	310	0.6	34.7			22.9		0.18	0.4	0.62	0.66	0.68			
																	Days of exposure					Water	n/d	n/d
																	7	14	28	56	70	absorption		
2	T. Ozbakkaloglu et al. 2017	RCA	0	0	0	0	1065	0	237	380	0.6236842	40.9	3.7	5.17	29.3	220	0.217	0.261	0.357	0.427	0.458	5.8		
			0	0	204	0	799	25	236	380	0.6210526	41	3.4	4.7	29	180	0.224	0.287	0.382	0.487	0.512	6.03		
			0	0	408	0	533	50	236	380	0.6210526	40.5	3.11	4.63	28.2	125	0.241	0.299	0.414	0.464	0.513	6.104		
			0	0	816	0	0	100	235	380	0.6184211	40.3	2.84	3.74	27.2	115	0.263	0.334	0.441	0.52	0.549	6.104		
			0	0	0	0	1012	0	227	380	0.5973684	40.1	3.82	5.29	28.1	235	0.15	0.203	0.244	0.3	0.332	4.91		
			0	394	0	0	506	50	218	380	0.5736842	41.2	3.43	5	27.9	155	0.164	0.218	0.268	0.329	0.349	5.03		
			0	787	0	0	0	100	209	380	0.55	40.8	3.11	3.89	25.7	125	0.177	0.235	0.278	0.345	0.3805	4.72		
3	C. Zhou et al. 2017	RCRA	0	0	0	0	1193	0	195	398	0.4899497	43.57	n/d	5.07	46.4	n/d	n/d					n/d	n/d	n/d
		(crushed rock)	0	0	119	0	1074	10	196 6	398	0.4939698	42.32		4.27	44.66									
			0	0	239	0	954	20	198 2	398	0.4979899	44.31		6.28	39.74									
			0	0	358	0	835	30	199 8	398	0.5020101	40.7		5.19	38.53									
			0	0	477	0	716	40	201.4	398	0.5060302	42.33		4.31	38.29									
			0	0	597	0	597	50	203	398	0.5100503	42.2		5.11	39.5									
			0	0	716	0	477	60	204 6	398	0.5140704	33.82		4.8	40.87									
			0	0	835	0	358	70	206 2	398	0.5180905	38.33		3.96	40.43									
			0	0	954	0	239	80	207 8	398	0.5221106	39.54		4.2	40.78									
			0	0	1074	0	119	90	209.4	398	0.5261307	29.66		4.31	41.27									
			0	0	1193	0	0	100	211	398	0.5301508	37.01		4.3	40.8									
		RPC	0	0	0	0	1228	0	208.4	404	0.5158416	35.27	n/d	6.3	44.39	n/d	n/d					n/d	n/d	n/d
		Pebble	0	0	123	0	1105	10	208.9	404	0.5170792	26		5.11	39.33									
			0	0	245	0	982	20	209.3	404	0.5180693	35.22		6.39	39.36									
			0	0	368	0	860	30	209.7	404	0.5190594	32.67		6.29	39.59									
			0	0	491	0	737	40	210.1	404	0.5200495	30.68		5.54	36.5									
			0	0	614	0	614	50	210 6	404	0.5212871	29.09		5.48	41									
			0	0	737	0	491	60	211	404	0.5222772	27.08		5.85	35.77									
			0	0	860	0	368	70	211.4	404	0.5232673	28.59		5.8	36.46									
			0	0	982	0	245	80	211 8	404	0.5242574	28.86		5.52	38.24									
			0	0	1105	0	123	90	212.3	404	0.525495	25.8		4.87	34.18									
			0	0	1228	0	0	100	212.7	404	0.5264851	26.82		5.2	36.33									
4	L. Berredjem et al.2020	RCA	0	0	0	185	928	0	87	400	0.4675	34.7	3.35	n/d	n/d	65	n/d					4.39	n/d	n/d
			0	0	0	168	928	0	238	400	0.595	31.8	2.87			75						6.23		
			0	176	874	0	0	100	226	400	0.565	32.5	3.13			70						5.38		
			0	160	874	0	0	100	265	400	0.6625	30.6	3.17			75						7.18		
			0	44	219	139	696	25	208	400	0.52	33.4	3.52			65						4.69		
5	Gómez-Soberón 2002	RCA	0	0	0	710	304	0	207 6	400	0.519	39	3.7	n/d	29.7	n/d			0.374				0.16	n/d
			0	69	84	604	259	15	207 6	400	0.519	38.1	3.7		29.1				0.3763				0.135	
			0	134	164	488	209	30	207 6	400	0.519	37	3.6		27.8				0.3524				0.138	
			0	258	315	268	115	60	207 6	400	0.519	35.8	3.4		26.6				0.4104				0.153	
			0	406	497	0	0	100	207 6	400	0.519	34.5	3.3		26.7				0.4029				0.158	
6	C.S Poon 2004	RCA	0	0	0	360	720	0	221	353	0.6260623	43.3	n/d	n/d	n/d	145	n/d					n/d	n/d	
		Oven dry state	0	67	135	284	569	20	230	353	0.6515581	39.7				130								
			0	164	332	175	349	50	247	353	0.6997167	43.2				120								
			0	317	642	0	0	100	271	353	0.7677054	40.2				109.2								
7	M. Etxeberria et al. 2007	RCA	0	0	0	627.8	579.2	0	65	300	0.55	38.26	2.84	n/d	32.129	n/d	n/d					n/d	n/d	n/d
			0	137.4	128.3	470.8	434.4	25	65	300	0.55	39.42	3.01		32.84									
			0	279 8	256.6	319.5	289.4	50	65	318	0.5188679	38.79	3.36		32.5									
			0	732 2	391.2	0	0	100	62	325	0.4984615	35.53	2.79		28.635									
8	G. Andreu et al 2014	RCA	0	0	0	302.1	784.5	0	135.4	380	0.3563158	102.09	5.13	6.47	50.41	n/d	n/d					n/d	n/d	n/d
		RCA 60MPa	0	0	195	241.6	627.6	20	138 2	380	0.3636842	102.48	6.32	7.98	47.79									
			0	0	487.5	151	392.2	50	149 8	380	0.3942105	103.1	5.1	6.8	44.28									
			0	0	975.1	0	0	100	170.4	380	0.4484211	100.78	5.88	6.33	40.09									
		RCA 40 Mpa	0	0	187.8	241	627.6	20	139.7	380	0.3676316	104.28	5.31	6.7	48.29									
			0	0	469.4	151.1	392.3	50	153.1	380	0.4028947	96.84	6.21	6.83	43.04									
			0	0	938.8	0	0	100	175.3	380	0.4613158	91.23	4.2	6.53	37.15									
																	Shrinkage at 91 days of curing							Expansion at 91 days of curings
9	Limbachiya et al.2012	RCA	0	0	0	0	1260	0	80	275	0.6545455	25.56	n/d	3.9	18.29	70	0.29					n/d	n/d	0.125
		PC20	0	0	378	0	882	30	80	275	0.6545455	25.04		3.8	16.51	70	0.32							0.11
			0	0	635	0	635	50	80	295	0.6101695	25.56		3.4	14.57	60	0.45							0.1
			0	0	1240	0	0	100	80	310	0.5806452	24.71		2.86	11.46	40	0.65							0.06
		PCFA20	90	0	0	0	1311	0	60	215	0.744186	29.85		4.28	16.43	40	0.19							0.145
			90	0	393	0	918	30	60	215	0.744186	29.45		3.81	16.97	20	0.26							0.19
			100	0	657	0	657	50	60	230	0.6956522	28.66		3.98	14.44	50	0.25							0.19
			105	0	1280	0	0	100	60	245	0.6530612	28.76		4.28	13.37	30	0.45							0.22
		PC30	0	0	0	0	1245	0	80	330	0.5454545	31.19		4.49	18.7	120	0.34							0.1
			0	0	373	0	872	30	80	330	0.5454545	33		4.68	16.01	80	0.34							0.12
			0	0	623	0	623	50	80	355	0.5070423	34.3		4.09	14.53	60	0.52							0.08
			0	0	1252	0	0	100	80	372	0.483871	27.2		4.22	11.92	70	0.63							0.08
		PCFA30	110	0	0	0	1285	0	60	260	0.6153846	37.5		5.32	21.89	30	0.215							0.09
			110	0	386	0	900	30	60	260	0.6153846	35		4.11	17.42	20	0.24							0.145
			120	0	641	0	641	50	60	280	0.5714286	34.88		5.93	15.39	60	0.43							0.11
			126	0	1267	0	0	100	60	295	0.5423729	37.06		4.81	14.11	70	0.55							0.135
		PC35	0	0	0	0	1245	0	80	355	0.5070423	37.53		5.032	19.57	40	0.28							0.12
			0	0	373	0	872	30	80	355	0.5070423	31.76		5.12	14.24	20	0.32							0.13
			0	0	613	0	613	50	80	385	0.4675325	40		4.58	14.9	30	0.425							0.13
			0	0	1226	0	0	100	80	409	0.4400978	44.7		4.9	12.5	50	0.81							0.14
		PCFA35	120	0	0	0	1282	0	60	280	0.5714286	38.63		4.708	20.57	10	0.195							0.14
			120	0	384	0	898	30	60	280	0.5714286	42.84		5.181	19.99	30	0.25							0.14
			130	0	631	0	631	50	60	300	0.5333333	39.43		4.7	16.51	20	0.425							0.065
			138	0	1257	0	0	100	60	322	0.4968944	36.022		5.31	13.74	20	0.695							0.1

																	Shrinkage					Water									
																	7	14	28	56		absorption						n/d			
10	W. H Kwan et al.2012	RCA	0	0	0	0	1048.3	0	190	328	0.5792683	40.6	n/d	n/d	n/d	n/d	0.078	0.2267	0.375	0.719		1.79									
			0	0	157.2	0	891.1	15	190	328	0.5792683	38.5					0.14	238	0.4	0.781		2.85									
			0	0	314.5	0	733.8	30	190	328	0.5792683	37.06					0.1	0.26	0.504	0 859		2.86									
			0	0	629	0	419.3	60	190	328	0.5792683	28.12					0.111	0.305	0.6636	1 078		3.49									
			0	0	838.6	0	209.7	80	190	328	0.5792683	26.015					0.1288	0.437	0.82	1.1956		3.95									
																	Shrinkage														
																	7	30	60	90	180	n/d	n/d					n/d			
11	S. Manzi et al. 2013	RCA	0	0	0	0	1800	0	168	350	0.48	41.3	3 8	6.4	31.4	190	0.056	0.236	0.359	0.415	0.503										
			0	0	419	0	1331	31.48009	168	350	0.48	51.4	3 2	5.8	30.3	100	0.159	0.399	0.559	0 635	0.72										
			0	0	1024	0	675	100	168	350	0.48	45.6	3	4.9	24.9	200	0.153	0.426	0.639	0.738	0.853										
			0	0	604	0	1154	52.33969	168	350	0.48	44.7	4.1	4.8	26.9	210	0.066	0.319	0.475	0.551	0.64										
			0	0	604	0	1144	52.7972	168	350	0.48	41.9	3.3	5.7	30.6	130	0.053	0.336	0.508	0.581	0.673										
																	Shrinkage at 112 days					water absor	Creep at 120 days								
12	Kou and Poon 2012	RCA	0	0	0	0	1048	0	225	410	0.5487805	48.6	n/d	n/d	n/d	n/d	0.404					3.27	0.494					n/d			
		series I	0	0	204	0	840	20	225	410	0.5487805	45.3					0.446						0.525								
			0	0	506	0	524	50	225	410	0.5487805	42.5					0.475					4.41	0.553								
			0	0	1017	0	0	100	225	410	0.5487805	38.1					0.539					6.06	0.618								
			25	0	0	0	1048	0	225	410	0.5487805	43.6					0.383					2.62	0.435								
			25	0	204	0	840	20	225	410	0.5487805	42.8					0.414						0.455								
			25	0	506	0	524	50	225	410	0.5487805	41.7					0.451					4.02	0.485								
			25	0	1017	0	0	100	225	410	0.5487805	36.8					0.477					5	0.522								
			35	0	0	0	1048	0	225	410	0.5487805	40.7					0.352					2.02	0.401								
			35	0	204	0	840	20	225	410	0.5487805	41					0.386						0.42								
			35	0	506	0	524	50	225	410	0.5487805	37.1					0.423					3.09	0.446								
			35	0	1017	0	0	100	225	410	0.5487805	25.2					0.44					4.08	0.496								
		Series II	0	0	0	0	1048	0	225	410	0.5487805	48.6					0.404					3.27	0.494								
			0	0	204	0	840	20	225	410	0.5487805	45.3					0.446						0.525								
			0	0	506	0	524	50	225	410	0.5487805	42.5					0.475					4.41	0.553								
			0	0	1017	0	0	100	225	410	0.5487805	38.1					0.539					6.06	0.618								
			25	0	0	0	992	0	225	512.5	0.4390244	52.9					0.363					1.912	0.405								
			25	0	193	0	794	20	225	512.5	0.4390244	50.1					0.386						0.423								
			25	0	482	0	496	50	225	512.5	0.4390244	48.1					0.41					2.92	0.449								
			25	0	963	0	0	100	225	512.5	0.4390244	45.3					0.434					3.99	0.484								
			35	0	0	0	1048	0	225	553.5	0.4065041	68.9					0.346					1.48	0.383								
			35	0	204	0	840	20	225	553.5	0.4065041	63					0.376						0.399								
			35	0	506	0	524	50	225	553.5	0.4065041	58.5					0.398					2.38	0.415								
			35	0	1017	0	0	100	225	553.5	0.4065041	54.5					0.423					3.477	0.465								
13	J. Xiao et al. 2004	RCA	0	0	0	0	1295	0	185	430	0.4302326	35.9	n/d	n/d	27.5	42	n/d					n/d	n/d					n/d			
			0	0	374	0	872	30	185	430	0.4302326	34.1				33															
			0	0	609	0	609	50	185	430	0.4302326	29.6				41															
			0	0	832	0	357	70	185	430	0.4302326	30.3				40															
			0	0	1149	0	0	100	185	430	0.4302326	26.7				44															
14	Topçu and Sengel 2003	RCA	0	0	0	0	914	0	209	327	0 6391437	17.6	n/d	2 63	n/d	110	n/d					n/d	n/d					n/d			
		C16	0	0	510	0	743	30	202	316	0 6392405	13.3		2.75		100															
			0	0	860	0	564	50	197	310	0 6354839	12.4		2.59		95															
			0	0	1205	0	188	70	196	307	0 6384365	13.1		2.54		85															
			0	0	1764	0	0	100	184	289	0 6366782	11.8		2 29		90															
		C20	0	0	0	0	898	0	209	366	0.5710383	18.5		2.19		95															
			0	0	501	0	730	30	202	354	0.5706215	15.5		2 02		90															
			0	0	844	0	553	50	197	346	0.5693642	14.5		1 82		70															
			0	0	1185	0	185	70	196	343	0.5714286	14.4		1 81		90															
			0	0	1738	0	0	100	184	323	0.5696594	13.7		1 63		80															
15	Adessina et al. 2019	RCA	0	0	0	432	561.2	0	159.6	380	0.42	66.38	n/d	n/d	43.47	200	n/d					n/d	n/d					n/d			
			0	77.02	99.63	345.6	448.96	20	159.6	380	0.42	64.57			41.24	215															
			0	154.03	199.26	259.2	336.72	40	159.6	380	0.42	59.25			40.17	220															
			0	231.05	298.89	172.8	224.48	60	159.6	380	0.42	57.17			38.4	205															
			0	308.52	398.52	86.4	112.24	80	159.6	380	0.42	58.6			35.71	194															
			0	385.08	498.14	0	0	100	159.6	380	0.42	55.88			34.79	185															
16	Kou and Poon 2013	RCA	0	0	0	0	1048	0	225	410	0.5487805	46.7	3 21	n/d	29.5	150	n/d					n/d	n/d					n/d			
			0	0	506	0	524	50	225	410	0.5487805	41.3	3 09		25.8	170															
			0	0	1017	0	0	100	225	410	0.5487805	36.5	2.98		21.6	195															
			25	0	0	0	1048	0	225	307.5	0.7317073	42.3	3.14		28.5	165															
			25	0	506	0	524	50	225	307.5	0.7317073	39.8	3 01		27.1	190															
			25	0	1017	0	0	100	225	307.5	0.7317073	35.2	2.91		23.1	210															
			35	0	0	0	1048	0	225	266.5	0 8442777	38.9	2 81		27.4	185															
			35	0	506	0	524	50	225	266.5	0 8442777	35.9	2.72		23.9	225															
			35	0	1017	0	0	100	225	266.5	0 8442777	29.7	2.48		20.7	250															
			55	0	0	0	1048	0	225	184.5	1 2195122	34.9	2.58		25.4	190															
			55	0	506	0	524	50	225	184.5	1 2195122	29.9	2.36		21.3	230															
			55	0	1017	0	0	100	225	184.5	1 2195122	25.6	2.19		19.5	255															
17	Barbudo et al. 2013	RCA	0	n/a	n/a	n/a	n/a	0	189	350	0.54	49.78	10 85	n/d	38.74	110	n/d					n/d	n/d					n/d			
			0	n/a	n/a	n/a	n/a	20	189	350	0.54	50.8	8.5		37.93	121															
			0	n/a	n/a	n/a	n/a	50	189	350	0.54	48.2	7 8		36.52	116															
			0	n/a	n/a	n/a	n/a	100	189	350	0.54	45.4	9.58		31.67	124															
18	H. Mefteh et al. 2013	RCA	0	n/a	n/a	n/a	n/a	0		0.54	0.54	30.5	3 03	n/d	n/d	90	n/d					n/d	n/d					n/d			
			0	n/a	n/a	n/a	n/a	20		0.54	0.54	36.25	3.37			70.15															
			0	n/a	n/a	n/a	n/a	40		0.54	0.54	34.95	2.92			59.2															
			0	n/a	n/a	n/a	n/a	60		0.54	0.54	26.15	2.58			29.8															
			0	n/a	n/a	n/a	n/a	80		0.54	0.54	27.83	2 66			20															
			0	n/a	n/a	n/a	n/a	100		0.54	0.54	27.96	2 69			15															
																	Shrinkage (mm/m) (Days of exposure)					Water	Creep (mm/m) days of exposure								
																	7	30	60	90	180	absorption	7	30	60	90					
19	Pedro et.al 2017	RCA	0	0	0	859	1027	0	150.5	350	0.43	72.6	4.56	n/d	44.5	135	0.115	0.174	0.224	0 261	-	12	0.271	0.321	0.375	0.417	-				
			0	206	245	641	766	25	156.6	350	0.4474286	68.9	3.71		37.7	138	0.154	0.286	0.396	0.418	-	14.37	0.433	0.514	0.565	0.587	-				
			0	413	490	427	511	50	158.1	350	0.4517143	63.8	3.46		35.6	136	0.144	0.289	0.404	0.429	-	15.64	0.483	0.57	0.639	0.657	-				
			0	821	975	0	0	100	180.2	350	0.5148571	61	2 82		31.9	130	0.143	0.348	0.471	0.539	-	20.38	0.548	0.692	0.799	0.884	-				
																							Creep (mm/m) days of exposure								
																							50	100	150	200	250				
20	Gayarre et al. 2019	RBA	0	0	0	0	810	0	142	400	0.355	59.8	n/d	n/d	42		0.045	0.108	0.159	0.189		n/d	0.448	0.553	0.634	0.675	0.71				
		recycled brick	0	271	37	0	648	20	176	400	0.44	55.6			36		0.056	0.156	0.219	0 266			0.457	0.585	0.655	0.7036	0.741				
		aggregate	0	474	65	0	527	35	202	400	0.505	52.8			31		0.084	0.184	0.266	0.322			0.507	0.626	0.718	0.778	0.822				
			0	677	93	0	405	50	228	400	0.57	54.1			28.5		0.109	0.214	0.31	0.38			0.451	0.583	0.644	0.703	0.774				
			0	947	129	0	243	70	263	400	0.6575	46.8			22.5		0.118	0.263	0.401	0.483			0.522	0.688	0.782	0.868	0.916				
			0	1354	184	0	0	100	314	400	0.785	43.4			16.5		0.125	0.332	0.54	0 642			0.525	0.833	1.025	1.08	1.119				
																	Shrinkage (mm/m) (Days of exposure)					Water	Creep (mm/m) days of exposure								
																	7	28	90	180	365	absorption	50	100	150	200	250				
21	Seara et al. 2016	RCA	0		0	307.93	665.44	0	190	380	0.5	60.7	n/d	n/d	36.3	160	0.065	0.163	0.172	0 23	0.294	1.38	0.208	0.311	0.393	0.424	0.417				
			0		173.07	246.34	532.35	20	190	380	0.5	53.5			32.9	170	0.047	0.1	0.185	0 268	0.34	1.81	0.271	0.31	0.3945	0.472	0.466				
			0		432.68	153.97	332.72	50	190	380	0.5	51.8			31.6	160	0.061	0.109	0.234	0.328	0.424	1.75	0.179	0.215	0.319	0.358	0.381				
			0		865.36	0	0	100	190	380	0.5	42.9			25.9	190	0.1	0.147	0.274	0.428	0.505	2.6	0.436	0.489	0.583	0.664	0.62				
			0		0	457.65	486.19	0	178.75	275	0.65	46.9			35.2	60	0.083	0.111	0.19	0 258	0.307	2.63	0.321	0.636	0.594	0.709	0.782				
			0		168.84	366.12	388.95	20	178.75	275	0.65	46.7			32.5	100	0.044	0.071	0.231	0 245	0.364	2.95	0.3016	0.492	0.573	0.586	0.549				
			0		422.1	228.83	243.1	50	178.75	275	0.65	42.2			27.4	120	0.052	0.086	0.294	0.35	0.42	2.83	0.2618	0.416	0.481	0.618	0.569				
			0		844.2	0	0	100	178.75	275	0.65	32.4			24.1	160	0.072	0.083	0.357	0.402	0.597	3.8	0.4868	0.662	0.876	0.919	0.918				
	C b l	RC				5					5	54	/d	/d		7	4 6	6	57	6		/d	6	5	6	44	4				

22	Cabo et al. 2009	RCA	0		0	121.59	882.2	0	190	380	0.5	54.8	n/d	n/d	33.308	170	0.0416	0.096	0.157	0.161	0.199	n/d	0.216	0.258	0.36	0.3944	0.429				
		Mixture A	0		189.24	91.69	665.28	20	190	380	0.5	47.3			32.36	250	0.0416	0.0923	0.157	0.165	0.209		0. 04	0.363	0.488	0.533	0.582				
			0		471.12	57.07	414.06	50	190	380	0.5	47.4			33.516	50	0.061	0.1144	0.1818	0.1976	0.234		0. 06	0.371	0.515	0.563	0 618				
			0		874.04	0	0	100	190	380	0.5	45.25			30.337	190	0.0492	0.1504	0.2324	0.272	0.339		0. 67	0.445	0.576	0.61	0 669				
		Mixture B	0		0	121.59	882.2	0	190	380	0.5	54.1			36.223	170															
			0		189.24	91.69	665.28	20	190	380	0.5	50.2			32.36	150															
			0		471.12	57.07	414.06	50	190	380	0.5	47.7			34.072	50															
			0		874.04	0	0	100	190	380	0.5	45.85			30.995	180															
																	Shrinkage(mm/m) (Days of exposure)					Water	Creep (mm/m) Days of exposure								
																	15	28	70	140	180	absorption	15	28	70	140	180				
23	He et al.2020	RCA	0	0	0	755	1085	0	160	340	0.4705882	48.91	n/d	n/d	32.2	n/d	0.141	0.195	0.277	0.296	0.302	1.06	0.279	0.375	0.544	0.5733	0.586				
		RCA30	0	755	085	0	0	100	160	340	0.4705882	34.25			23.58		0.221	0.293	0.435	0.457	0.457	6.43	0.408	0.55	0.806	0.877	0 881				
		RCA80	0	755	085	0	0	100	160	340	0.4705882	42.33			29.49		0. 66	0.226	0.325	0.341	0.347	4.75	0.331	0.445	0.639	0.669	0.68				

				Alka i-silica reaction (days of expansion)		
	Author	RCA used	%RCA	14	28	56
24	Johnson et al. 2016	RCA Alberta aggre	0	0.36		
			25	0.234		
			50	0.312		
			100	0.338		
		RCA Bermier Aggre	0			
				0.17		
			50	0.082		
			100	0.132		
		RCA Postdam Aggr	0	0.09		
			25	0.065		
			50	0.066		
			100	0.073		
		RCA Springhill Agg	0	0.46		
			25	0.22		
			50	0.3		
			100	0.366		
		RCA Quebec demo	100	0.241		
25	Adam et al. 2013	RCA Al-R	25	0.198		
	Outdoor exposure block ma	mixed mineralogy	50	0.281		
			100	0.309		
		RCA Be-R	25	0.082		
		Argillaceous limest	50	0.091		
			100	0.11		
		RCA Po-R	25	0.051		
		sandstone	50	0.061		
			100	0.071		
		RCA Sp-R	25	0.203		
		greywacke	50	0.291		
			100	0.321		
	Consisted of silicious river g	RCA- Ca-R	20	0.281		
			50	0.441		
			100	0.502		
	Concrete with alkali aggrega	RCA St-R	20	0.079		
			50	0.071		
			100	0.064		
		RCA Op-R	20	0.075		
			50	0.062		
			100	0.056		
		Waste Used	RCA conte	**A kali-s lica reaction**		
26	Grattan-Bellew et al. 2004			**Days of expansions**		
				14	28	56
		RCA- Bernier	0	0.048	0 085	0.154
			100	0.038	0 069	0.1338
		RCA- Postdam	0	0.063	0.118	0.213
			100	0.054	0.107	0.189
		RCA - Springhill	0	0.08	0.142	0.236
			100	0.06	0.107	0.1832
				CPT	AMBT	
27	Lu et al. 2005	Natural Agg		1 year	14 days	
	Phenolite Canada	PH	0	0.027	0 056	
	River Gravel Australia	RG	0	0.035	0.31	
	Quartzite USA	MQ	0	0.094	0 265	
	Greywacke Australia	QL	0	0.12	0.342	
	Quartzitic sandstone	PQ	0	0.13	0 093	
	Quartzite Norway	NQ	0	0.15	0.185	
	Greywacke USA	PEN	0	0.167	0.357	
	Greywacke Canada	CO	0	0.196	0.42	
	Reddish sandstone	NRS	0	0.21	0.337	
	Greywacke Canada	SPH	0	0.217	0.463	
	Devitrified acidic tuff	RE	0	0.299	0.426	
				CPT		
				1 year		
28	Shehata et.al 2010	Spratt	0	0.202		
		Spratt 2	0	0.23		
		RCA1	100	0.227		
		RCA2	100	0.206		
		Washed RCA	100	0.19		
				CMBT (days)		
				14	28	
		Spratt	0	0.114	0.187	
		RCA1	100	0.046	0.177	
		RCA2	100	0.025	0.128	
				AMBT		
	Virgin aggregate	Spratt	0	0.408		
	Secondary crushing	RCA	100	0.29		
	Primary crushing	RCA	100	0.146		

4.2 Relationship between mechanical properties of RC Vs CC data analysis

The mechanical properties' relationship of recycled concrete is analysed by using the statistical linear regression method. These properties are then compared with available conventional concrete's design code and standard's equations. Moreover, the 95% confidence and prediction interval were calculated and plotted together for each regression lines.

Brown (2001) provides a step-by step guidance to calculate both prediction and confidence interval by using Microsoft Excel spreadsheet. The two mathematical equations to determine these intervals are;

$$Y_{\text{pred.}} \pm t_{0.05} \sqrt{\frac{\sum (Y - Y_{\text{pred.}})^2}{n-2}} \cdot \sqrt{\frac{1}{n} + \frac{(X - \bar{X})^2}{SS_x}} \quad \textbf{Eq. (1)}$$

$$Y_{\text{pred.}} \pm t_{0.05} \left[1 + \sqrt{\frac{\sum (Y - Y_{\text{pred.}})^2}{n-2}}\right] \cdot \sqrt{1 + \frac{1}{n} + \frac{(X - \bar{X})^2}{SS_x}} \quad \textbf{Eq. (2)}$$

Where; Y_{pred} = prediction of Y values; n = number of data points; $T_{0.05}$ = t critical value for 95%; X = mean value of known X; SS_x = the sum of squares of the standard error of X values

The following excel functions are used to calculate the prediction and confidence interval bands in the Microsoft Excel spreadsheet:

Table 4.3 Microsoft Excel functions for 95% prediction and confidence data intervals

No	Descriptions	Excel function
1	Prediction of Y values (Y_{pred})	= TREND (known Y, known X)
2	Statistics linear data points values, including; Slope, Intercept, Standard Error of slope, standard error of intercept, R square, standard error of y values, Variances, degree of freedom, unexplained variation and explained variation	= LINEST (known Y, known x, True, True) Slope 0.427988 8.489803 Interc n 117 SEslope 0.028186 1.383156 SE intercep xm 46.06882 RSQ 0.667221 5.154553 SE y ssxx 33444.92 F 230.5746 115 d.f. t.95 1.980808 SSregr 6126.233 3055.483 SS res SE 5.154553
3	Number of cases (n)	= COUNT (known x)
4	Average x values (Xm)	= AVERAGE (known x)
5	Sum of squares of deviations (SSx)	= DEVSQ (known x)
6	Two-tailed inverse function ($t_{0.05}$)	= T.INV.2T (probability, degree of freedom)
7	Standard error (SE)	= SQRT (SS_{res}/d.f)
8	95% confidence interval 95% Prediction interval	= Y± $t_{0.05}$ *SE*SQRT(1/n+(X-Xm)^2/SSx) = Y± $t_{0.05}$ *SE*SQRT(1+1/n+(X-Xm)^2/SSx)

4.3 Data plotting with Matlab program

Data plotting is another crucial part in data analyses' processes for this research project. Graphs or plots are used to visually illustrate the relationship between variables in the data series. As mentioned in the previous discussion, the strength characteristics of RC are analysed together with their RA percentage replacement and water/cement ratio respectively. Thus, contour plot was selected to present the data w.r.t x, y and z variable. Matlab has a special function to easily graph the data into contour plots. Below is the Matlab function to create contour plots from the database in this project.

```
%inputs
%Recycled aggregate replacementlevel
x = RCA;
xnodes = min(RCA):10:max(RCA);

%water/cement ratio
y = wc;
ynodes = min(wc):0.1:max(wc);

%Outputs
z = targets;

%%
%w/c Vs RCA replacement level

%fit data to surface
Z2 = gridfit(x,y,z,xnodes,ynodes);
%plot the file

figure
[A,b]= contourf(xnodes,ynodes,z2);
clabel(A,b)
%title ('Compressive strength Vs w/c, %RCA')
xlabel ('% RCA replacement')
ylabel ('Water / cement ratio')
```

Figure 4.1 Matlab function for contour plot

4.4 Analysis of results and data interpretation

4.4.1 Compressive strength

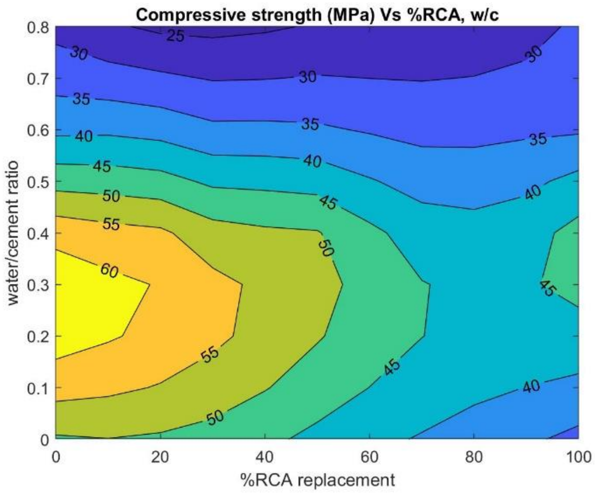


Figure 4.2 Compressive strength of RC Vs %RCA, w/c

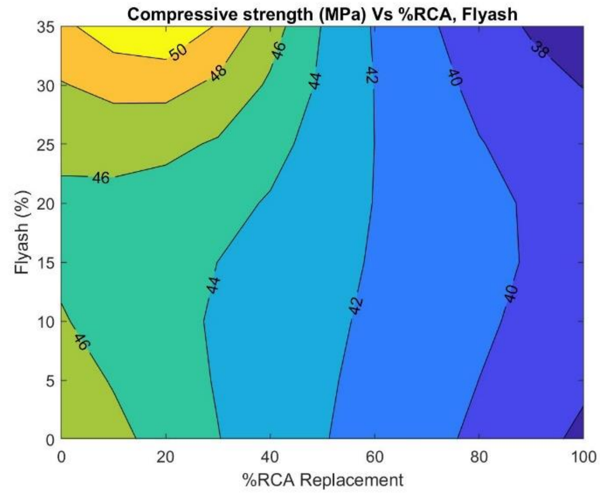


Figure 4.3 Effect of Flay ash addition in RC

The analysis results confirm that reduction in compressive strength of concrete structure depends on the percentage of recycled aggregate substitution (%RCA) and water/cement ratio in the concrete mix.

Figure 4.2 shows that as recycled aggregate replacement percentage increases, the compressive strength of RC decreases and vice versa. In addition, the compressive strength of RC gradually decreases with the increase in water/cement ratio. However, a standard compressive strength of 55MPa can be achieved, when recycled concrete contains less than 30% of RA replacement and 0.45 w/c ratio. A few studies also show that substituting recycled aggregate from concrete waste into a new concrete production does not affect the functionality requirements of the concrete structure.

Meanwhile, figure 4.3 illustrates that this lower compressive strength can be improved by adding fly ash into the concrete mixture. The highest compressive strength values can be seen when concrete structure has 0%-30% RCA replacement with 30% fly ash addition.

4.4.3 Tensile strength

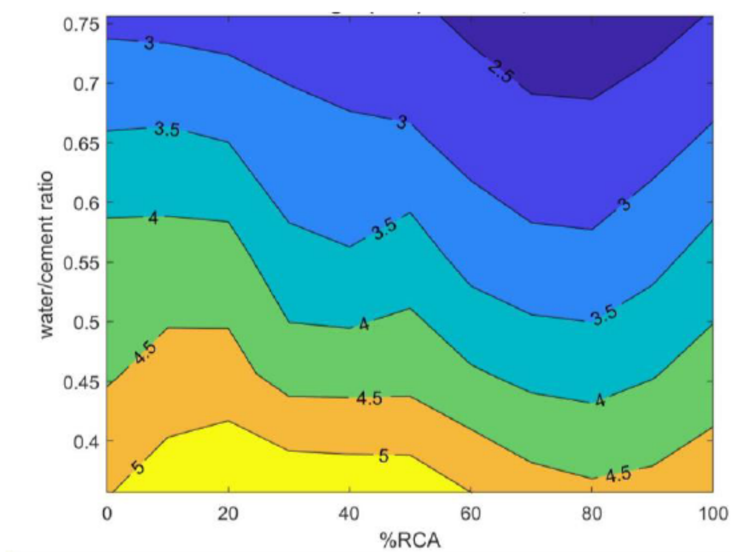


Figure 4.5 Tensile strength of Recycled Concrete

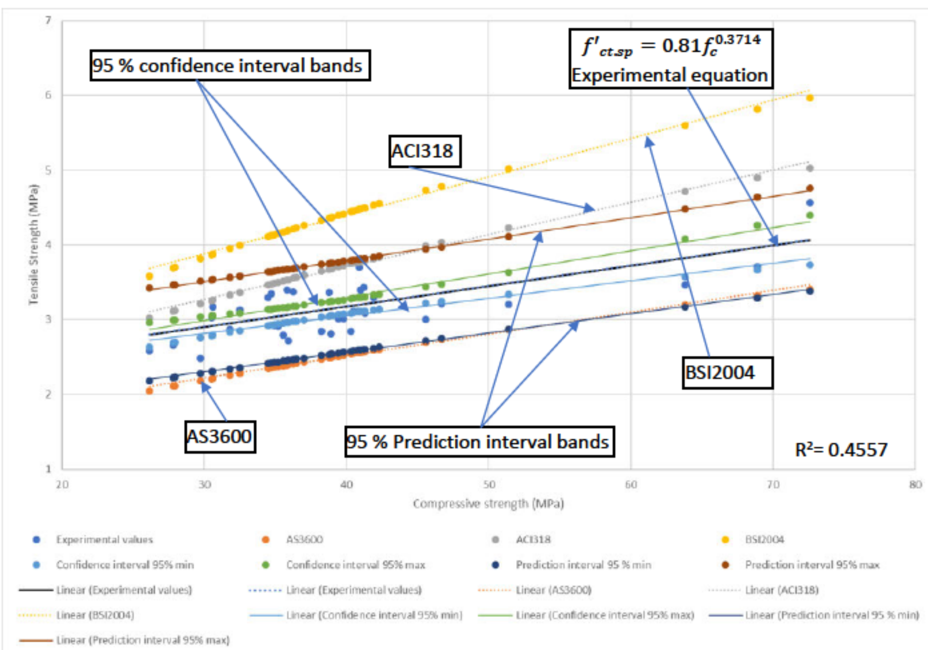


Figure 4.6 Relationship between tensile strength and compressive strength

Figure 4.5 shows a strong relationship between RCA percentage replacement and water/cement ratio. The tensile strength of RC decreases as the water/cement ratio and %RCA replacement increase. McNeil and Kang (2005) mentioned that the adhered old mortar in RCA acts as a weak point to fail under compressive load which results in lower split tensile strength. The high value of tensile strength of 5 MPa can be maintained with RCA content for up to 60% substitution and w/c ratio of less than 0.4.

Figure 4.6 shows a scatter plot of the tensile strength versus the compressive strength. The proposed linear regression line for the experimental data between these two variables is represents as;

$$f'_{ct.sp} = 0.81 f_c^{\ 0.3714} \qquad \text{Eq. (3)}$$

The Australian standard (AS3600), American Concrete Instituted Code (ACI318) and European code (BSI2004) provide design equation to describe the relationship between the tensile strength and compressive strength for conventional concrete.

As can be seen on figure 4.6, both AS3600 and ACI318 lies within the 95% prediction intervals, where BSI2004 lies above the upper prediction interval. Moreover, all design equations for conventional concrete fall outside the upper and lower confidence interval boundaries of Eq. (3). That is, the AS3600 underestimate the tensile strength value, while ACI318 and BSI2004 overestimate the tensile strength value. Therefore, the application of the current code and standard for CC to predict splitting tensile strength as a function of compressive strength is not suitable when RC is used. Further research and experimental data resources are required to generate a higher r2 value to provide a better equation for estimating the recycled concrete's properties.

4.4.4 Flexural strength

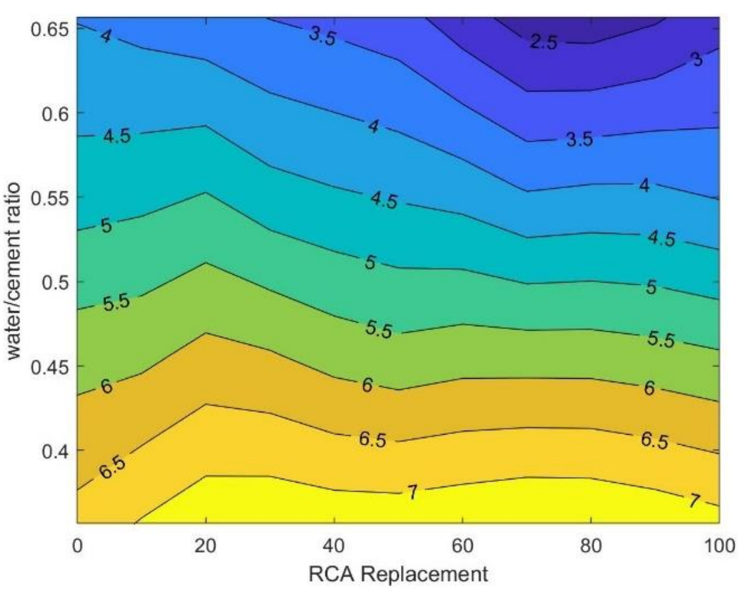


Figure 4.7 Flexural strength of Recycled Concrete

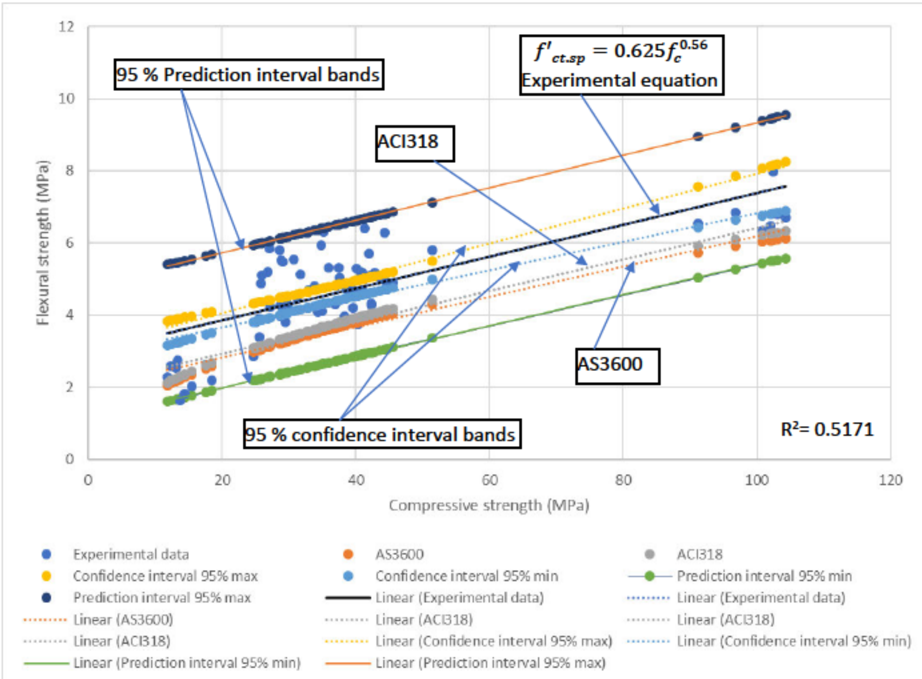


Figure 4.8 Relationship between flexural strength and compressive strength

Figure 4.7 shows that the flexural strength of RC has no significant difference to that of conventional concrete. However, the flexural strength gradually decreases as water/cement ratio increases. Bairagi et al. (1993) in their experimental studies also confirmed a significant difference in the RC's flexural strength at different w/c ratio than the conventional concrete.

Figure 4.8 illustrated the relationship between the flexural strength and compressive strength of RC against the design code and standard equation of flexural strength for ordinary concrete. As can be seen in the figure 4.8, when the compressive strength increases, the flexural strength increases too. Moreover, the ratio of flexural to compressive strength increases as the compressive strength increases. The proposed linear regression equation for the experimental data is represented as;

$$f'_{ct.f} = 0.625 f_c^{0.56} \quad \text{Eq. (4)}$$

The 95% confidence and prediction intervals for experimental data were also calculated and plotted in figure 4.8. That means 95% probability of any design equation of CC's stands within the confidence intervals of Eq. (4). The results show that both AS 3600 and ACI318 equations fall below the lower confidence interval of Eq. (4), but still lies within the 95% prediction interval boundaries. That means, both design equations provided by both standards underestimate the flexural strength for recycled concrete. Hence, application of design equations of conventional concrete would provide a conservative design of recycled concrete structures in terms of flexural strength.

4.4.5 Modulus of elasticity

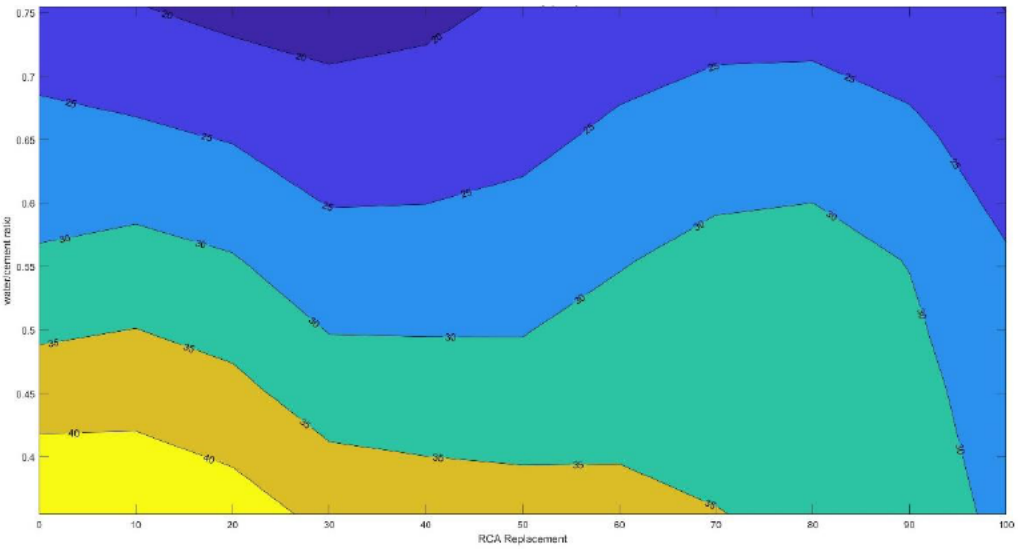


Figure 4.9 Modulus of elasticity (GPa) of Recycled Concrete

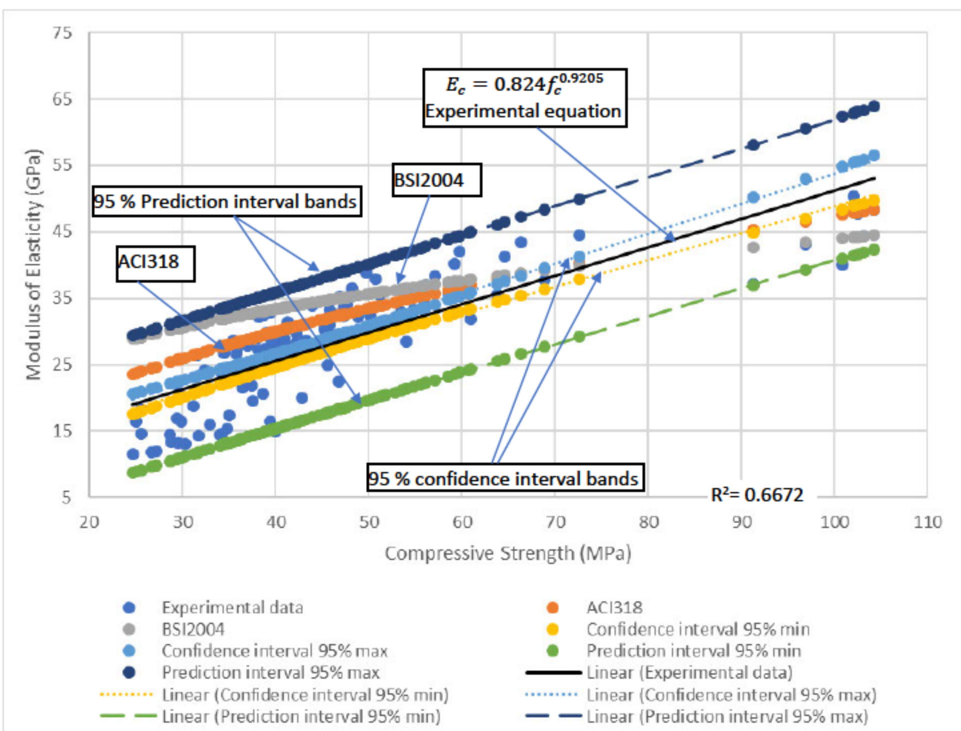


Figure 4.10 Relationship between Modulus of elasticity and compressive strength

As depicted in figure 4.9, the modulus of elasticity is considerably affected by RCA percentage replacement and water/cement ratio. The combination of a higher recycled aggregate replacement and higher water/cement ratio yield a lower modulus of elasticity. The plot also shows that the modulus of elasticity of RC with 100% recycled aggregate content is reduced by 25% compared to the natural aggregate concrete. Behera et al. (2014) reported that RC behaves in a more brittle manner than the conventional concrete due to the old adhered mortar attached to the surface of RA, thus leading to a lower modulus of elasticity.

Figure 4.10 represents a linear regression model of the correlation between the elastic modulus and compressive strength of RC. As can be seen in figure 4.10, the ACI318 and BSI 2004 design equation lies within the 95% prediction interval. However, both equations stand above the upper limit of the confidence interval of the experimental data's trendline. That means the design equations provided by both standards for conventional concrete overestimate the flexural strength of recycled concrete.

Thus, the application of design standard equation of CC is not suitable to estimate the modulus of elasticity of recycled concrete. The proposed equation obtained from the regression analysis provides a better linear correlation between the two variables with R^2 value of 0.6672. The proposed equation is given as;

$$E_c = 0.824 {f_c}^{0.9205} \qquad \text{Eq. (5)}$$

4.4.6 Shrinkage

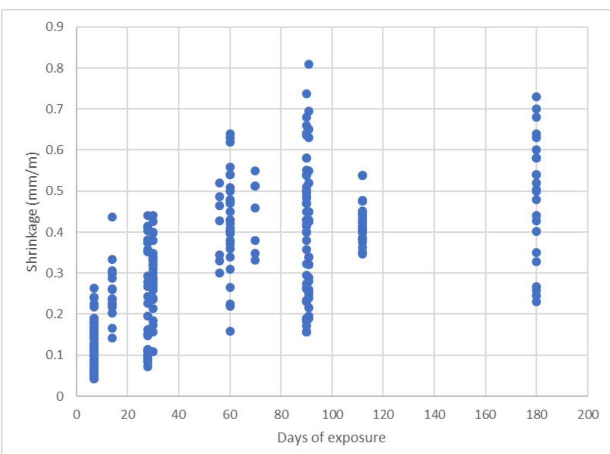


Figure 4.11 Shrinkage of RC Vs Days of exposure

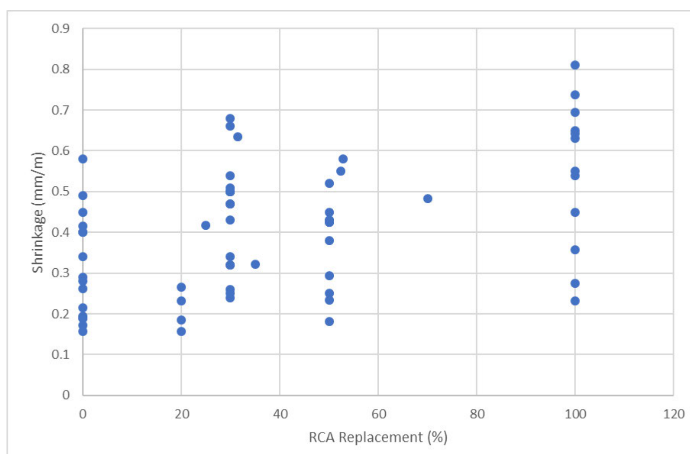


Figure 4.12 Shrinkage of RC Vs % RCA Replacement

Figure 4.12 shows that the incorporation of RA substitution into concrete exhibits more drying shrinkage than conventional concrete. The shrinkage in recycled concrete shows 15% higher than normal concrete with 30% RA substitution. Additionally, its deformation increases for up to 70% with 100% RA content after a period of 180 days. However, the shrinkage development of RC shows a similar behaviour to conventional concrete at lower substitution level (20%) and at early age of curing.

Meanwhile, Figure 4.11 indicated that shrinkage of RC increases nonlinearly over time, growing more significantly at the beginning and tending to stabilise over time. Many researchers concluded that this may be due to the lower modulus of elasticity in recycled concrete aggregate's properties, and so offers less resistance to the potential shrinkage of cement paste.

4.4.7 Creep

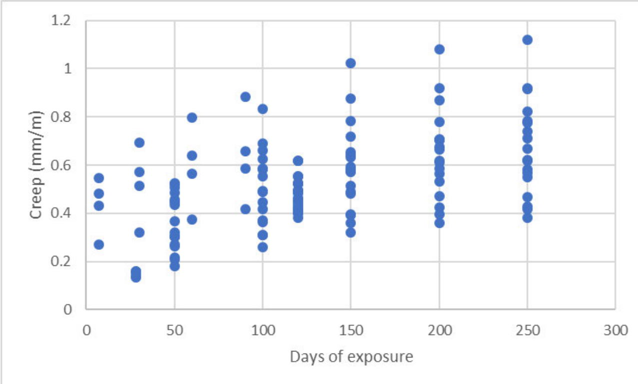


Figure 4.13 Creep (mm/m) of Recycled Concrete

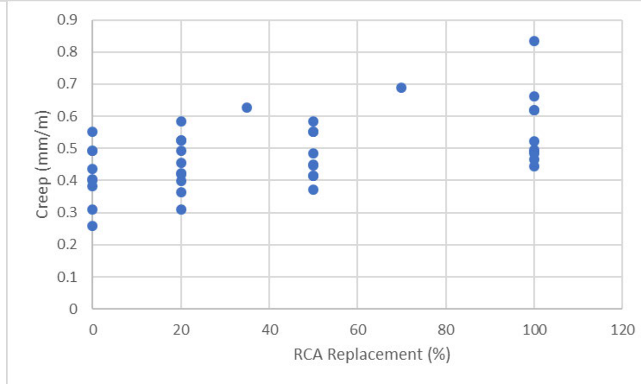


Figure 4.14 Creep (mm/m) Vs %RCA Replacement

As can be seen in Figure 4.13 and Figure 4.14, the creep development of recycled concrete tends to have a similar reaction as its drying shrinkage property. The creep value of RC increases as recycled aggregate substitution percentage increases. This is due to the amount of old mortar attached on RA which results in considerably higher creep value (Behera et al. 2014).

Based on the figure 4.14, the creep deformation increases for up to 50% in recycled concrete with 100% recycled aggregate replacement. However, the creep development in RC tends to stabilise over time and recorded only 35% lower than conventional concrete after 250 days of exposure.

4.4.8 Alkali-silica reaction

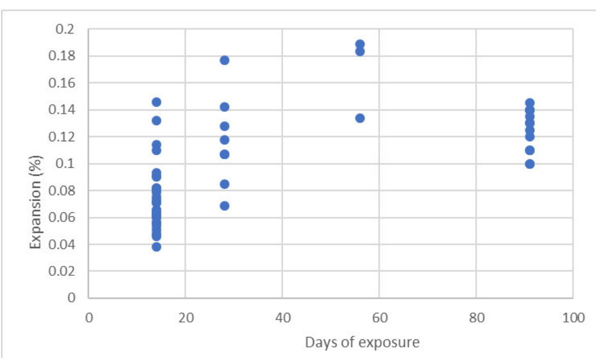


Figure 4.15 Alkali-silica expansion of Recycled Concrete

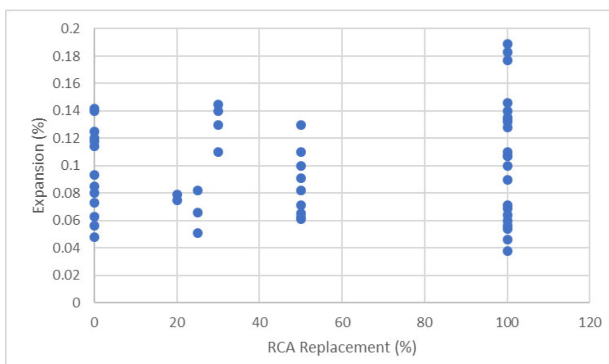


Figure 4.16 Alkali-silica expansion VS RCA Replacement

Figure 4.15 displays a small variance of recycled concrete's expansion due to its alkali-silica reaction over time. The analysis results show a higher expansion in early age and tend to stabilise (0.15%) at 90 days of exposure. This means, RCA substitution for new concrete production presents little reactivity and poses small risk of alkali-silica reaction (González-Fonteboa et al. 2018).

The high variation of expansion values for conventional concrete (0% RCA substitution) (figure4.16) mainly depends on the type of the natural aggregate used in the concrete production. While the high variability values of RC with 100% RA replacement mostly depend on the siliceous sand present in the old adhered mortar (Etxeberria et al. 2010).

Additionally, it can be inferred from figure 4.16 that the expansion value of RC increases as recycled aggregate substitution percentage increases. However, a replacement level of 20% does not affect a significant increase in alkali-silica reactivity. Santos et al. (2020) concluded that to mitigate Alkali silica reaction in RCA, a high amount of mineral additions such as fly ash and silica fume are recommended to achieve lower expansion level as natural aggregate concrete. Their investigation also revealed that recycled concrete composed with non-reactive natural aggregate and non-reactive adhered mortar, do not have significant expansion caused by alkali silica reaction. This expansion only increases when recycled concrete is entirely composed of high alkali reactive of natural aggregate.

4.4.9 Water absorption

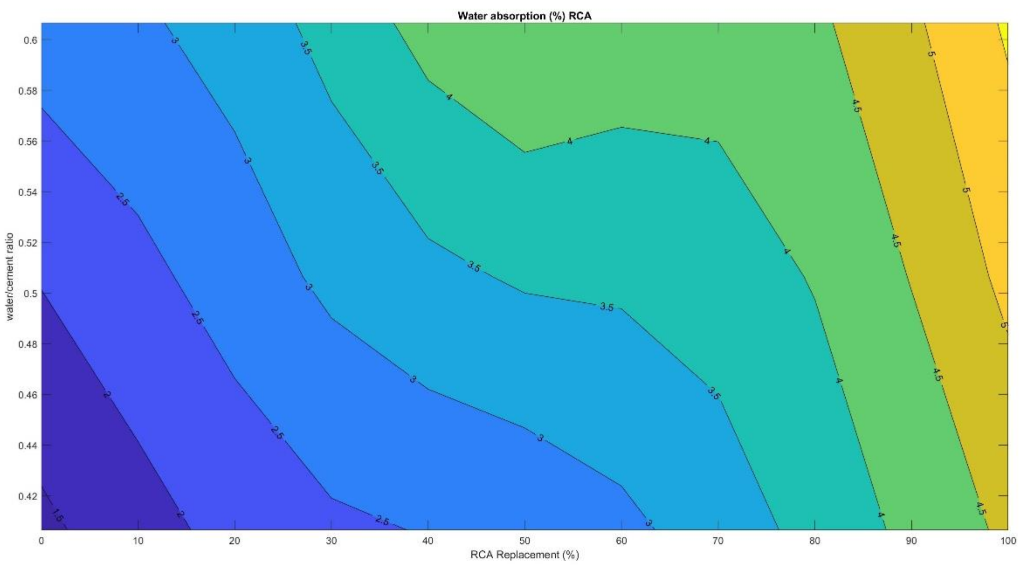


Figure 4.17 Water absorption (%) of Recycled Concrete

Figure 4.17 confirms that RC has higher water absorption than natural aggregate concrete. Water absorptivity increases as RCA percentage replacement increase. The water absorption increases for up to 70% when 100% RA is used in the concrete mix design. As previously discussed in chapter 2, this is due to the old mortar attached on the recycled aggregate surface. Additionally, Berredjem et al. (2020) specified that concrete containing fine RCA required more water to maintain consistency of fresh concrete workability. Furthermore, Poon et al. (2004) explained, during the vibration process, the water absorbed by RCA tends to move toward the cement matrix, thus forming a high porosity region in recycled concrete structure.

4.4.2 Slump

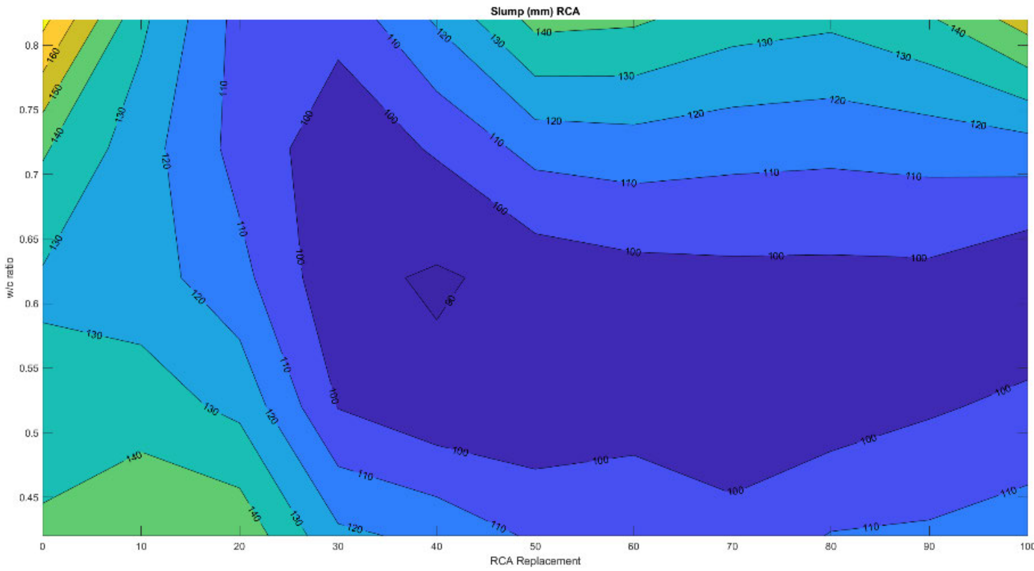


Figure 4.4 Slump (mm) value of Recycled Concrete

Figure 4.4 indicates that the slump values of recycled concrete gradually decrease as the recycled aggregate replacement increases. Many researchers stated that this is due to the higher water absorption in recycled aggregate compared to the conventional concrete. The figure also confirms that adding extra water into the concrete mix design leads to an increase in the workability of the fresh RC properties.

Chapter 5

Conclusion and Recommendation

5.1 Conclusion

The increasing infrastructure and construction development have led to significant demand for natural aggregates which will inevitably cause serious damage to the ecological environment. Moreover, the increasing rate of the demolition of old structures has generated a significant amount of construction and demolition (C&D) wastes. Concrete as the mainstream of solid waste is ineffectively disposed of in landfills at a significant cost and results in depletion of landfill spaces. Thus, eliminating this waste and preserving natural resources have become two of the main sustainable challenges in construction industry.

Many researchers have already recognised the importance of employing recycled concrete as substitution for natural aggregate. They investigated the strength characteristics of recycled concrete (RC) through various experimental studies. Literature review reveals that mechanical and durability properties of RC are generally lower than conventional concrete. Studies show that this is mainly due to the higher presence of adhering old mortar in recycled concrete aggregate, which results in the higher water absorption in the concrete structure.

The purpose of this research project is to investigate the mechanical and durability properties of recycled concrete (RC) as replacements of natural aggregates and comparing these properties with that of conventional concrete. A database from 28 experimental data reports is developed to analyse the behaviour of new concrete structure by incorporating the water/cement ratio and recycled aggregate percentage replacement. Computer software such as Microsoft Excel and Matlab are used to analyse the data and the results of this data analysis confirm that;

1. The reduction in mechanical and durability properties of concrete structure depends on the percentage of recycled aggregate substitution (%RCA) and water/cement ratio in the concrete mix design.
2. The mechanical properties of recycled concrete such as compressive strength, tensile strength, and modulus of elasticity decrease as the recycled aggregate replacement percentage and water/cement ratio increase, and vice versa.
3. The flexural strength of RC has no significant difference to that of conventional concrete. However, its strength significantly decreases as water/ cement ratio increases.
4. Concrete manufactured with RCA for up to 30% substitution satisfies the standard concrete strength of 55 MPa and does not affect the functionality requirements of the concrete structure.
5. Design equation provided by AS 3600 for conventional concrete underestimate the tensile and flexural strength for recycled concrete. This means the application of this equation would provide a conservative design of RC in terms of these mechanical properties.
6. Design equations provided by both BSI2004 and ACI 318 standards lie above the upper 95% confidence interval. That means both design equations overestimate the modulus of elasticity of

RC. Thus, the application of design standard equation of CC is not suitable to estimate the modulus of elasticity of recycled concrete.

7. The durability properties of RC such as shrinkage, creep and expansion from alkali-silica reaction increase as recycled aggregate substitution percentage increases. Additionally, these properties increase nonlinearly over time, growing more significantly at the beginning and tending to stabilise over time.
8. RCA present little reactivity and pose small risk of alkali-silica reaction despite high %RA substitution.
9. The strength characteristics of RC can be improved by reducing the w/c ratio, increasing the use of finer RA size, and the use of minerals and chemicals admixtures such as fly ash, silica fume and superplasticizer.

5.2 Project outcomes

This research project is primarily based on the theoretical approaches. To successfully achieve the project outcomes, a database is developed to analyse the behaviour of new concrete structure when recycled coarse aggregate concrete are used in the concrete mix design.

Outlined below is a summary of the project outcomes achieved;

- *Literature review of the general properties of recycled concrete as coarse aggregates*

  Chapter 2 provides a comprehensive literature review of mechanical and durability properties of recycled concrete. It was found that, the strength characteristics of recycled concrete is generally lower than the conventional concrete. However, many researchers have been exploring various techniques in order to limit the negative effect of using RA in RAC.

- *To collect the experimental data of RCA and establish a comprehensive data summary according to the designated range parameters*

  Chapter 3 and chapter 4 discuss the data collection process and data summary results. Data extraction tool such as WebPlotDigitizer was used to extract the experimental data which presented only in figures or graphs. It also shows how the data is evaluated from designed parameters and the results are summarised into a spreadsheet.

- *To compare the mechanical and durability properties of recycled concrete with the conventional concrete properties*

  Chapter 4 contains data analysis results and discussion on the recycled concrete's properties and comparison to conventional concrete. The analysis results confirm that the reduction of strength characteristics of RC was highly affected by water/cement ratio and RA replacement in the concrete mix design. The 95% confidence and prediction intervals for experimental data were also calculated and plotted in the figures. This method provides better understanding of mechanical properties' relationship between recycled concrete and conventional concrete's design equation.

- *To develop a mathematical relationship between recycled concrete's properties and conventional concrete*

  Chapter 4 also provides mathematical equation for recycled concrete's mechanical properties by using statistical linear regression analysis in Microsoft Excel. The general results show that the majority of design equation of conventional concrete is not suitable to estimate the mechanical properties of recycled concrete.

- *To undertake analysis results and recommendation for further research area*

  As mentioned in the previous discussion, chapter 4 contains detailed of research analysis and interpretation of the results, while the conclusion and recommendation are further discussed in chapter 5. Due to limited time and resources, the practical part of this research project was unfulfilled. This part of project activity still needs to be done, so that more valid data results can be achieved.

5.3 Recommendation

This research demonstrates a process to theoretically analyse the mechanical and durability properties of recycled concrete based on the various published experimental data reports. As previously discussed in chapter 4, the strength characteristics of recycled concrete is very variable. That means the data report from one researcher is prominently different from other researcher's experimental results. This is largely due to different approaches proposed by each researcher during concrete production. Based on this reason, generating a good equation relationship between variables is very challenging, particularly when the data scatter randomly with low r^2 value. Therefore, it is highly recommended for future research projects to gather more experimental data related to recycled concrete's properties, so that better accuracy of the proposed equations can be achieved.

Literature reviews also reveal that recycled aggregate from concrete waste is still not widely used in large-scale concrete production. This is mainly due to its inferior strength characteristics compared to natural aggregates. Further studies on improving mechanical and durability properties of recycled concrete are required, so that a design mix standard for recycled concrete can be developed. It is anticipated that the final recommendations from future project will provide a detailed design standard for high strength recycled concrete to promote a wider use of recycled aggregate for our sustainable future in construction industry.

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Appendix A

Project Specification

ENG4111/4112 Research Project

PROJECT SPECIFICATION

For: Milasari Brady

Title: Investigation on mechanical and durability properties of sustainable concrete using recycled concrete aggregate

Major: Civil Engineering

Supervisor: Dr Weena Lokuge

Enrolment: ENG4111 – EXT S1, 2020

ENG4112 – EXT S2, 2020

Project aim: This project aims to investigate the mechanical and durability properties of recycled concrete based on the previous experimental studies reports. The results are then to be compared with The Australian standard (AS 3600: 2009), The American Concrete Institute (ACI 318: 2011) and Eurocode (BSI 2004) of natural aggregate concrete. It also aims to provide guidelines as indicator to predict the effect of recycled concrete as natural coarse aggregates replacement in the concrete properties.

Programme: Issue V2, 13^{th} April 2020

1. Literature review of the general properties of recycled concrete aggregates, emphasizing mechanical and durability properties.
2. Gather various experimental project reports on recycled concrete aggregates and collect the data on the mechanical properties such as, slump, compressive strength, flexural strength, modulus of elasticity, tensile strength and the durability properties such as Shrinkage, creep, water absorption and Alkali silica reaction.
3. Evaluate the data and generate relationship and comparison of developmental theories based on the trend lines given from the various data researched.
4. Analyse and compare the results against the concrete design standards.
5. Complete and submit the final research project dissertation.

If time and resources permit:

1. Conduct the experimental part of the project by testing the concrete with the recycled concrete aggregates vs 100% natural aggregates concrete.

2. Further studies for improving the properties of recycled concrete aggregate and sustainability evaluation such as cost analysis and the environmental impact.

Appendix B

Consequential Effects and Ethical Responsibility

The ethical responsibility for this project has been adapted from the Engineers Australia Code of Ethics, which include;

1.Demonstrate integrity

- The selected project research's topic is within the area of study expertise, i.e. civil engineering major; hence, good background knowledge of the subject is essential in discerning and do what approach is right for the project's success
- Throughout the project, there will be regulars' reviews and feedbacks provided by the USQ supervisor after each critical project phase. These feedbacks will act appropriately and in a professional manner when something to be wrong
- Accept the feedback positively, as well as give, honest and fair criticism
- Be prepared to explain and present the work done during professional practice 2
- Ensure that the material presented in the report is own work and appropriately cite the material of other authors
- Treat others who are involve in the project with courtesy and without discrimination or harassment

2. Practise competently

- Continue to seek peer reviewto achieve high quality project results
- Maintain continuing professional development and continue to develop knowledge and skills

3. Exercise leadership

- Continue to have reasonable efforts to communicate honestly and effectively with the USQ supervisor on important issues such as risks, outcomes and any related project issues

4. Promote sustainability

If the time permit to conduct the experimental part of the project;

- Inform the supervisor or course examiner of the possible consequences of proposed activities on the community and the environment
- Promote health, safety and wellbeing of personal, community and the environment related to the experimental activities.

Appendix C

Project Risk Assessment

As this project is heavily based on the analytical approach, the risk assessment will be mainly related to personal safety and timely completion of the project. However, if the time permitted to conduct the experimental part of the project, the project's risk assessment will be adapted from USQ's Risk Assessment to identify and evaluate the risks associated with hazards and proposes control measures to either eliminate hazards or reduce the potential risks.

Risk Matrix					
	Consequence				
Probability	**Insignificant** No Injury 0-$5K	**Minor** First Aid $5K-$50K	**Moderate** Med Treatment $50K-$100K	**Major** Serious Injury $100K-$250K	**Catastrophic** Death More than $250K
Almost Certain 1 in 2	M	H	E	E	E
Likely 1 in 100	M	H	H	E	E
Possible 1 in 1,000	L	M	H	H	H
Unlikely 1 in 10,000	L	L	M	M	M
Rare 1 in 1,000,000	L	L	L	L	L

Recommended Action Guide	
Extreme:	E= Extreme Risk – Task ***MUST NOT*** proceed
High:	**H** = High Risk – Special Procedures Required (Contact USQSafe) Approval by VC only
Medium:	**M**= Medium Risk - A Risk Management Plan/Safe Work Method Statement is required
Low:	**L**= Low Risk - Manage by routine procedures.

Risk Register and Analysis				
		Risk Assessment		
Risk Description	**Consequence**	**Probability**	**Risk Level**	**Mitigation strategy**
Project Preparation Phase				
Approval to commence project not given by USQ	Medium	Unlikely	Low	Commence early discussions with potential USQ supervisor and ensure approval is received prior to starting project.
Resources are not sufficient to commence project	Medium	Possible	Medium	Start resource acquisition as soon as project is approved. If resources cannot be acquired, discuss with the supervisor and use alternative methods to continue with the project
Modelling of data Phase				
Microsoft Excel and M. Word cannot be accessed	High	Rare	Low	Ensure secondary computer is available to access Microsoft office; save all the data frequently and have an external hard drive as a back-up
Incorrect data entered into models or errors in modelling	Medium	Possible	Medium	Ensure accurate data is input into the spreadsheet. Undertake full model review to check all data. Complete simple hand calculation to ensure results are reasonable
Data Collection Phase				
Insufficient data present in the research papers	Medium	Unlikely	Low	Ensure data collection commences early to enable collection to be extended if required. Collect data over a sufficient period of time to ensure at least 5 different study papers can be analyse
Data has high variance and low reliability	Low	Possible	Low	Ensure the data is input correctly and undertake a quick review to compare the values between the data set. Investigate the outlier
Data Analysis Phase				
Data interpretation and analysis take longer than anticipated	Medium	Possible	Medium	Ensure sufficient time has been set aside for data interpretation and analysis. Start data analysis early
Repetitive strain injury in completing analysis	Medium	Unlikely	Low	Take regular breaks during analysis. Set up work area ergonomically
Write up and Present Results Phase				
Insufficient time available to adequately write up or present results	High	Unlikely	Rare	Start writing draft dissertation at the beginning of the project before results are obtained. Regularly commit time to writing dissertation. Seek review of draft dissertation

Appendix D

Microsoft Excel Experimental Data Spreadsheet

Tensile strength Vs Compressive strength

Tensile strength (Mpa)	Compressive strength (Mpa)	AS3600	ACI318	BSI2004 (5% fractile)	BSI 2004 95%fractile	Pred y	Confidence min	confidence max	Prediction min	prediction max
3.7	40.9	2.558124	3.773233	4.476718	8 313904	3.201146	3.10541812	3 29687433	2 592684	3.809609
3.4	41	2.56125	3.777843	4.482187	8 324062	3.203869	3.10801637	3 29972166	2 595387	3.812351
3.11	40.5	2.545584	3.754737	4.454773	8 273149	3.190255	3.09492649	3 28558366	2 581855	3.798655
2.84	40.3	2.539291	3.745455	4.44376	8 252697	3.184809	3.08962109	3 27999791	2 576432	3.793187
3.43	41.2	2.567489	3.787046	4.493106	8 344339	3.209315	3.11318355	3 30544563	2.600789	3.81784
3.11	40.8	2.554995	3.768618	4.471241	8 303734	3.198423	3.10281004	3 29403684	2 589979	3.806868
3.35	34.7	2.356268	3.475496	4.123469	7.657872	3.032333	2.92549105	3.13917572	2.422024	3.642643
2.87	31.8	2.25566	3.327098	3.947404	7 330894	2.953373	2.83094342	3.07580166	2 340142	3.566603
3.13	32.5	2.280351	3.363518	3.990614	7.41114	2.972432	2.85419835	3.09066576	2 360025	3.584839
3.17	30.6	2.212691	3.263719	3.872209	7.191245	2.920699	2.7905548	3.05084337	2 305882	3.535516
3.7	39	2.497999	3.684549	4.371499	8.118497	3.149413	3.05415834	3 24466817	2 541025	3.757801
3.6	37	2.433105	3.58883	4.257934	7 907591	3.094958	2.99635044	3.19356457	2.486036	3.703879
3.4	35.8	2.393324	3.530153	4.188317	7.778303	3.062284	2.95991205	3.16465605	2.452741	3.671827
3.3	34.5	2.349468	3.465465	4.111569	7.635771	3.026888	2.91913734	3.13463828	2.416419	3.637357
2.84	38.26	2.474187	3.649425	4.329827	8.041107	3.129265	3.03321834	3 22531092	2 520752	3.737777
3.01	39.42	2.511414	3.704336	4.394974	8.162095	3.160849	3.06580105	3 25589688	2 552493	3.769205
3.36	38.79	2.491265	3.674615	4.359713	8.09661	3.143695	3.04827093	3 23911988	2 535281	3.75211
2.79	35.53	2.384282	3.516816	4.172493	7.748916	3.054933	2.95154884	3.1583162	2.445219	3.664646
3.8	41.3	2.570603	3.791639	4.498555	8.35446	3.212037	3.11575256	3 30832219	2.603487	3.820588
3.2	51.4	2.867752	4.229934	5.018566	9 320193	3.487039	3.33838237	3.6356955	2.868039	4.106039
3	45.6	2.701111	3.984139	4.726944	8.77861	3.329117	3.21798597	3.44024853	2.718042	3.940192
3.3	41.9	2.589208	3.819082	4.531115	8.414927	3.228374	3.1309656	3 3257826	2.619645	3.837103
3.21	46.7	2.733496	4.031906	4.783618	8.883862	3.359068	3.24199851	3.47613732	2.746885	3.971251
3.09	41.3	2.570603	3.791639	4.498555	8.35446	3.212037	3.11575256	3 30832219	2.603487	3.820588
2.98	36.5	2.416609	3.564499	4.229066	7.85398	3.081344	2.98131755	3.18136958	2.47219	3.690497
3.14	42.3	2.601538	3.837269	4.552692	8.454999	3.239265	3.14092035	3 33761015	2.630386	3.848145
3.01	39.8	2.52349	3.722147	4.416107	8 201341	3.171196	3.0761824	3 26620872	2 562845	3.779546
2.91	35.2	2.373184	3.500446	4.153071	7.712846	3.045947	2.94125008	3.15064457	2.43601	3.655885
2.81	38.9	2.494795	3.679822	4.365891	8.108082	3.14669	3.05136028	3 24202066	2 538291	3.75509
2.72	35.9	2.396664	3.53508	4.194163	7.789159	3.065007	2.96299476	3.16701891	2.455524	3.674489
2.48	29.7	2.179908	3.215365	3.814839	7.084702	2.896194	2.75988724	3.03250076	2 280043	3.512345
3.03	30.5	2.209072	3.258382	3.865876	7.179485	2.917976	2.78716216	3.04879044	2 303017	3.532936
3.37	36.25	2.408319	3.55227	4.214558	7.827036	3.074537	2.97371974	3.17535345	2.465253	3.68382
2.92	34.95	2.364741	3.487993	4.138297	7.685408	3.03914	2.93339335	3.14488736	2.429022	3.649259
2.58	26.15	2.045483	3.017087	3.579595	6.647819	2.799535	2.63654689	2 96252318	2.176937	3.422133
2.66	27.83	2.110166	3.112495	3.69279	6.858039	2.845278	2.69532462	2 99523112	2 225965	3.464591
2.69	27.96	2.115089	3.119756	3.701405	6.874038	2.848817	2.699845	2 99778998	2 229741	3.467894
4.56	72.6	3.408225	5.027132	5.964394	11.07673	4.06427	3.72900602	4 39953385	3 376182	4.752357
3.71	68.9	3.320241	4.897355	5.810422	10.79078	3.963527	3.66276587	4 26428772	3 291575	4.635479
3.46	63.8	3.194996	4.712619	5.591243	10.38374	3.824665	3.57070504	4.07862419	3.172317	4.477013

Slope	0.027228	2.087526	**Interc**	**n**	40
SEslope	0.004828	0.197323	**SE intercep**	**xm**	39.701
RSQ	0.455667	0.296822	**SE y**	**ssxx**	3780.341
F	31.81019	38	**d.f.**	**t.95**	2.024394
SSregr	2.802583	3.347927	**SS res**	**SE**	0.296822

Flexural strength Vs Compressive strength

%RCA	w/c	Compressive strength (Mpa)	Flexural strength (Mpa)	AS3600	ACI318	Pred y	Confidence min	confidence max	Prediction min	prediction max
0	0.623684	40.9	5.17	3.837186	3.965093	4.777643	4.5614444	4.9938426	2.9010766	6.6542104
25	0.621053	41	4.7	3.841875	3.969937	4.782037	4.5657424	4.998331	2.9054588	6.6586145
50	0.621053	40.5	4.63	3.818377	3.945656	4.760071	4.5442074	4.9759339	2.8835425	6.6365989
100	0.618421	40.3	3.74	3.808937	3.935901	4.751284	4.5355619	4.9670067	2.8747723	6.6277963
0	0.597368	40.1	5.29	3.799474	3.926123	4.742498	4.5268982	4.9580976	2.866	6.6189958
50	0.573684	41.2	5	3.851234	3.979608	4.790823	4.5743249	5.0073213	2.9142217	6.6674244
100	0.55	40.8	3.89	3.832493	3.960242	4.77325	4.5571419	4.9893587	2.8966938	6.6498067
0	0.48995	43.57	5.07	3.960455	4.09247	4.894942	4.6746817	5.1152022	3.0179028	6.771981
10	0.49397	42.32	4.27	3.903229	4.033337	4.840027	4.6220576	5.0579963	2.9632553	6.7167986
20	0.49799	44.31	6.28	3.993945	4.127077	4.927452	4.7055207	5.1493825	3.0502157	6.8046875
30	0.50201	40.7	5.19	3.827793	3.955386	4.768857	4.5528349	4.9848792	2.8923106	6.6454036
40	0.50603	42.33	4.31	3.903691	4.033814	4.840466	4.6224812	5.0584512	2.9636928	6.7172397
50	0.51005	42.2	5.11	3.897692	4.027615	4.834755	4.6169699	5.0525403	2.9580048	6.7115054
60	0.51407	33.82	4.8	3.489298	3.605608	4.466605	4.2456698	4.68754	2.5894865	6.3437233
70	0.51809	38.33	3.96	3.714674	3.838496	4.664738	4.4494321	4.8800444	2.788274	6.5412024
80	0.522111	39.54	4.2	3.77285	3.898612	4.717896	4.5025433	4.9332486	2.8414264	6.5943655
90	0.526131	29.66	4.31	3.26766	3.376582	4.283848	4.0501496	4.5175459	2.4051844	6.1625111
100	0.530151	37.01	4.3	3.650151	3.771822	4.606748	4.390733	4.8227629	2.7302023	6.4832937
0	0.515842	35.27	6.3	3.563313	3.68209	4.530306	4.3121603	4.7484523	2.6535141	6.4070985
10	0.517079	26	5.11	3.059412	3.161392	4.123057	3.8730025	4.3731108	2.2422886	6.0038246
20	0.518069	35.22	6.39	3.560786	3.679479	4.52811	4.3098827	4.7463367	2.6513081	6.4049113
30	0.519059	32.67	6.29	3.429461	3.543776	4.416083	4.1923044	4.6398618	2.5386279	6.2935383
40	0.52005	30.68	5.54	3.323372	3.434151	4.328658	4.0987063	4.5586105	2.4504574	6.2068595
50	0.521287	29.09	5.48	3.236109	3.343979	4.258807	4.0228525	4.4947606	2.3798612	6.1377518
60	0.522277	27.08	5.85	3.122307	3.226384	4.170503	3.9257196	4.4152868	2.2904287	6.0505777
70	0.523267	28.59	5.8	3.208177	3.315116	4.236841	3.998815	4.4748661	2.3576339	6.1160471
80	0.524257	28.86	5.52	3.22329	3.330733	4.248702	4.0118058	4.4855985	2.3696383	6.1277661
90	0.525495	25.8	4.87	3.047622	3.149209	4.11427	3.8632022	4.3653383	2.2333672	5.9951733
100	0.526485	26.82	5.2	3.107282	3.210858	4.159081	3.9130606	4.4051012	2.2788449	6.0393168
0	0.356316	102.09	6.47	6.062376	6.264455	7.465843	6.8035953	8.1280901	5.4876282	9.4440573
20	0.363684	102.48	7.98	6.073944	6.276409	7.482976	6.8170749	8.1488775	5.5035354	9.462417
50	0.394211	103.1	6.8	6.09229	6.295367	7.510214	6.8384993	8.1819288	5.52881	9.4916181
100	0.448421	100.78	6.33	6.023355	6.224133	7.408292	6.7582999	8.0582836	5.4341463	9.3824373
20	0.367632	104.28	6.7	6.127055	6.33129	7.562054	6.8792588	8.2448488	5.5768661	9.5472415
50	0.402895	96.84	6.83	5.904439	6.101254	7.2352	6.62189	7.8485094	5.2728262	9.1975733
100	0.461316	91.23	6.53	5.730864	5.921893	6.988741	6.4271177	7.5503646	5.0419022	8.9355802
0	0.654545	25.56	3.9	3.033414	3.134528	4.103727	3.8514267	4.3560264	2.2226587	5.9847944
30	0.654545	25.04	3.8	3.002399	3.102479	4.080882	3.8258576	4.3359063	2.1994467	5.9623172
50	0.610169	25.56	3.4	3.033414	3.134528	4.103727	3.8514267	4.3560264	2.2226587	5.9847944
100	0.580645	24.71	2.86	2.982549	3.081968	4.066384	3.8095924	4.3231763	2.1847087	5.94806
0	0.744186	29.85	4.28	3.278109	3.38738	4.292195	4.0592231	4.5251666	2.4136217	6.170768
30	0.744186	29.45	3.81	3.256071	3.364607	4.274622	4.0401061	4.509138	2.3958568	6.1533873
50	0.695652	28.66	3.98	3.212102	3.319172	4.239916	4.0021853	4.4776462	2.3607465	6.119085
100	0.653061	28.76	4.28	3.217701	3.324958	4.244309	4.0069973	4.4816206	2.3651927	6.1234253
0	0.545455	31.19	4.49	3.35088	3.462576	4.351064	4.12284	4.5792875	2.4730735	6.229054
30	0.545455	33	4.68	3.446738	3.561629	4.430581	4.2076738	4.6534875	2.5532292	6.3079322
50	0.507042	34.3	4.09	3.513972	3.631105	4.487692	4.2677803	4.7076042	2.610694	6.3646905
100	0.483871	27.2	4.22	3.129217	3.233524	4.175775	3.9315551	4.4199949	2.2957738	6.0557763
0	0.615385	37.5	5.32	3.674235	3.796709	4.628275	4.412615	4.8439343	2.7517699	6.5047795
30	0.615385	35	4.11	3.549648	3.667969	4.518445	4.2998481	4.7370412	2.6416001	6.3952893
50	0.571429	34.88	5.93	3.543558	3.661676	4.513173	4.2943658	4.7319798	2.6363037	6.3900419
100	0.542373	37.06	4.81	3.652616	3.774369	4.608945	4.3929709	4.8249183	2.7324037	6.4854855
0	0.507042	37.53	5.032	3.675704	3.798227	4.629593	4.4139512	4.8452341	2.7530899	6.5060953
30	0.507042	31.76	5.12	3.381361	3.494073	4.376105	4.1496952	4.6025148	2.4983343	6.2538756
50	0.467532	40	4.58	3.794733	3.921224	4.738105	4.5225595	4.9536498	2.861613	6.6145963
100	0.440098	44.7	4.9	4.011484	4.1452	4.944585	4.7216818	5.1674884	3.067234	6.8219362
0	0.571429	38.63	4.708	3.729182	3.853488	4.677918	4.4626623	4.8931733	2.8014594	6.5543762
30	0.571429	42.84	5.181	3.927136	4.058041	4.862872	4.6440313	5.0817118	2.9859986	6.7397446
50	0.533333	39.43	4.7	3.767599	3.893185	4.713063	4.4977426	4.9283843	2.8365975	6.5895293
100	0.496894	36.022	5.31	3.6011	3.721136	4.563343	4.3462834	4.7804029	2.6866769	6.4400094
0	0.48	41.3	6.4	3.855905	3.984435	4.795216	4.5786094	5.0118232	2.9186024	6.6718302
31.48009	0.48	51.4	5.8	4.301628	4.445015	5.23893	4.9903812	5.4874778	3.3583611	7.1194979
100	0.48	45.6	4.9	4.051666	4.186722	4.984124	4.7587398	5.209508	3.1064766	6.8617711
52.33969	0.48	44.7	4.8	4.011484	4.1452	4.944585	4.7216818	5.1674884	3.067234	6.8219362
52.7972	0.48	41.9	5.7	3.883813	4.013273	4.821575	4.604223	5.038928	2.9448754	6.6982756
0	0.639144	17.6	2.63	2.517141	2.601046	3.754028	3.4529926	4.055063	1.8658055	5.6422501
30	0.639241	13.3	2.75	2.18815	2.261088	3.56512	3.232915	3.8973255	1.6716785	5.4585619
50	0.635484	12.4	2.59	2.112818	2.183245	3.525581	3.1865378	3.864625	1.6309279	5.4202349
70	0.638436	13.1	2.54	2.171635	2.244023	3.556334	3.2226174	3.8900502	1.6626264	5.4500412
100	0.636678	11.8	2.29	2.061068	2.12977	3.499222	3.1555668	3.8428776	1.603738	5.3947064
0	0.571038	18.5	2.19	2.580698	2.666721	3.793567	3.4986939	4.0884394	1.906317	5.6808162
30	0.570621	15.5	2.02	2.362202	2.440942	3.661771	3.3458456	3.9776956	1.7711173	5.5524239
50	0.569364	14.5	1.82	2.284732	2.36089	3.617839	3.2945939	3.9410833	1.7259485	5.5097288
70	0.571429	14.4	1.81	2.27684	2.352735	3.613445	3.2894612	3.9374297	1.7214288	5.5054621
100	0.569659	13.7	1.63	2.220811	2.294838	3.582693	3.2534952	3.9118908	1.6897766	5.4756094

Slope	0.043932	2.980825	**Interc**	**n**	75
SEslope	0.004969	0.221211	**SE intercep**	**xm**	38.85069
RSQ	0.517075	0.93531	**SE y**	**ssxx**	35427.92
F	78.16207	73	**d.f.**	**t.95**	1.992997
SSregr	68.37662	63.86082	**SS res**	**SE**	0.93531

Modulus of elasticity Vs Compressive strength

Author	%RCA	w/c	Modulus of elast c ty (Gpa)	Compress ive strength (Mpa)	ACI318	BS 2004	Pred y	Confidence min	confidence max	Pred ct on min	pred ct on max
Co naldes 2010	0	0 4	37.3	58 6	36.23142	37 39314	33.5699	32.394971	34.744839	23.292348	43 847462
	0	0.45	36.9	56 1	35.45014	36 90724	32.49993	31.402368	33.597501	22.230934	42 768935
	0	0 5	35.6	51 2	33.86659	35 90903	30.40279	29.4163482	31.389238	20.145075	40 660512
	0	0 6	33.9	43 9	31.35947	34 28957	27.27848	26.3268143	28.230146	17.024048	37 532912
	30	0 4	28.6	43 3	31.14443	34.1483	27.02169	26.065182	27.978192	16.766805	37.27657
	30	0.45	28.6	39 6	29.78407	33 24538	25.43813	24.4274687	26.448794	15.178056	35 698207
	30	0 5	27.2	38 1	29.21454	32 86247	24.79615	23.7526254	25.839673	14.532784	35 059514
	30	0.55	26.7	34 5	27.80008	31 89836	23.25539	22.1116362	24.399148	12.981352	33 529432
	30	0 6	26.4	31 6	26.60603	31 06911	22.01423	20.7718341	23.256619	11.728739	32 299714
	30	0 4	32.7	46 1	32.13564	34 79629	28.22005	27.276121	29.163987	17.966336	38 473771
	30	0.45	33.3	45 8	32.03091	34.7282	28.09166	27.1476069	29.035708	17.837929	38 345386
	30	0 5	27.7	39 9	29.89668	33 32073	25.56653	24.5617286	26.571327	15.307028	35 826028
	30	0.55	24	36 3	28.51608	32 38879	24.02577	22.9356052	25.115936	13.757559	34 293983
	30	0 6	22.9	34 7	27.88054	31 95373	23.34099	22.203502	24.478477	13.067646	33 614334
T. Ozbakkaloglu et al. 2017	0	0.623684	29.3	40 9	30.26901	33.5691	25.99452	25.0074586	26.981573	15.736738	36 252293
	25	0.621053	29	41	30.30599	33.5937	26.03731	25.0518752	27.022754	15.779693	36 294937
	50	0.621053	28.2	40 5	30.12063	33 47027	25.82332	24.8295049	26.817136	15.564891	36 081751
	100	0.618421	27.2	40 3	30.04616	33.4206	25.73772	24.7403577	26.735088	15.478949	35 996497
	0	0.597368	28.1	40 1	29.97151	33 37075	25.65213	24.6510985	26.653152	15.392994	35 911256
	50	0.573684	27.9	41 2	30.37981	33 64278	26.12291	25.1406212	27.105203	15.865592	36 380232
	100	0.55	25.7	40 8	30.23198	33 54445	25.95172	24.9630131	26.940421	15.693781	36 209653
Gómez-Sobe ón 2002	0	0 519	29.7	39	29.55758	33 09345	25.18134	24.1582271	26 20445	14.920029	35 442648
	15	0 519	29.1	38 1	29.21454	32 86247	24.79615	23.7526254	25.839673	14.532784	35 059514
	30	0 519	27.8	37	28.78972	32 57491	24.32536	23.2542139	25.396511	14.059152	34 591573
	60	0 519	26.6	35 8	28.31901	32.2543	23.81178	22.7073812	24.916172	13.542044	34 081509
	100	0 519	26.7	34 5	27.80008	31 89836	23.25539	22.1116362	24.399148	12.981352	33 529432
M. Etxebe a et al. 200	0	0.55	32.129	38.26	29.27581	32 90381	24.86463	23.8248805	25.904374	14.601646	35 127609
	25	0.55	32 84	39.42	29.71631	33 19997	25.36109	24.3467964	26.375391	15.100659	35 621528
	50	0.518868	32.5	38.79	29.47789	33 03989	25.09146	24.0637702	26.119152	14.829694	35 353228
	100	0.498462	28.635	35.53	28.21202	32 18113	23.69622	22.5839245	24.808515	13.425635	33 966805
G. And eu et.al 2014	0	0.356316	50 41	102.09	47.82204	44 16901	52.18311	48.9161041	55.450109	41.462984	62 903229
	20	0.363684	47 79	102.48	47 9133	44 21956	52.35002	49.0621683	55.637875	41.623527	63 076517
	50	0.394211	44 28	103 1	48.05802	44 29965	52.61537	49.2943486	55.9364	41.878665	63 352084
	100	0.448421	40 09	100.78	47.51423	43 99821	51.62244	48.425388	54.819496	40.923429	62 321455
	20	0.367632	48 29	104.28	48.33225	44 45115	53.1204	49.7361604	56 50464	42 36397	63 876831
	50	0.402895	43 04	96.84	46.57618	43 47495	49.93617	46.9485731	52.923765	39.297868	60.57447
	100	0.461316	37 15	91.23	45.20696	42 70355	47.53516	44.8429037	50.227408	36.975992	58.09432
L mbach ya et al 2012	0	0.654545	18 29	25.56	23.92858	29 15352	19.42918	17.9452475	20 91311	9.111729	29 746628
	30	0.654545	16 51	25.04	23.68392	28.9743	19.20662	17.7001796	20 71307	8.885913	29 527337
	50	0.610169	14 57	25.56	23.92858	29 15352	19.42918	17.9452475	20 91311	9.111729	29 746628
	100	0.580645	11 46	24.71	23.52734	28 85921	19.06539	17.5445411	20.586237	8 7425649	29 388213
	0	0.744186	16 43	29.85	25.85882	30.5426	21.26525	19.9572213	22.573274	10.971626	31 558869
	30	0.744186	16 97	29.45	25.68498	30 41923	21.09405	19.7704683	22.417636	10.798442	31 389663
	50	0.695652	14 44	28.66	25.33813	30.1721	20.75594	19.4010745	22.110809	10.456263	31.05562
	100	0.653061	13 37	28.76	25 3823	30 20364	20.79874	19.4478728	22.149608	10.499587	31 097894
	0	0.545455	18.7	31.19	26.43286	30 94762	21.83875	20.5813556	23.096148	11.551441	32 126062
	30	0.545455	16.01	33	27.18902	31 47581	22.61341	21.420359	23.806461	12.333766	32 893054
	50	0.507042	14 53	34 3	27.71938	31 84278	23.16979	22.0196961	24.319893	12.895047	33 444542
	100	0.483871	11 92	27 2	24.68431	29 70252	20.13108	18.7165976	21.545561	9 8233891	30 438769
	0	0.615385	21 89	37 5	28.98359	32 70635	24.53936	23.481117	25.597596	14.274485	34 804228
	30	0.615385	17 42	35	28.00081	32 03635	23.46939	22.3411589	24.597613	13.197064	33 741709
	50	0.571429	15 39	34.88	27.95276	32 00336	23.41803	22.2861168	24.549938	13.1453	33 690755
	100	0.542373	14 11	37.06	28.81305	32 59075	24.35104	23.2814725	25.420611	14.084996	34 617087
	0	0.507042	19 57	37.53	28.99518	32.7142	24.5522	23.4947127	25.609679	14.287402	34.81699
	30	0.507042	14 24	31.76	26 6733	31 11622	22.0827	20.8461016	23.319308	11.797915	32 367495
	50	0.467532	14.9	40	29.93412	33 34576	25.60933	24.6064273	26.612226	15.350013	35.86864
	0	0.571429	20 57	38.63	29.41703	32 99895	25.02298	23.9917271	26.054239	14.760858	35 285108
	30	0.571429	19 99	42.84	30.97856	34 03906	26.82481	25.8638228	27.785803	16.569511	37 080115
	50	0.533333	16 51	39.43	29.72007	33 20249	25.36537	24.3512804	26.379466	15.104959	35 625788
	100	0.496894	13 74	36 022	28.40668	32 31417	23.90679	22.8087775	25.004802	13.637742	34 175838
S. Manz et al. 2013	0	0.48	31.4	41 3	30.41666	33 66725	26.16571	25.1849503	27.146472	15.908538	36 422885
	31.48009	0.48	30.3	51 4	33.93267	35 95105	30.48839	29.4986454	31.478136	20.230354	40 746427
	100	0.48	24.9	45 6	31.96089	34 68264	28.00606	27.0617658	28.950354	17.752309	38 259811
	52.33969	0.48	26.9	44 7	31.64392	34 47585	27.62087	26.6738508	28 56789	17.366868	37 874873
	52 7972	0.48	30.6	41 9	30.63681	33 81325	26.4225	25.450302	27.394706	16.166145	36 678863
J. X ao et al. 2004	0	0.430233	27.5	35 9	28.35853	32.2813	23.85458	22.7530679	24.956083	13.585153	34 123998
	30	0.430233	14 46	34 1	27.63845	31 78696	23.0842	21.927683	24.240711	12.808729	33 359665
	50	0.430233	13.2	29 6	25 7503	30 46563	21.15825	19.8405235	22.475978	10.863392	31 453109
	70	0.430233	13 06	30 3	26.053	30 68001	21.45784	20.1670807	22.748604	11.1664	31 749284
	100	0.430233	11.8	26 7	24.45638	29 53766	19.91709	18.4816927	21.352478	9 6065048	30 227665
Adess na et al. 2019	0	0.42	43 47	66.38	38.56161	38 81806	36.89965	35.4242184	38.375086	26.583421	47 215883
	20	0.42	41 24	64.57	38.03224	38 49745	36.12499	34.7257316	37.524256	25.819381	46 430606
	40	0.42	40 17	59.25	36 4318	37 51709	33.8481	32.6511994	35.044995	23.568006	44 128189
	60	0.42	38.4	57.17	35.78661	37 11702	32.95788	31.828664	34.0871	22 68545	43 230313
	80	0.42	35 71	58 6	36.23142	37 39314	33.5699	32.394971	34.744839	23.292348	43 847462
	100	0.42	34 79	55.88	35.38056	36 86376	32.40578	31.3144268	33.497128	22.137439	42 674115
Kou and Poon 2013	0	0 54878	29.5	46 7	32.34409	34 93154	28.47685	27.532258	29.421435	18.223069	38 730625
	50	0 54878	25.8	41 3	30.41666	33 66725	26.16571	25.1849503	27.146472	15.908538	36 422885
	100	0 54878	21.6	36 5	28.59453	32 44222	24.11137	23.0267459	25.195991	13.843743	34 378993
	0	0.731707	28.5	42 3	30 7827	33 90977	26.5937	25.6266004	27.560798	16.337823	36 849575
	50	0.731707	27.1	39 8	29.85919	33 29566	25.52373	24.5170025	26.530455	15 26404	35 783418
	100	0.731707	23.1	35 2	28.08069	32 09116	23.55498	22.4328336	24.677134	13.283327	33 826641
	0	0.844278	27.4	38 9	29.51966	33 06797	25.13854	24.1132618	26.163818	14.877014	35 400065
	50	0.844278	23.9	35 9	28.35853	32.2813	23.85458	22.7530679	24.956083	13.585153	34 123998
	100	0.844278	20.7	29 7	25.79376	30 49647	21.20105	19.8872118	22.514887	10.906688	31 495411
	0	0.54	38 74	49.78	33.39365	35 60731	29.79505	28.8286463	30.761454	19.539239	40 050861
	20	0.54	37 93	50 8	33.73404	35 82464	30.2316	29.2514054	31 21179	19.974479	40 488717
	50	0.54	36 52	48 2	32.85943	35 26442	29.11883	28.1674281	30 07023	18.864421	39 373237
	100	0.54	31 67	45 4	31.89073	34 63693	27.92046	26.9757927	28.865132	17.666677	38 174248
Ped o et al 2017	0	0.43	44.5	72 6	40.32783	39 87527	39.56174	37.8053009	41.318175	29.201584	49 921892
	25	0.447429	37.7	68 9	39.28675	39 25441	37.97818	36.3920608	39.564303	27 64554	48 310824
	50	0.451714	35.6	63 8	37.80479	38 35914	35.79544	34.4276075	37.163278	25 49405	46 096835
	100	0.514857	31.9	61	36.96591	37 84614	34.59708	33.3377471	35.856405	24.309529	44 884623
Gaya e et al. 2019	0	0 355	42	59 8	36.60051	37 62123	34.08349	32.8674719	35.299509	23.801155	44 365826
	20	0.44	36	55 6	35.29181	36 80825	32.28594	31.2023518	33.369529	22.018425	42 553456
	35	0 505	31	52 8	34.39169	36 24206	31.08757	30.0715851	32.103563	20.826972	41 348176
	50	0.57	28.5	54 1	34.81249	36 50748	31.64396	30.5989456	32.688971	21.380442	41 907475
	70	0.6575	22.5	46 8	32 3787	34 95396	28.51965	27.574832	29.464459	18.265847	38 773444
Sea a et al. 2016	0	0 5	36.3	60 7	36 8749	37 79021	34.46868	33.2203745	35.716985	24.182476	44 754883
	20	0 5	32.9	53 5	34.61891	36 38554	31.38717	30.3560816	32 41825	21.125058	41 649273
	50	0 5	31.6	51 8	34.06445	36 03476	30.65959	29.6628972	31.656275	20.400877	40 918295
	100	0 5	25.9	42 9	31.00025	34 05335	26.85049	25.8901248	27.810859	16.595248	37 105736
	0	0.65	35.2	46 9	32.41328	34 97635	28.56244	27.6173731	29.507515	18.308622	38 816267
	20	0.65	32.5	46 7	32.34409	34 93154	28.47685	27.532258	29.421435	18.223069	38 730625
	50	0.65	27.4	42 2	30.74629	33.8857	26.5509	25.5825716	27.519229	16.294908	36 806893
	100	0.65	24.1	32 4	26.94071	31 30302	22.35662	21.1427904	23.570444	12.074541	32 638693
Cabo et al. 2009	0	0 5	33.308	54 8	35.03699	36 64855	31.94355	30.8811822	33.005918	21.678252	42 208848
	20	0 5	32 36	47 3	32.55121	35 06558	28.73364	27.787209	29 68007	18.479692	38 987587
	50	0 5	33.516	47 4	32 5856	35.0878	28.77644	27.8295859	29.723291	18.522452	39 030425
	100	0 5	30.337	45.25	31.838	34 60256	27.85626	26.9112264	28.801302	17.602445	38 110083
	0	0 5	36.223	54 1	34.81249	36 50748	31.64396	30.5989456	32.688971	21.380442	41 907475
	20	0 5	32 36	50 2	33.53423	35 69717	29.9748	29.003104	30.946506	19.718494	40 231116
	50	0 5	34.072	47 7	32.68855	35 15428	28.90483	27.9565207	29.853149	18.650713	39 158957
	100	0 5	30.995	45.85	32.04839	34 73957	28.11306	27.1690466	29.057067	17.859332	38 366782
He et al 2020	0	0.470588	32.2	48.91	33.10056	35 41946	29.4227	28.465534	30.379867	19.167756	39 677645
	100	0.470588	23 58	34.25	27.69917	31 82884	23.1484	21.9966997	24.300091	12.873468	33 423322
	100	0.470588	29 49	42.33	30.79361	33 91698	26.60654	25.6398031	27.573274	16.350697	36 862381

Slope	0.427988	8.489803	Interc	n	117
SEslope	0.028186	1.383156	SE ntercep	xm	46.06882
RSQ	0.667221	5.154553	SE y	ssxx	33444 92
F	230.5746	115	d.f.	t.95	1 980808
SSregr	6126.233	3055.483	SS res	SE	5 154553