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Investigating the Compressive Strengths of Guanapo Recycled Aggregate Concrete as Compared to that of its Waste Material

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Abstract: *The use of construction and demolish wastes and industrial wastes as construction materials represents an attractive solution to landfill disposal of waste, especially in small Caribbean islands where the arable land is very scarce. In this paper, an investigation was conducted to determine and compare the compressive strength parameters of concrete manufactured using recycled Guanapo coarse and fine aggregates and that of its source waste material using sustainable blended cement. Compressive strength testing was conducted according to ASTM C39 and correlations on the data obtained from testing were determined using the one-way ANOVA statistical method. The results show that it is indeed a viable option to use recycled Guanapo aggregates as a suitable substitute to natural aggregate and that waste material from construction demolition waste (CDW) can easily be recycled to produce concrete of comparable properties to that of its source waste material.*

Keywords: *Recycled Aggregate, Guanapo Aggregate, Compressive Strength, Waste Material, ANOVA*

1. Introduction

The depletion of natural resource remains one of the most critical problems of our time. In Trinidad and other Caribbean islands the scarcity of land and other resources for managing the construction demolition waste (CDW) will in the near future, force the authorities to find alternative ways to manage CDW waste: Recycling is considered as one of the most promising ways (Kou, Poon and Wan 2012). Construction and demolition waste represents both the largest waste stream as well as an increasingly utilised supply of material to the construction industry in many parts of the world. Reduce, reuse and recycle are the key principles of a sustainable construction material.

Much research has been conducted regarding the use of recycled concrete aggregates in concrete mixes recycled from parent concrete of natural source aggregates, referred here as *first generation* (Marie and Quiasrawi 2012). It is now widely recognised and steadily accepted that there is a significant potential for reclaiming and recycling demolished debris for use that is value-added applications to maximise environmental and possible economic benefits. Indeed, it is widely acknowledged that recycling of CDW for reuse as coarse aggregate in new concrete production is a technically viable; and under certain circumstances environmentally sustainable and economically feasible,way to convert this material into a valuable resource (Limbachiya, 2010).

In Trinidad and Tobago, the production of CDW and the demand for construction materials have increased dramatically over the past ten years, mainly due to a construction boom, which has only begun to taper recently due to the global economic slowdown. Nevertheless, the demand for construction aggregates in particular has ballooned to a point where the lush tropical rainforests of the Northern Range Mountains have begun to suffer illegal quarrying operations. A greater effort is needed by those in the construction industry and government who can affect policies to ensure that better utilisation of CDW becomes mainstream practice in Trinidad and Tobago.

2. Progress on the Use of Recycled Aggregates

2.1 In the International Context

The recycling of CDW for manufacturing recycled aggregate concrete (RAC) is not a new idea, as the earliest known study of this nature can be attributed to Glushge in Russia (Glushge, 1946). It is expected that the world demand for construction aggregates is forecasted to expand 2.9% annually through to 2013 to 28.7 billion tonnes (WCA, 2009) as natural aggregates are the major component for the manufacturing of Portland Cement Concrete and are known to occupy 55-80% of concrete volume.

Initially, the recycling of demolished concrete was carried out after the Second World War (Hansen, 1992). The use of RAC started mainly about 60-65 years ago when large quantities of concrete debris became available from World War II damaged structures and suddenly a great need for aggregate rose up when these structures were to be re-constructed or repaired (Kheder and Al-Windawi, 2005). In recent years, the recyclable potential of CDW has made it a target of interest and the main focus of waste management policies encouraging minimisation, reuse, recycling and valorization of the waste as opposed to disposal in landfills (Esin and Cosgun, 2007; Solis-Guzman et al, 2009). Such policies are yet to be made and enforced in the local construction industry of Trinidad and Tobago.

The largest proportion of demolition waste is generated from concrete rubbles and it has been shown from numerous studies over the years that crushed concrete rubble after being separated from other CDW and sieved, can be used as a substitute for natural coarse aggregates in concrete or as a sub-base layer in pavements (Hansen, 1992; Mehta et al., 1993; Collins, 1994; Sherwood, 1995). Among the conclusions by Frondistou-Yannas (1977) was that recycled concrete suggests itself as a useful substitute for aggregate in regions where concrete disposal is a problem or where natural aggregates are not available. Properties such as workability, compressive strength and elastic modulus were found to be very similar and even match in some cases to that of conventional concrete. Buck (1977) also showed that it is possible to produce new concrete from crushed concrete coarse aggregate. Buck (1977) studied concrete mixes that contained recycled concrete as coarse aggregate as well as mixes that contained recycled concrete both as fine and coarse aggregate. His findings are that recycled concrete can best be used as a substitute for coarse aggregate only.

Utilisation of recycled concrete has been taking place and steadily growing every year. In 2001, 42 million tonnes of construction and demolition waste including concrete were recycled in the United Kingdom (UK). That represents an increase of 382% since the early 1990s ; andthe use of primary aggregates for construction has decreased by 28% between the years 1989 to 2002.

In addition, it was proposed by Poon et al. (2002) that the replacement level of recycled course aggregate at air-dried state should not exceed 50% to produce concrete having less workability and higher compressive strengths. On the other hand, it was observed from tests carried out by Khatib (2005) that the 91-day compressive strength of concrete having recycled fine aggregate with a replacement level below 50% was similar to that of concrete with only natural aggregates and only 10% reduction was recorded for concrete with a replacement level of 100%. As reported by Li et al. (2004), RAC with a water/cement ratio of 0.5, volume ratio of coarse aggregate of 42%, 100% natural river sand, 0% crushed brick and as-is recycled aggregate without water-washed aggregate exhibited in a concrete slump of 180mm and a compressive strength of 30.17 MPa at 28 days which is applicable for most concrete structures. Tu et al. (2006) also tested high performance concrete having recycled aggregates with high water absorption and concluded that the recycled aggregates have a minor effect on the initial slump of concrete but an adverse effect on the workability with time.

The limited use of recycled aggregate in structural concrete is due to the inherent deficiency of this type of material in comparison with natural, normal weight aggregate: recycled aggregates are weaker, more porous and have higher values of water absorption. The results of research studies by Hendriks et al. (1998) show that when recycled aggregates obtained from crushed concrete are used to replace up to 20% by weight of the coarse natural aggregate in concrete, little effect on the properties of concrete is noticed (Kumutha and Vijai, 2010). The concrete strength decreases when recycled concrete was used (Barra et. al., 1996) and the strength reduction could be as low as 40% (Katz, 2003) and Chen et al., 2003). However, no decrease in strength was reported for concrete containing up to 20% fine or 30% coarse recycled concrete aggregate, but beyond these levels, there was a systematic decrease in strength as the content of recycled aggregates increased (Dhir et al., 1999). The results of this study showed similar trends for the compressive and splitting tensile strengths(Lalla and Mwasha, 2012).

Although the economic and environmental benefits of concrete produced with RCA are significant, the construction industry has not totally embraced it, especially for structural applications, partly due to previous findings that have concluded that RCA-concrete is inherently inferior to conventional concrete made with natural aggregate (Fathifazl et al., 2007).

Many have conducted studies on RAC and concluded that the material may have inherent defects that may be as a result of the condition of the recycled aggregate and the method of processing, however they have compensated for this lack of properties by enhancement of the material using mineral admixtures. Amongst the conclusions of a study by Kou et al. (2011), which compared natural and recycled concretes prepared with the addition of different mineral admixtures, was that the mineral admixtures improved the performance of the recycled aggregate concrete and its performance was higher than that of natural aggregate concrete.

Previous research results on the mechanical behavior of RAC have been reviewed by Hansen (1992) and Li (2004). It was revealed that, in fact, none of the previous results indicated that the recycled aggregate concrete is unsuitable for structural applications. Recent investigations on the performance of beams (Sogo et al., 2004; Maruyma et al., 2004; Dolara et al., 1998), columns (Konno et al., 1997), beam-column joints (Corinaldesi, 2003) and slabs (Cyllok, 2002) made from RAC all gave positive results, which further supports the possibilities of using RAC in civil engineering structures. The results of this study also agree with these positive findings for the greater use of RAC in construction. This paper reports on the potential of RAC to achieve compressive strengths comparable, or greater in some instances, to that of its source waster materialin Trinidad and Tobago (T&T).

2.2 In the T&T Context

The use of recycled aggregates and RAC in Trinidad and Toabgo (T&T) is minimal at best; however interest in its future usage in the local industry is beginning to increase as evidenced by this paper and additional research being carried out at The University of the West Indies (UWI). Also, the Trinidad Cement Limited (TCL) recently conducted an extensive seminar on the use of recycled aggregates in T&T and the Ministry of Housing and the Environment is paying a more attention to the construction of homes in a more sustainable and environmentally friendly way.

In T&T, recycled aggregates are only used in the most common ways—as road filler in road construction and in low-level applications due to impurities and defects associated with recycled aggregates (Mwasha and Mark 2008). Recent renovations and reconstruction of the administration building, chemical engineering building and senior common room at UWI, St Augustine campus are examples of of the use of recycled aggregates locally. Recently with the creation of the campus recycling committee, greater volumes of construction and demolish wastes will be turned to useful aggregates which would serve to supplement the demand for natural aggregates for construction projects at UWI, St. Augustine in addition to minimising the demolition wastes that are deposited in the Beetham Land Fill. Presently, the Beetham Land Fill is used to deposit 65% of solid waste produced in Trinidad (SWMCOL, 2010).

At UWI, St Augustine campus the recycling committee has come up with many ways to minimise solid waste reaching the Beetham landfill whilst at the same time the People's Partnership Government manifesto of 2010 has emphasised the need for sustainable development with environmental preservation and management being the cornerstone of such a drive. This paper aims to present the results of RAC materials thereby showing that the recycled aggregate materials can be used to manufacture concrete that meets with local and international standards. In order to do this, the recycled aggregate material was tested and compared with conventional concrete products of the same mix design. This information would be vital in ensuring customer confidence in recycled aggregate concrete products.

3. Availability of Natural and Recycled Aggregates in T&T

In Trinidad and Tobago, the local quarrying industry comprises of fifty-six (56) active quarries of which thirty-eight (38) produce mainly sand and gravel. The total output of the quarrying sector for 2002 was approximately seven (7) million cubic yards (5.3 million cubic meters) of which 4.5 million cubic yards (3.4 million cubic meters) were sand and gravel (Draft Quarry Policy for Trinidad and Tobago 2005).

The majority of quarrying operations in Trinidad occur within the Northern Range of mountains, which are an extension of the Andean Mountains in the South America. This area has primeval tropical rainforests, renowned for their diversity of flora and fauna. Typically, the rainforest includes over 2,300 plant species with 700 species of orchids, and provides a habitat for over 430 species of birds, 620 species of butterflies, 100 species of mammals, 70 species of amphibians and freshwater fish, and 70 species of reptiles. Unfortunately, the regions with the greatest biodiversity are also often least protected because of difficult access, and poor law enforcement for controlling poaching and illegal mining.

From a geological perspective, the Northern Range region comprises primarily low-grade metamorphic rocks of the Caribbean Group belonging to the Maraval formation. Limestones and recrystallised limestones are the most common rocks of the region, inter-laid by thinly bedded phyllitic limestones at some locations together with inter-bedded phyllites which are often calcareous. These are the oldest rocks in the Northern Range. The majority of aggregates used for construction in Trinidad and Tobago are natural aggregates derived from either limestone or quartzite rock. The destructive process for obtaining these rocks in small islands of the Caribbean has contributed to wide ranging negative environmental impacts.

The need for reducing the environmental impact of concrete should be pursued by each one involved in the construction industry, especially concrete technologists who are currently challenged to lead and develop concrete technology in a way that protects environmental quality whilst projecting concrete as a construction material of choice. Sustainability should be responsibly addressed regarding climate change resulting from the increased concentration of global warming gases caused by the extraction and manufacturing process of concrete components (Mehta, 2001, Concrete International, 2001).

Given the current decrease in the availability of relatively cheap and high quality aggregate and the increase in the demand for such materials for the production of concrete in Trinidad and Tobago, it is certain that new sources of aggregate will have to be identified. This research paper presents the results of such tests which includes compressive strength and splitting tensile strength of concrete and it seeks to give a comparison of both naturally made concrete and recycled Guanapo Quartzite aggregate concrete, as well as comparisons of recycled aggregate concrete and the original refuse concrete the recycled aggregates were manufactured from.

4. Experiment and Testing Materials

4.1 Portland Cement and Water

The composition of typical cement used in this experiment is given in European Standards ENV 1974. Natural (i.e., ordinary tap water) pipe borne water was used. Natural pipe borne water in Trinidad is slightly acidic. The content of humic and organic acids was at minimum.

4.2 Natural and Recycled Aggregates

Quartzite aggregates used in this work were extracted from a number of quarry sites in Valencia, Trinidad. Guanapo Quartzite is a non-foliated rock produced by forces of intense metamorphism as can occur in regional metamorphism. High pressures and temperatures have transformed the quartz-rich sandstone protolith to the Guanapo quartzites in Valencia, Trinidad. This local metamorphic rock is granular or sugary in appearance, hard, highly weather-resistant and of very low porosity; its specific gravity is 2.65 and its moisture content is about 2.25%. It breaks with an uneven, splintery or conchoidal fracture with the fractures cutting the grains rather than going around the grains as is the case in sandstones. The variations of moisture content in the mixes were adjusted accordingly, taking into account this increase in moisture, so as to maintain specified water/cement ratios.

All coarse and fine recycled aggregates used to produce the recycled aggregate concrete were manufactured at the UWI Civil Structural Laboratory, using refuse 150mm concrete cylinders tested in compression (source waste material), obtained from the Geotechnical Laboratory of Trintoplan Consultants Limited. All natural aggregates used to produce natural aggregate concrete were obtained from the laboratory storage depots and the natural aggregates were sourced from the National Quarries Limited Guanapo quarry.

4.3 Cement

A sample of Portland-Pozzolan Cement manufactured at Trinidad Cement Limited was used. Table 1 shows the component name and percentages and their CAS Registry Numbers. This type of cement contains 15-40% by weight of pozzolan (fly ash) (FHA, 2013).

Table 1. Components and physical properties of the TCL Type 1 cement

Components		
COMPONENT NAME	%	CAS NO.
Tri-calcium silicate	15-25	12168-85-3
Di-calcium silicate	75-85	10034-77-2
Tetra-calcium-alumino-sulphate	10-15	12068-35-8
Calcium sulphate	1-4	13397-24-5
Tri-calcium Aluminate	7-10	12042-78-3
Calcium Carbonate	0-5	1317-65-3
Magnesium Oxide	0-3	1309-48-4
Calcium Oxide	0-1	1305-78-8
Chromates	0-0.005	
Physical data		
pH (in water) – 12 to 13		
Solubility in water – Slight (0.1 to 1.0 %)		
Specific gravity - ~3.04		
Appearance and Odour – solid, grey powder; no odour.		

Source: TCL (2013)

5. Methodology: Manufacturing and Testing Samples

5.1 Mix Design

The concrete mix used in this study was designed to achieve a 28-day concrete compressive strength of 30 MPa as the design strength of the source waste material concrete was the same. The mix design was carried out in accordance with the Absolute Volume Method from Section 6.2 ACI 211.1-91 using metric units of measure. Table 2 shows the proportions of materials and mix ratios that constitute the mix design of the source waste material (Seereeram Brothers Limited) and this study's new mix design.

5.2 Manufacturing of Concrete Samples

Two types of concrete were manufactured--firstly natural aggregate concrete (NAC), and secondly recycled aggregate concrete (RAC). Different proportions of recycled aggregate (RA) and natural aggregate (NA) were used to manufacture four variations of concrete. For each of the four variations of concrete (sixty (60) cylinders per concrete variation), two batches (thirty (30) cylinders per concrete batch) of each concrete variety were manufactured. Natural Aggregate Mix 1 and 1A contained no RA and consisted of 100% NA. Recycled Aggregate Mix 2 and 2A contained 25% RA and 75% NA, whilst Recycled Aggregate Mix 3 and 3A contained 50% RA and 50% NA. Finally, Recycled Aggregate Mix 4 and 4A contained 100% RA and 0% NA. It should be noted that the proportional percentages indicated for each mix refers to both the coarse and fine aggregates.

Table 2. Mix Design Quantities and Ratios (based on $1m^3$ batch)

Concrete Mix	Concrete Design Strength/MPa	Water Content/kg	Cement Content/kg	Coarse Agg. Content/kg	Fine Agg. Content/kg	Water/Cement Ratio	Coarse/Fine Ratio
Source Waste Material	30	176	395	1050	765	0.45	1.37
New Mix Design	30	205	380	930	830	0.54	0.62

5.3 Testing of Samples

Two types of tests were performed on the 150mm concrete cylinders samples produced. These two tests were compressive strength and splitting tensile strength testing and they were carried out according to ASTM C39 and ASTM C496, respectively. For each of the concrete batches, thirty (30) cylinder samples were tested in compressive strength and splitting tensile strengths respectively; and for each thirty sample setsix (6) samples were tested at each age break of 3, 7, 14, 21 and 28 days. Mwasha and Lalla (2012) have previously presented the results of both the compressive strength and splitting tensile strength testing. This paper presents the results of the compressive strength testing of the RAC samples in comparison to the compressive strengths of the waste material concrete cylinders (also 150mm cylinder size).

5.4 Testing of Aggregates

Various tests were performed on both the NA and RA to provide supportive data for the tests performed on the concrete cylinders produced from the concrete batches. Aggregate tests performed include moisture content, specific gravity and absorption and particle size analysis. The results of these aggregate tests will be presented and correlated to the achieved strengths in subsequent papers.

6. Analysis

Statistical analyses of data obtained from the concrete testing phases of this investigation were carried out using one-way ANOVA method. Microsoft Excel 2007 software was used to perform this analysis.

Analyses to determine significant differences were carried out in three sections as follows:

1) Analysis of Splitting Tensile Strength Results (NAC versus RAC).
2) Analysis of Compressive Strength Results (NAC versus RAC).
3) Analysis of Original/Refuse Compressive Strength versus RAC Compressive Strength Results.

It should be noted that the results and analysis of the first two items listed above (i.e. Analysis of Splitting Tensile Results and Analysis of Compressive Strength Results) were discussed in Mwasha and Lalla (2012) and only the third point above will be explored in the subsequent sections.

Of the many waste material concrete cylinders used in this study and the substantial compressive strength data obtained from the prior, compressive testing of these cylinders, six (6) representative values for compressive strength had to be chosen from the mass of compressive strength data collected. These six representative samples were compared to the six, twenty-eight day average compressive strengths obtained for each of the three (3) RAC varieties produced (see Section 5.2). Only twenty-eight (28) day compressive strengths were used for this analysis.

The criteria for selecting the six representative compressive strengths from the waste material concrete compressive strength data set are as follows:

1) The highest compressive strength value observed
2) The lowest compressive strength value observed
3) The average compressive strength value calculated from the data set
4) The most frequently occurring compressive strength value observed (i.e. Mode)
5) The second most frequently occurring value observed
6) The third most frequently occurring value observed

The averages of the six (6) waste material concrete cylinders CS and that of each of the three (3) RAC batches were compared using one-way ANOVA to determine the significant differences and the variance of each group.

7. Results and Discussion

Tables 3 and 4 show the 28-day waste material representative sample strengths and strengths of the three (3) RAC batches (tested in compression), respectively. The results of the 28-day compressive strength data collected in this study indicate that the recycled aggregate concrete mixes (which are of the same mix design as the waste material concrete mix) outperform the waste material concrete mix in terms of average 28-day compressive strengths and rates of hydration. The three recycled aggregate mixes which contained 25%, 50% and 100% recycled aggregate all attained the design strength of 30MPa at 28 days, whilst the recycled aggregate mixes that contained 50% and 100% recycled aggregates both achieved the design strength at 14 days and surpassed the 30MPa mark at 28 days.

To elaborate on the implications of the statistical data presented in Table 5, Concrete Mix 2 (25% RA) needs to be examined. This concrete mix exhibited the least CS variance at 28 days old as compared to the waste concrete and the other two RAC batches. Also, the variance observed in the other RAC batches indicates that greater replacement percentages of RA can be used to produce RAC consistently attaining the set mix design

Table 3. Waste Concrete Cylinder Representative Compressive Strengths

Group – Waste Concrete Cylinders			
Sample ID	**Sample Age**	**Sample Compressive Strength/ MPa**	**Sample Description**
REP 1	28	39.00	Highest Value
REP 2	28	29.82	Average Value
REP 3	28	31.00	Most Occuring
REP 4	28	30.00	2nd Most Occuring
REP 5	28	29.00	3rd Most Occuring
REP 6	28	15.60	Lowest Value

Table 4. 28-Day Recycled Aggregate Compressive Strengths

Sample Age / Days	Sample ID And Compressive Strength / MPa						Average Compressive Strength / MPa
	Group – Recycled Aggregate Mix 2						
	RA$_{25}$25	**RA$_{25}$26**	**RA$_{25}$27**	**RA$_{25}$28**	**RA$_{25}$29**	**RA$_{25}$30**	
28	30.4	30.1	29.4	28.0	31.1	29.4	29.73
Sample Age / Days	**Sample ID And Compressive Strength / MPa**						**Average Compressive Strength / MPa**
	Group – Recycled Aggregate Mix 3						
	RA$_{50}$25	**RA$_{50}$26**	**RA$_{50}$27**	**RA$_{50}$28**	**RA$_{50}$29**	**RA$_{50}$30**	
28	38.3	36.6	34.5	34.7	34.1	35.4	35.60
Sample Age / Days	**Sample ID And Compressive Strength / MPa**						**Average Compressive Strength / MPa**
	Group – Recycled Aggregate Mix 4						
	RA$_{100}$25	**RA$_{100}$26**	**RA$_{100}$27**	**RA$_{100}$28**	**RA$_{100}$29**	**RA$_{100}$30**	
28	33.9	32.6	35.7	35.3	34.3	33.4	34.20

Table 5. Summary of Results of Analysis Performed for Compressive Strength Data of RAC vs Source Material

Twenty-Eight (28) Day Compressive Strength Statistical Data Analysis				
Groups	**Sample Count**	**P Value Bet. Groups (Significance = 0.01)**	**Average Compressive Strength**	**Variance**
Waste Material Concrete Cylinders	6	0.02	29.07	57.04
Recycled Aggregate Mix 2 (25% RA)	6	0.02	29.73	1.13
Recycled Aggregate Mix 3 (50% RA)	6	0.02	35.60	2.52
Recycled Aggregate Mix 4 (100% RA)	6	0.02	34.20	1.35

strength. Concurrently, the p-value observed between groups of data was less than the significance value of 0.01 used for analysis (see Figures 1 and 2). This suggests that the null hypothesis (assuming that there is no difference between the compressive strengths of the groups) can be rejected.

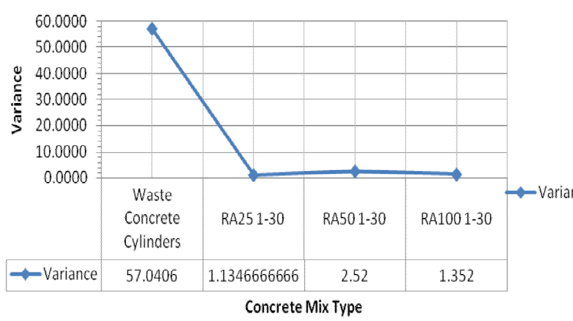

Figure 1. Variance of Waste Cylinder vs RAC cylinder 28-day Compressive Strengths

As a result of rejecting the null hypothesis, the percentage of recycled aggregate added to each concrete mix would affect the compressive strengths achieved as can be observed from the data collected for at the 28-day age break. Therefore, from the compressive strength results obtained and the statistical data calculated, it is very possible to reproduce, with very little variance, the design strength of the waste material concrete using the recycled aggregates produced from the very same waste concrete.

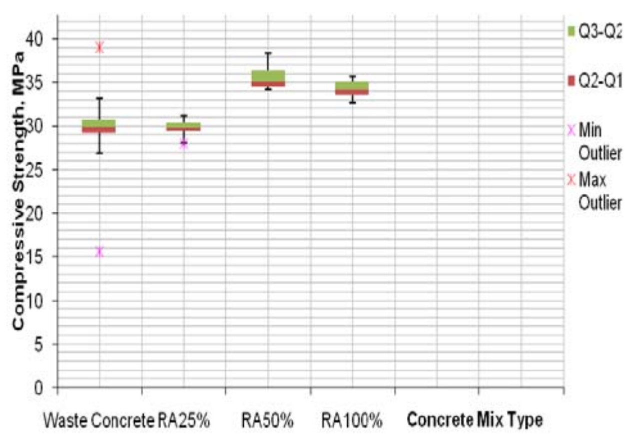

Figure 2. Variance of 28-day Waste Concrete and RAC Cylinder Compressive Strengths vs Concrete Mix Type

8. Conclusion and Recommendations

The data collected from the CS testing of RAC batches as compared to that of its waste material concrete show that RAC can indeed achieve the CS of it source material quite easily, with very little variance in strengths, and at times, surpass the CS of the original waste material. From the statistical analyses, the RAC batch with 25% replacement exhibited the least variance whilst the other two RAC batches also had very low variances when compared to the CS data set of the waste material.

The results of this study are supportive of the potential for reuse of CDW. However, it should be noted that this is an isolated, very controlled study where the waste material (tested 150mm concrete cylinders) was collected from a laboratory and the variability of the composition, mix and impurities presented in the waste material were negligible. Therefore greater research is needed to explore the effects of various sources of CDW in T&T and the differing properties of such materials on the properties of RAC.

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