Recycled Aggregates for Green Concrete

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Abstract

In this paper a Fuller and Thompson equation and gradation curves were applied to 100% Recycled Coarse Aggregates (RCA). A total of 300 samples of concrete made up 100% RCA were analysed and tested at 7, 14 and 28 days according to BS EN 12390-3, 2002. The average compressive strengths achieved for the Recycled Aggregates Concrete was approximately 83.0 mPa, the highest ever recorded compressive strength from the concrete manufactured using 100% recycled course aggregates.

Keywords: Recycled aggregates concrete, high strength, packing density

1.0 Introduction

Today there is impressive increase in the use of recycled concrete, but basically these recycled aggregates are used as fillers in road construction and in low-level applications due to impurities and defects associated with recycled aggregates.(Tu, *et al.* 2006). In analyzing research works done by Yehia *et al*. (2015), Sivakumar *et al*. (2014), Fennis and Walraven (2012), Motwani *et al*. (2013), Mwasha and Lalla (2011, Mwasha and Lalla (2012), Richarson *et al*. (2010), Fennis et al. (2009) Mwasha and Mark (2008), Movassaghi (2006), Shing Chai *et al*. (2004) and Limbachiya *et al*. (2000) it was found that all these authors agreed that many benefits which promote sustainability were offered from producing recycled aggregate concrete. Some of these benefits include reduction in the amount of natural aggregates required due to coarse recycled aggregate replacement and converting tons of building construction and demolition wastes from landfill. Despite the economic and environmental benefits of concrete produced with Recycled Concrete Aggregates (RCA) and steadily increased usage of the material, 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 (Mas *et al.,* 2012), Richardson *et al*. (2010), (Fathifazi, *at. el.* 2009) and (Katz, 2003). These authors have also concluded that Recycled Aggregate Concrete is lower than that of virgin aggregate concrete due to the occurrence of porous residual mortar coating the Recycled Aggregates.

This paper seeks to provide a solution to the construction industry for using Recycled Concrete Aggregates (RCA) in an efficient and sustainable manner to produce High Strength Recycled Aggregate Concrete (RAC) for use in high strength structural applications. To achieve these aims the three categories of aggregates were tested under laboratory conditions, natural aggregates (C1) as the control sample, High Strength Recycled Aggregates (C2) and Low Strength Recycled Aggregates (C3). The PPO methods based on Fuller and Thompson equation and gradation curves were applied to 100% Recycled Coarse Concrete Aggregates. A total of 96 samples were analyzed and tested at 7, 14 and 28 days according to BS EN 12390-3, 2002. The results showed that by applying PPO to recycled aggregates it is possible to achieve high strength concrete with compressive strengths above 80 MPa. This high compressive strength for RAC is rare and worth to explore more.

2.0 Materials, Equipment and tests
2.1 Equipment
- Hand tools - Sledge hammer, scoop, bowls, basins, buckets, trays, trowel, ruler, wheel barrow.
- Sieve stacks
- Concrete crusher
- Scale/balance
- Measuring cylinders
- Concrete mixer

- Slump tools – Slump cone, scoop, tamping rod.
- Metal cubes – 150m and 100mm
- Vibrating table
- Water bath
- Crushing machine

2.2 Materials
2.2.1 Aggregates Properties – Shape, texture, size, color.
The following gives a list of all the materials that were used in the manufacture of the concrete samples for testing.

- Natural aggregates - Guanapo Quartzite
- Recycled concrete (cylinder samples manufactured with Guanapo Quartzite)
- Premium Plus cement – This cement contains approximately 30% pozzolanic material and 70% OPC.
- Micro Silica
- Water
- Super-plasticizer (Conplast SP430)

2.2.2 Shape
The shapes of the aggregates were found to be noticeably different between the Natural Aggregates (N.A) and the Recycled Aggregates (R.A). The natural aggregates for this experiment were more rounded whereas the recycled aggregates were found to be more angular. This was due to the difference in the weathering process and manufacturing process. The natural aggregates would have gone through a weathering process (Mwasha 2012) whereas the recycled aggregates were only crushed with no environmental weathering process.

2.2.3 Texture
The textures of the natural aggregates were found to have smooth edges whereas the recycled aggregates had sharp edges. Squeezing the recycled aggregates in one's hand felt like spikes compared to the natural aggregates.

2.2.4 Color
Guanapo quartzite aggregates used in this work were extracted from a number of quarry sites in Valencia, Trinidad. Guanapo Quartzite is classified as a non-foliated metamorphic rock. This is probably because these rocks were once exposed to high temperature conditions, but not to high directional pressure conditions. The parent rock for the Guanapo quartzite was probably a quartz rich sandstone deeply buried and rising temperature fused the grains together forming highly strong aggregates with low porosity. These aggregates are highly weather-resistant making them excellent construction material. The Valencia quartzite tends to have a sugary appearance, and when broken, the fractures cut through the sand grains and not around them as with sandstone (Mwasha, 2009). The specific gravity of these aggregate was 2.65 and the moisture contents of approximately 2.25%. The recycled concrete was obtained from Ready Mix Trinidad in the form of cylinder samples of known compressive strengths. The low strength recycled aggregates were of a lighter grey when compared to the high strength recycled aggregates. This was due to the difference in the water cement ratios of the parent concrete.

Figure 1. Color, shape & size comparison between natural aggregates (cream in Color) and recycled aggregates (Grey in color)

2.2.5 Size

The different aggregate sizes were easily sieved from the natural aggregates, however for the recycled aggregates the crusher had to be adjusted until the desired sizes were achieved. Aggregate shape, texture, and grading have a significant effect on the performance of fresh concrete as postulated by Quiroga and Fowler (2004) and Mindess *et al*. (2005.It should be noted that the fine aggregates have a high water requirement due to their high specific surface area as suggested by several authors including Mindess *et al*. (2005) as well as Metha and Monteiro (2004).

2.3 Sieve Analysis

Sieve analyses were conducted on the three categories of aggregates i.e. the natural aggregates, the high strength recycled aggregates and the low strength recycled aggregates. The sieve analysis to obtain the required gradation was calculated according to Fuller distribution for the n = 0.45 power curve using a maximum size aggregate (d_{max}) of 19mm as shown in Figure 2 and highlighted in dash line. The Fuller equation 1 was applied to the selected particle sizes to obtain the percent passing each sieve as shown in table 1. The particle sizes selected were based on the similar research done by Jeenu *et al.* 2012.

$$ P_{(d)} = \left(\frac{d}{d\max} \right)^q \qquad\qquad 1 $$

$P(d)$ Size cumulative distribution function [-]
d Particle diameter being considered [m]
d max Maximum particle diameter in the mixture [m]
q Parameter (0.33-0.5) which adjusts the curve for fineness
or coarseness

In concrete aggregates act compositely in the combined state. Grading envelopes given in standards such as ASTM 33 when plotted as a combined grading curve often show deficiencies of certain particle sizes. These lead to gaps that represent less than ideal combined grading (Alexander and Mindess 2005). For this reason the Fuller distribution was chosen to achieve close to optimum combined aggregate grading.
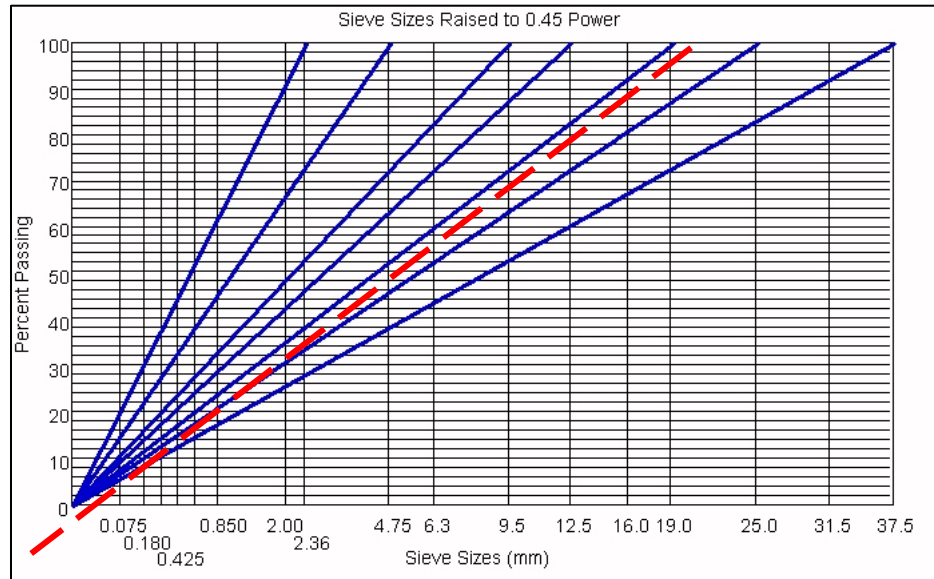

Figure 2. Maximum density curves for 0.45 Power gradation graph. (Roberts et al. 1996)

In order to pack particles of different sizes together the sieve analysis formed an integral part of the process. The gradation of the particles followed the Fuller and Thompson 1907 theory on optimum gradation to obtain high packing density using the Fuller Equation 1. Having applied the Fuller equation, the percent passing for each individual particle size is represented in the Table 1.

Table 1. Showing the percentage passing for each particle size according to the Fuller equation

Particle Size mm	Passing (decimal)	% passing
19.00	1.000	100.00
12.50	0.828	82.83
9.50	0.732	73.20
4.75	0.536	53.59
2.00	0.363	36.31
0.30	0.155	15.46
0.075	0.083	8.29

In conducting the initial sieve analysis on the coarse recycled aggregates the percent passing for the different sizes did not match the percent passing as calculated by the Fuller equation. In order to obtain close to the desired results different percentages of the particles sizes were used in a trial and error method until the closest match was obtained. Ideal grading is difficult to achieve in practice therefore using close to ideal and adjusting to ranges above and below the ideal curve gave better results, which was also identified by Alexander and Mindess (2005).

2.4 Packing densities
The overall objective of the sieve analysis exercise was to obtain a gradation of particles that when combined would give a densely compacted arrangement with little voids in accordance to the Fuller equation and grading curves. Therefore having attained close to what the Fuller distribution required, different percent combinations of coarse to fines aggregates were blended to achieve the highest packing densities. In this way it has been proven that the combination that conformed closest to the Fuller gradation (% passing) resulted in the combination of aggregates that had the highest packing density. The highest packing density increased consistently and progressively for the three categories of aggregates C1, C2 and C3. Natural aggregates (C1) as the control sample, High Strength Recycled Aggregates (C2) and Low Strength Recycled Aggregates (C3). It should be noted that the different percentage combination of various aggregates sizes are represented by M1 to M10. M1 to M10 are constant for all categories.

Based on the types and sizes of aggregates 10 different combinations of aggregates with varying proportions of each particle size were mixed to determine which combination would give the highest packing density. This method is similar to the one used by De Larrard and Sedran (1996 Table 2 gives the packing density results for all categories.
It was found in this study that as the coarse aggregate content increased towards 50 % there was a general increase in packing density observed for all categories of aggregates ranging from C1 to C3. This finding supports Jeenu *et. al.* (2012) who concluded that mixes with 30 – 50 % coarse aggregates resulted in mixes with higher packing densities. It was found that the packing density was better for the natural aggregates followed by the high strength recycled and then the low strength recycled aggregates. The aggregate descriptions and their average packing densities are given in Table 3.

The mixes in each category that gave the highest packing densities were C1M5, C2M5 and C3M5 as shown in table 3. This has proven that the gradation according to the Fuller distribution resulted in the mix with the highest packing density. The M5 combination gave 50% coarse aggregates and 50% fines aggregates with, 5% - 19mm, 15% - 12.5mm, 13% - 9.5mm, 17% - 4.75mm and 50% fine aggregate. It should be remembered that uniform grading with proper amounts of each size result in aggregate blends with high packing and in concrete with low water demand. Optimized aggregate blends have high packing, requiring low amounts of paste. As a result, they are less expensive and will have less durability problems caused by the paste such as heat generation, porosity, and drying shrinkage (Quiroga and Fowler 2004.

2.5 Coarse aggregate content, mix type and packing density
When analyzing the packing density in comparison to the coarse aggregate content it was found that the general trend was an increase from M1 to M5 and then a decrease for M6 to M10 in all categories (C1-C3)
For the natural aggregates (C1) there was an anomaly observed for C1M4 where a sudden dip in the packing density was observed from 76.4 to 71.8, this is shown in table 2, otherwise the same general trend is observed.
For the Low strength recycled aggregtaes dips in the packing density were observed for C3M2 to C3M4, otherwise the same general trend was observed shown in Table 2. Most likely the sudden drop in packing density before attaining highest packing density was induced by the loosening effect and as the amount of course aggregates increase the wall effect is triggered. The wall effect might have been triggered as the course aggregates increase more than 50%.

Table 2. Showing mixes, % particle sizes and related packing density

Mix - Catergory 1, Natural aggregates	Percentage of Particle sizes					Coarse aggregate content (%)	Packing density (%)
	19.00	12.50	9.50	4.75	2.00-.075		
C1M1	0	10	10	10	70	30	74.5
C1M2	5	10	10	10	65	35	76.4
C1M3	5	10	15	10	60	40	76.4
C1M4	0	15	13	17	55	45	71.8
C1M5	5	15	13	17	50	50	78.3
C1M6	10	15	15	10	50	50	76.9
C1M7	10	25	10	10	45	55	74.2
C1M8	10	20	15	15	40	60	70.5
C1M9	10	20	25	10	35	65	70.4
C1M10	15	20	20	15	30	70	69.2

Mix - Catergory 2, High strenght recycled aggregates	Percentage of Particle sizes					Coarse aggregate content (%)	Packing density (%)
	19.00	12.50	9.50	4.75	2.00-.075		
C2M1	0	10	10	10	70	30	71.80
C2M2	5	10	10	10	65	35	72.80
C2M3	5	10	15	10	60	40	75.10
C2M4	0	15	13	17	55	45	74.90
C2M5	5	15	13	17	50	50	76.60
C2M6	10	15	15	10	50	50	76.00
C2M7	10	25	10	10	45	55	74.00
C2M8	10	20	15	15	40	60	74.40
C2M9	10	20	25	10	35	65	73.10
C2M10	15	20	20	15	30	70	69.20

Mix - Catergory 3, Low strenght recycled aggregates	Percentage of Particle sizes					Coarse aggregate content (%)	Packing density (%)
	19.00	12.50	9.50	4.75	2.00-.075		
C3M1	0	10	10	10	70	30	73.80
C3M2	5	10	10	10	65	35	72.60
C3M3	5	10	15	10	60	40	70.40
C3M4	0	15	13	17	55	45	71.50
C3M5	5	15	13	17	50	50	74.30
C3M6	10	15	15	10	50	50	71.50
C3M7	10	25	10	10	45	55	71.00
C3M8	10	20	15	15	40	60	71.00
C3M9	10	20	25	10	35	65	69.50
C3M10	15	20	20	15	30	70	69.10

Table 3. Aggregates category and its average packing density

Aggregate Category	Aggregates descriptions	average packing density
C1	Natural aggregates	73.9
C2	High strength recycled	73.8
C3	Low strength recycled	71.5

3.0 Effect of packing density on the Concrete density and the Compressive Strengths
3.1 The effects of water/cement ratio on the properties of the N.A/H.S.R.A/L.S.R.A Concrete.
Many important characteristics of concrete are influenced by the ratio (by weight) of water to cementitious materials used in the mixture. By reducing the amount of water, the cement paste will have a higher density, which results in higher paste quality. An increase in paste quality will yield higher compressive and flexural strength, lower

permeability, and increase resistance to weathering, improve the bond of concrete and reinforcement, reduce the volume change from drying and wetting, and reduce shrinkage cracking tendencies (PCA, 1998).

The concrete mix design used carried a very low water cement ratio of 0.23 and hence the above paragraph characterizes the properties of the concrete produced. The average density of concrete with NA under normal circumstances is 2400kg/m^3 however densities of 2592kg/m^3 were recorded after 28 days.

Another factor that impacts on concrete density is the pozzolanic material. The utilization of pozzolanic materials (micro silica in this case) in high-strength concrete leads to a reduction of the size of the crystalline compounds, particularly, calcium hydroxide, whereby increasing the particle size distribution. Consequently, there is a reduction of the thickness of the Interfacial Transition Zone (ITZ) in high-strength concrete. The densification of the interfacial transition zone allows for efficient load transfer between the cement mortar and the coarse aggregate, contributing to the strength of the concrete. For very high-strength concrete where the matrix is extremely dense, a weak aggregate may become the weak link in concrete strength (Metha and Monteiro 2004). From the density results obtained the micro silica did have the effect as described above.

Table 4. Average densities for different concrete types over time

Curing time	Densities/Kg/m^3		
Days	L.S - R.A	H.S - R.A	N.A
7	2454.20	2460.50	2552.60
14	2453.50	2455.00	2565.50
28	2390.81	2448.74	2592.15

As shown in table 4 the NAC carried the highest density followed by the HSRA concrete and then the LSRA concrete. The trend observed for the NAC was an increasing density from 7 to 28 days, however the opposite was observed for the RAC's.

Brown (2002) cited by Richardson *et al.* (2010) have concluded that the density of RAC is lower than that of virgin aggregate concrete due to the occurrence of porous residual mortar coating the RA, which the results above conforms to and is observed that for all categories of recycled aggregates. The lowest average 28 day sample density was recorded for the LSRA concrete as 2390kg/m^3, which is very close to the 2400kg/m^3 for regular concrete.

Figure 3 shows the density of the three categories of concrete plotted against the curing time recorded at 7, 14 and 28 days. For the NAC, density was found to increase with curing. This means that the hydration during the curing process allowed water to soak into the paste over time making it denser as the paste cured.

For the RAC the density was found to decrease with curing. This means that water was being expelled. One explanation for this phenomenon is that the water absorbed into the RA during mixing was sucked out as the paste over it cured with time. So initially the old mortar paste would suck water because of its high absorption capacity however when the new cement paste begins to cure, the water absorbed in the old mortar paste aids the new mortar paste during curing as the water is used in hydrating the new mortar paste, which accounts for the reducing density as it cures.

3.2 Compressive strength results

The compressive strengths results achieved were very positive for all categories of aggregates. Compressive strengths for all samples were recorded at 7, 14 and 28 days. Table 5 gives the summary of these results. Compressive strength tests were carried out according to BS EN 12390-3, 2002. The compressive strength trend observed is a general increase from 7 to 28 days during curing for all categories. This is the expected behavior of the concrete during curing.
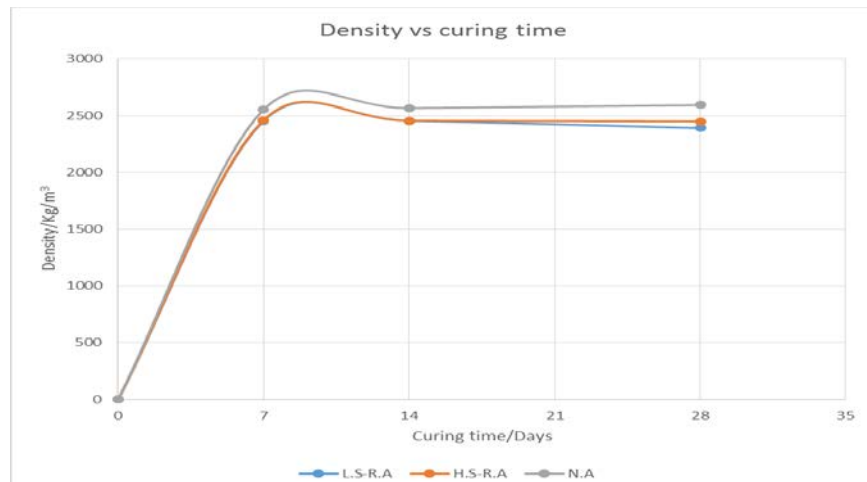
Figure 3. The average density of the concrete produced over time, for all categories

Table 5. Showing compressive strength results of sample

Mix - Category 1, Natural aggregates	Percentage of Particle sizes					Packing Density (%)	7 Day Compressive strength (MPa)	14 Day Compressive strength (MPa)	28 Day Compressive strength (MPa)
	19.00	12.50	9.50	4.75	2.00 - 0.075				
C1M1	0	10	10	10	70	74.5	66.50	91.00	98.67
C1M2	5	10	10	10	65	76.4	59.00	80.00	85.78
C1M3	5	10	15	10	60	76.4	86.00	76.00	84.44
C1M4	0	15	13	17	55	71.8	72.00	81.50	80.00
C1M5	5	15	13	17	50	78.3	79.50	91.00	85.56
C1M6	10	15	15	10	50	76.9	85.00	80.00	73.33
C1M7	10	25	10	10	45	74.2	80.50	82.50	80.00
C1M8	10	20	15	15	40	70.5	78.00	83.50	99.11
C1M9	10	20	25	10	35	70.4	66.00	67.50	106.22
C1M10	15	20	20	15	30	69.2	77.00	79.00	80.00

Mix - Category 2, High strength recycled aggregates	Percentage of Particle sizes					Packing Density (%)	7 Day Compressive strength (MPa)	14 Day Compressive strength (MPa)	28 Day Compressive strength (MPa)
	19.00	12.50	9.50	4.75	2.00 - 0.075				
C2M1	0	10	10	10	70	71.80	65.50	83.50	71.56
C2M2	5	10	10	10	65	72.80	59.50	75.00	75.56
C2M3	5	10	15	10	60	75.10	63.00	73.50	82.67
C2M4	0	15	13	17	55	74.90	77.00	79.00	74.22
C2M5	5	15	13	17	50	76.60	57.50	67.50	81.78
C2M6	10	15	15	10	50	76.00	71.50	75.50	78.67
C2M7	10	25	10	10	45	74.00	53.50	81.50	82.67
C2M8	10	20	15	15	40	74.40	76.00	78.00	81.11
C2M9	10	20	25	10	35	73.10	64.50	70.00	74.44
C2M10	15	20	20	15	30	69.20	51.00	63.50	62.67

Mix - Category 3, Low strength recycled aggregates	Percentage of Particle sizes					Packing Density (%)	7 Day Compressive strength (MPa)	14 Day Compressive strength (MPa)	28 Day Compressive strength (MPa)
	19.00	12.50	9.50	4.75	2.00- 0.075				
C3M1	0	10	10	10	70	73.80	63.00	66.50	73.11
C3M2	5	10	10	10	65	72.60	67.50	57.00	76.67
C3M3	5	10	15	10	60	70.40	56.00	64.50	76.89
C3M4	0	15	13	17	55	71.50	48.00	59.50	58.89
C3M5	5	15	13	17	50	74.30	52.00	64.00	65.78
C3M6	10	15	15	10	50	71.50	55.50	57.50	61.56
C3M7	10	25	10	10	45	71.00	61.00	64.50	61.56
C3M8	10	20	15	15	40	71.00	53.00	54.50	55.56
C3M9	10	20	25	10	35	69.50	43.00	30.00	57.11
C3M10	15	20	20	15	30	69.10	48.50	52.00	58.44

The maximum compressive strengths achieved for C1, C2 and C3 were 106.22Mpa, 82.67Mpa and 76.89Mpa respectively as shown in table 6.

3.2.1 Compressive Strength and curing time relationship for Recycled Aggregate Concrete

Figure 4 shows the relationship between the RAC average compressive strengths and the curing time after 7, 14, and 28 days. The results show that there is a continuous increase in compressive strength as the concrete cures over the 28 day period. It was observed that the high strength recycled aggregates (C2) produced concrete with higher compressive strengths. This was due to the stronger mortar paste (higher quality recycled aggregate) coating of the C2 aggregates which was able to resist more loading before failure hence resulting in higher compressive strengths. This proves that the strength of the RAC is dependent on the parent concrete strength and by extension the strength of the old mortar paste as discussed above   (Refer to appendix 5 for calculation sheet).
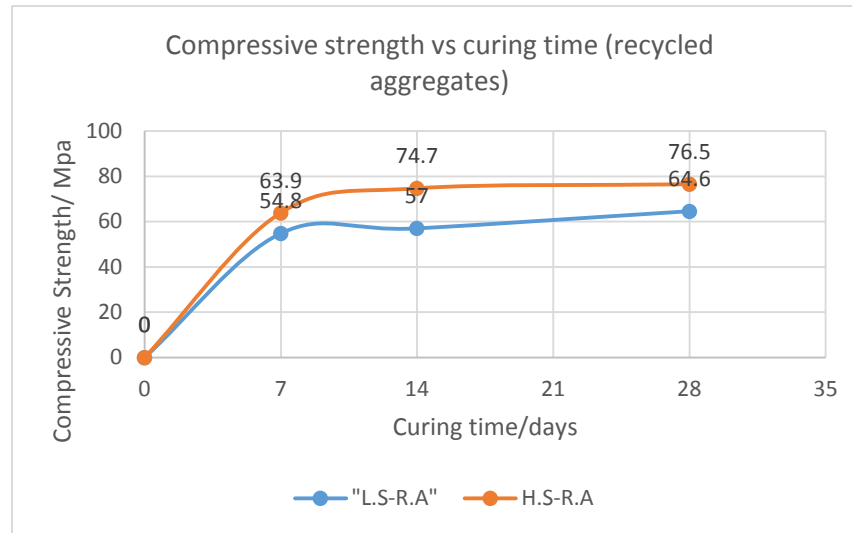

Figure 4. Average compressive strength against curing time for the recycled aggregates

3.2.1 Ratio of Compressive Strengths (Natural Aggregate Concrete compressive strength to Recycled Aggregate Concrete compressive strengths)

This ratio was done to show the difference in strength gains when comparing the NAC gains to the RAC gains. The NA in all cases produced concrete with the higher compressive strengths followed by the high strength and then the low RA. The ratio of the NAC's average compressive strengths to the RAC's average compressive strengths after 7, 14 and 28 days is shown in the figure 5. For the Low strength RAC a maximum difference of 42 % in compressive strength is recorded in relation to the NAC. This means that the NAC was 42% stronger in compressive strength at 14 days however after 28 days it was reduced to 35 %. This is in accordance with the trend of previous research where the average compressive strength reduction for RAC is within 30 % – 40 % when using LSRA (Yehia *et al*. 2015). For the high strength RAC a maximum difference of 17% is recorded, which means that the NAC was only stronger by 17% at 7 days and reduced to 14% after 28 days

These results show that the NAC had higher earlier strength gains than the RAC due to the slower water absorption process from the RA during curing, which is in accordance with the finding of Shing Chai (2004). The general trend observed was a reduction in strength difference with curing time. This shows that the RAC strength gains are slower when compared to NAC. This means that higher strengths are possible beyond 28 days for RAC as it continues to gain strength reducing the gap towards the NAC. It is hypothesized that the RAC would have greater strengths gains beyond the 28 days when compared to the NAC.
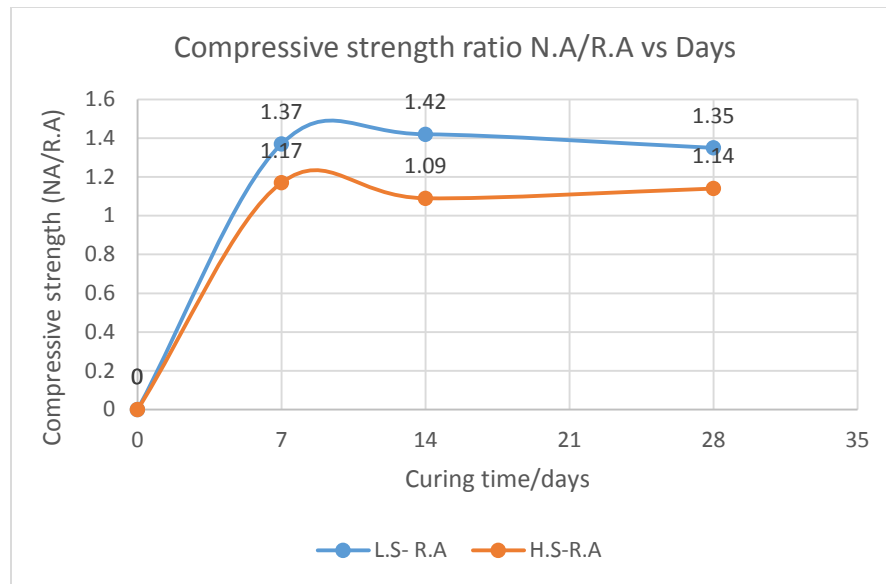
Figure 5. Compressive strength ratio of natural aggregate concrete to recycled aggregate concrete

3.2.2 Ratio of Compressive strength to Density

The Compressive strength to density ratio was done to analyze weight to strength relationship. A light weight concrete with high compressive strength at an econnoimical cost would be highly desirable by the construction industry. The compressive strengths obtained for the RAC were high and the densities were lower than the NAC.
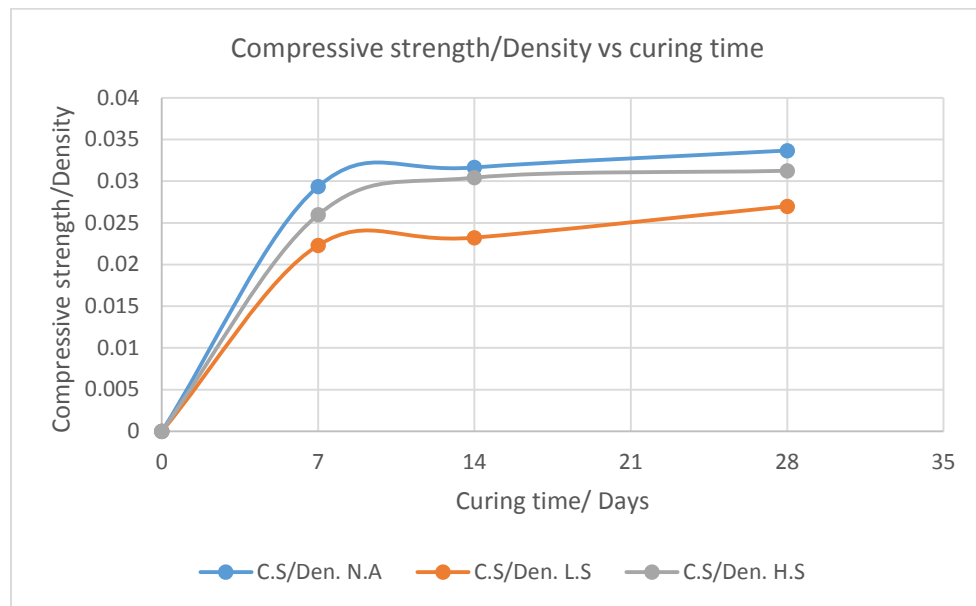

Figure 6. The compressive strength to density ratio for the different concrete types

If the values obtained for the compressive strength to Density ratio were greater for the RAC it would confirm that this type of concrete is better when it comes to the strength density relationship, however the NAC proved to maintain the better properties with higher ratio values as shown in Figure 6. It was also observed that, the Compressive Strength/Density ratios over time for 7, 14 and 28 days for the different types of concrete manufactured, the NAC maintained the highest ratios followed by the HSRA and then the LSRA. However there was a minor gap between the ratios for the NAC and the HSRA concrete with very similar ratios after 14 days.

Table 6. Average and maximum compressive strength for the different aggregate categories (C1-C3

Aggregate Category	Average compressive strength / (mpa)			Maximum compressive strength attained / (mpa)
	7 days	14 days	28 days	
Category 1, Natural aggregates	74.95	81.2	87.31	106.22
Category 2 , High strength recycled aggregates	63.90	74.70	76.53	82.67
Category 3 , Low strength recycled aggregates	54.75	57.00	64.56	76.89

This comparison shows when RAC is manufactured with high strength RA some properties of the concrete produced is not much different from the concrete manufactured using NAC. These properties are compressive strength and density relationship. The average 28 day compressive strengths achieved by all aggregate categories are well over 40 MPa. The original strength of the C2 concrete was 40-45Mpa the average strength achieved for the RAC produced is 76.53Mpa, this shows an approximate increase of 31Mpa.

Similarly the C3 aggregates (25-30Mpa) resulted in an approximate increase in compressive strength of 34Mpa for its original compressive strength. The results show that whether using LSRA or HSRA, RAC of high compressive strengths can be achieved.

The NA performed as expected since similar maximum compressive strength results (111MPa) were obtained by Jeenu *et al*. (2012), when a similar methodology was applied, but only to NA using the same high performance concrete mix design.

The results for the RAC are quite impressive, since achieving these high strengths are not very common. The results show that as early as 7 days the compressive strength to qualify the concrete as high strength were already achieved. Not even one of the samples in the low strength category (C3) was below 40Mpa after 7 days. The average 28-day compressive strength for RAC (C2 & C3) was found to be 70.5Mpa.

4.0 Investigation the effects of Recycled Aggregates sizes on the absorption of moisture

In order to understand the effects of RA sizes on the absorption of moisture, three different sizes of aggregates namely 9.0, 12,5 and 20 mm were weighed dry and then soaked for 1, 60 and 1440 minutes. The moisture content was calculated as postulated in AASHTO T 85 and ASTM C 127: Specific Gravity and Absorption of Coarse Aggregate
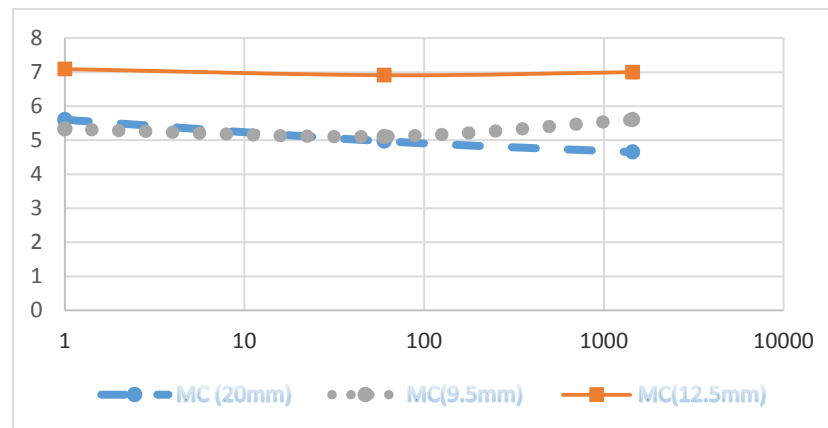

Figure 7. Water absorption of the aggregates

As shown in figure 7 all particles absorbed water instantly. It seems the long term soaking of aggregates has no effect on the amount of moisture absorbed. It was also observed in this research that the absorption of water varied with the

particle sizes. Particles 12.5 mm and 9,5 mm had approximately the same water absorption capacity however 20 mm absorbed almost 40% more moisture content. The most likely reasons are that 20 mm aggregates contained a large portion of hardened mortar which absorbs more water compared to particles 12.5 and 9mm.

. **4.1 Workability**

The workability of the concrete produced was measured by conducting slump tests that are presented in the figure 8. In this study it was found that the water absorption in aggregates was time dependent and has impact on the workability of the fresh concrete. This observation was done by comparing the soaked and un-soaked RCA.The results showed that the slump for the soaked aggregates were lower than the slump for the un-soaked aggregates. The most likely reason for this is because with the soaked aggregates there was no additional free water available to assist with the workability (only mixing/hydrating water was added at mixing, the absorption water was already contained in the soaked aggregates). Whereas for the un-soaked aggregates the absorption of water (free water) assisted with the workability since the water was not absorbed instantaneously at mixing but rather it took some time. This delayed absorption of water was most likely due to the effectiveness of the recycled aggregates porosity. Further it can be explained that the pores in cement paste surrounding recycled aggregates have more closed porosity and less free and active porosity. The effective porosity depends on the specific surface area, the viscosity of the pore water in the cement paste and its hydraulic conductivity. The other reason for the delayed absorption of moisture could be caused by the higher surface area of the cement mortar compared to the course aggregates which delayed in the lubrication or absorption of pore water.
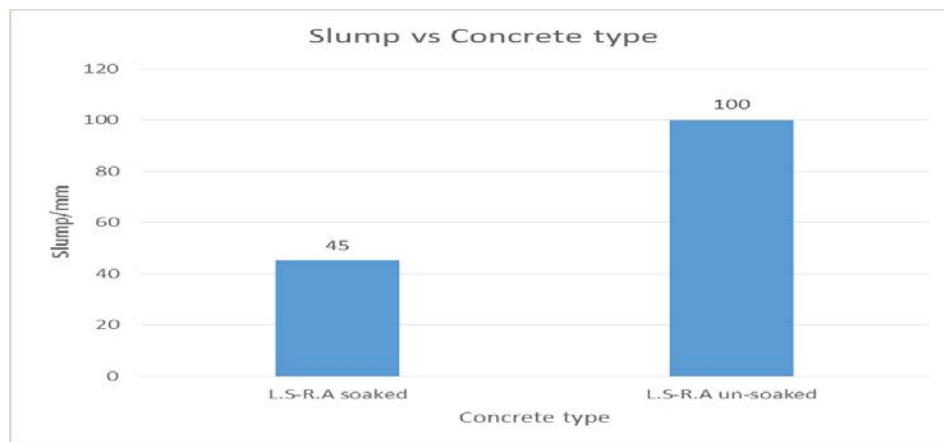

Figure 8. Showing the slump for soaked and un-soaked LSRA

These results are contrary to finding of Gonzalez *et al*. (2004) who also cited Poon *et al*. (2004) where they both recorded higher slumps for mixes with soaked RA. The reason for the difference in their findings compared to this research is that, the overall water in the mixes increased with the increase of the saturated RA hence with more water in the mix the slumps recorded were higher. In summary when RA are pre-soaked concrete compressive strength is increased due to long term transformation of Ca(OH)2 into Calcium Silicate hydrate (CSH) at the Interfacial Transition Zone (ITZ) on presence of latent hydraulic cement and extra water from the moist soaked aggregates.

4.2 Compressive strengths

 Table 7 shows the 7 and 28 day compressive strengths achieved for these samples.

Mix - Category 3, Low strength recycled aggregates	Percentage of Particle sizes					Coarse aggregate content (%)	7 Day Compressive strength (MPa)	28 Day Compressive strength (MPa)
	19.00	12.50	9.50	4.75	2.00- 0.075			
C3M5	5	15	13	17	50	50	52.00	65.78
C3M6	10	15	15	10	50	50	55.50	61.56
C3M5s	5	15	13	17	50	50	53.00	65.78
C3M6s	10	15	15	10	50	50	57.50	74.00

Table 7: showing the 7 and 28 day compressive strengths for the soaked and un-soaked recycled aggregate concrete samples

The results in table 7 shows that there was an increase in compressive strengths both at 7 and 28 days, for the concrete samples produced from the soaked aggregates. The increase after 7 days is by 1 and 2 MPa for C3M5s and C3M6s respectively. After 28 days the C3M5s gave the same compressive strength as C3M5 whereas C3M6s was higher than C3M6 by approximately 13MPa. From these results it can be concluded that soaking the RA prior to concrete manufacture results in concrete with higher compressive strengths. The reason for this is reported by Motwani *et al.* (2013), where the internal moisture provided by the soaked aggregates is better able to assist with the curing of the new cement paste creating stronger bonds between the particles.

This means that even though additional water is added to cater for the absorption capacity of the aggregates during mixing as in C3M5 and C3M6, it is possible that not all of the additional water is absorbed by the aggregates, therefore increasing the w/c ratio by some degree, weakening the cement paste. By pre-soaking the aggregates for at least 24 hours ensures that the absorption capacity of the aggregates are fully satisfied (optimum moisture status is reached) and the w/c ratio is not increased. These results are depictive of this since there is only a marginal increase in compressive strength.
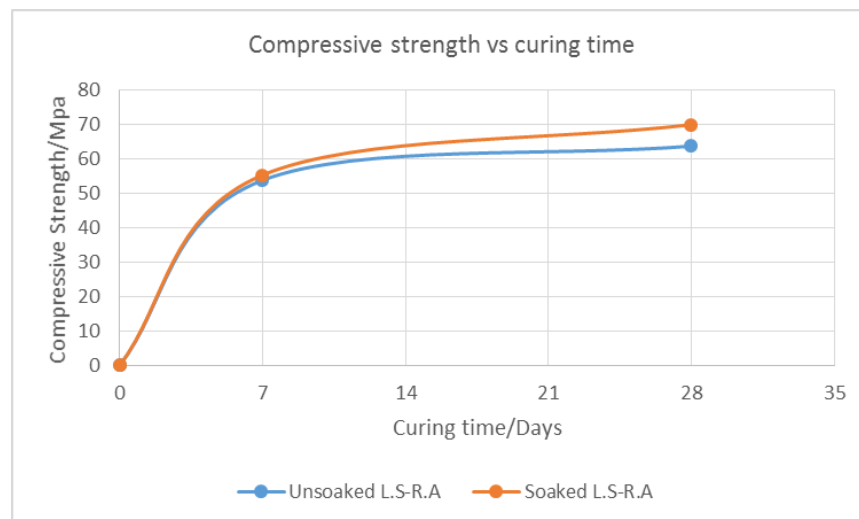

Figure 14: showing the average compressive strength for soaked and un-soaked RA plotted against curing time

Figure 14 shows the average compressive strength for the concretes with soaked and un-soaked RA plotted against the curing time. The results reflect although no significant increase in compressive strength, that the compressive strength for the soaked aggregates is higher (Refer to appendix 5 for calculations).

These findings are opposite to Gonzalez *et al.* (2014) who also cited Mefteh *et al.* (2013) where they both found that when aggregates are pre-soaked the compressive strengths are reduced. The reason for their findings is because the water absorbed in the RA was not considered as additional water. The aggregates having been soaked and with test mixes of increasing RA content, the overall amount of water in the mix increased since the mixing/hydrating water added remained the same despite the increase in saturated RA. With increase in the overall amount of water in the mix it increases the w/c ratio and hence weakens the mix, resulting in lower compressive strengths, hence the reason for their findings. If the mixing/hydrating water was reduced as the saturated recycled aggregate content increased

then the w/c ratio would be maintained and higher compressive strengths would be expected for the saturated aggregate mixes.

The water absorption capacity must be considered for the RA and the total overall amount of water in the mixes must be the same, i.e absorption water and mixing/hydrating water, when comparing mixes with dry RA against mixes with saturated surface dried RA. This was considered in the experiments for this research project, where additional water was added to the original w/c ratio content for mixes with dry recycled aggregates to cater for their water absorption capacity, whereas the original water cement ratio was maintained for the mixes containing the soaked RA.

There were no trends observed to confirm that the saturated particles resulted in better packing density or resulted in samples of higher concrete density.

Table 8: Different studies and the associated compressive strengths

Study/Paper	Author/s	Max. Compressive strength recorded /Mpa
Strength and durability evaluation of recycled aggregate concrete	Yehia et al. 2015	52
Experimental studies on High strength concrete using Recycled concrete aggregates	Sivakumar et al. 2014	37
High Strength concrete using recycled aggregates	Motwani et al. 2013	41
Analysing the strength parameters of concrete using natural and recycled Guanapo quartzite	Mwasha and Lalla. 2012	35
Concrete with crushed graded and washed recycled construction demolition waste as a coarse aggregate replacement	Richardson et al. 2010	28.7
Potential for the use of Recycled aggregates in Trinidad and Tobago	Mwasha and Mark. 2008	58.9
Durability of concrete incorporating Recycled aggregates	Movassaghi 2006	50.1
High Strength Structural Concrete with recycled aggregates	Shing Chai et al. 2004	48.1
Use of recycled concrete aggregates in high strength concrete	Limbachiya et al. 2000	74

Most researchers shown in Table 8 have observed the general trend in reduction of the compressive strength with increase in the RA percent. However in this paper 100% recycled coarse aggregates were utilized and the results obtained have surpassed the trend, that when using 30-40% RA replacement, only can high compressive strengths be maintained.

4.0 Conclusions and Recommendations

This paper has demonstrated that recycled aggregates can be used to manufacture high strength concrete. Using high strength concrete manufactured using recycled concrete aggregates promotes sustainability this is because it is environmentally friendly and the landfills are relieved from concrete debris as well as both embodied energy and embodied pollution is reduced.

The aim of this paper was set out to determine whether by applying particle packing optimization to recycled concrete aggregates and pre-soaking duration of the recycled aggregates would result in high strength concrete. It was found in this paper that gradations calculated according to the Fuller equation results in an aggregate combination with highest packing density. Having graded the natural and recycled aggregates according to the Fuller and Thompson (1907) equation/gradation charts has proven to result in an aggregate combination that carried the highest packing density when compared to combinations above and below this gradation curve. It was found that natural aggregate concrete produced the highest compressive strengths (106.2 MPa) followed by the HSRA concrete (82.7 MPa) and then the LSRA concrete (76.9MPa). These results are superior to those obtained from the published research on using recycled aggregates as shown in Table 7. The high compressive strength might have been induced about by the utilization of micro silica. Micro silica like other pozzolanic materials leads to a reduction of the size of the crystalline compounds, particularly, calcium hydroxide, consequently, there is a reduction of the thickness of the Interfacial Transition Zone (ITZ) in high-strength concrete. The densification of the interfacial transition zone allows for efficient load transfer between the cement mortar and the coarse aggregate, contributing to the strength of the concrete. For very high-strength concrete where the matrix is extremely dense, a weak aggregate may become the weak link in concrete

strength (Metha and Monteiro 2004). From the density results obtained the micro silica did have the effect as described above.

4.1 Recommendations
4.1.1 Recommendations for future research work

- A major factor to be taken in account is how particles of different shapes (recycled aggregate particles) interface with the bonding mortar paste between them. This would be a step closer in understanding the true in depth relationship between particle packing and compressive strength, hence it is recommended that further research be done in this area.

- It was found that the rate at which water absorption takes place during mixing of the RAC is slower than expected leaving free water available to aid in workability. An investigation into how this water is absorbed is also recommended in determining whether the w/c ratio of the mix is increased resulting in a lower mortar paste quality lowering the concretes' compressive strength.

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Biography

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