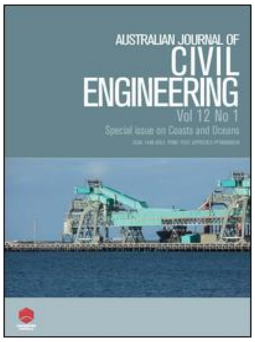

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ARTICLE

Marble waste and recycled concrete aggregates in self compacting concrete (SSC): an evaluation of fresh and hardened properties

Olatokunbo Ofuyatan, Olatokunbo Ofuyatan, Kayode-Thomas Enoch, Oluwafuminiyi Ogundeji and David Omole

Department of Civil Engineering, College of Engineering, Covenant University, Ota, Lagos, Nigeria

ABSTRACT
Abundant waste is being generated in the demolition or renovation in the construction industry. Improper disposal of this waste creates environmental concern as they form huge landfills without proper use. This study examined the fresh, hardened, durability, and microstructural analysis of self-compacting concrete made with recycled aggregates (RA) and marble waste as a 10–30% granite substitute. Slump flow test, T50cm test, V-funnel test, and L-box test were conducted on the fresh concrete. Compressive strength, split tensile strength, flexural strength, microstructural properties, and carbonation of the hardened concrete were determined. The physical tests revealed that though the recycled aggregates and marble waste do not have properties as good as the natural coarse aggregates, recycled aggregates were observed to exhibit a better strength than marble waste. SCC with marble waste had better fresh state properties than those with recycled aggregates. SCC with recycled aggregates had better-hardened state properties than those with marble waste. It can be inferred from the microstructural analysis that the utilisation of partial granite replacement improved the interaction between the concrete constituents. However, the sample with recycled aggregate was still better than that with marble waste in this regard.

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KEYWORDS
Recycled aggregate; self-compacting concrete; marble waste; properties

1. Introduction

The infrastructure and construction industry is a vital sector in the development of any country. The construction industry has experienced an enormous collapse of buildings in recent times, particularly in Nigeria. About 235 cases have been reported between 2007 and 2020 (The conversation). The construction and infrastructure summit group reported the country loses between 2.03tn and 3.05 tons annually to an infrastructure deficit. Old dilapidated dwelling units needed to be demolished due to restructuring, planning, and population growth. This further added to the generation of waste in renovation and demolition which is a growing concern. The housing sector needed to demolish old dilapidated structures due to restructuring, planning, and development of new facilities in some parts of my country. This further increased the demolition/renovation waste that was normally used as landfills which have generated concern. Figure 1 shows the percentage of waste produced yearly. Waste minimisation and efficient waste management is the most pressing issue in most developing countries (Aruntas et.al., 2010). The recycling of construction and demolition waste C&DW provides energy savings by reducing the blasting processing of huge rocks to produce the waste (Ismail and Ramli 2013)). Marble is used for aesthetics and decoration for the interior and exterior parts of a building. It forms 70% of finishes in buildings and the waste been generated is dumped illegally. Some used to patch potholes on roads in my country creating wear and tear on tires, and some are returned to the factories for recycling. Previous works have used marble waste as dust but there are limited studies on its recycling and reuse. (Terzi and Karas¸ 2003; Gazi et al., 2012). Marble wastes are the by-products generated from industrial processes. They can be generated during marble quarrying and marble processing (Tunc 2019). The waste generated from these processing leads to the pollution of the environment when not properly discarded or utilised. Both recycled concrete aggregates and marble waste were considered in the current paper.

Self-compacting concrete (SCC) is an innovative type of concrete undergoing consolidation owing to its weight (Brouwers and Radix 2005; Rantung, Supit, and Nicolaas 2019) and it fills the formwork reaching complete compaction without the need for internal vibration even when the formwork is congested with reinforcements (Ofuyatan and Edeki 2018a; Ofuyatan et al. 2019). Self-compacting concrete offers a rapid rate of concrete placement and hence faster construction time. It eliminates the issues of noise pollution encountered while using a machine for compactions

CONTACT Olatokunbo Ofuyatan olatokunbo.ofuyatan@covenantuniversity.edu.ng Department of Civil Engineering, College of Engineering, Covenant University, Ota, Lagos, Nigeria

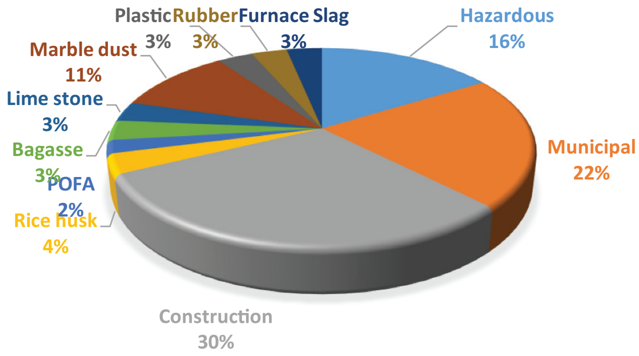


Figure 1. Waste been generated Source: Waste management, Ota.

(Sasanipour, Aslani, and Taherinezhad 2019). SCC offers a very high level of homogeneity; minimises concrete void spaces and has uniform concrete strength and also offers superior finishing rates and structural durability (Bauchkar and Chore 2014; Okamura and Ouchi 2003). SCC also exhibited the same engineering features and toughness as vibrated concrete (Ofuyatan and Edeki 2018b). The use of SCC has become more commonly accepted in recent years (Panda and Bal 2013). SCC allows for the use of recycled aggregates in concrete without causing major mechanical property degradation in the short and long term. (Manzi, Mazzotti, and Bignozzi 2017; Mastali and Dalvand 2016 ; Demirel Bahar 2010).

Using crushed concrete or Recycled Concrete Aggregate (RCA) has been evidenced particularly to be suitable for high-performance concrete, from the experimental research works studied and tests carried out (Mohammed Omrane) and some overviews of normal concrete manufactured with RCA interpreting the fresh state () (Revilla et al 2020). The compressive strength (Abhishek 2020)), mechanical performance (Behera, Minocha, and Bhattacharyya 2019), durability (Kanish Kapoor, Singh, and Singh 2016), and use of fine RCA behaviour (Kou and Poon 2009). Generally, aggregates occupy 70–80% of the concrete volume and have a significant impact on their characteristics (Mistri et al. 2020) and (Pan et al. 2019). They are granular materials, mostly obtained from natural rock (crushed stone or natural gravel) and sand (Tuladhar, Marshall, and Sivakugan 2020). Besides their use as economical filler, aggregates usually provide better dimensional stability and wear resistance to concrete. Recycled aggregate is materials derived from the processing of concrete previously used in the construction industry (kumar et al 2020)(Mistri et al. 2020) and (Faraj et al 2019). The strength of the recycled aggregate is generally lower compared to that of the natural aggregate and it also has higher water absorption hence making the use of this material is scarce (Pliya et al. 2019) and (Bahrami et al 2019).

This research aims to determine the properties of self-compacting concrete made with recycled aggregates and marble waste as a partial substitute for granite in both fresh and hardened states. Slump flow test, T50cm test, V-funnel test, and L-box test were conducted on the fresh concrete. Compressive strength, split tensile strength, flexural strength, and microstructural properties of the hardened concrete were determined. The importance of this study is justified as it helps to provide information on the properties that will be exhibited by the SSC incorporating recycled aggregates and marble waste. This will reduce the need/pressing demand for the excavation of the naturally occurring aggregate and foster waste utilisation (Guo et al. 2020). These are fundamental approaches that would help create a more sustainable environment.

2. Research significance

According to the results, the use of marble wastes and recycled aggregates from construction demolition sites can provide advantages in the sustainable use and application of self-compacting concrete for the sustainability of buildings and the environment in some Nigerian regions.

3. Methodology

3.1. Materials

Ordinary Portland limestone cement (Dangote cement of grade 42.5 r, (Nigeria) was used for this study conforming to ASTM C150.1 /C150M-20, and the qualities are presented in Table 1. The coarse aggregate used was granite of size 20 mm in accordance with ASTM C33 for coarse aggregate. For the fine aggregate, ASTM C136 standard for particle size 0–5 mm sieve analysis was used. Its function is to fill the voids that exist in the pore structure usually next to the coarse aggregate. The recycle aggregate used shown in Figure 2a was gotten from the crushing of waste concrete within Covenant University, Civil Engineering Department, and a demolished site located around Ota, Ogun State. The size of the

Table 1. Chemical and Composition qualities of cement and marble waste.

Chemical qualities %	Cement	Marble waste
Composition		
SiO_2	19.10	42.18
Fe_2O_3	4.54	2.12
Al_2O_3	4.95	1.29
CaO	71.86	45.49
MgO	3.03	0.23
SO_3	2.63	
Cl	-	-
Loss of ignition	-	-
K_2O	-	1.90
Na_2O	-	2.65
Physical properties		
Specific gravity	3.17	2.91

Marble waste aggregate and recycled aggregate with a minimum size of 18 mm were used. The marble waste aggregate is shown in Figure 2b was gotten from the crushing of waste marble tiles in a warehouse in Ota. The chemical admixture used agreed with IS: 9103–979 a water reducing agent (superplasticizer Conplast SP430) used for improving the flow and workability without compromising the compressive strength. The water used was from the tap water in Covenant University Ota, Ogun State. The water-cement percentage used for this research was 0.4.

3.2. Preparation of concrete

For the study, batching by weight method was used for the concrete preparation. The mix design used was 1:1:1.5 with a water to cement ratio of 0.4. The percentage of superplasticizer was 2% and kept constant. After the principal blend outline, the trial mixes were carried out for the initial properties of SCC as indicated by (Efnarc 2002) rules to get the exact mix to use. The details of the mix proportion used in the study are presented in Table 2. The materials were batched using the weighing method and mixed thoroughly in the mixer to achieve a homogenous mixture. After the dry mixing had been done properly, the measured quantity of water and chemical admixture of 2% (superplasticizer) was then added.

Table 2. Physical Properties of Aggregates.

Properties	Natural coarse aggregate	Fine aggregate	Recycled aggregate	Marble waste
Specific gravity	2.65	2.50	2.02	1.40
Water absorption (%)	0.63	0.15	5.56	3.13
Impact value (%)	21.6	-	22.4	27.3

3.3. Experimental programme and proportions used

In the preparation of all SCC samples, cement contents were kept constant at 450 kg/m3. The water binder ratio of 0.4 was constant for all the samples prepared. The superplasticizer admixture added to the mix was 2% for all the samples prepared, while the grain size distribution was kept constant. The grain size distribution curve obtained was 60% coarse aggregate and 40% fine aggregate. The sieve analysis for the aggregates used is given in Table 2. In the mixed proportions, the aggregate was partially replaced by marble waste and recycled aggregate, respectively. Table 3 indicates the volume of mixture per cubic metre by weight. SCC mix design was performed

Table 3. Mix Proportioning.

Mixes	Cement (kg)	Sand (kg)	Recycled aggregate (kg)	Marble waste aggregate (kg)	Water (kg)
Control	25	25	37.5	-	10
RA 10%	25	25	33.75	3.75	10
RA 20%	25	25	30.0	7.5	10
RA 30%	25	25	26.25	11.25	10
MW 10%	25	15	33.75	3.75	10
MW 20%	25	15	30.0	7.5	10
MW 30%	25	15	26.25	11.25	10

(a). Recycled aggregates (b) marble waste used in the SCC

Figure 2. (a) Recycled aggregates (b) marble waste used in the SCC.

according to the absolute weighing method. The unit composition of the series also given in Table 2. The aggregate content of SCC samples decreased with the water content. Alternatively, with the same water to binder ratio, aggregate content may be modified by using a different form of aggregate. The variations in the amount of sand and aggregates for each sample are due to the aggregates' specific gravity.

On fresh SCC, slump flow, T50 flow, L-box, and V-funnel experiments were carried out. The slump flow test was used to determine the deformability, flow-ability, and flow velocity of the concrete in the absence of obstacles and to assess the filling ability of the concrete. In the cone used in accordance to EN 12350-8 B (2010) collapse test, fresh concrete was mounted with the aid of a hand trowel; the cone was then pushed upward gradually, and the T50 time was determined from the time the upward push started to the time the concrete reached a diameter of 50 cm.

Figure 3. Slump Flow $T_{50.}$

Figure 4. L-box flow.

Then, at right angles, the largest diameter of the concrete flow and the largest diameter of the dispersion is estimated, and the average is the slump flow. Two perpendicular diameters were used to calculate the slump-flow of SCC after the cone was lifted Figure 3.

During the slump-flow test, the required time of SCC to reach a 500 mm length slump-flow radius (T500) was measured. The V-funnel test is to determine concrete flow-ability with coarse aggregate size of 20 mm. The concrete mix was poured into the V-funnel and the time in secs was noted to know the time taken to flow was recorded. About 10 litres of concrete mix was used. The L-box test was used to evaluate the filling-passing-ability and segregation of the mixed sample and this was visually observed. It is made of component sections, a vertical and horizontal rectangular-section box to form an 'L' shape as shown in Figure 4. The sections are divided by a moveable

(a) (b)

Figure 5. (a) (b) Crushing of the cubes (b).

Figure 6. Flexural Strength.

Figure 7. Splitting strength.

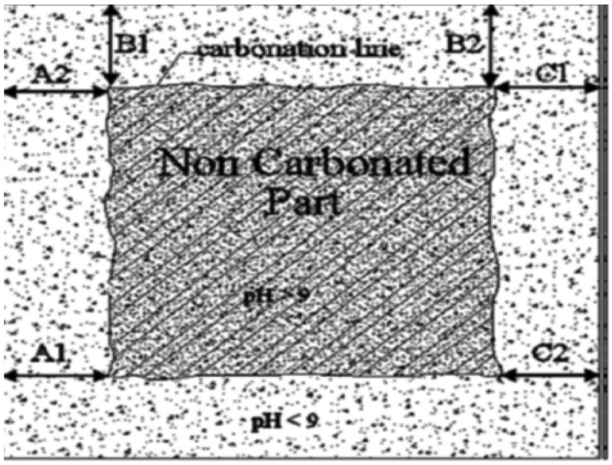


Figure 8. Carbonation depth D = A1± A2± B1± B2± C1± C2 6.

gate that is raised to allow the concrete mix to pass through the narrow spaces created by the horizontal rectangular section's reinforcement bars. Before the separating gate was raised to allow flow into the horizontal portion, fresh concrete was poured into the vertical rectangular section. After the concrete had completely flowed into the horizontal section, the height H2 and H1 reflect the height of the concrete at the end and beginning of the horizontal segment, respectively.

The compressive strength was determined in conformity to BS EN 12,390 and ASTM-C39/C39M-20 cube size of 150 mm × 150 mm × 150 mm, cylindrical dimension of 150 × 300 mm for the split tensile test Figure 7 was according to ASTM: C 496 as shown in , b. Figure 5a, b was determined, and 100 × 100 × 400 mm beams for the flexural strength test as shown in Figure 7 and Figure 6. The moulds were properly lubricated before the concrete was poured into them for ease of removal after the concrete had been properly set. The concrete was also placed without the need for vibration as the concrete is self-compacting. The concrete samples were

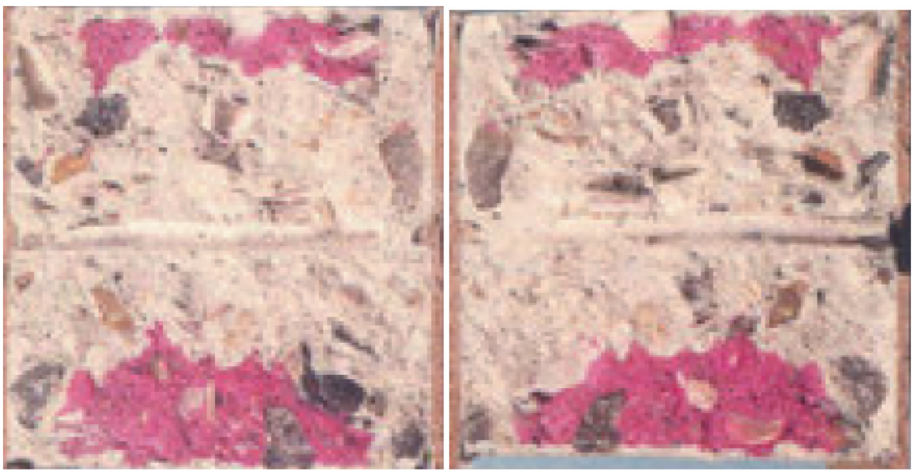


Figure 9. Samples when sprayed with 1% phenolphthalein.

removed after 24 h and put in the curing tank for 7, 14, and 28 days.

3.4. Microstructural analysis

Scanning electron microscopy (SEM) is a technique used in the characterisation of concrete microstructure. It helps to understand the root cause of concrete behaviour by giving an in-depth visualisation of the microstructure, arrangement of its spatial particles, bond configuration. The microstructural analysis of the compositional characteristics of the sample was conducted using a Scanning Electron Microscope (SEM). The (SEM, Phenom ProX, Phenom-World BV, The Netherlands) was used at a microspore acceleration voltage of 15 kV and magnification of ×1500 (Adeniyi, Ighalo, and Onifade 2020).

3.5. Carbonation Assessment

In the determination of the accelerated carbonation test according to Kianoosh et al., (Vaidevi, 2020) assessment. The test was carried out on a 100 mm sample, sprayed with 1% phenolphthalein and 50% alcohol as shown in Figure 9. Relative humidity of 55% was considered and the $C0_2$ diffusion concentration was 30% and 50%. An accelerated carbonation test was performed on 100 mm cube samples according to Song (Sasanipour, 2019). With humidity of 40%, three separate CO2 acid gas concentrations (40%, 60%, and 80%) were considered. A total of 15 sample cubes were used. The cubes were left to cure for 30 and 60 days, respectively. For four hours, all of the specimens remained undamaged in the accelerated carbonation chamber. The depth of carbonation Figure 8 check was measured as per (RILEM Recommendation, 1988) when the specimens were removed from the carbonation chamber. The specimens were sprayed with hydrogen ion concentration indicator (1% phenolphthalein and 80% ethyl alcohol). The non-carbonated areas changed colour to purple-red colour and effervescent areas colourless. The pH concentration of the non-carbonated space was quite 7.2. The depth of the 3 specimens were noted.

4. Results and discussions

4.1. Physical tests on aggregate

The sieve analysis determines the fine and coarse aggregate gradation. The fine aggregate requirement norm, according to ASTM C33, is particles passing a 4.75 mm sieve. Figures 10 and 11 indicate the

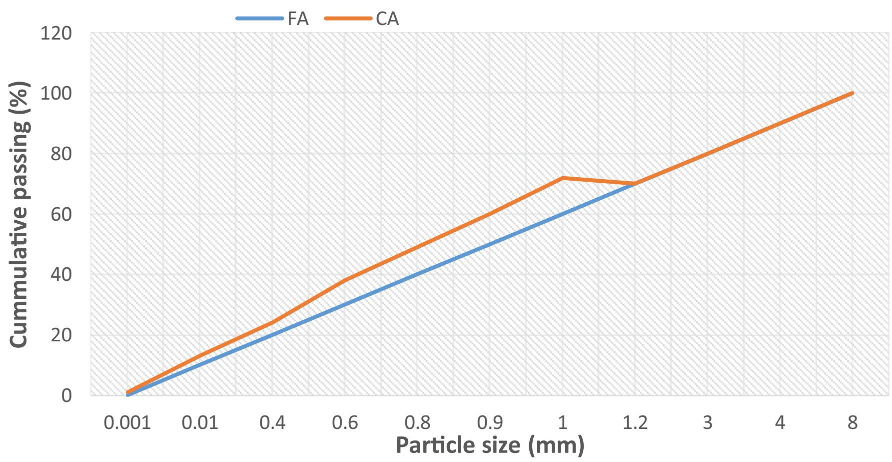


Figure 10. The particle size distribution of fine and coarse aggregate.

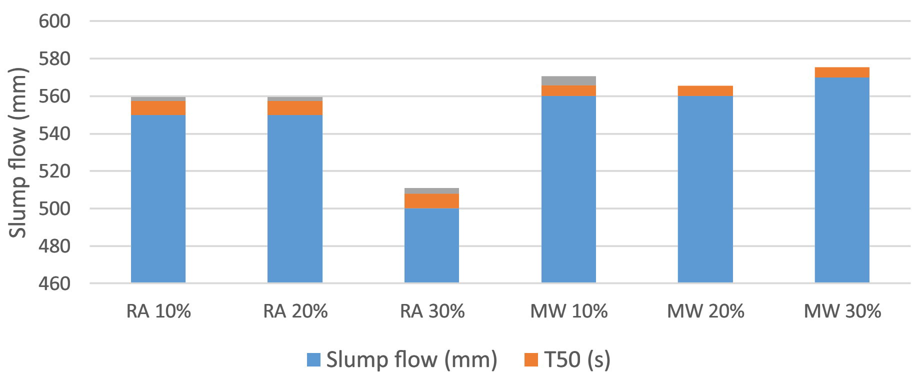


Figure 11. Results of slump flow and T_{50cm} test.

average result for sand and granite aggregates. According to the fine aggregate sieve analysis findings, the prevalent (>80%) particle size is less than 2 mm, which meets the fine aggregate requirement according to ASTM C136/C136M-19. According to the coarse aggregate sieve analysis data, the majority (>90%) of particle sizes are above 4.75 mm, which meets the ASTM C136 criterion for coarse aggregate (greater than 4.75 mm).

Specific gravity and water absorption are important properties of aggregate and are needed when it comes to the design of concrete structures. Materials with low specific gravity are said to be weak, hence a higher specific gravity is needed for aggregates. From Table 2, it can be observed that the specific gravity of both the recycled aggregates and marble waste was lesser than for the fine and coarse aggregates. However, further tests will need to be conducted on the hardened properties to determine to what extent the reduced specific gravity affects the hardened properties of the concrete.

The water absorption test determines the amount of moisture that the aggregate will consume and retain. It also gives us an idea of the aggregate's consistency. Coarse aggregate with a high water absorption value is usually porous and poor in strength. The outcome of the recycled aggregates' water absorption test and marble waste are shown in Table 2. The water absorption of the recycled aggregates and marble waste were 5.56% and 3.13% respectively. In comparison with that of granite (0.63%), we see that partial replacement using these waste aggregates will likely reduce the hardened properties of the SCC.

The impact value of granite can be used to assess the aggregate batch's intensity and suitability for a particular application. Table 4 shows the results obtained for recycled aggregates and marble waste. The impact value of the coarse aggregate was calculated to be 21.6%. This is consistent with other studies' impact values (17–23%) for granite, and it is suitable for concrete production (Jethro, Shehu, and Olaleye 2014). The higher impact value for the recycled aggregates and marble waste show that they are more susceptible to break at impact when compared to the natural coarse aggregate. In general, though the recycled aggregates and marble waste do not have properties as good as the natural coarse aggregates, recycled aggregates are observed to be better than marble waste in this domain.

Table 4. Physical Properties of Aggregates.

Properties	Natural coarse aggregate	Fine aggregate	Recycled aggregate	Marble waste
Specific gravity	2.65	2.50	2.02	1.40
Water absorption (%)	0.63	0.15	5.56	3.13
Impact value (%)	21.6	-	22.4	27.3

4.2. Properties of fresh concrete

4.2.1. Slump flow and T50cm tests

The slump flow test shows provide information on the flow-ability of the fresh concrete. From the results in Figure 11, it can be observed that slump flow increased with increasing partial replacement with marble waste (from 560 to 570 mm). Furthermore, an increase in the amount of recycled aggregate also reduces the slump flow of the concrete (from 550 to 500 mm). This is due to the high water absorption rate of the recycled aggregate due to the presence of cement from its parent source. The acceptable slump spread for SCC according to Efnarc (2002) is between 550 mm to 800 mm. The results for marble waste were within acceptable limits but that of recycled aggregate (>20 wt % partial replacement) was not. For the T50cm, it was observed that the time it takes for the concrete to reach the 50 cm mark on the flat board seems to increase with an increase in the recycled aggregate percentage (from 7.40 to 8.00 s). This is because of the low flow-ability of the concrete. This is different in the case of marble waste, as the percentage of marble waste is increased there a reduction in the time taken for the concrete to reach the 50 cm mark (from 5.65 to 5.36 s). It can be summarised that the use of recycled aggregate as a partial replacement for granite reduced the flowability of the SCC whilst the use of marble waste increased it. The positive effect of marble on workability and flow-ability is in agreement with other studies (Vardhan, Siddique, and Goyal 2019).

4.2.2. V-funnel and L-Box tests

The V-funnel and L-box test was carried out to determine how the addition of the recycled aggregate and the marble waste affects the flow-ability and workability of the concrete. From the results in Figure 12, it was observed that as the percentage of the recycled aggregate was increased there was also an increase in the flow time of the concrete (from 8.10 to 9.32 s) which means that as the amount of recycled aggregate increase the flow-ability is decreased. The opposite was the case for marble waste (from 7.45 to 7.10 s). These observations were in agreement with those obtained for the slump flow test and T50cm test.

Concrete with higher values of blocking ratio possesses good passing ability to pass through confined spaces of dense reinforcement and also good flowability to compact on its weight (Ofuyatan, Olutoge, and Olowofoyeku 2015). From Figure 13, it can be observed that SCC with marble waste had higher blocking ratios than that with recycled aggregates. However, the blocking ratios reduced with increasing partial replacement from 0.84 to 0.80 and from 0.95 to

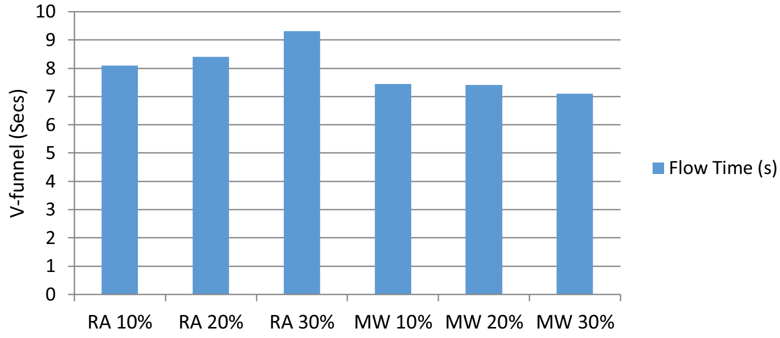


Figure 12. Results of V-funnel Test.

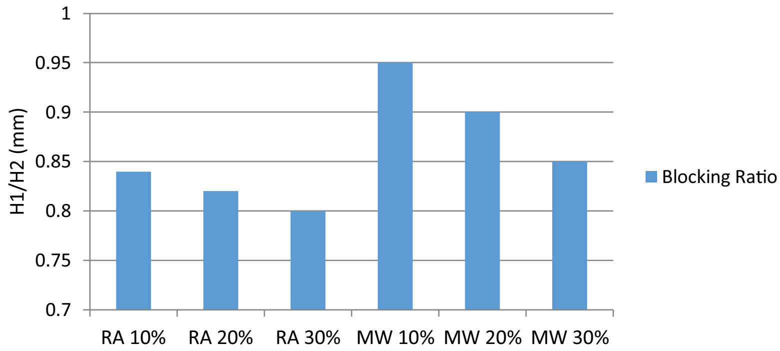


Figure 13. L-box test.

0.85 for recycled aggregates and marble waste SCC respectively.

4.3. Properties of hardened concrete

4.3.1. Compressive strength

Compressive strength is one of concrete's significant characteristics as it is the quantity of load that the concrete can bear before it fails. The concrete's compressive strength will determine its use, durability, and toughness. Figure 14 shows the effect of adding marble waste and recycled aggregate on the compressive strength of the self-compacting concrete compared to the strength of the normal concrete that serves as a control sample. The compressive strength of the replacement samples is noted to be smaller compared to the compressive strength of the control sample. The poorer quality of recycled aggregates (in comparison to granite) leads to weaker interfacial transition zones within the SCC and thus resulting in a lower compressive strength than the control sample (Aslani et al. 2018). Similar observations have been made by other researchers (Gesoglu et al. 2015). It can also be observed from Figure 14 that increased curing time improved the compressive strength of the SCC. Generally, SCC with recycled aggregates as a partial replacement had better compressive strength than those with marble waste. Higher partial replacement of granite led to poorer compressive strength. The best compressive strength for the samples with partial

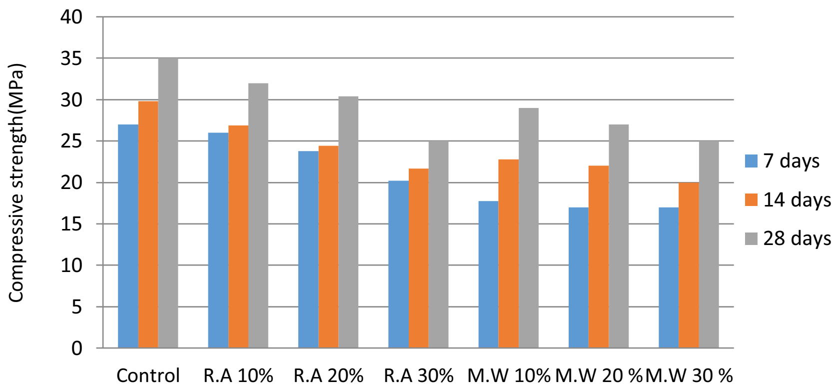


Figure 14. Compressive strength test.

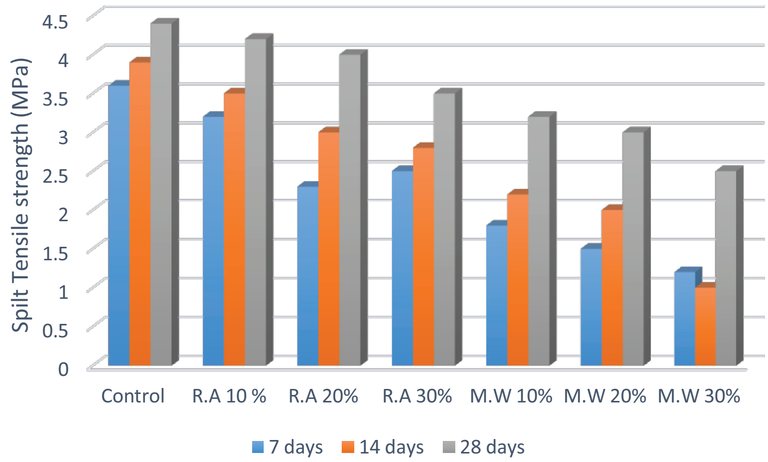


Figure 15. Split tensile strength test.

replacement was (at 10% partial replacement and 28 days curing time) 32 MPa and 29 MPa for recycled aggregates and marble waste SCC respectively.

4.3.2. Split tensile strength

The results shown in Figure 15 reveal that the control sample had the largest value for the tensile strength relative to the recycled aggregate and marble dust. The observations are in agreement with those of other studies (Manzi, Mazzotti, and Bignozzi 2017; Vaidevi, Kala, and Kalaiyarrasi 2020). It was also observed from Figure 15 that increased curing time improved the tensile strength of the SCC. Similar to the compressive strength, SCC with recycled aggregates as a partial replacement had better tensile strength than those with marble waste. Higher partial replacement of granite led to poorer tensile strength. The best tensile strength for the samples with partial replacement was (at 10% partial replacement and 28 days curing time) 4.2 MPa and 3.2 MPa for recycled aggregates and marble waste SCC respectively.

4.3.3. Flexural strength

Flexural strength is a measure of a concrete's mechanical capacity to withstand failure owing to bending. The flexural strength for the samples was obtained after 7 and 28 days of curing. From Figure 16, it is noted that all specimens have the greatest flexural strength after 28 days. The control sample had a higher flexural strength indicating that partial replacement was detrimental to this property. The observations are in agreement with those of other studies (Vaidevi, Kala, and Kalaiyarrasi 2020). It can also be observed from Figure 14 that SCC with recycled aggregates as a partial replacement had slightly better flexural strength than those with marble waste. Higher partial replacement of granite led to poorer flexural strength. The best flexural strength for the samples with partial replacement was (at 10% partial replacement and 28 days curing time) 2.0 MPa and 1.86 MPa for recycled aggregates and marble waste SCC respectively.

4.4. Accelerated carbonation depth

In Figure 17 shows the carbonation depths for both the control and sample mix. Marble waste Concrete had the maximum carbonation depth. This finding was consistent with a previous literature study (Song, 2007), which found that the rate of carbonation was influenced significantly by the pore size of the concrete structure, the percentage of moisture in the concrete, and the relative humidity of the surrounding environment. The

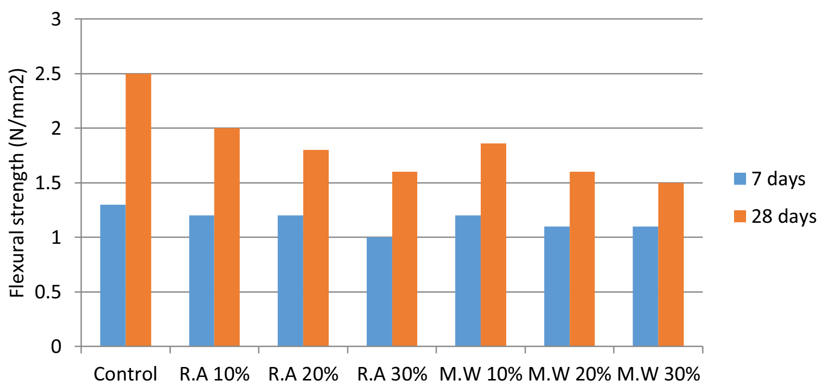


Figure 16. Flexural strength test.

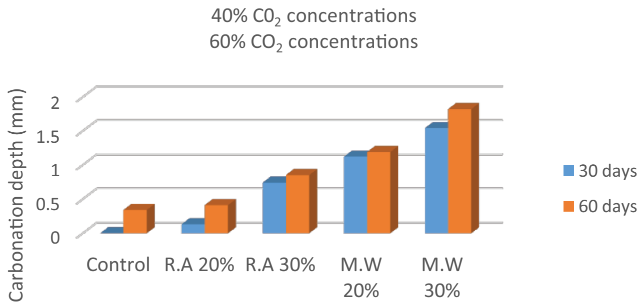
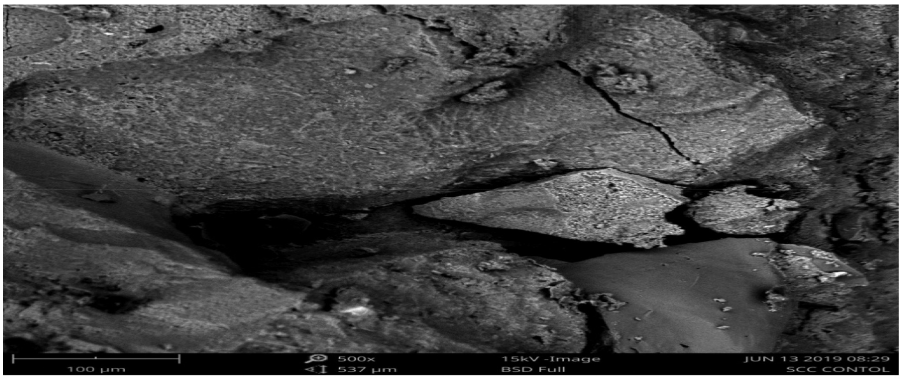
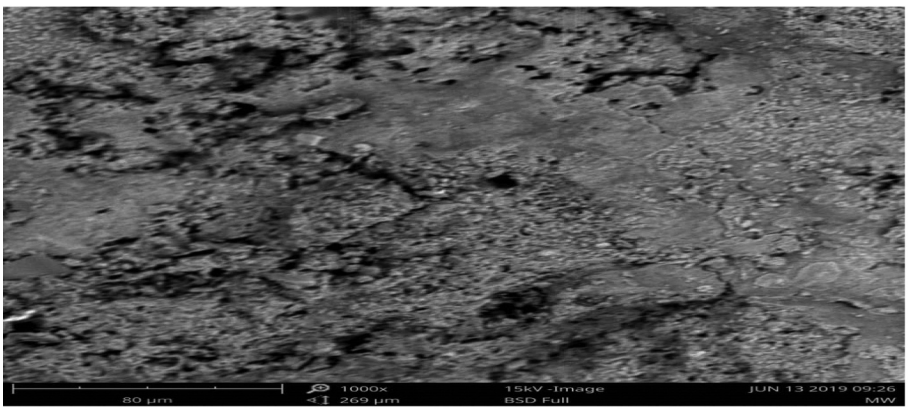


Figure 17. Carbonation depth at different CO_2 concentrations.



a. SEM micrograph of the control sample

. SEM Micrograph of recycled aggregate at 10% replacement



. SEM Micrograph of marble waste at 20% replacement

Figure 18. (a) SEM micrograph of the control sample. (b) SEM Micrograph of recycled aggregate at 10% replacement. (c) SEM Micrograph of marble waste at 20% replacement.

percentage increase in CO2 concentration increased with the carbonation rate, which was particularly noticeable at high water to powder ratios, where transport occurred within the concrete matrix's pore structure (Mastali, 2016). By filling the pores with hydration products, pozzolanic material could minimise the depth of carbonation, according to (Vardhan, 2019).

4.5. Microstructural analysis

The concrete microstructure was analysed using the SEM. The micrographs of the control sample (Figure 18a), the SSC with 10% partial replacements with recycled aggregate (Figure 18b), and the SCC with 10 wt% partial replacements with marble waste (Figure 18c) were analysed. The SEM examines the sample bond structure on a micro-scale. In other to comprehend and interpret the general behaviour arising from the nature of the construct, the particular features that occur between the concrete bonded parts are observed (Sudarshan and Vyas 2019). These can tell us about the concrete behaviour/performance under multiple kinds of loading that include the compressive, flexural, and tensile. From the micrographs of the control sample (Figure 18a), poor interaction between the concrete constituents was observed which might have caused the large voids and deep cracks observed on the microstructure of the concrete. From the micrographs of the SCC with 10% partial replacements with recycled aggregate (Figure 18b), it was observed that the interfacial interactions and mixing of the concrete properties were improved for the control sample. A smoother surface was observed with no cracks and voids. From the micrographs of the SCC with 10% partial replacements with marble waste (Figure 18c) it was observed that good interaction of the cement constituents was achieved (albeit to a lesser extent than for the SCC with recycled aggregate). It can be inferred from the microstructural analysis that the utilisation of granite replacement improves the interaction between the concrete constituents. However, the sample with recycled aggregate performed better than that with marble waste in this regard.

5. Discussions and conclusions

The fresh and hardened properties of self-compacting concrete developed using recycled aggregates and marble waste as a partial replacement for granite was evaluated and the results are given as follows:

1. The workability of SCC was observed to be dependent on the texture and shape of the aggregate. However, the use of recycled aggregate as a partial replacement for granite reduced the flowability of the SCC whilst the use of marble waste increased it.

2. Physical tests revealed that though the recycled aggregates and marble waste do not have properties as good as the natural coarse aggregates, recycled aggregates were observed to still be better than marble waste in this domain.

3. SCC with recycled aggregates had better-hardened state properties than those with marble waste. For all hardened properties, curing improved the final value but the partial replacement was detrimental to the properties (in comparison with the control sample). The best compressive strength for the samples with partial replacement was (at 10% partial replacement and 28 days curing time) 32 MPa and 29 MPa for recycled aggregates and marble waste SCC respectively. The best tensile strength for the samples with partial replacement was (at 10% partial replacement and 28 days curing time) 4.2 MPa and 3.2 MPa for recycled aggregates and marble waste SCC respectively. The best flexural strength for the samples with partial replacement was (at 10% partial replacement and 28 days curing time) 2.0 MPa and 1.86 MPa for recycled aggregates and marble waste SCC respectively. From the microstructural analysis, the utilisation of partial granite replacement improved the interaction between the concrete constituents. However, the sample with recycled aggregate was still better than that with marble waste in this regard.

4. From the SEM analysis, poor interaction between the concrete constituents was observed which might have caused the large voids and deep cracks observed on the microstructure of the concrete. However, the sample with recycled aggregate performed better than that with marble waste.

5. The compressive and splitting tensile strength values of carbonated concrete specimens are higher than non-carbonated concrete specimens due to the carbonation process.

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Notes on contributors

Olatokunbo Ofuyatan (Dr) a lecturer in the Department of Civil Engineering, Covenant University, Ota, Ogun State. Her research interest includes reuse and recycle of waste materials in self compacting concrete, construction materials, concrete technology, and cement based composites.

Kayode-Thomas Enoch is presently a post graduate student.

Oluwafuminiyi Ogundeji is presently a post graduate student.

David Omole (Prof) is a lecturer in the Department of Civil Engineering, Covenant University, Ota, Ogun State and the

Dean of College of Engineering. His research focus is into water quality and solid waste management.

ORCID

Olatokunbo Ofuyatan http://orcid.org/0000-0001-9052-2758
David Omole http://orcid.org/0000-0002-8294-4819

Compliance with Ethical Standards

This article does not contain any studies involving human or animal subjects.

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