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Sustainable alternative aggregates: Characterization and influence on mechanical behavior of basalt fiber reinforced concrete

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HIGHLIGHTS

- The leaching of hazardous metal from SSA and RCA were well below the standard limits.
- Compressive and flexural strengths of concrete are improved by using SSA.
- BMF improved the mechanical properties of concrete made with RCA and NLA.
- Both SSA and RCA showed promising potential as sustainable alternative aggregates.

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ABSTRACT

Demands to assess the feasibility of utilizing alternative sustainable aggregates in concrete have been raised because of the rapid depletion of virgin aggregates resources. In this study, a comparison of the physio-chemical properties of commonly used natural gabbro aggregates (NGA) and natural limestone aggregates (NLA) and their possible sustainable alternatives recycled concrete aggregates (RCA) and steel slag aggregates (SSA) is presented. The suitability of these alternate aggregates is assessed through several standardized tests. Chemical compositions, mineralogical and morphological properties of these aggregates are also reported. To determine the possible leachates of hazardous metals into the environment when used as concrete aggregates, the inductively coupled-plasma atomic emission spectroscopy was carried out on acid digestions of these aggregates. Additionally, basalt macro-fibers (BMF) were incorporated to improve the mechanical properties of concrete made with RCA and local NLA which are deemed as weak and unfit for use as aggregates in structural concrete. Experimental results revealed that both RCA and SSA could be used as sustainable alternative aggregates to have a cleaner production of structural concrete. They had acceptable leachate limits of the hazardous elements. The soundness test results and expansion under autoclave of SSA were well below the acceptable limits. The concrete made with SSA showed higher mechanical properties than the concretes made with other aggregate types. As expected, BMF improved the mechanical properties of concrete made with the low-strength NLA and RCA.

1. Introduction

It is estimated that about 10 billion tons of concrete are produced annually worldwide consuming huge amounts of raw materials [1,2]. Coarse aggregates (CA) make up the majority of the concrete's constituents with about 55% to 75% by volume [3]. The worldwide annual CA demand had reached up to 48.3 billion tons in 2015 [4]. Such high demands initiated a rapid depletion of natural source quarries. Furthermore, the scarcity of good quality aggregates, in most parts of the world, necessitates their transportation from remote quarries which in turn increases transportation costs, energy consumption, and CO_2 emissions. That is why the feasibility of utilizing recycled materials and industrial by-products in concrete manufacturing has been examined by several researchers [5,6].

Examples of potential aggregate sources from industrial by-products or discarded materials are steel slag aggregates (SSA) and recycled concrete aggregates (RCA). Up to 20% by mass of crude steel is discarded as slag during the steel-making process. About 250 million tons of steel slag are estimated to be produced annually worldwide [7], of which 20 million metric tons are produced in the US [8], 90 million tons are produced in China [9,10], and 400,000 tons are produced in Qatar [11]. In developed countries, almost 100% of slag is recycled either by extracting steel back or by utilizing it in construction works. Whereas in developing

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countries, waste slag is mostly stockpiled at factories or dumped into useful lands [9,11]. It has been observed that employing the SSA as a partial replacement of virgin aggregates improves the mechanical properties of asphalt and structural concrete [12-15]. Pellegrino and Gaddo [12] reported a 38% higher compressive strength with electric arc furnace (EAF) SSA compared to traditional aggregates. Saxena and Tembhurkar [16] and Biskri et al. [17] also reported similar results. On the contrary, there are concerns over the possible adverse effects of employing SSA as CA in concrete [18,19]. However, several studies showed that the steel slag generates no health risk to human, neither cause any harm to the environment when employed to different construction applications [20]. Since the iron contents in SSA are expected to be high, corrosion of these iron contents could generate rust product which could adversely affect the concrete integrity. However, Heniegal et al. [21] indicated that concrete specimens made with SSA have better corrosion resistance compared to their counterpart control specimens made of the conventional aggregates. Pang et al. [22] demonstrated that carbonation treatment could considerably enhance the volume stability of SSA and reduce free calcium oxide.

Likewise, construction and demolition (C&D) applications have become one of the leading sectors in the world with the increased number of repetitive repair/renovation/maintenance of buildings, roads, bridges, and other structures. However, each year, significant amounts of solid waste are generated as a result of the above-mentioned applications requiring to be tackled properly. Around 145 million tons of C&D waste are generated annually worldwide [23]. It is estimated that 20,000 tons of C&D debris are produced in Qatar daily, half of which is now been converted to RCA [24]. Recycling C&D waste into concrete aggregates has been a very successful idea in terms of sustainable development [5,25-29]. It reduces the cost required to blast, crush, and transport the virgin aggregates, and reduces landfill waste. On the other hand, it is well documented that the mechanical and durability performance of RAC is normally inferior to that of concrete with virgin aggregates [26,30-32]. This is due to the adhered cement mortar on the surface of RCA from crushed concrete which creates a weaker interfacial transition zone (ITZ) between fresh cement matrix and aggregates. Moreover, the demolition and crushing processes weaken the parent aggregates. Qatar Construction Specifications (QCS)-2014 [33] limits the replacement of virgin aggregates by RCA to 20% in structural concrete. A concrete with 100% RCA shows a 20 to 25% lower compressive strength than that of conventional concrete [34]. Similar results were observed by Poon et al. [35] and Talamona and Hai Tan [27]. Different techniques are used to remove or improve the adhered cement mortar. Adding silica fume and fly ash in the concrete mix improves the performance of RAC. Moreover, the use of carbonated RCA could reduce the porosity of adhered cement mortar. Dimitriou et al. [34] treated the RCA at a higher temperature to remove the adhered cement. The study involved the addition of fly ash and silica fume to RAC. The test results revealed an improvement in the mechanical and durability properties of concrete. Sahoo et al. [23] added the bacteria that produce calcium carbonates which fill the pores in the adhered mortar and improve the quality of RAC.

Concerning concrete compressive strength, the aggregate type has a more pronounced effect on high-strength concrete compared to the normal strength concrete [36-38].

Natural limestone aggregates (NLA), locally available in Qatar, are characterized by their heterogeneity, high water absorption, and low abrasion resistance compared to natural gabbro aggregate (NGA). That is why the locally available NLA are only recommended to be employed as a subbase material for pavements [24,33]. Hence, good quality NLA and NGA are transported from neighboring countries into Qatar.

The ITZ between aggregate and cement matrix is the weakest part in terms of strength and durability. Previous studies showed that using different aggregates generates different compositions and lengths of the ITZ in concrete [39]. Hence, it is important to understand the chemistry of the potential aggregates to predict their behavior in concrete.

In an effort to improve the concrete quality when local NLA and RCA are employed, fiber reinforced concrete (FRC) was used in the current study. Different types of discrete fibers are currently available such as steel and polypropylene fibers [40]. Recently, basalt macro-fibers (BMF) have emerged as a promising alternative to conventional steel and polypropylene fibers [41-43]. Basalt fibers are made from basaltic rocks that comprise 33% of earth's crust, hence, the raw material is abundantly available. A number of studies have demonstrated that the addition of BMF to concrete can enhance its tensile strength and toughness [44-47].

The present study evaluates the physio-chemical properties of natural aggregates (NGA and NLA) and their possible alternatives (SSA and RCA). The chemical composition and possible leachate of these aggregates into the environment were also studied. The influence of the type of aggregates on compressive and flexural strengths of plain and basalt FRC specimens at two different compressive strengths was also evaluated. Moreover, BMF were employed to observe whether they could yield an acceptable concrete quality with low-strength aggregates. The study will help designers and engineers to select the appropriate aggregate's type based on the strength requirements and geographic limitations.

2. Material and methods

2.1. Materials

2.1.1. Aggregates

Fig. 1 shows photographs of the four types of studied aggregates. NLA were quarried from local limestone sedimentary rocks in Qatar. These NLA have fine-grained texture and white to gray

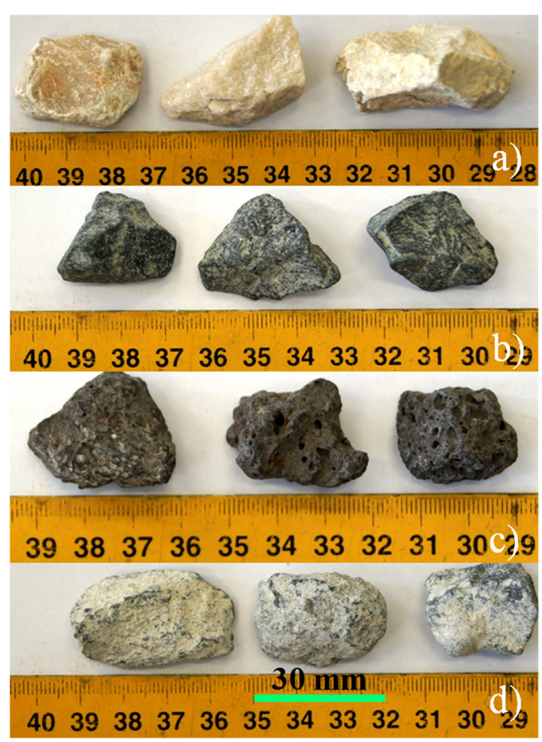

Fig. 1. Studied coarse aggregates, a) limestone, b) gabbro, c) steel slag, d) recycled concrete aggregates.

color with a tinge of brown and yellow due to the presence of iron and carbon, respectively. The NGA were imported from Oman and are coarse-grained, intrusive, mafic igneous rock, and dark gray to greenish-black in color with crystalline texture. In general, NGA are chemically equivalent to basalt aggregates. Futhermore, SSA were manufactured by crushing the EAF steel slag generated at Qatar Steel Company. The SSA were brownish-black in color with a very porous texture. The RCAs were crushed from C&D waste generated in Qatar.

2.1.2. Basalt macro-fibers (BMF)

Fig. 2 presents the BMF used in this study. These BMFs are discrete thin fibers made from a composite of basalt fibers and polymeric resin to form a small prototype of basalt fiber reinforced polymers bars. The length of BMFs was 43 mm (l_f) with a diameter of 0.66 mm (d_f), giving an aspect ratio (l_f/d_f) of 65.15. The surface of the BMFs has been mechanically treated to form a helical shape to improve the mechanical interlock with the surrounding concrete. The tensile strength of these BMFs was 1000 MPa whereas the elasticity modulus was 45 GPa, as per the manufacturer's datasheet. The BMFs were added to concrete mixtures to improve the mechanical performance of concrete. The specific gravity of these fibers is close to that of concrete (1.9 g/cm^3), hence, the concrete workability is not significantly affected by their addition.

2.2. Physio-chemical characterizing tests

Physical properties such as bulk unit weight (ASTM C29/C29M-17a) [48], Los Angeles abrasion (ASTM C131 – 12)[49], water absorption (ASTM C1585-13) [50], and specific gravity (ASTM-C128-97, 2007) [51] were measured to characterize SSA, NGA, RCA, and NLA. Particle shape was studied using flakiness and elongation index according to BSI-1998 [52]: sections 105.1 and 105.2, respectively.

On the other hand, during the service life of a structure, the concrete absorbs water from the atmosphere. This water could bring in expansive agents like salts that could penetrate in aggregates and cause the expansion. This scenario is especially important in the freeze-and-thawing process of water inside aggregates. It is essential to test the soundness of aggregates before employing them in concrete. The aggregate soundness test was carried on SSA and the values were compared with their corresponding values of two natural aggregates (NGA and NLA), in accordance with ASTM C88/C88M − 18 [53]. Aggregate samples of sizes 9.5 mm to 12.5 mm and 12.5 to 19 mm were selected. The weight of former size was 330 ± 5 g and of latter was 670 ± 10 g after washing and drying, as per recommendations of ASTM C88/C88M−18 [53]. All tested aggregates were immersed under a saturated magnesium sulfate solution for 18 h. Then, aggregates were dried for 15 min and were placed in a preheated oven at 110 ± 5 °C for 4 h. Meanwhile, the weight of the samples was monitored to achieve a constant weight. Then, the samples were again cooled and immersed in a magnesium sulfate solution for the next 18 h. This cycle was repeated 5 times. Finally, the samples were washed and sieved through 8 mm opening siever and the weight loss was measured.

Fig. 2. Basalt macro-fibers.

Furthermore, there are concerns over the expansion of SSA due to the hydration of free CaO and MgO, which could result in concrete cracking if the expansion forces exceeded the modulus of rupture of the concrete. The disruption ratio test was performed as recommended by Wang [54], where it is recommended to autoclave about 50 to 100 SSA particles at 137 °C and 357 KPa pressure for 1 h. In this study, 42 aggregates particles of size 10 to 20 mm were autoclaved at 134 °C at 200 KPa for 130 min, as shown in Fig. 3. The disruption ratio was calculated by $R(\%) = \frac{N_c}{N_t} \times 100$, were N_c are the number of broken/cracked or powdered particles and N_t is the total number particles tested.

Moreover, it is important to know the chemical composition, mineralogy, and morphology of aggregates used in concrete mixes. That is because aggregates are one of the major sources of internally present deleterious agents such as chlorides, sulfates, and alkalis in concrete. Some aggregates chemically react with cement matrix and produce harmful products such as alkali-silica gel, thaumasite and ettringite formations. These products adversely affect the structural integrity by deteriorating the concrete matrix. The scattered electron microscopy (SEM) was performed on the broken surface of aggregates to study morphology and microstructural characteristics using FE SEM NOVA® instrument. X-ray diffraction (XRD) was performed on powdered samples to observe the mineralogy and crystalline phases. Corresponding intensities of various compounds were obtained at 2θ from 5 to 90°. The X-ray diffractometer PAN analytical® EMPYREAN with C_uK_α radiations was used for XRD analysis. X-ray fluorescence (XRF) analysis was performed using S2 Puma Bruker ® instrument to obtain major and trace oxides in these aggregates.

Futhermore, steel slag and C&D wastes when dumped in landfills leach hazardous metal ions into the earth or in the atmosphere. Also, when used in concrete, free ions of calcium and silicon instigate the alkali-aggregate-reaction. Inductively coupled plasma-atomic emission spectroscopy (ICP-AES) was performed to observe the acid dissolvable elements in aggregate samples. Aggregates were ground to powder form and were dissolved in nitric acid and hydrofluoric acid according to US-EPA 3050B [55]. Digestion was ensured under microwave heating up to 1000 °C. The solution was filtered by centrifugal stirring and dissolved material was tested under ICP-AES [73]. The pH of aggregates was also measured according to British Standards Institution-1990 [57].

2.3. Concrete ingredients and mixture proportion

In total, 28 different concrete mixtures were prepared with four different types of aggregates (NGA, NLA, RCA and SSA), four volume-fractions of BMF, V_f, (0, 0.25, 0. 5 and 1%) and two water-to-cement ratios, w/c, (0.51 and 0.36). The w/c of 0.51 and 0.36 were employed to achieve two target compressive strengths of 30 (C30) and 45 MPa (C45), respectively. The rationale behind

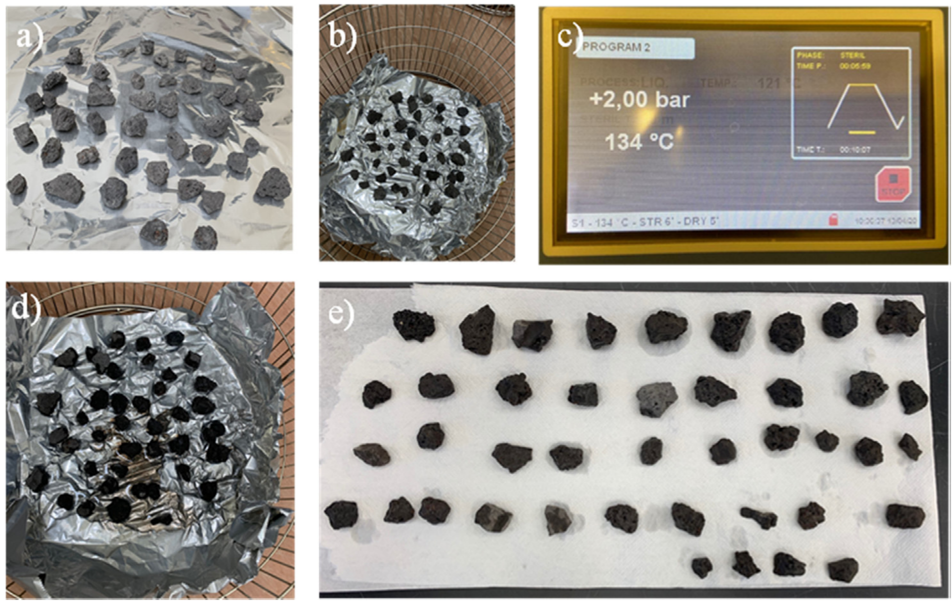

Fig. 3. Autoclave test for disruption ratio, a) SSA before testing, b) Autoclave basket placement, c) Equipment setting, d) After 90 min, and e) Observation on SSA particles for breaking or cracks after autoclave.

selecting these two grades was to observe whether the studied aggregates behave differently based on the strength of the matrix. Moreover, these two grades are commonly employed in the local construction industry. Proportions of concrete mixtures are presented in Table 1. The concrete mixtures were labeled in the following order: the type of coarse aggregate and the target compressive strength. A similar mixture proportion was employed for the four types of aggregates. Weight proportions of water and CA were kept similar in all mixtures. Ordinary Portland cement (CEM I) and washed sand of 0/4.75 mm were used. Particle size distribution curves of the studied coarse aggregates are presented in Fig. 4. Nominal aggregate sizes were between 4.75 and 19 mm. Fig. 4 also depicts the maximum and minimum grading limits recommended by [58]. As per ASTM C33-16 [58], it was observed that both SSA and RCA were complying with the upper limit of grading requirement, while the NGA and NLA gradings were between upper and lower limits. Coarser grading of SSA and RCA would help in better aggregate interlocking with the concrete matrix.

In total, 168 concrete samples including 84 cylinders (150 × 300 mm) and 84 prisms (150 × 150 × 500 mm) were cast. Three identical cylinders and prisms for each concrete mixture were used to measure the compressive and flexural strengths, respectively. It is important to note that the focus of the study is to observe the mechanical behavior of alternative aggregates (RCA and SSA) and local NLA which are considered weak and deemed not fit to be used in structural concrete. Thus, the concrete mixture made with NGA was omitted from the testing matrix for concrete with a target compressive strength of 45 MPa. The compressive and flexure strengths at 28 days were tested in accordance with ASTM C39/C39M-17 [59] and ASTM C78 / C78M – 15a [60], respectively.

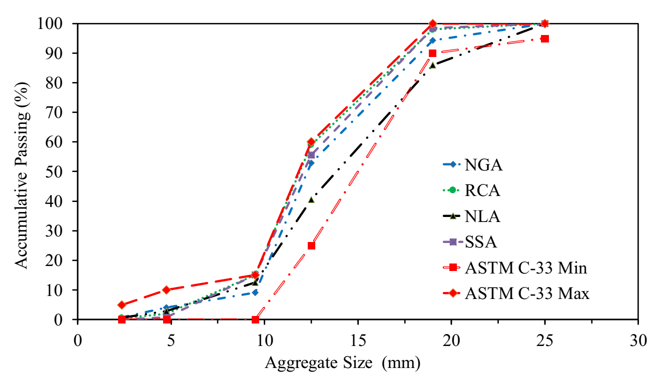

Fig. 4. Particle size distribution curves of NGA, NLA, RCA and SSA.

3. Results and discussion

3.1. Physical properties of aggregates

Table 2 presents the physical properties of the studied aggregates. The SSA showed higher specific gravity and unit weight than NGA, RCA, and NLA. A higher mortar paste is required to carry these heavy aggregates. This poses a problem with the workability

Table 1
Proportions of concrete mixtures with different types of aggregates.

Concrete Mix	Ingredients				
	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Coarse Aggregates (kg/m^3)	BMF (% by Volume)
NGA-30	365	185	900	960	0, 0.25, 0.5 and 1%
NLA-30	365	185	900	960	0, 0.25, 0.5 and 1%
RCA-30	365	185	900	960	0, 0.25, 0.5 and 1%
SSA-30	365	185	900	960	0, 0.25, 0.5 and 1%
NLA-45	480	185	900	960	0, 0.25, 0.5 and 1%
RCA-45	480	185	900	960	0, 0.25, 0.5 and 1%
SSA-45	480	185	900	960	0, 0.25, 0.5 and 1%

Table 2
Physical properties of four types of coarse aggregates.

Aggregate Type	Bulk Specific Gravity (Dry) (%)	Bulk Specific Gravity (SSD [a]) (%)	Bulk Specific Gravity (APP [b]) (%)	Absorption (%)	Flakiness Index (%)	Elongation Index (%)	LA Abrasion (%)	Soundness Test (%)
SSA	3.24	3.31	3.48	1.06	1.00	13.00	14.86	0.5
NGA	2.88	2.89	2.93	0.65	8.00	24.00	8.10	2.17
RCA	1.96	2.04	2.13	4.06	6.34	8.00	27.84	–
NLA	2.51	2.59	2.73	3.26	15.42	15.70	21.00	13.7
QCS 2014 Limitation [72]	–	–	–	2	30	35	30	18[c]

[a] Saturated surface dry, [b] Apparent, [c] ASTM C88 limitation.

of the fresh concrete mix. Although, the main focus of the study was to observe the effects of aggregate type on the mechanical properties of concrete, however, it was observed that the workability of concrete with SSA was considerably less than concrete with other aggregates. Loss of workability was also observed by Roslan et al. [61] while employing SSA. The water absorptions of SSA, NGA, RCA, and NLA were 1.06%, 0.65%, 4.06% and 3.26%, respectively. Guidelines such as ACI Committee 318 [62] and QCS-2014 [33] limit water absorption of coarse aggregate to 2%. Both RCA and NLA exceeded this limit. That is why soaking of RCA aggregates in water for 24 h before using in concrete is recommended [25,63]. The water correction needs to be carefully applied in the case of NLA and RCA to obtain the desired strength and flowability of concrete.

The flakiness indices were 1, 8, 6.34 and 15.42% for SSA, NGA, RCA, and NLA, respectively. While the elongation indices were 13, 24, 8 and 15.70% for SSA, NGA, RCA, and NLA, respectively. QCS-2014 [33] limits the flakiness index to a maximum of 30% and the elongation index to 35%. Although, RCA were heterogeneous, porous and showed rough surface, however, they were equidimensional to NGA. All aggregates had lower values of flakiness and elongation indices than the recommended upper limit. Given flakiness and elongation indices, the SSA are quasi-round in shape which improves the packing of these aggregates in the concrete matrix. Also, the roundness would counter the rheological issues due to the higher unit weight of SSA. LA abrasion values according to ASTM C131-12 [49] were 14.86, 8.1, 27.84 and 21%, for SSA, NGA, RCA and NLA, respectively. Qatar construction specifications [33] limit the LA abrasion to 30%. SSA showed higher abrasion loss than NGA, while the NGA showed the highest abrasion resistance. RCA had the lowest abrasion resistance due to the adhered cement mortar on the RCA surface and weakened aggregates during the demolishing and crushing.

The soundness of the SSA, NGA, and NLA was 0.15, 2.2 and 13.7%, respectively. As could be noticed, soundness values for all the tested aggregates are well below the standard limit of 18% in order to be used in concrete, as stated in the ASTM C88 standard [53]. The penetration of magnesium salt followed by drying puts internal pressure on the aggregates, which mimics the icing of water during the freezing. Hence, a lower soundness value would suggest higher freezing and thawing resistance.

Furthermore, after autoclave, none of the SSA particles showed any pulverization or cracks. Hence the disruption ratio R was observed to be zero. Wang [54] observed 2 to 5% of disruption ratios for three basic oxygen furnace (BOF) SSA sizes. SSA produced by the BOF process have different chemical compositions than SSA produced through EAF. The aggregate in their study had 35.1 to 40.06% of CaO and 8.8 to 11.3% of MgO, which are the basic oxides causing the internal expansion of SSA in concrete. The oxide compositions through XRF showed that the studied SSA have 19% CaO and 5% of MgO. Another reason for the zero disruption could be the iron oxide contents, which were 47% in these aggregates. While Wang [54] reported iron oxide as 21.5 to 28.1%. Rondi et al. [65] reported the expansion due to the free lime of 0.25% in fresh SSA generated through the EAF process, however, after aging them under open air for 3–4 months the expansion was reduced to 0.02% only. These values were well below 0.5% which is the limit set by ASTM D2940-98 [74] for aggregates to be used in concrete. In this study, the SSA were aged up to 12 months before using in concrete. Moreover, at the time of autoclave testing, SSA were aged for 18 months. As a result, no expansion or internal forces were generated due to the free lime. Moreover, the soundness ratio under magnesium sulfate also was negligible.

3.2. Chemical composition of aggregates

Figs. 5 to 8 present XRD analysis of NGA, NLA, RCA and SSA, respectively. NGA are crushed from igneous rocks formed due to the cooling of magma. The main mineral compounds are calcium-alumino-silicates, $CaAl_2Si_2O_8$,(the chemical name is anorthite) and ferromagnesium (plagioclase minerals). The pyroxene mineral, such as fersilitcite, iron oxide and magnetite are also present, as seen in Fig. 5. Due to the presence of these pyroxene minerals, NGA have a higher unit weight and abrasion resistance. Traces of alkalis such as potassium and sodium make the gabbro aggregates alkaline with a pH around 11.

NLA are composed of calcium carbonate, $CaCO_3$, dolomite, $CaMg(CO_3)_2$, chromite, $FeCr_2O_4$, and silica, SiO_2, as shown in Fig. 6. Tasong et al [39] suggested that the presence of Ca^+ ions in limestone aggregates results in a higher amount of portlandite formation in ITZ during cement hydration compared to other aggregates. A higher amount of portlandite ($Ca(OH)_2$) and less amount of calcium-silicate hydrate (C-S-H) weaken the ITZ. Such formation facilitates the concrete carbonation as portlandite reacts with CO_2 in the presence of water to form carbonic acid. This carbonic acid further reacts with water to convert into calcium carbonates.

RCA had several impurities such as sodium nitrate ($NaNO_3$), carbon dioxide (CO_2), portlandite ($Ca(OH)_2$), dipotassium sulfates (K_2SO_2) and alkalis, as seen in Fig. 7. These impurities make ITZ weaker and reduce the compressive strength of RAC. Porous ITZ would allow the ingress of deleterious agents reducing the durability of reinforced concrete. The presence of anorthite indicated that the studied RCA were originally the gabbro aggregates.

Fig. 8 presents the XRD analysis of SSA. These aggregates were obtained from the slag produced in EAF. To remove the impurities, the fluxes of calcite ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$) are added in molten iron ores. The choice of the added minerals affects the chemical composition of the SSA. The mineral composition of slag could also be different depending upon the procedure adopted for steel production. Major minerals in the studied SSA were dicalcium silicates (Ca_2SiO_2), dicalcium-sodium-aluminates, forsterite (Mg_2SiO_2) and ferroan. The strength of SSA is attributed to the presence of iron minerals. A high amount of calcium was also present. This is because lime was burnt with iron ores. Brand and Roesler

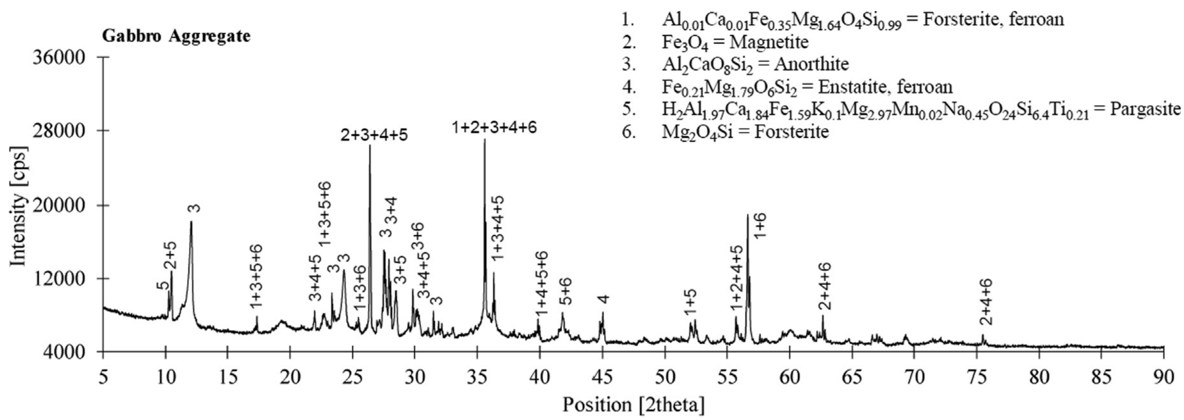

Fig. 5. XRD analysis of NGA.

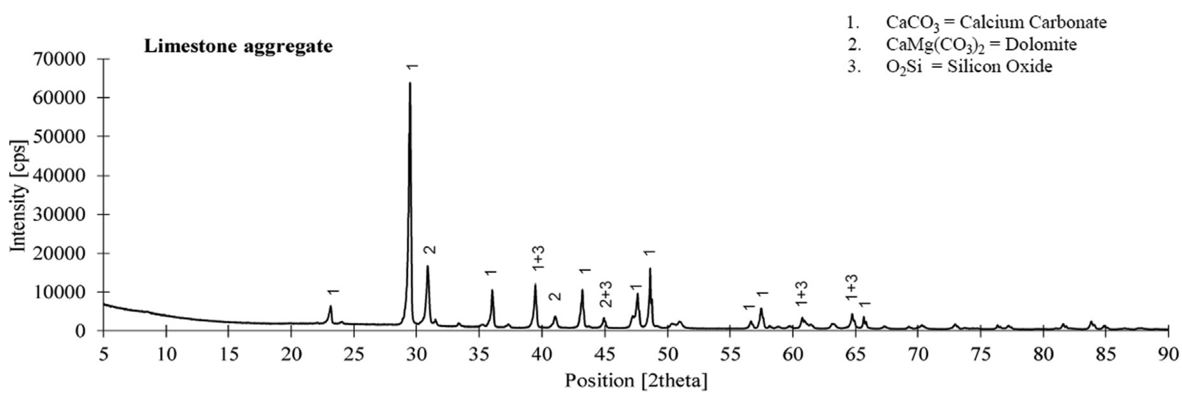

Fig. 6. XRD analysis of NLA.

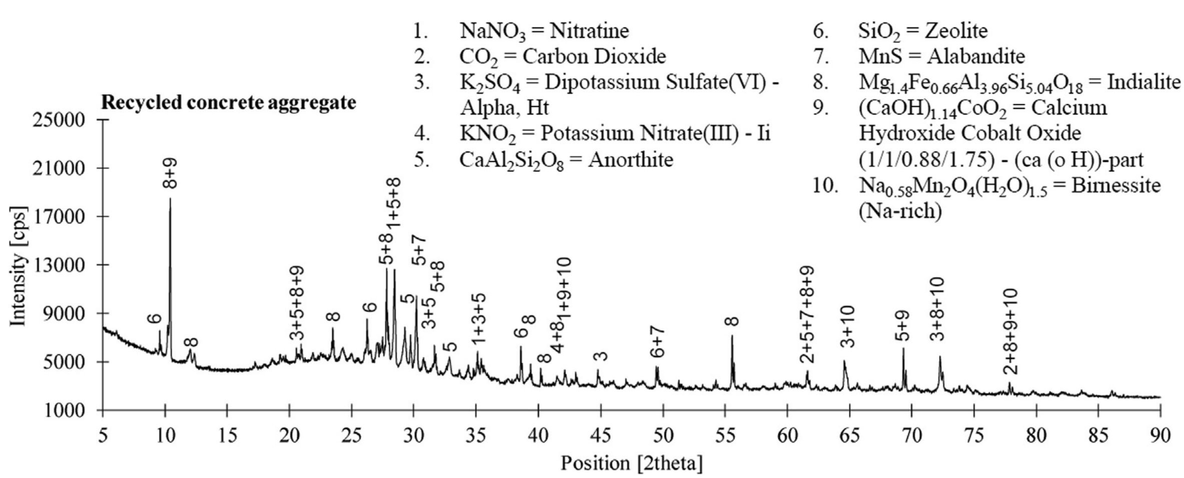

Fig. 7. XRD analysis of RCA.

[14] observed similar mineral composition in EAF slag and basic oxygen furnace slag. Biskri et al. [17] observed the calcite and metallic iron as major components of blast furnace slag aggregates.

Table 3 presents the results of XRF analysis, which provides the composition of the studied aggregates in the form of oxides. The NGA are siliceous as the amount of silica (SiO_2) is high with 44.9%. Other important oxides are alumina(Al_2O_3), calcium oxide (CaO) and iron oxide (Fe_2O_3). Small quantities of sulfates and alkalis in the form of sodium oxides are also present. These results are in accordance with XRD mineralogical composition presented in Fig. 5. On the other hand, NLA showed a higher amount of calcium oxide of 58.3%. Silica (SiO_2) and magnesium oxide (MgO) are 22.1% and 13.9%, respectively. The composition is in accordance with the XRD analysis, where calcium carbonate and dolomite($CaMg(CO_3)_2$) were the major compounds of NLA. A small quantity of alumina (Al_2O_3), iron oxides (Fe_2O_3), and alkalis (Na_2O) are also present. Sulfates are missing from the oxide composition of NLA. RCA showed the highest amount of silica. This is due to the adhered cement mortar on the surface of RCA. Sulfates, alkalis, phosphates and other impurities are present as also indicated by XRD analysis.

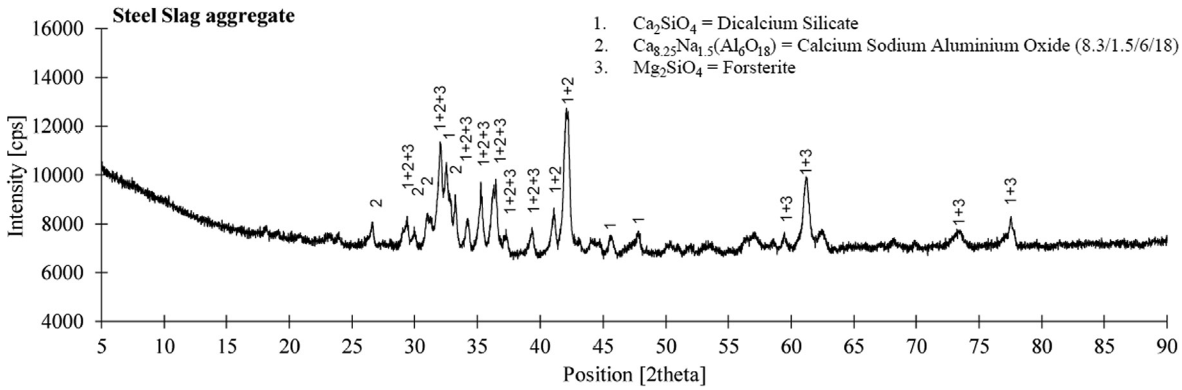

Fig. 8. XRD analysis of SSA.

Table 3
Oxide composition of NGA, NLA, SSA and RCA through XRF analysis.

Oxides	Gabbro	Limestone	Steel slag	RCA
SiO_2(%)	44.9	22.1	18.8	53.9
Fe_2O_3(%)	16.5	2	47	18.2
MgO(%)	6.7	13.9	5.8	12.5
CaO(%)	13.8	58.2	19.7	10.8
Al_2O_3(%)	15.1	1.7	3.7	1.7
Na_2O(%)	2.3	1.6	0.8	1.1
SO_3(%)	0.1	–	0.1	0.8
MnO(%)	0.1	–	1.3	0.2
Cr_2O_3(%)	–	–	0.1	0.2
K_2O(%)	–	–	–	0.2
NiO(%)	0.1	–	–	0.2
P_2O_5(%)	–	–	0.3	0.1
V_2O_5(%)	–	–	1	–
TiO_2(%)	–	–	1	–
BaO(%)	–	0.2	0.1	–
CoO(%)	–	–	0.1	–
ZrO_2(%)	–	–	0.1	–
Sb_2O_3(%)	0.1	0.1	0	–
SnO_3(%)	–	0.1	–	–
Total(%)	99.7	99.9	99.9	99.9

SSA have iron oxide (Fe_2O_3) of 47%, silica (SiO_2) of 18.2% and calcium oxide (CaO) of 19.5% as major components. As already stated, that composition could vary depending upon the steelmaking procedure. However, the values presented through XRF agree with the reported range by different researchers [9,11,17]. A higher amount of iron oxide ensures that SSA are strong and could resist higher loads before crushing. SSA also have traces of titanium oxides, vanadium oxides, chromium oxides, and phosphorous oxides. The XRF instrument is not able to detect the lighter elements' oxides, that is why the composition shown is up to 99.7% in NGA and 99.9% in other aggregates.

Table 4 presents the results of ICP-AES analysis on the acid-soluble leachates of SSA, NGA, NLA and RCA. The RCA had higher Ca^+ ions release than NGA, which is attributed to C-S-H and portlandite contents in adhered cement paste. The higher amount of silica (47%) in NGA would make it prone to react with alkalis in the concrete matrix and cause the alkali-silica gel. Fernandes et al. [66] suggested that the presence of Si and a small amounts of Fe and Mg in the cement matrix could be considered as potential ingredients/indicators of the alkali reactivity of the used rock. Heavy metals like chromium and vanadium were present in the leachates of SSA and in small amounts in RCA. These two materials are normally dumped in landfills so it is important to find out the amount of heavy and hazardous metal. The hazardous elements such as chromium, lead, zinc, and vanadium had the value of 1089 mg/kg, 0.4 mg/kg, 10 mg/kg, and 1765 mg/kg in the acid digested leachates of SSA, respectively. NSW EPA-2014 [67] recommends that SSA should not be used in concrete or other applications if acid digested chromium exceeds 2000 mg/kg. Hence the SSA obtained from Qatar Steel had much less amount of chromium. Similarly, the amounts of lead and zinc were also less than the limit recommended by NSW EPA-2014 [67]. Rondi et al. [65] studied the hazardous metal leaching from the fresh and aged SSA made through EAF process. It was observed that all the hazardous metal in SSA produced by EAF process were under the limit set by the Italian standards [68].

The pH of NGA, SSA, NLA and RCA were 11.03, 11.66, 9.69 and 10.09, respectively. For NGA, SSA, and RCA, the pH was basic. Hence, would not affect the alkalinity of the concrete matrix. However, the pH of NLA was less alkaline compared to other tested aggregates. This could play an important role in pH of concrete pore solution to be more acidic, which in turn can initiate the corrosion of the reinforcement.

3.3. Microstructure of aggregates

Fig. 9 shows the microstructure of NGA. It can be observed that the NGA have a smooth, dense, and homogenous microstructure with negligible surface porosity. Crystalline shaped plagioclase minerals are embedded in finer ferromagnesium (pyroxene) minerals. This dense microstructure is the reason for less water absorption and LA abrasion values of NGA. That is why NGA and

Table 4
ICP-AES analysis of acid dissolved elements of NGA, NLA, SSA and RCA.

Elements	NGA	SSA	NLA	RCA	Max limit [a] [67]
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Aluminum	34,394	22,138	1050.13	24,511	–
Calcium	39,684	223,297	265,427	143,429	–
Copper	51.65	90.307	4.914	42.064	40
Iron	26,093	188,722	1149.2	19,520	–
Chromium	82.545	1089.99	23.42	101.443	2000
Vanadium	72.962	1765.06	9.847	13.955	–
Lead	<0.4	<0.4	11.69	6.74	20
Magnesium	26,640	65,616	83,020	58,707	–
Manganese	598.98	13,341	157.101	314.863	–
Phosphorus	147.12	2293.58	82.227	118.205	–
Potassium	818.69	683.686	594.016	806.088	–
Phosphorus (PO_4^{3}-P)	451.09	7032.91	252.229	362.522	–
Sodium	5160.04	4757.68	1029.32	2165.45	–
Sulfur	1103.38	5538.49	5581.53	3710.22	–
Zinc	13.12	10.57	<0.04	6.128	100
Total alkali (Na_2O + 0.658K_2O)	5698.74	5207.54	1420.19	2695.85	–
Silica (%)	47.89	15.73	1.56	33.86	–
pH	11.03	11.66	9.69	10.09	7–13

[a] Limit defined by NSW EPA-2014 [67] to be hazardous to be allowed as concrete aggregates.

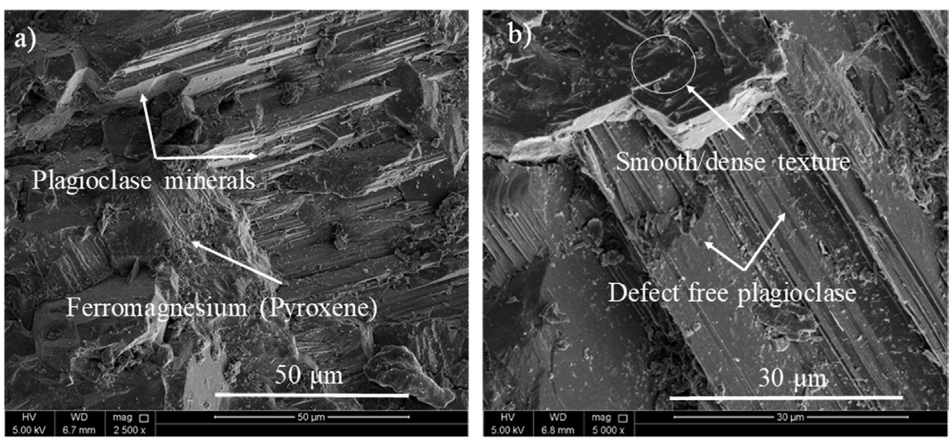

Fig. 9. SEM images of NGA at: a) 2500x and b) 5000x magnifications.

similar aggregates (i. e. diabase, basalt) offer improved durability and better strength. Fig. 10 shows the microstructures of NLA where the pores and cracks are visible on the surface. These cracks increase water absorption and result in higher LA abrasion values. Surface inhomogeneity and cracks of NLA produce low strength concrete. Efflorescence was also observed at NLA surface, which indicates the presence of chlorides and other salts.

Fig. 11 presents the microstructure of RCA where cement hydration products are visible on the aggregate surface. At higher magnification, the formations of needle-like ettringite and crystals of portlandite are visible. These impurities cause a weak ITZ between aggregates and concrete matrix and increase water absorption. This affects the mechanical and durability performance of concrete. To overcome these shortcomings resulted from the adhered mortar, researchers are proposing different solutions, such as, carbonation of RCA before using in concrete [75], exposing RCA to bacteria species that are capable of microbial induced calcium carbonated precipitation [23], treatment at high temperature or using silica fume and fly ash alongside RCA to improve ITZ of RAC [34]. Fig. 12 presents the microstructure of SSA, where a large sized-pore network could be seen with the rough surface of SSA. These pores are quasi-spherical with up to 1 mm diameter. The pores help generate better interlocking with the cement matrix, hence, increasing the compressive and tensile strengths. At higher magnification, SSA show a very rough surface with several impurities combined with iron oxide. These rough surfaces and porous structure would help increase the contact area with cement matrix, which could increase the interlocking and thus the strength of the ITZ is improved [69]. Pang et al. [69] reported dense ITZ in SSA than normal aggregates. Due to this reason and the high strengths of SSA, the compressive strength is increased when they are employed even in normal strength concrete. Furthermore, they also observed that carbonated steel slag aggregates generate even more defect free ITZ than non-treated SSA.

3.4. Effects of aggregate type on compressive strengths

Fig. 13 (a) and (b) shows the effect of aggregate type on the concrete compressive strength for concrete mixtures with w/c of 0.51 and 0.36, respectively. All the mixes presented are with no added BMF. As expected, the obtained trend in Fig. (a) and (b) revealed that the type of coarse aggregates has a significant effect on concrete compressive strength for both normal and higher strength concrete. The SSA produced concrete with the highest compressive strength. For example, SSA concrete specimens with no added BMF and w/c = 0.51 showed 36, 35 and 19% higher compressive strength than concrete made with RCA, NLA, and NGA, respectively. At the w/c of 0.36, SSA produced 29 and 21% more strength than concrete

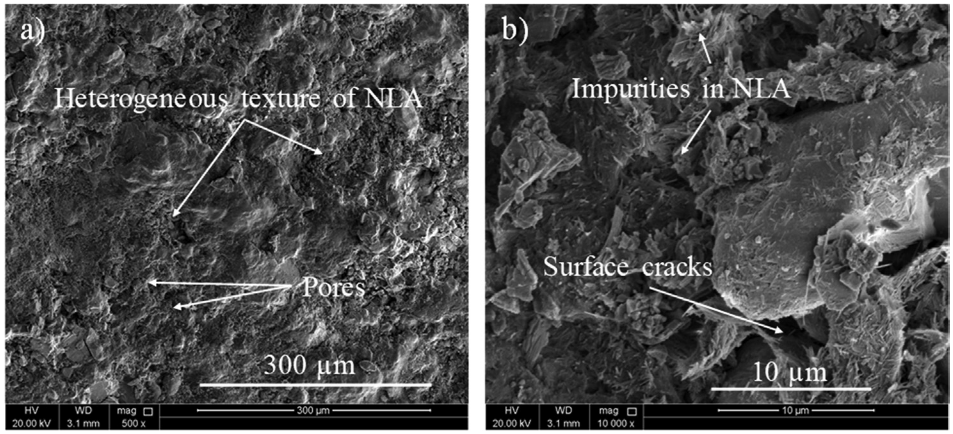

Fig. 10. SEM images of NLA at: a) 500x and b) 10000x magnifications.

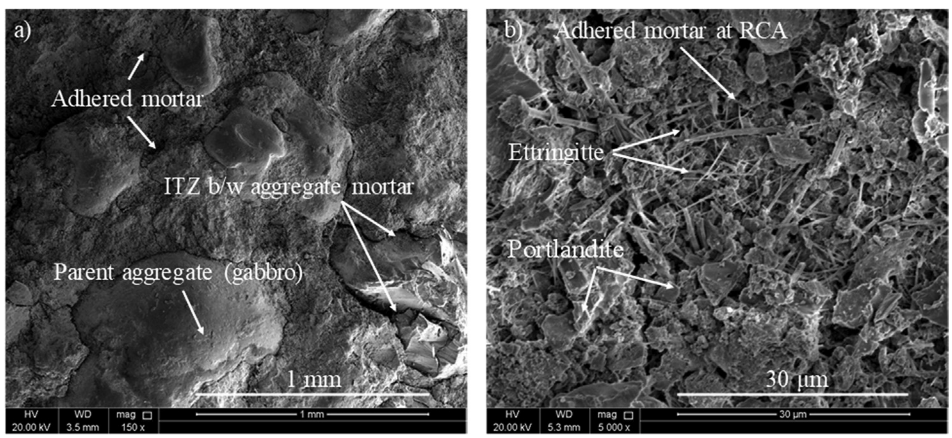

Fig. 11. SEM images of RCA at: a) 150x and b) 5000x magnifications.

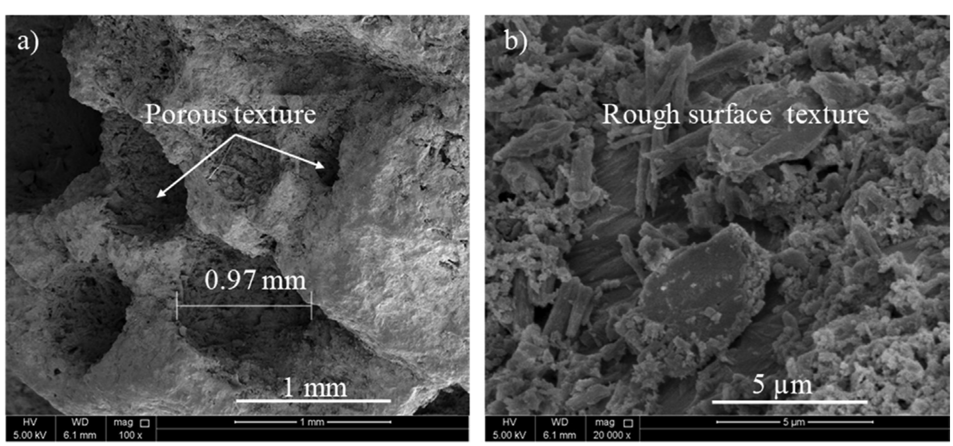

Fig. 12. SEM images of SSA at: a) 100x and b) 20000x magnifications.

with RCA and NLA. This substantial enhancement in concrete strengths when using SSA are attributed to their large pore network and very rough surface. The pores help generate a very dense ITZ between aggregate and cement matrix. Wang [70] reported the micro-hardness of ITZ near aggregates, they observed that the ITZ was denser and had higher hardness in case of SSA compared to normal aggregate, given the same concrete matrix. Large pores and rough aggregate surface also create higher interlocking with the concrete matrix. Arribas et al. [71] also observed higher hardness of ITZ around SSA, and attributed this to the slow migration of lime from the core of aggregates and its chemical reactions to form calcium carbonate rendering a better quality ITZ. In addition, SSA are very strong aggregates due to the presence of iron oxide, and would resist a major share of applied stresses. Similarly, the improved strength of NGA concrete is attributed to their angularity which produces better interlocking compared to NLA and RCA.

It can also be observed that RCA and NLA produced the least compressive strengths at same mixture proportions compared to NGA and SSA. The lower compressive strength of RCA concrete could be attributed to the double ITZ zones. One is between

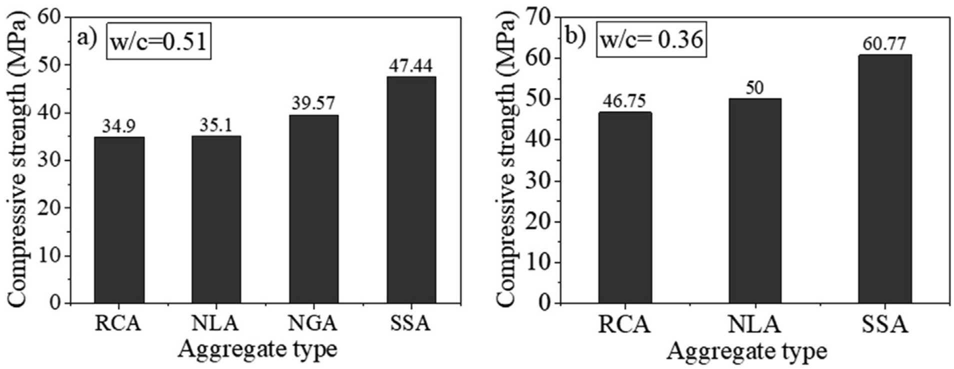

Fig. 13. Effect of aggregate type on the compressive strength of concrete, a) at w/c = 0.51, b) at w/c = 0.36.

adhered cement mortar and parent aggregate, and the second is with the whole RCA and new concrete matrix. For NLA, as indicated by SEM analysis, there were several impurities and microcracks present on the surface. These default lines would make NLA resists lesser stresses. Moreover, as the calcium ions contents are very high in NLA which results in a higher amount of portlandite in the vicinity of ITZ between cement matrix and aggregates. With lesser amount of C-S-H and higher $Ca(OH)_2$, the ITZ is weakened and could initiate the failure at smaller loads.

3.5. Effect of aggregate type on flexural strength

Fig. 14 presents the average flexural strength of plain concrete under four-point bending test. Similar to compressive strength results, SSA concrete showed 8% and 24% higher flexural strength compared to RCA and NLA concrete at w/c of 0.51. The effect was more pronounced in high strength concrete made with w/c of 0.36 (i.e. 24% higher flexural strength was achieved with SSA compared to RCA, as seen in Fig. 14 (b)). NGA generated 5% and 22% higher flexural strengths than RCA and NLA at 0.51 w/c, respectively. The improved flexure strengths in SSA and NGA concrete samples are attributed to their dense ITZ, which improves the transfer of the stresses from concrete matrix to aggregates. Moreover, the higher mechanical interlocking helps in the stress transfer and improves the strength of concrete.

3.6. Effect of BMF on compressive strength

Another aim of the study was to observe whether BMF could improve the concrete made with NLA and RCA. Fig. 15 shows the compressive strength of all the aggregates at different volume fractions of BMF. It was observed that increasing the % V_f of BMF resulted in an improvement in the concrete compressive strength regardless of the type of aggregates. Comparing the compressive strength with 0% BMF to 0.25%, at w/c of 0.51, the compressive strength was increased by 17.5, 3.9 and 5.7% in concretes with NGA, SSA, and RCA, respectively. However, the compressive strength was decreased in concrete with NLA, this might have originated from an error in mix design calculation or mishandling during mixing and pouring of concrete. With 0.5% V_f of BMF, an increase of 11.4, 6.3, 4 and 6.3% in compressive strength was observed for SSA, NGA, NLA and RCA, respectively. While with 1% V_f of MBF, the increase in compressive strength was 15.4, 15.7, 9.5, and 6.2% in NGA, SSA, NLA and RCA, respectively. While at w/c of 0.36 and 1% V_f of MBF, the increase in compressive strength was 13.7, 11, and 17.4% increase in NLA, RCA, and SSA, respectively were observed. This enhancement can be attributed to the localized reinforcing ability of BMF, as their presence in the concrete matrix around coarse aggregates halts the widening of the microcracks already existing in the concrete. This resulted in improving the both compression and tension straining capacity of the concrete. However, the improvement in the tensile straining capacity is more pronounced compared to the compressive strain capacity.

In light of these results, it is worth mentioning that changing the concrete mixture from 0% V_f of BMF with w/c ratio of 0.51 to 1% V_f with w/c of 0.36 resulted in an increment of 62 and 49% in the compressive strength of concrete made with NLA and RCA, respectively. These results show that even though NLA and RCA aggregates possess lesser strength and have several impurities, a good quality concrete can be manufactured in combination with BMF and appropriate w/c ratio.

3.7. Effect of BMF on flexure strength

Fig. 16 presents the effect of BMF on the flexural strength of concrete. As could be noticed, adding BMF to concrete mixtures

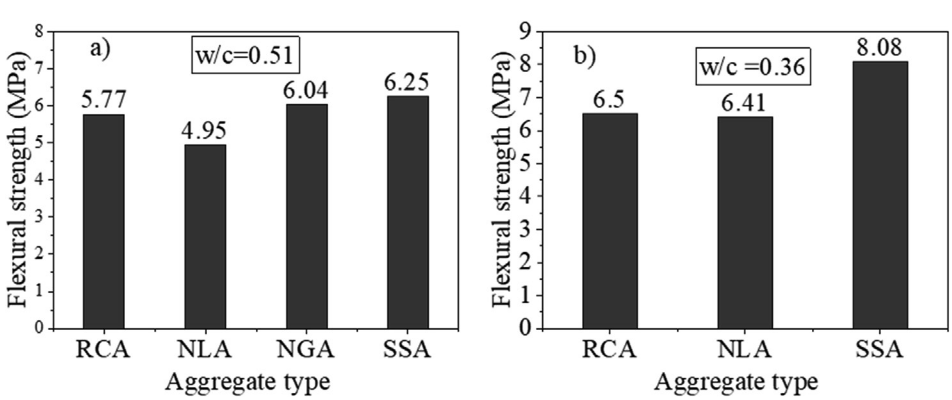

Fig. 14. Effect of aggregate type on the flexural strength of concrete, a) at w/c = 0.51, b) at w/c = 0.36.

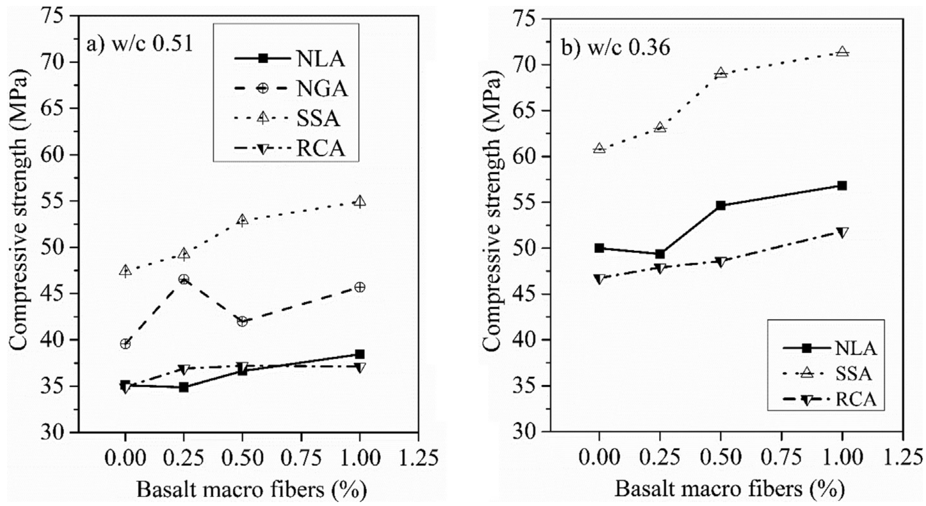

Fig. 15. Compressive strength values for all types of aggregates at different fiber volume fraction, a) at w/c = 0.51, b) at w/c = 0.36.

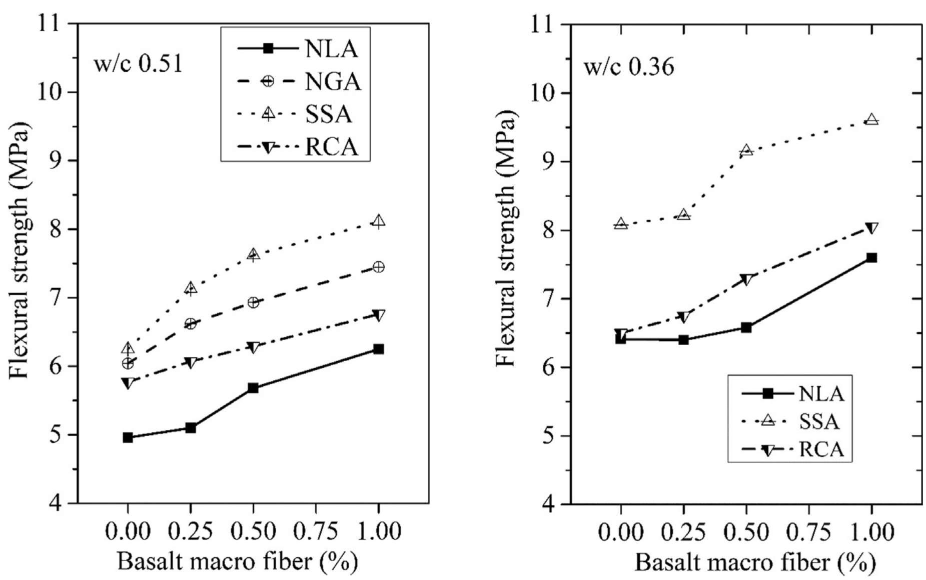

Fig. 16. Flexural strength for all types of aggregates at different fiber volume fraction, a) at w/c = 0.51, b) at w/c = 0.36.

resulted in a significant improvement in their flexural capacities compared to their plain concrete counterparts regardless of the type of aggregates. In concrete manufactured using NLA, an increase of 2.9, 14.5, and 26% was observed when $V_f$of 0.25, 0.5 and 1% were employed, respectively. For SSA concrete, the increment was 14, 21 and 29%. For NGA concrete, it was 9, 14 and 23%, while for RCA concrete, 5, 9 and 17% increase was observed when BMFs were added by 0.25, 0.50 and 1% by volume of concrete, respectively. It is worth to note the addition of 1% of BMF to RCA concrete with w/c = 0.51 resulted in a higher flexural strength than that of SSA and NGA concrete with no added fibers. In addition, as expected, reduction in w/c ratio further improved the flexural capacity of concretes. When w/c was reduced from 0.51 to 0.36 in concrete with no added fibers, an increase in flexural strength of 29, 29, and 12% was observed in concrete with NLA, SSA and RCA, respectively.

The enhancement in the flexure strength was more pronounced compared to the compressive strength with the addition of BMF. Furthermore, the aggregates having higher compressive strengths themselves showed better improvement in compressive and flexural strengths with the addition of BMF. This could be attributed to the fact that fibers improve the ITZ, and could bridge the crack development. Fibers would also help in distributing the stresses away from the ITZ.

4. Conclusions

In order to emphasize the suitability and benefits of using RCA and SSA in concrete manufacturing, their physio-chemical properties were assessed in comparison to the locally available NLA and imported NGA. The XRD, XRF, SEM and ICP-AES analysis were performed to investigate the chemistry and morphology of these aggregates, which could play an important role in concrete' strength and durability. The effect of aggregates type on compressive and flexure strengths was studied. The following conclusions are inferred from this study;

- The physical properties of SSA such as moisture contents (1.06%), flakiness index (1%), elongation index (13%), LA Abrasion (14.86%), and soundness in magnesium sulphate (0.5%) are below the standardized limits set by different international codes (QCS-2014, ACI −318).

- Compressive and flexural strengths of concrete are improved by using SSA. This enhancement was more pronounced on high-strength concrete specimens with w/c = 0.36. The microstructure of the SSA indicated a very porous structure with a pore size up to 1 mm. These pores and surface roughness generate a better aggregate interlocking and would improve the interfacial transition zone between aggregates and cement matrix.
- Another major conclusion of the study is that the low-strength and low-quality concrete produced by NLA and RCA could be improved by incorporating BMF. Both compressive and flexural strengths of concrete were improved with the addition of BMF. However, the improvement was more pronounced in the flexural strength of the FRC specimens.
- NGA showed relatively dense, defect free, and least porous microstructure compared to the NLA, SSA, and RCA.
- SEM images of NLA showed a porous and weak structure. This causes lower strength concrete when using NLA. Similarly, RCA showed very heterogeneous microstructures. Moreover, the type of aggregates used in parent concrete debris immensely affects the properties and behavior of RCA in concrete. High LA abrasion value and high water absorption were observed in RCA. That is why RCA produced lower strength concrete compared to steel slag, gabbro, and limestone aggregates.
- SSA showed only 0.5% aggregates-soundness value under magnesium sulphate test, and zero disruption ratio (no expansion cracks or breaking) under autoclave test. While NLA showed 13% of aggregates soundness in magnesium sulphate, which is also well below recommended value of 18%.
- The leaching of hazardous metal such chromium, vanadium, lead, and zinc from SSA and RCA were well below the limit set by NSW Environment Protection Authority-2014.

Finally, this study showed that both SSA and RCA showed promising potential as sustainable alternative aggregates to have a cleaner production of concrete. However, further studies are essential to investigate the long-term behavior of concrete made with SSA or RCA.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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