Self-compacting geopolymer concrete with spend garnet as sand replacement

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ABSTRACT

Garnets being the waste spin-off of surface treatment operations remain a major environmental concern worldwide. Robust engineering properties of these waste garnets offer the opportunity to get efficient construction materials via their appropriate recycling. In this spirit, we evaluate the capacity of spent garnets as sand replacement for achieving self-compacting geopolymer concrete (SCGPC). Such SCGPC specimens are prepared using ground granulated blast furnace slag (GGBFS) wherein the river sand is replaced by spent garnet at varying contents (0–100%) under constant Liquid/Binder (L/B) mass ratio of 0.4. Performance evaluations of the developed SCGPC samples are made using several tests including durability, workability, flexural, compressive, splitting tensile strength conforming the EFNARC standard. Test results revealed an enhancement in the workability of the proposed SCGPC specimen with the increase of spent garnet contents. Furthermore, other strengths are discerned to be lower compared to the control sample at all stages of replacement. It is established that the spent garnet is prospective candidate for sand replacement up to 25% in terms of environmental amiability, cost effectiveness and conservation of natural resources.

1. Introduction

Lately, intensive researches have proven that modified concretes obtained via waste materials incorporation can lead to sustainable product development. Such concrete structures not only allow greener environmental growth in the construction sector but also protect the excessive consumption of natural fine aggregates that depletes the innate resources [32]. Rapid industrial growth has witnessed the ever-increasing utilization of river sand for building purposes where river beds are worn-out. Several problems are emerged including the increase of river bed depth, lowering of the water table, increasing salinity and destruction of river embankments [10]. Thus, exploration of alternative materials as a fine aggregate in concrete to replace the river sand became an absolute necessity. In this regard, garnets are emerged as a promising candidate to fulfil such requirements.

The generic word so called "garnet" refers to a group of complex silicate minerals having analogous lattice crystalline structures and varied chemical compositions [3]. Interestingly, the angular fractures and hardness properties of garnets together with their ability to be recycled make them advantageous for numerous abrasive functions. Garnet has chemical composition of $A_3B_2(SiO_4)_3$ [A: Ca, Mg, Fe or Mn; B: Al, Cr, Fe or Ti]. Garnets have major industrial uses such as water jet cutting, abrasive blasting media, water filtration granules, abrasive powders, etc [9]. A recent assessment on a Malaysian shipyard industry revealed that this country imported $\approx$ 2000 million tons of garnets in the year 2013 alone and a large quantity was dumped as wastes. Generally, abrasive blasting technique is used to prepare the surfaces for coating and painting [26]. This technique is used for the construction of vessels, ship maintenance and repair activities. Thus, blasting process creates large quantities of exhausted garnet wastes mixed with surface elements such as paint chips and oil. Such garnet wastes cause many environmental and health hazards such as water contamination when these materials are entered in the waterways during flood or through runoffs. Therefore, spent garnets pose a threat to the ecological balance and biodiversity.

Garnets can be reused about 3–5 times keeping their overall properties intact. Finally, these recycled garnets degrade to an extent where they cannot be further reutilized for abrasive discharge. Then, they are

taken away from the shipyards and designated as "spent garnet" [6]. Recently, it is recognized that the exploitation of these spent garnets as replacement for fine aggregates in SCGPC may open up new avenue towards the realization of alternative construction materials to the conventional Portland cement (PC) based concrete. Universally, PC due to its good mechanical properties, approximately low cost, easy availability and good durability is the most commonly applied binder for the manufacture of construction materials. Thus, PC concrete is preferable in diversified applications [4]. Nonetheless, the production of PC has some main obstacle such as the depletion of natural habitats, manufacturing of fossil fuels, and huge amount of CO_2 which is released and other greenhouse gases unless inhibited. To surmount these limitations, many dedicated efforts are made to search for efficient alternative method such as alkali-activated materials (AAMs) (often interpreted as geopolymer) [23].

It is realized that the spent garnets may be advantageous for sustainable development compared to PC (the principal binder) upon their usage as a partial precursor substance. Additionally, based on the implemented raw minerals and alkaline substances, the final outcome displays improved characteristics than PC concrete. Some of the modified properties include low heat of hydration, swift development of early strength, formation of strong aggregates–matrix boundary, low thermal conductivity, high resistance against acid and fire attack [24]. Generally, alkali activated materials are classified in two categories: (a) a high calcium system with usual precursor such as GGBFS, where the primary chemical product is the C-A-S-H type gel, (b) raw materials with low Ca substance, Class F fly ash (FA) and metakaolin wherein the main reaction product is the 3D-network based N-A-S-H type gel [15].

Categorically, self-compacting concretes (SCCs) flow that under their own weight without requiring any external vibration for compaction has revolutionized the concrete placement. SCC was first introduced in the late 1980s by Japanese researchers. It was asserted that being an extremely practicable concrete, SSC can stream throughout constrained segments with no separation or flow [14]. Comparatively lower yield of these concretes ensures their elevated flow capacity, modest viscosity to stand firm against separation and bleed. On the top, they must retain the homogeneity throughout transport, insertion and cure to guarantee a sufficient structural feat and endurance.

Despite many researches toward sand replacements for concrete infrastructures exploitation of spent garnet waste as construction material product is seldom focussed. Considering these notable engineering properties of spent garnet waste we explore the feasibility of incorporating different levels of spent garnet as a replacement for river sand to achieve an enhanced SCGPCs. Synthesized SCGPC specimens are thoroughly characterized to determine their compressive, flexural, splitting tensile strengths, durability and workability as a function of varying percentages of spent garnet inclusion.

2. Materials

2.1. Spent garnet

In this study, the spent garnet was obtained from southern Johor (Malaysia). These heavy minerals sand being the category of ore deposits remain the main source of rare-earth building blocks and engineering minerals. Such ore deposits are typically appeared in beaches according to their contents involving the minerals specific gravity [12]. Total heavy mineral (THM) components typically contain 1–50% of Zircon, 10–60% of Ilmenite, 5–25% of Rutile and 1–10% of Leucoxene [13]. The remaining bulk of the THM is comprised of trash minerals such as magnetite, chromite. It is worth mentioning that the beach sands are the most recently originated mineral deposits that are originated in the southern hemisphere because of continental drift. Actually, the movement among dissimilar plates and repetitive thermodynamic processes including heating and cooling fracture the rocks, allowing water penetration and subsequent formation of erosion mediated
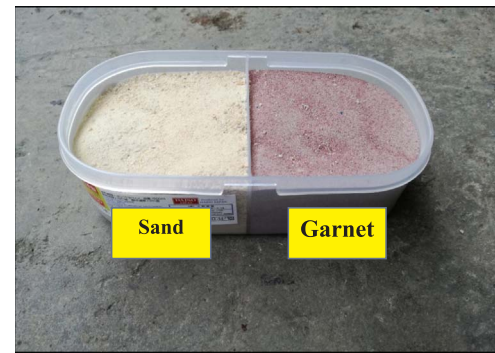

Fig. 1. Fine aggregate used in the concrete production.

deposits [28]. The weathering and erosion of the parent rocks allow them to transfer with the water and eventually sediment in an appropriate sea basin. Persistent attrition occurs because of the flow of air and water where the concentrations keep on increasing over time. The erosion regions of the river are the major source of heavy mineral sands where the worn-out minerals flow into the ocean water and thereby the deposits are trapped in a stretched shoreline drift [31]. These heavier rocks are often worn out straight by sea tides spread onto the beaches, while the lighter minerals are blown by the wind. Thus, the resources of rocks and the composition decide the economy of the minerals produced. Granite is usually the resource of Rutiles, Zircons, Monazites, as well as few Ilmenites. Garnet is mostly obtained from metamorphic rocks and precious metals are deposited inside such rocks [7]. A visual appearance of spent garnet and sand used as fine aggregate are shown in Fig. 1.

2.2. Physical and chemical properties of the materials used

The spent garnets used in the present work were stored in plastic bags (air tight) inside chamber under controlled humidity. Table 1 enlists the physical properties of the materials used. All the tests were conducted following the National Code 2nd Edition [20].

Fig. 2(a) and (b) show the results of FESEM for garnet and natural river sand. Throughout the mixing procedure, the spent garnet was kept on the saturated surface dry to diminish the absorption of water. Furthermore, the garnet was separated via 2.35 mm sieve and maintained at 212 μm. Fig. 3 illustrates the sieve dependent percentage passing of the garnet. The GGBFS was acquired from a source in Johor (Malaysia). The presence of enriched aluminosilicate, economic and abundant nature of slag makes them suitable for the manufacturing of geopolymer concrete. Table 2 summarizes the chemical composition of the spent garnet and slag obtained from the X-ray fluorescence measurement.

2.3. Leaching test

The contents of weighty metals such as As, Ba, Cd, Cr, Pb, Se, Ag, Zn and Cu in the raw garnet are tested to guarantee the materials safety. Poisoning Characteristics Leaching Procedure (TCLP) established by the United States Environmental Protection Agency (US EPA) in employed

Table 1
Physical properties of used garnet and river sand.

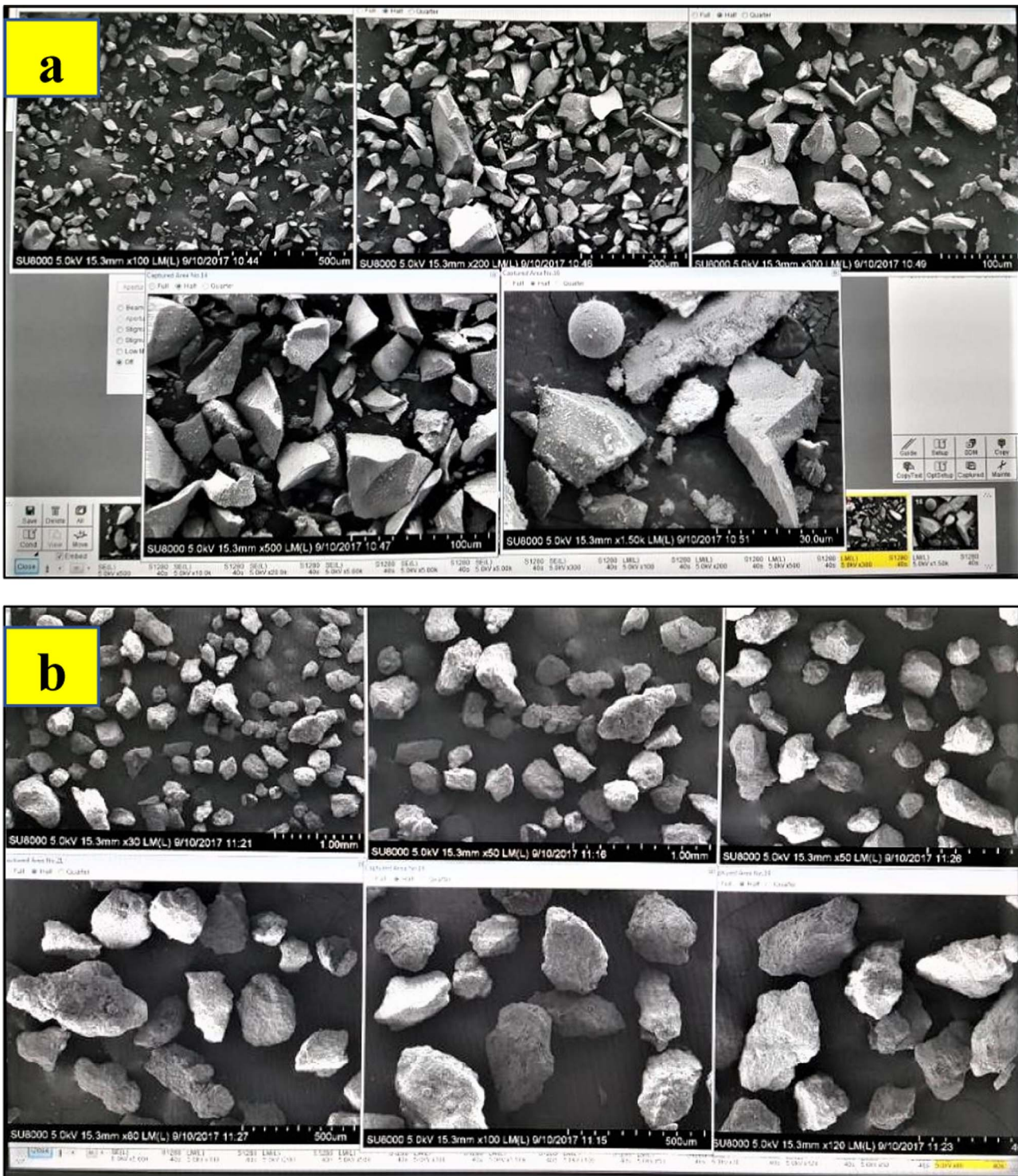| Properties	Garnet	River sand
pH	8.3	7.25
Melting point	1250 °C	1649 °C
Specific gravity	2.9	2.6
Hardness	7.5–8.0 Mohs	5 − 6 Mohs
Bulk density	2.3 t m^{-3}	1.64 t m^{-3}
Water absorption	6%	3%

Fig. 2. Field emission scanning electron microscopy (magnification 35 X) for (a) garnet (b) natural river sand.

to determine the contents of weighty metals in the garnet (Table 3). Two test samples were agitated with the revolution of 30 rpm for 24 h (Fig. 4). The weighty metals concentrations were discerned to be lower than the control limits. Thus, the spent garnet used in this study can be considered as safe material [18] with the following specifications (Table 3):

Lor: Level of reporting
NR: Non-Reactive (Cyanides < 250 mg kg^{-1}, Sulphides < 500 mg kg^{-1})

USEPA: United States Environmental Protection Agency
Std*: Maximum concentration for the toxicity characteristic Leaching Procedure (TCLP)

2.4. Fine and coarse aggregates

Locally obtained sand having specific gravity of 2.62 was used under saturated surface dry condition to guarantee that water cement ratio remains unaffected. The sand replacing ratio with the spent garnet was selected to be 25%, 50%, 75% and 100%. Crushed granite obtained
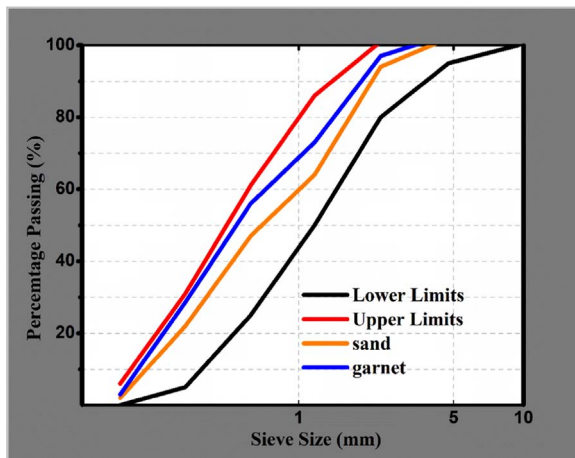
Fig. 3. Sieve analysis of the spent garnet.

Table 2
Chemical composition of the spent garnet and GGBFS obtained from XRF analysis.

Chemical compounds	Garnet (%)	GGBFS (%)
Fe_2O_3	43.06	0.4
SiO_2	33.76	33.80
Al_2O_3	13.88	13.68
CaO	4.15	43.2
MgO	2.91	0.46
K_2O	0.14	0.21

Table 3
TCLP analysis of spent garnet.

Analysis description	Units	Lor	Std*	Garnet
Corrosivity (PH)	–	0.1	5.5–12	8.3
Ignitability (flash Point)	˚C	1	–	> 300
Reactivity (HCN & H_2S)	mg/kg	1	–	NR
After Toxicity, Characteristic Leaching procedure (TCLP) Extraction				
Arsenic	Mg. l^{-1}	0.05	5	< 0.05
Barium	Mg. l^{-1}	0.1	100	0.6
Benzene	Mg. l^{-1}	0.005	0.5	< 0.005
Cadmium	Mg. l^{-1}	0.01	1	< 0.01
Carbon Tetrachloride	Mg. l^{-1}	0.005	0.5	< 0.005
Chlordane	Mg. l^{-1}	0.005	0.03	< 0.005
Chlorobenzene	Mg. l^{-1}	0.005	100	< 0.005
Chloroform	Mg. l^{-1}	0.02	6	< 0.02
Chrornium	Mg. l^{-1}	0.01	5	< 0.01
Cresol	Mg. l^{-1}	0.05	200	< 0.05
2,4-D	Mg. l^{-1}	0.05	10	< 0.05
1,4-D Dichlorobenzene	Mg. l^{-1}	0.05	7.5	< 0.05
2,4-Dinitrotoluene	Mg. l^{-1}	0.05	0.13	< 0.05
Endrin	Mg. l^{-1}	0.005	0.02	< 0.005
Heptachlor (and its epoxide)	Mg. l^{-1}	0.005	0.008	< 0.005
Hexachlorobenzene	Mg. l^{-1}	0.05	0.13	< 0.05
Hexachlorobutadine	Mg. l^{-1}	0.05	0.05	< 0.05
Hexachloroethane	Mg. l^{-1}	0.05	3	< 0.05
Lead (Pb)	Mg. l^{-1}	0.05	5	< 0.05
Lindane	Mg. l^{-1}	0.05	0.4	< 0.05
Mercury	Mg. l^{-1}	0.001	0.2	< 0.002
Methoxychlor	Mg. l^{-1}	0.05	10	< 0.05
Methyl ethyl Ketone	Mg. l^{-1}	0.05	200	< 0.05
Nitrobenzene	Mg. l^{-1}	0.05	2	< 0.05
Pentachlorophenol	Mg. l^{-1}	0.05	100	< 0.05
Pyridine	Mg. l^{-1}	0.05	5	< 0.05
Selenium	Mg. l^{-1}	0.1	1	< 0.1

from the quarry were used as coarse aggregates with specific gravity of 2.66 and water absorption of 0.5% was used as coarse aggregate in all the mixes.

3. Experimental details

3.1. Mixture proportion

Table 4 summarizes the mix ratios design in consistent with the particularization of the British Standards and EFNARC guidelines. The binder devoid of cement was prepared utilizing GBFS obtained from Ipoh (Malaysia). The coarse aggregates were grounded granite minerals with a highest size of 10 mm and a specific gravity of 2.66 in saturated surface-dry (SSD) states. In geopolymer synthesis, the nature of alkaline solution decides the dissolution of silica and alumina present in the source material, and the catalysis of the polymerization reaction. In this study, a mixed solution of alkaline NaOH and Na_2SiO_3 was selected. Highly pure analytical grade reagents of Na_2SiO_3 (Grade A53) with water content of 55.52%, SiO_2 content of 29.75%, and Na_2O content of 14.73% was used. For achieving the activator solution, pellets of NaOH (99% purity) was dissolved with distilled water minimum one hour to neutralize the influence of impurities. The solution molarity for every mix was fixed at 8 M, where 1 kg of this solution required 36.1% of pellets. A superplasticizer (Sika Visco Crete-3430) of 3.28% of binder was used to get the appropriate workability for fresh SCGPC. Following EFNARC 2002 the tap-water was added to the mix. Five SCGCP mixes with garnet ratios of 0%, 25%, 50%, 75%, and 100%, designated by TR0, TR1, TR2, TR3, and TR4, respectively were prepared to inspect the effects of garnet as a substitute for sand on the specimens' fresh and hardened characteristics. Irrespective of mixes, the ratio of Na_2SiO_3 to NaOH solution by mass was kept at 2.5, and the mass ratio of the fine aggregates to the GBFS was 2.125. The mechanical properties of these freshly prepared SCGPC concrete mix was evaluated using essential workability tests such as Slump flow, V- funnel, and L-box.

3.2. Specimen casting

For each SCGPC specimens in the form of cubes with sides 100 mm, cylinders of dimension (100 mm × 200 mm), and prisms of dimension (100 mm × 100 mm × 500 mm) were prepared. Experimental specimens in the form of cubes, prisms, and cylinders were tested to determine the compressive strength, the tensile strength and the flexural strength, respectively. All the samples were moulded after 24 h of casting and subsequently kept in the air at room temperature until the testing age was attained.

3.3. Test results on the fresh properties of SCGPC

The SCGPC specimens' fresh performances were assessed in terms of three abilities such as filling, passing, and segregation resistance. These properties were determined using various tests including slump flow, T50 cm slump flow, V-funnel, and L-box as emphasized hereunder.

3.3.1. Slump flow test
Fig. 5 showed slump flow test. Generally, this test is performed to evaluate the flow ability of SCGCP. The equipment for this test was comprised of traditional slump cone and the concrete placed in the mould was untamped. The test was conducted by putting the slump cone onto non-absorbent and rigid levelled, which was then filled with concrete under non-tamped condition. Afterward, it was aligned in to a vertical arrangement so that the concrete could flow out liberally. The concrete diameter was estimated in two mutually perpendicular directions to calculate their averages. The slump flow value was obtained following the EFNARC standards, where SCGCP is considered to possess good capacity of filling and consistency for diameter spreads range between 650 mm and 800 mm. Table 5 enlists the test results [5].

3.3.2. T50 cm slump flow
In this test, the time (seconds) taken is measured upon raising the cone up to a level to ensure the flow spread attainment at 500-mm

Fig. 4. leaching test.

Fig. 5. Slump flow test.

circle. This flow time also known as the T50 cm Slump flow. It is a measure of the relative viscosity and renders a comparative evaluation of the SCGCP free flow rate where shorter time signifies better flow ability.

It is worth noting that longer T50 time is less significant and varies rapidly for high viscous specimens. Usually, this test is not utilized as a rejection aspect for a SCGPC group, however used as a quality control yardstick. Table 5 depicts the results obtained from this test [5].

3.3.3. L-box test

This test is utilized to evaluate the capacity of SCGPCs filling and passing. The L-box equipment consists of an L-shaped box having a horizontal and vertical section isolated by a portable door and vertical reinforcement bars are placed in front of the door. Prior to the test begun, the L-box was put on a fixed levelled ground and its vertical section was filled with concrete, where the door isolating the horizontal and vertical sections was lifted. Next, the concrete was flown through the narrowly separated reinforced bars at the bottom of the box. The blocking ratio (H_2/H_1) was calculated by measuring the height of the concrete at the edges of the horizontal (H2) and vertical (H1) sections. when the concrete stops flowing. Table 5 summarizes the results obtained from this test [5].

3.3.4. V-funnel test

This test was mainly used to measure the filling ability (flow ability) to evaluate the segregation resistance of SCGPC specimens where the equipment consisted of a V-shaped funnel. Around 12 l (0.4 ft^3) of concrete was used to fill the funnel completely with it without any compaction or tapping. Then, the trapdoor at the bottom was opened where the gravity allowed the concrete to flow out. The time taken for all the concrete to flow out through the orifice was recorded as the funnel flow time. A funnel flow time of between 6 and 12 s was required for SCGPC. Table 5 depicts the results acquired from this test [5].

3.3.5. Field emission scanning microscopy

The surface morphology (microstructures) of the synthesized SCGPC samples was captured using FESEM imaging (GEMINI model).

Table 5
SCGPC acceptance criteria as per EFNARC standard.

Mix no.	Slump flow (mm)	T50 cm slump flow (s)	V-funnel (s)	L-box ratio (H_2/H_1)	Compressive strength 28 days	Remark as per EFNARC specification
TR0	671	5.5	12	0.91	79.84	Ok
TR1	675	5	11.5	0.92	78.21	Ok
TR2	681	4.5	11	0.93	76.32	Ok
TR3	692	4	7.5	0.95	75.45	Ok
TR4	700	3.5	6.5	0.97	70.32	Ok
Minimum	**650**	**2**	**6**	**0.8**	Acceptance criteria as per EFNAR
Maximum	**800**	**5**	**12**	**1**	

3.4. Durability analyses

3.4.1. Drying shrinkage test

This test was performed on three concrete prisms of dimension (100 mm × 100 mm × 500 mm) following the specifications of ASTM C157 where the length and the setting were slightly varied. Digital gauge studs were clumped on the sample at a separation of 100 mm using demec gauge. The sample was preserved in the humidity-controlled chamber at relative humidity of (51 ± 4 and temperature of (24 ± 1) ˚C. Subsequent readings registered for 7, 28 and 90 days to calculate the averages.

3.4.2. The water absorption

This test was performed on hardened SCGPC cubic specimens (BS 1881: Part 122, 1983; [2]) each of dimension 100 mm × 100 mm × 100 mm cured for 28 days. Then, the cured specimens were first oven dried at (105 ± 5) ˚C for (72 ± 2) h and subsequently cooled down to room temperature in a dry airtight chamber for (24 ± 0.5) h before being weighed. Next, the cooled SCGPC specimens were submerged for (30 ± 0.5) min inside a tank filled with potable water. Afterward, every SCGPC specimen was isolated, shaken thoroughly, and free water was removed by wiping with a cloth. Again, it was weighed to determine the

Table 4
Mix proportions design (kg/m^3).

Mixes	AS/B	Slag	Sand	Garnet	Coarse	NaOH	M	Na$_2$SiO$_3$	SP	E. W.
TR0	0.4	475	950	0	890	58	8	145	15.6	62
TR1	0.4	475	712.5	237.5	890	58	8	145	15.6	62
TR2	0.4	475	475	475	890	58	8	145	15.6	62
TR3	0.4	475	237.5	712.5	890	58	8	145	15.6	62
TR4	0.4	475	0	950	890	58	8	145	15.6	62

M = Molarity, E.W. = Extra Water, AS/B = Solution/Binder.

percentage (*W*) of water absorption via the expression:

W = (Ww − Wd)/Wd × 100%

where Ww and Wd are the weight of wet and dry specimen, respectively.

3.4.3. Carbonation depth

Following the procedure of BS 1881-210:2013, the accelerated carbonation test was performed in a chamber by exposing the SCGPC specimens in the carbonated environment. This set up used a plastic box connected to a CO_2 gas cylinder. The SCGPC specimens under test were first vacuumed inside the chamber to a pressure of 600 mmHg at 55–60% relative humidity for 3 min. Then, CO_2 gas was passed through the container at 26 °C and 4% pressure for 60 days duration. The pressure inside the curing plastic box was permanently monitored using digital pressure gauge positioned between the CO_2 cylinder and the gas plastic box. Two cylindrical SCGPC samples of dimension 100 mm × 200 mm were tested. After 60 days of storage in the CO_2 chamber these samples were divided into two parts. Later, phenolphthalein solution with concentration of 1% was sprayed on the cubic cross sections. The un-carbonated area revealed purple colour and the carbonated area stayed colourless. eventually, the carbonation depth of the sample was determined by calculating the distance between the purple colour boundary and the boundary of the sample.

3.4.4. Acid resistance test

Synthesized SCGPC in the form of cubes of dimension 100 mm were prepared and cured in the air at room temperature for 28 days before being immersed in 5% H_2SO_4 solution. Before immersion, these cubic SCGPC specimens were dried at room temperature for 48 h and weighed. The acid solution was altered periodically in every 4 weeks interval to maintain the solution concentration fixed. The resistance of these SCGPC specimens against acidic environment were assesses in terms of mass loss performance.

4. Results and discussions

4.1. Fresh properties of SCGPC

Table 5 provides the fresh properties of the prepared SCGPC specimens obtained using slump flow test, L-box test, and V-funnel test. The mix sample TR0 was selected as control sample whereas the TR1, TR2, TR3 and TR4 specimens were chosen as the spent garnet samples. The quantitative and qualitative analysis indicated that all the concrete mixes achieved the desired fresh properties which conformed to the EFNARC limits of SCGC [5]. Slump flow, T50, L-box test and V-funnel values (Table 5) of the proposed SCGPC specimens revealed that substitution of the spent garnet for the river sand could enhance the workability of the concrete. Compared to control, the slump flow of SCGPC was found to enhance as much as 29% when the garnet level in the concrete mix was increased to 100%. The fresh usual GPC was less cohesive as well as workable than GPC consisted of spent garnet. This observation was ascribed to the shape, surface morphology and the particle size distribution of the garnet that modified the overall fresh state behaviour of the concrete [16]. Moreover, the fineness modulus of garnet (2.05) was much less than the minimum value (2.3) that of sand as specified by ASTM C33 standard.

4.2. Compressive strength

Table 6 summarizes the values of the compressive strength for the control and the spent garnet concrete mixes. Results revealed that the compressive strength of the garnet concrete was lower than the control during all of curing durations. Decrease in the ratio of compressive strength than the control after 28 days was discerned to be − 2.04%, − 4.41%, − 5.50%, and − 11.92% for TR1, TR2, TR3 and TR4

Table 6
Curing time dependent compressive strength of synthesized SCGPC specimens.

Mix	Compressive strength (MPa)		
	3 days	7 days	28 days
TR0	70.24	73.29	79.84
TR1	71.63	73.13	78.21
TR2	67.50	70.42	76.32
TR3	65.91	69.18	75.45
TR4	61.42	66.23	70.32
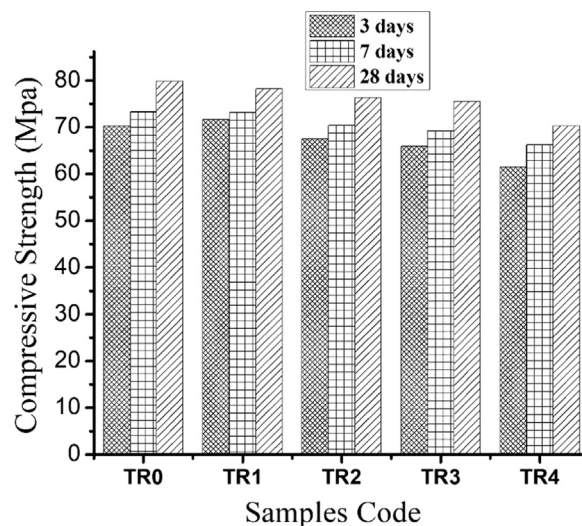
Fig. 6. Curing time dependent compressive strength of various SCGPC specimens.

specimens, respectively. This reduction in the compressive strength was majorly attributed to the fineness of spent garnet particles, lacking appropriate gradient and shape to fill the pores and optimize the pores structure. However, the coarse and angular texture of the spent garnet materials enhanced the bonding between the slag and aggregates interface, causing the high strength [30]. This behaviour may be likely explained by considering the onset of the Interfacial transition zone between the largest sand particles and the geopolymeric matrix. However, the compressive strength results are in agreement with previous papers [17] and [11].

Fig. 6 displays the curing time dependent compressive strength of various SCGPC specimens. The strength of the GPC was decreased as the percentage of garnet was increased, where the substitution of normal sand with spent garnet up to 100% was favourable for producing GPC due to the absence of strength degradation. However, SCGPC specimens casted with 25% spent garnet substitution for normal sand yielded the maximum strength all over the curing period and thereby selected as the best mixture.

4.3. Splitting tensile strength

Fig. 7 shows the splitting tensile strength of the prepared SCGPC. The splitting tensile strength of the GPC was decreased with increasing percentages of the spent garnet. The tensile strength values were decreased after 7 and 28 days of curing. Besides, sudden declination in the splitting tensile strength of the SCGPC was observed. The values of the splitting tensile strength for TR1, TR2, TR3, and TR4 specimens after 28 days were dropped by − 13.51%, − 22.78%, − 23.47%, and − 32.28%, respectively which were lower than that of control mixture. The decrease in tensile strength with increasing inclusion of spent garnet into the mix was ascribed to the weakening of the bonding between the spent garnet particles of tiny sizes and the binder paste [15].
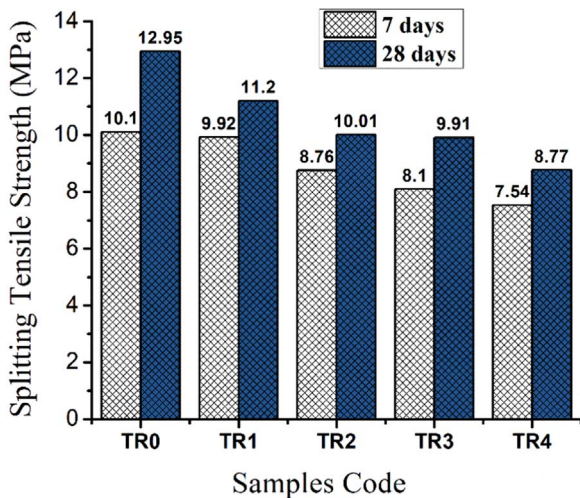
Fig. 7. Curing time dependent splitting tensile strength of various SCGPC specimens.

Table 7
Water absorption VS curing time.

Samples	Curing age (days)		
	7 days	28 days	90 days
TR 4	5.47	5.22	5.01
TR 3	5.16	5.06	4.72
TR 2	4.67	4.36	4.10
TR 1	4.05	3.87	3.42
TR 0	3.86	3.62	3.34

could be attributed to the high-water absorbability of the garnet particles as discussed in Table 1 and. Meanwhile, with decreasing curing duration the water absorption of the GP specimens was decreased. At 7 days, the percentage of water absorbed by the TR4, TR3, TR2, TR1 and TR0 specimens were 5.47%, 5.16% 4.67%, 4.05% and 3.86%, respectively and at 90 days these values were 5.01%, 4.72%, 4.10%, 3.42% and 3.34%, respectively. In fact, there was a reduction by 8%, 8.6%, 12%, 15% and 13% at 90 days for TR4, TR3, TR2, TR1 and TR0 specimens, respectively, as compared to 7 days curing. This could be attributed to continuous hydration of the cementitious materials in the garnet, where fine garnet particles could fill the voids to create more compact structure. This achieved reduction in the water absorption of the prepared spent garnet incorporated GPC with increasing curing age was in good agreement with other report [21]. Generally, the water absorption of all the specimens was lower compared to the permissible limits of 10% recommended by Neville [22]. Sanni and Khadiranaikar [27] acknowledged that higher water adsorption could increase the concrete permeability.

4.4. Flexural strength

By definition, the flexural strength of a material is its capability to oppose the bending force applied on the concrete or other slabs placed on the ground. The flexural strength determination is prerequisite for the design of concrete mixtures to examine the compliance with established standards of an engineering structure. In the present work, flexural strength was measured at room temperature obeying the specifications of ASTM D790. Fig. 8 depicts the flexural strength of the prepared TR0, TR1, TR2, TR3, and TR4 SCGPC specimens which were discerned to be 1.26 N/mm^2, 1.22 N/mm^2, 0.98 N/mm^2, 0.92 N/mm^2, 0.89 N/mm^2, after curing for 7 days, and 1.50 N/mm^2, 1.35 N/mm^2, 1.20 N/mm^2, 1.11 N/mm^2, and 0.98 N/mm^2 after 28 days of curing, respectively. It was evident that the values of flexural strength obtained for the spent garnet incorporated GP mixes in both cases were lower than that of the control sample (TR0). This was attributed to the reduction in the sand ratio which led to the weakening of the bonding between fine aggregates and binder [15].

4.5. The water absorption capacity

Table 7 presents the results of water absorption test that was conducted on 0.4 AS/B ratios at 7, 28 and 90 days. Results displayed that the permeability of the prepared GPC was decreased slightly with increasing age. Furthermore, the control specimen (TR0) absorbed less water throughout the curing period as compared to all other GP specimens This
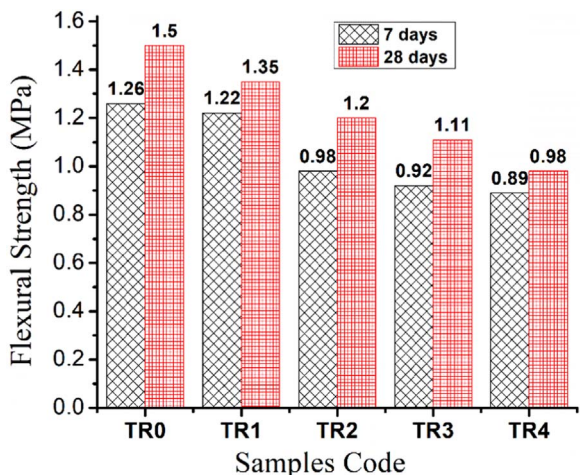
4.6. Drying shrinkage

Fig. 9 illustrates curing time dependent drying shrinkage of synthesized SCGPC specimens. The drying shrinkage of the spent garnet included GPCs were observed to be lower than the one without containing spent garnet. In the entire test duration, the drying shrinkage of the control specimen was higher than the one composed of spent garnet. The shrinkage values for TR1, TR2, TR3 and TR4 at 90 days were 24% and 49%, 74% and 86%, respectively, which were lower than TR0 specimen. These lower values of drying shrinkage of the garnet included GPCs were attributed to the nature of fine garnet particles that filled the micro-pores of the GPC to optimize the pore structures. This result is consistent with the observation of Zhou [34]. Other factor for occurrence of drying shrinkage reduction of garnet mixed concretes may be related to the self-cementing properties of the finer garnet particles. Similar findings revealed that the replacement of river sand by iron ore tailings in concrete could lower the shrinkage [8]. This was further supported by study of
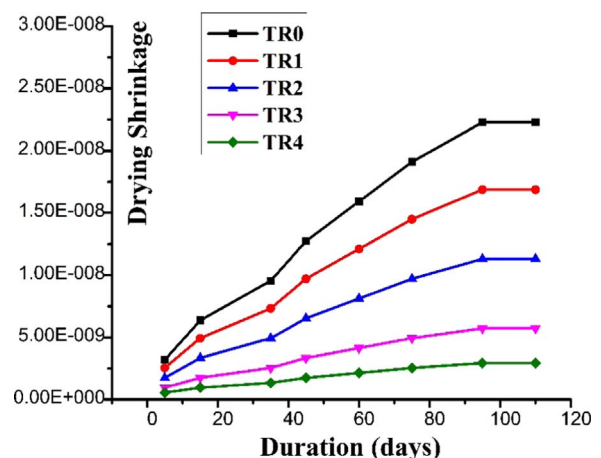

Fig. 8. Curing time dependent flexural strength of various SCGPC specimens.

Fig. 9. Curing time dependent drying shrinkage of synthesized SCGPC specimens.
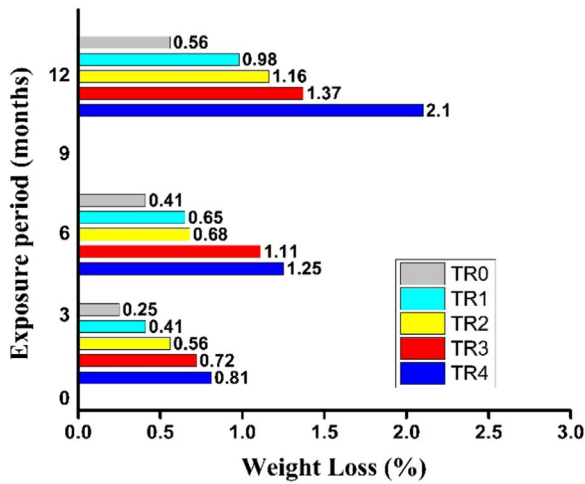
Fig. 10. Exposure duration dependent weight loss of synthesized SCGPC specimens due to acid attack.
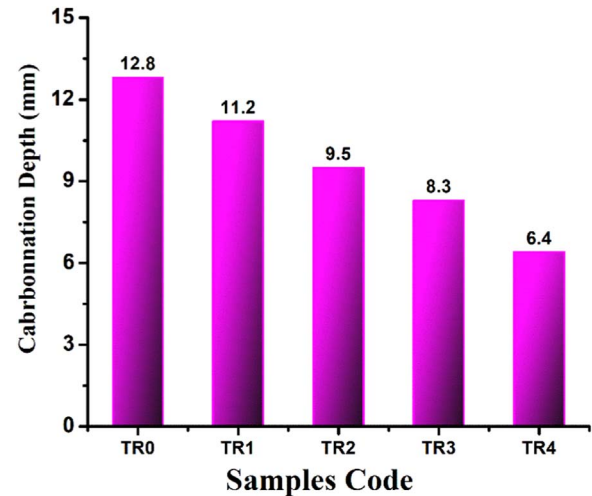

Fig. 12. Carbonation depth of prepared SCGPCs.

Zhang et al. [33] on conventional concrete containing high volume of iron ore tailings and river sand replacement. It was acknowledged that the drying shrinkage of iron ore tailings concrete was less than the concrete based on river sand. However, the dry shrinkage for control and garnet samples decreased after 90 days curing. In a related study, [19] reported similar trend when furnace bottom ash (FBA) was used as sand. [25] found that geopolymer mortar specimens showed a very slight shrinkage upon drying and the drying shrinkage increased as the slag content increased in the mortar matrices.

4.7. Resistance to acid attack

Fig. 10 shows the results of the weight loss of the respective GPC mixes due to sulphuric acid attack. All the SCGPC specimens revealed similar decreasing trend in the mass over the entire duration of immersion (7, 28 and 90 days). Throughout the duration of exposure, the weight of control samples (TR0) was reduced less than other specimens containing spent garnet. GPC with spent garnet revealed very little change in the appearance after 90 days of immersion in the sulphuric acid. Some softening of the surface cover and insignificant change of the colour was noticed in the GP specimens after the acid exposure (Fig. 11). Furthermore, the garnet samples exhibited the highest weight loss of 2.1%. Conversely, GP specimen TR0 manifested the least weight loss of 0.5% at the same period of 90 days. These higher values of weight loss of the garnet included GPCs were attributed to the high-water absorbability of the garnet particles.

The observation of lower weight loss of control samples TR0 included GPC was attributed to their weak acid absorption tendency as
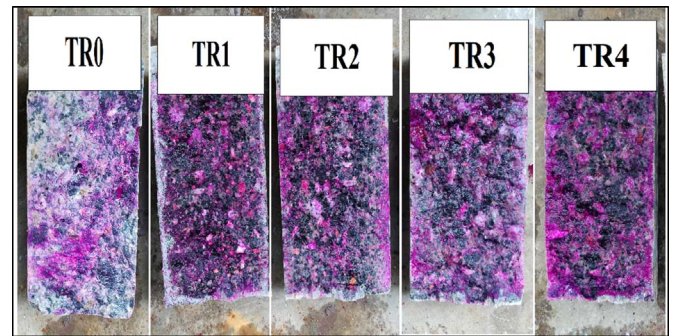

Fig. 13. Effect of carbonation on the prepared SCGPC specimens.

well as difference in the chemical and phase composition. Moreover, sand material that possessed low amount of calcium as observed in the chemical composition exhibited weak reactions with sulphuric acid. Singh et al. [30] also reported similar results on concrete made from high volumes of low-calcium coal bottom ash exposed to sulphuric acid.

4.8. Accelerated carbonation depth

The carbonation test was conducted on the SCGPC specimens (TR0, TR1, TR2, TR3 and TR4) containing different percentages of spent garnet. Figs. 12 and 13 shows the results for mean carbonation depth, which was reduced steadily with increasing percentage of spent garnet
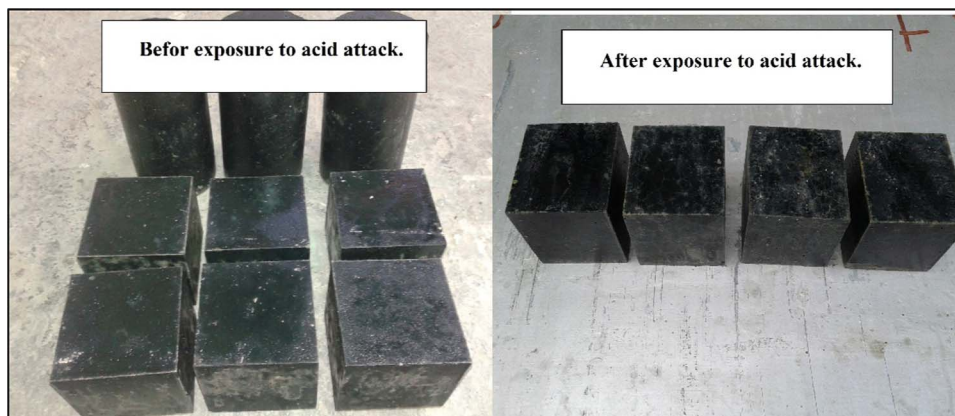
Fig. 11. Look of various concretes upon exposure to acid attack.

in the GP mixes. Thus, the prepared SCGPC revealed better performance throughout (all percentages) the replacement of river sand by spent garnet. This finding agreed with the reported one on waste materials by Siddiqui [29]. It was interpreted in terms of non-interconnected pores that facilitated the ingress of CO_2. Basheer et al. [1] also reported that the rate of carbonation of concrete can be primarily influenced by the tortuosity of the porous network together with the chemistry of the binding phases, water-cement ratio, porosity and carbon dioxide transport.

solid matrix developed good mechanical properties. The FESEM micrograph of the GP specimens demonstrated an alteration in the morphology due to the formation of bonds between the GP paste and the aggregate. This bonding allowed the nucleation of randomly oriented new crystal structures at small length scale (Fig. 10(b)). Eventually, big crystalline grains were spread over the entire specimen volume. This in turn generated cracks in the garnet GP paste and reduced the mechanical strength as seen in the compressive strength values of TR1 sample which was lower than purely river sand based GPC specimen
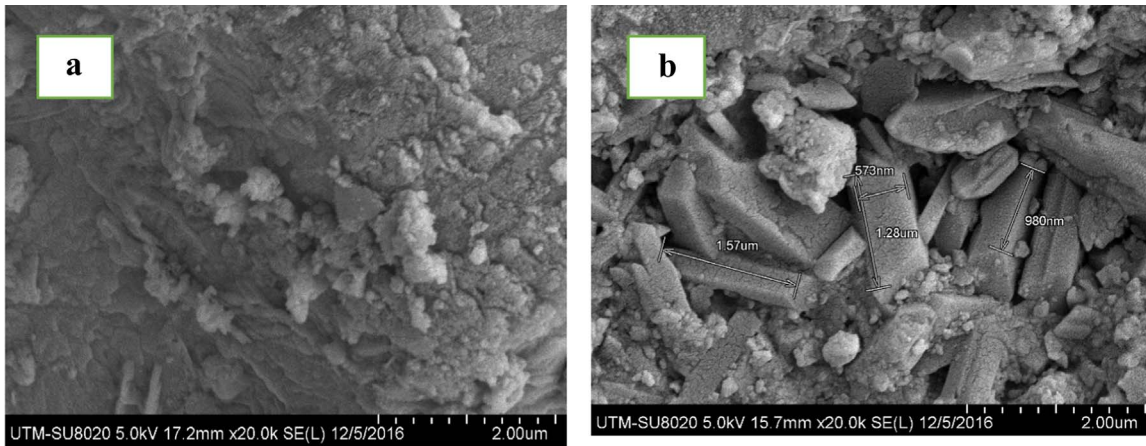
4.9. FESEM images

Fig. 14(a) and (b) show the FESEM images of GP mix containing natural river sand without any spent garnet replacement (TR0) and the spent garnet incorporated GP specimen (TR1). The FESEM image analysis showed a reduction the porosity due to the addition of slag in the GP, where the matrix became very compact with better space-filling properties through the slag activated formation of C-A-S-H gel. The

(TR0). It is demonstrated that presence of spent garnet in the mix had remarkably affected the surface morphology and micro-structural properties of the SCGPCs.

5. Conclusions

This paper reports the feasibility of using spent garnets at high percentage level as sand replacement to achieve enhanced SCGPCs for
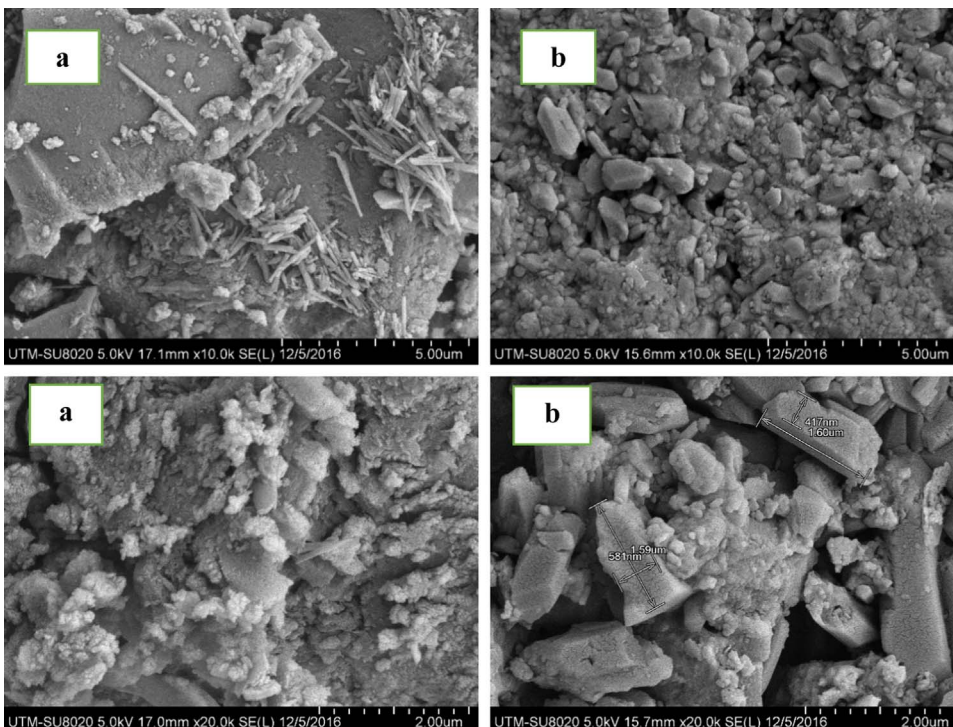

Fig. 14. FESEM images of GP specimen: (a) TR0, and (b) TR1.

economic and environmental friendly applications. The SCGPC specimens were prepared using GGBFS where spent garnet was used to replace the river sand. The effects of varying spent garnet contents on the fresh properties of prepared SCGPCs were determined. Performance of the proposed SCGPCs was evaluated in terms of compressive, flexural, splitting tensile strengths, durability and workability tests following EFNARC standard. The fresh properties of SCGPCs revealed satisfactory performance with high compressive strength. It was asserted that the GBFS as GP binder phase can synergistically be combined with conventional sand, spent garnet and coarse aggregates to attain enhanced SCGPCs. Spent garnet replacement level of 25% revealed the optimum performance regarding both flow ability and mechanical properties. An increase in the spent garnet replacement levels beyond 25% caused a reduction in the strength of SCGPCs. The irregular, high specific surface area and porous nature of spent garnet was found to play a significant role for achieving high performing SCGPCs. The high contents of silica, alumina and iron in the spent garnet were indeed responsible for such improved performance. The as-prepared SCGPCs displayed excellent resistance toward rapid carbon dioxide penetration up to 60 days of exposure in the carbon dioxide environment. Besides, the spent garnet incorporated GPCs manifested higher weight loss than the control samples under acid exposure over the entire period and did not show any detectable change in the appearance after 90 days of immersion in the sulphuric acid except some softening of the surface cover. In short, spent garnet was demonstrated to potential for sand replacement up to 25% for achieving enhanced SCGPCs.

Acknowledgements

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