

Development of multi-strength grade green lightweight reactive powder concrete using expanded polystyrene beads



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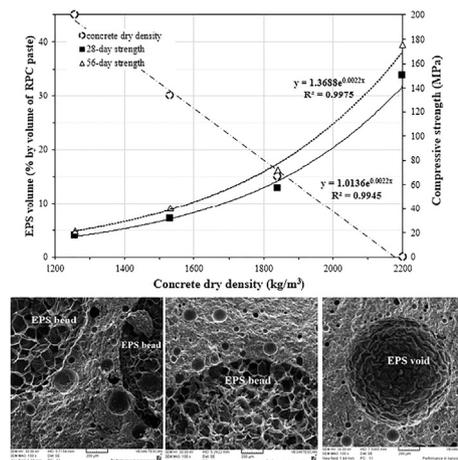
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HIGHLIGHTS

- Multi-strength grade lightweight reactive powder concretes are developed.
- Expanded polystyrene beads were used to reduce the concrete density.
- Quartz powder was replaced by GGBFS for environmental and cost effective purposes.
- Different standard water and heat curing conditions were applied.
- Properties of lightweight reactive powder concrete were investigated.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a new class of green light weight reactive powder concrete (GLRPC) was developed in different strength-grades by using expanded polystyrene beads. Quartz powder was totally substituted by ground granulated blast furnace slag as an industrial waste material to develop a more cost-effective and environmentally-friendly product. Various mixtures were studied by application of expanded polystyrene beads of the size between 0.5 and 2.3 mm, CEM-II Portland cement, silica fume, GGBFS, polycarboxylate based superplasticizer and water. The effects of different curing regimes including standard water curing and heat curing at 100, 150 and 200 °C on compressive strength, water absorption, and microstructure of GLRPC were investigated. Based on the measurements, density, compressive strength and water absorption values between 1257 to 1840 kg/m³, 20.8 to 85.6 MPa, 3.47 to 0.22% for GLRPC mixtures were achieved, respectively.

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1. Introduction

In the early 1990s, a new class of cement based composite with very high mechanical properties and durability, called reactive powder concrete (RPC) was developed in France [1]. RPC was

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obtained by modifying the microstructure according to the following basic principles [1–5]:

- 1) Expulsion of coarse aggregate and utilization of fine reactive powder (less than 600 μm) to enhance homogeneity in RPC and to achieve a compact microstructure.
- 2) Low water-to-binder ratio for reducing capillary porosity and incorporation of superplasticizer to enhance the rheology of the fresh concrete.
- 3) Addition of secondary cementitious materials such as silica fume (SF) to reduce pore volume by both filling mechanism and pozzolanic reactions consuming $\text{Ca}(\text{OH})_2$ to generate additional calcium silicate hydrate (C-S-H).
- 4) Heat-treatment after setting in order to accelerate pozzolanic reactions and also to crystallize hydration products that enhance microstructural behavior of the RPC matrix.
- 5) Incorporation of steel fibers to enhance ductility and tensile strength of the material.

Heat curing at temperatures between 50 °C and 250 °C after final setting time results in significant increase in ultimate compressive strength of RPC by improving the microstructure of C-S-H hydrates through increased hydration degree and activated pozzolanic reaction [1,6,7]. The pozzolanic reaction of silica fume strongly depends on temperature. When temperature is increased from 90 °C to 250 °C, the pozzolanic activity of silica fume enhances from 10% to 75% [8]. Furthermore, consumption of crushed quartz in hydration reactions was observed at 200 °C and 250 °C due to significant increase in its pozzolanic activity from 20% to 65% at these temperatures [8].

At about 100 °C, tobermorite is not crystallized, but curing at temperatures between 150 °C and 200 °C causes the formation of coarser and denser tobermorite crystals, whilst xonotlite appears at about 250 °C, which can increase the concrete compressive strength and improve its microstructure [3].

Following a rapid growth in the industrial waste materials and environmental pollution caused by them and the need to reduce production cost of concrete, some researchers replaced cement or aggregate with supplementary cementitious materials. Yazichi et al. [5] studied the mechanical properties of RPC reinforced with micro fiber and high volume GGBFS replacement at different curing conditions. They showed that production of RPC with cement contents as low as 375 kg/m^3 in comparison to the conventional RPC containing a much higher amount of cement (800–1000 kg/m^3) is possible. In addition, use of GGBFS as an alternative silica source in RPC enables partial replacement of SF content. Zhu et al. [9] showed that SF and cement content of RPC can be partially replaced by recycled powders from construction and demolition waste containing clay bricks and concrete solids. They successfully produced environmentally friendly and low cost RPC. Kushartomo et al. [10] showed that glass powder from waste glass shards material can be used at different proportions instead of quartz powder. In another study, Singh et al. [11] used GBFS instead of fine aggregate in normal concrete. They replaced sand by GBFS at different percentages and investigated the effect on compressive strength of concrete. Their results showed that there exist an optimum replacement level and compressive strength increases to a maximum value with increasing the replacement level and then decreases at higher replacement level. In addition, concrete with high content of GBFS showed higher compressive strength than control sample.

Shaheen and Shrive [12] have produced lightweight RPC with density of 1760 kg/m^3 and high compressive strength by replacing some amount of quartz with carbon fiber and application of heat treatment. Sadrkarimi [13] reduced density of RPC approximately to 1900 kg/m^3 without losing strength by increasing the SF content

of the concrete and by high temperature curing. Gokce et al. [14] reported that lightweight RPC of density ranging from 1840 to 2430 kg/m^3 and compressive strength values of 69–175 MPa can be produced by using pumice aggregate, applying pre-setting pressure (between 0 and 50 MPa) and application of heat curing.

Expanded polystyrene is a closed-cell foam that can be used as a lightweight material. Expanded polystyrene beads (EPS) can be added to concrete mix at different volume ratios to achieve different density and strength grade lightweight concretes for different applications [15]. The use of EPS in concrete mix, however, has two important technical disadvantages affecting the concrete quality significantly. These disadvantages include: 1) extreme lightness of the EPS beads that can results in significant segregation in the cement matrix, 2) hydrophobic property of EPS leads to a weak bonding with cement paste [16,17].

This paper aims mainly at investigating the application of commercially available EPS beads or even recycled EPS beads as lightweight aggregate for producing multi-strength grade green lightweight RPC (GLRPC) with a wide range of densities that provide the advantage of reducing the dead load of concrete structures that are exposed to earthquake. This new high strength and lightweight concrete provides new design and building options for tall construction projects and long-span bridges. In addition, for specific structures such as off-shore and oil platform structures, precast concrete columns made of this high strength lightweight concrete can be easily transported to the site by floating on the sea surface. For this purpose, different GLRPC mixtures were prepared by partial replacement of RPC paste volume with EPS beads. The effects of replacement level and curing conditions on compressive strength, density, the amount of water absorption and microstructure of the GLRPC were investigated.

2. Experimental

2.1. Materials

Portland cement CEM-II (PC) of strength grade 42.5 complying with ASTM C150, and manufactured by Tehran Cement Company in Iran, was employed in this study. The undensified SF conforming to ASTM C1240 containing about 90–95% SiO_2 supplied by Iranian ferro-alloys industries was used. Quartz powder and quartz sand were completely replaced by GGBFS as fine aggregate to enhance adhesion of EPS with paste and to improve the distribution uniformity of EPS beads in the RPC matrix. The physical and chemical properties of the materials utilized (PC, SF and GGBFS) are provided in Table 1. The particle size distribution of the materials utilized (PC, SF and GGBFS) are also given in Fig. 1. Polycarboxylate-based superplasticizer (SP) conforming to ASTM C494 was also utilized. Commercially available spherical-shaped EPS beads with properties presented in Table 2 were used as artificial lightweight

Table 1
Physical and chemical properties of Portland cement, silica fume and GGBFS.

Property	Portland cement	Silica fume	GGBFS
<i>Chemical</i>			
CaO	63.26	0.35	36.91
SiO_2	22.50	96.12	36.06
Al_2O_3	4.15	0.82	9.16
Fe_2O_3	3.44	0.59	0.70
MgO	3.25	0.29	10.21
K_2O	0.65	0.40	0.70
SO_3	1.80	0.10	1.15
LOI	0.61	0.63	
<i>Physical</i>			
Density (kg/m^3)	3150	2130	2600
Specific surface area (m^2/kg)	302	18,000	320

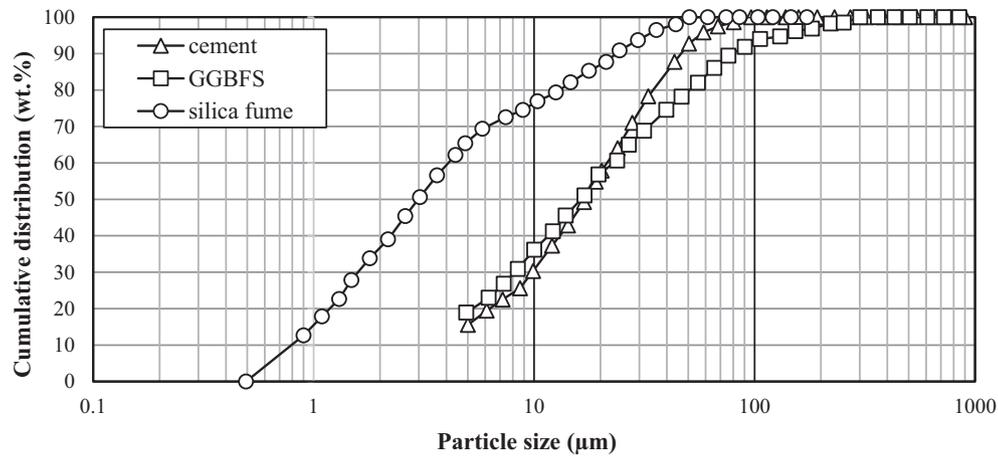


Fig. 1. Particle size distribution of the Portland cement, silica fume and GGBFS.

Table 2
Properties of EPS beads.

Property	Value
Average diameter (mm)	1.55
Maximum particle diameter (mm)	2.30
Density (kg/m ³)	18
Collapse point (°C)	110–120
Melting point (°C)	160
Complete volatilization point (°C)	460–500
Water absorption (%)	0

aggregate for producing lightweight RPC. The size distribution of EPS beads were also presented in Fig. 2.

2.2. Mix design

Table 3 demonstrates the mixture designs of GLRPC without EPS beads (as control) and with EPS beads. To incorporate EPS beads into the GLRPC mixtures, the volume of the binder paste (PC + SF + GGBFS + water) was partially replaced by EPS beads. All the weight proportions between the paste constituents including SF/PC (0.24), (PC + SF)/GGBFS (0.94), water/(PC + SF) (0.23), water/PC (0.285), SP/(PC + SF + GGBFS) (0.0118) were kept constant. All the mixture proportions were controlled at their optimum values for achieving maximum compressive strength. The amount of SF was controlled to adjust the total CaO/SiO₂ molar ratio of the binder at about 1.3 that is reported to be optimum [18]. The amount of water was controlled at the minimum possible value providing a suitable rheology in fresh GLRPC mixtures by adding optimum amount of superplasticizer. The quartz powder was totally

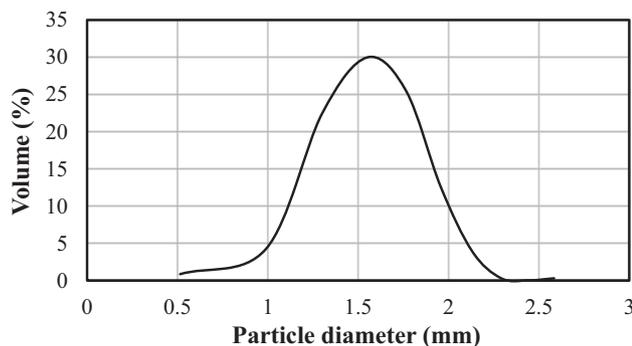


Fig. 2. Particle size distribution of EPS beads.

replaced by GGBFS keeping the (PC + SF)/GGBFS ratio constant at its optimum value [18]. EPS beads were incorporated at four different volumetric replacement levels including 0%, 15%, 30% and 45% and the GLRPC mixtures were named in accordance with volume replacement level. Table 3 represents the details of the mix proportions for each of the four GLRPC mixtures.

2.3. Mixing sequence

GLRPC mixing process was employed similar to conventional RPC based on previous studies:

- Ingredients (i.e. PC, GGBFS and SF) were dry mixed for 3 min at low speed.
- Half of the volume of binary mixture of water and superplasticizer was immediately added to the ingredients and re-mixed for 3 min at high speed.
- The remaining mixture of water and superplasticizer was added and mixed for 10 min at a high speed.
- EPS beads were then added and mixed for 3 min at very low speed.

To avoid the risk of segregation of EPS beads in matrix when casting, all 100 × 100 × 100 mm fresh concrete cubes were compacted by hand tamping. After casting, the cubes were kept in a humid chamber with relative humidity of 95 ± 3% for the first day and then demolded and submerged in water at 23.0 ± 2.0 °C.

2.4. Curing regimes

RPC generally requires heat curing for the silica fume and also quartz powder to effectively take part in the pozzolanic reactions and to accelerate hydration reactions [1,6–8]. By application of heat, the curing time of RPC can be noticeably reduced [19]. Since the optimum heat curing temperature depends on the type and composition of the RPC mixture constituents, different heat curing temperatures were selected and applied for a new composition incorporating high volume of GGBFS instead of quartz powder and EPS beads to investigate the effect of curing temperature on concrete properties and also on EPS beads:

- Water curing at 23.0 ± 2.0 °C (standard curing);
- Water curing at 23.0 ± 2.0 °C for 4 days followed by heat curing at 100 ± 1 °C for 48 h
- Water curing at 23.0 ± 2.0 °C for 4 days followed by heat curing at 150 ± 1 °C for 48 h

Table 3
Mix proportions of GLRPC mixtures in kg/m³.

Material	GLRPC0	GLRPC15	GLRPC30	GLRPC45
PC	799	681	560	441
SF	191.7	163.4	134.4	105.8
GGBFS	1054.7	898.9	739.2	582.1
Water	227.8	194.2	159.7	125.7
SP	24.0	20.4	16.8	13.2
EPS	0.0	2.7	5.4	8.1
Water/binder ^a	0.23	0.23	0.23	0.23
Water/cement	0.285	0.285	0.285	0.285
Fresh density	2300	1958	1610	1268

^a binder = PC + SF.

(D) Water curing at 23.0 ± 2.0 °C for 4 days followed by heat curing at 200 ± 1 °C for 48 h

2.5. Testing procedure

The compressive strength was measured in accordance with ASTM C39 and a uniaxial digital hydraulic compression instrument (SCL brand) of 3000 KN-capacity with $\pm 1\%$ accuracy and a loading rate of 0.25 ± 0.05 MPa/s was applied. For each measurement, three concrete cubes were used and the average of the measured compressive strengths was recorded as the result.

For evaluating the distribution of EPS beads in the matrix, typical concrete cubes of GLRPC15, GLRPC30 and GLRPC45 mixtures were cut into halves to expose the cut surface for image analysis using imagej 1.44P image processing software.

X-ray diffraction (XRD) patterns for standard water curing, heat curing at 100 and 200 °C samples were obtained by using a Philips PW 1800 X-ray diffractometer. The diffraction patterns were recorded for 2-Theta angles between 5° and 50°, with a 0.02 step size and a step time of 2 s.

In order to investigate the microstructure of the GLRPC and EPS beads in concrete cubes undergone heat curing, suitable fractured samples were prepared by cutting thin layer from the broken cubes. The prepared fractured samples were oven dried at 70 °C for 24 h and then gold coated prior to SEM microscopy studies. The microstructural studies were performed using secondary electron image (SE) mode of a TESCAN VEGA II Scanning Electron Microscope at 30 kV.

The amount of water absorption of GLRPC concrete cubes was determined using Eq. (1) and by measuring the mass (g) of surface-dried sample in air after water immersion at 21 °C for 72 h and the mass (g) of oven-dried sample in air at 70 °C to prevent EPS beads from shrinking.

$$\text{Water absorption}(\%) = \frac{(\text{SW} - \text{ODW})}{\text{ODW}} \quad (1)$$

SW = Saturated Weight

ODW = Oven Dry Weight

3. Results and discussion

3.1. Effect of EPS and standard water curing age on compressive strength

The results of compressive strength development with standard water curing age for different GLRPC mixtures are presented in Fig. 3. The results reveal that compressive strength depends significantly on EPS content (volume replacement level) and curing time. Control RPC mixture (GLRPC0) shows relatively high compressive strengths of about 95.4, 140.2, 150.1 and 175.6 MPa after 3, 7, 28 and 56 days of curing, respectively. A 15% replacement by volume of the paste reduces all age compressive strengths by about 60%.

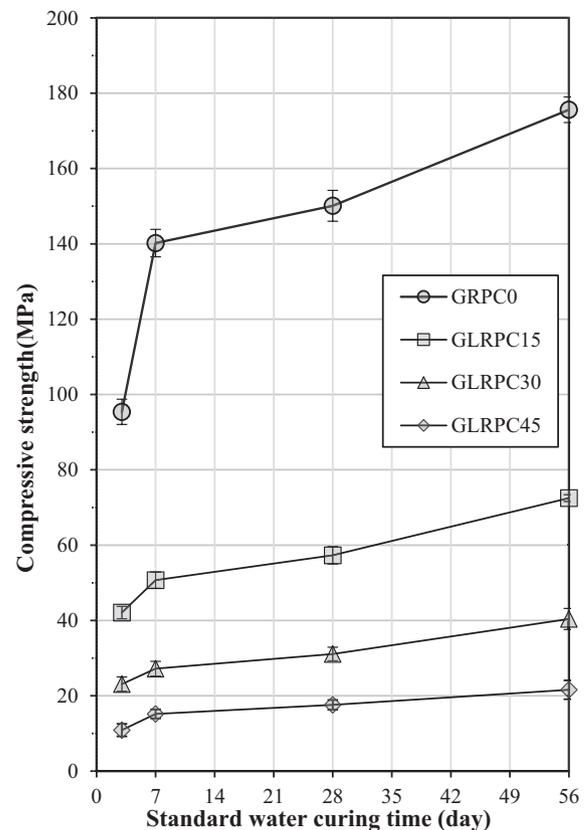


Fig. 3. Compressive strength versus standard water curing for different replacement levels.

The lowest compressive strengths, therefore, belongs to GLRPC45 which incorporates the highest volume of EPS beads at the replacement level of 45%. This GLRPC mixture exhibits 3-, 7-, 28- and 56-day compressive strengths of 10.9, 15.2, 17.6 and 21.6 MPa, respectively, which are still acceptable for many construction purposes.

To evaluate the distribution of EPS beads inside the GLRPC matrix, from each concrete mix, one 56-day cured concrete cube was cut into halves to expose the cut surface for image analysis. Fig. 4 represents images taken from the cut surfaces of GLRPC15, GLRPC30 and GLRPC45 mixtures from left to right, respectively. To evaluate the non-uniform distribution of EPS beads inside the GLRPC matrix, the images were rotated 90 degrees counterclockwise so that top surfaces of the concrete cubes with regions of high EPS beads contents are located on the left side in the images. As the images clearly show, the EPS beads were not uniformly distributed inside the GLRPC matrix and regions of low and high EPS beads contents can be simply distinguished. GLRPC15 and GLRPC30 clearly show the highest and the lowest densities of EPS beads

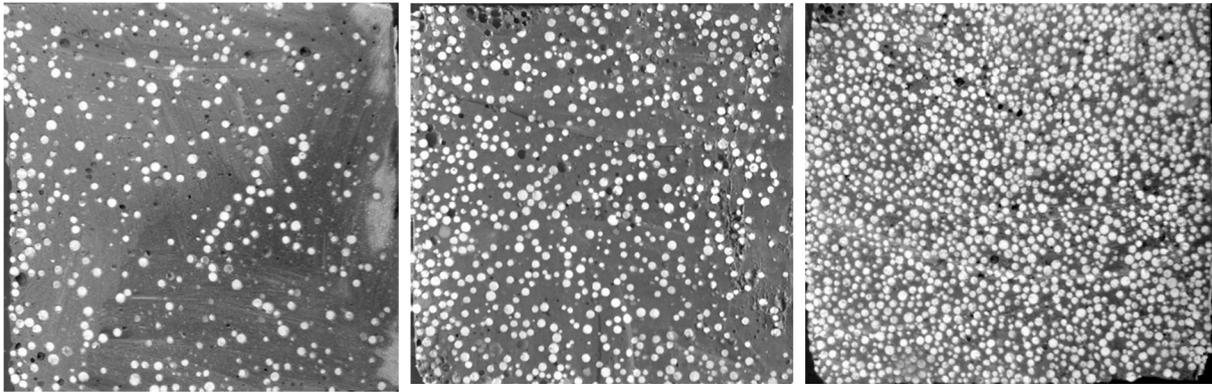


Fig. 4. EPS beads distribution inside GLRPC15, GLRPC30 and GLRPC45 from left to right, respectively with top surfaces of concrete cubes at the time of casting positioned on the left side.

on the left and right surfaces (the top and bottom surfaces of cubes at the time of casting), respectively. This observation confirms the EPS beads tendency for moving towards the top surface during the casting operation resulting in a significant non-uniformity. Such a non-uniform distribution of EPS beads caused by their surface hydrophobicity and their high density difference with GLRPC matrix, as investigated and confirmed by other researchers [16], could be considered as an important strength reducing factor. To evaluate the uniformity of the distribution of EPS beads in the GLRPC matrix of different mixtures quantitatively, the number of beads and the gray value (the amount of polystyrene in pixel scale) in terms of horizontal distance from the left vertical surface (the top surface of the cube at the time of casting) towards the right vertical surface (the bottom surface of the cube at the time of casting) were calculated using imagej 1.44P software and the results are displayed in Figs. 5 and 6. The variations in these two values reveal the non-uniformity of the EPS beads in the GLRPC matrix at different positions from the top surface to the bottom surface of the concrete cubes. Therefore, the values of standard deviations for both the number of beads and the gray value were also calculated and displayed in Table 4. As seen in Figs. 5 and 6, GLRPC15 mixture displays the highest non-uniformity from the top to the bottom surfaces compared to GLRPC30 and GLRPC45 mixtures. With a decreasing trend from top surface to the bottom surface, both the number of beads and the gray value have their maximum values at the top surface and their minimum values at the bottom surface. The non-uniformity in distribution, however, decreases at higher replacement levels and GLRPC45 mixture shows the highest

distribution uniformity for EPS beads. The calculated standard deviations also confirm such a trend in distribution uniformity. As seen in Table 4, GLRPC15, GLRPC30 and GLRPC45 mixtures represent standard deviations of 9.0, 6.1, and 5.5 for the number of beads and 16.5, 14.5, and 13.6 for the gray value, respectively. Significant decreases in standard deviations of both the number of beads and the gray value with increase in EPS beads content confirm a dependency between distribution uniformity of EPS beads and its volume content in the matrix.

Now comparing the distribution uniformity of EPS beads to the compressive strength reductions in GLRPC15, GLRPC30, and GLRPC45 mixtures compared to the reference GLRPC0 mixture, it can be seen that the poorest distribution uniformity of EPS beads in GLRPC15 with the lowest replacement level of 15% contributes to the highest decline of compressive strength at this replacement level. At higher replacement levels, however, the effect of EPS beads on total compressive strength reduction is relatively decreased due to the improvements brought about in distribution uniformity of EPS beads. Any improvement in distribution uniformity of EPS beads inside GLRPC matrix, therefore, can have an improving effect on compressive strength recovery.

In addition to non-uniform distribution of EPS beads in the GLRPC matrix and the resulting loss of integrity, weak mechanical nature of the EPS beads and their high density difference with GLRPC matrix along with inefficient compaction of GLRPC concretes during casting operation are among the important strength reducing factors. It is claimed that increasing the amount of silica fume in the lightweight concrete mixture improves the strength

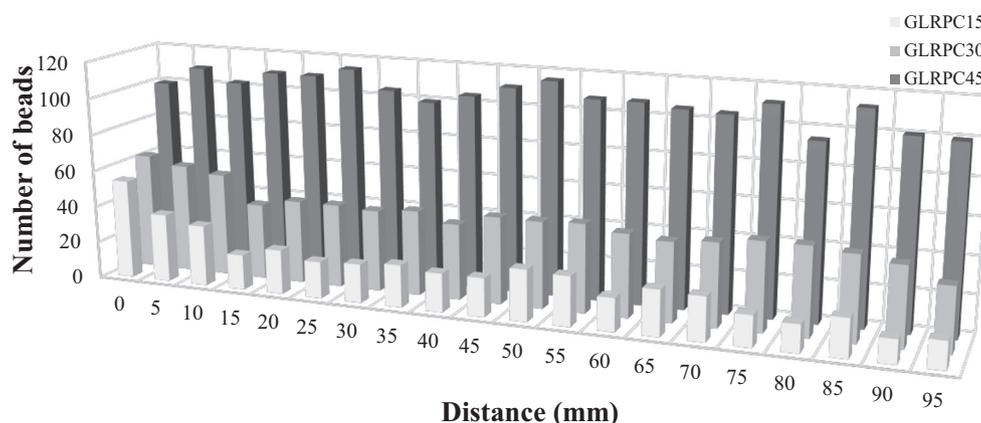


Fig. 5. The number of EPS beads versus distance from top surface of concrete cube.

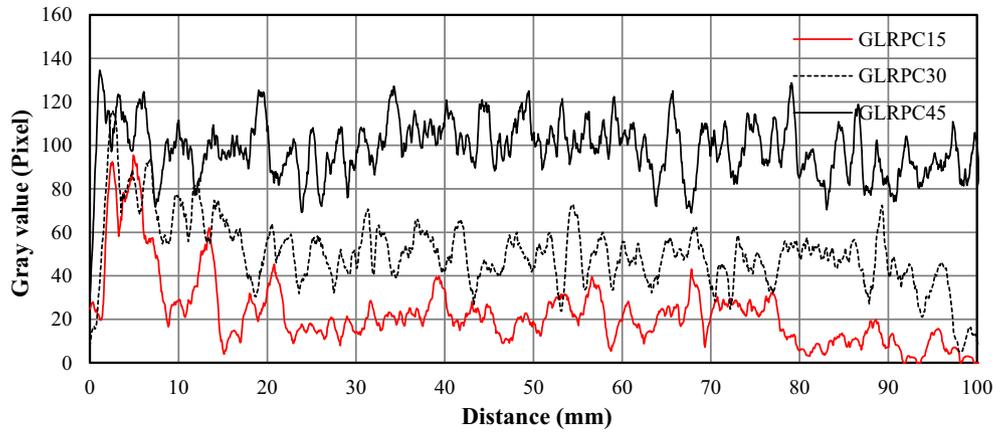


Fig. 6. The gray value (the amount of EPS beads in pixel scale) versus distance from top surface of concrete cube.

Table 4
The standard deviation of the number of beads and the gray value.

Scale		Standard deviation		
		GLRPC15	GLRPC30	GLRPC45
Number of beads	5 mm	9.00	6.1	5.5
Gray value	0.045 mm	16.5	14.5	13.6

properties of the material by increasing the adhesion between EPS beads and concrete matrix that improves the distribution of EPS in the binder paste [20,21].

As generally expected, compressive strength increases significantly with curing time (see Fig. 3). The compressive strengths of GLRPC15, GLRPC30 and GLRPC45 mixtures, which were 42.1, 23.1 and 10.9 MPa after 3 days, increased by about 35%, 37% and 61% to reach values of 57.3, 31.1 and 17.5 MPa at the age of 28 days and then increased again by about 27%, 27% and 20% to reach values as high as 72.5, 40.4 and 21.6 MPa after at 56 days of curing, respectively. As can be seen in Fig. 3, the rate of strength development

in GLRPC mixtures displays a variable slope. It exhibits the highest value at early ages between 3 and 7 days and then reduces at the ages between 7 and 28 days and once again increases at the ages between 28 and 56 days. This is because of GGBFS incorporation into the GLRPC mixtures. Incorporation of GGBFS, instead of quartz sand, is superlative to the strength of the hardened concrete at later ages [22]. It is also claimed that incorporation of EPS beads positively affects the thermal resistivity of concrete which in turn lowers the rate of dissipation of hydration heat and therefore lead to progression of cement hydration [23].

3.2. Effect of EPS on density of GLRPC

By partially replacing the GLRPC binder paste with EPS beads at different volume replacement levels, different concrete densities can be achieved. Variation of GLRPC density at different replacement levels along with 28- and 56-day compressive strengths are represented in Fig. 7. As seen, compared to the GLRPC0, 15%, 30% and 45% replacement levels can result in about 16%, 30% and 43%

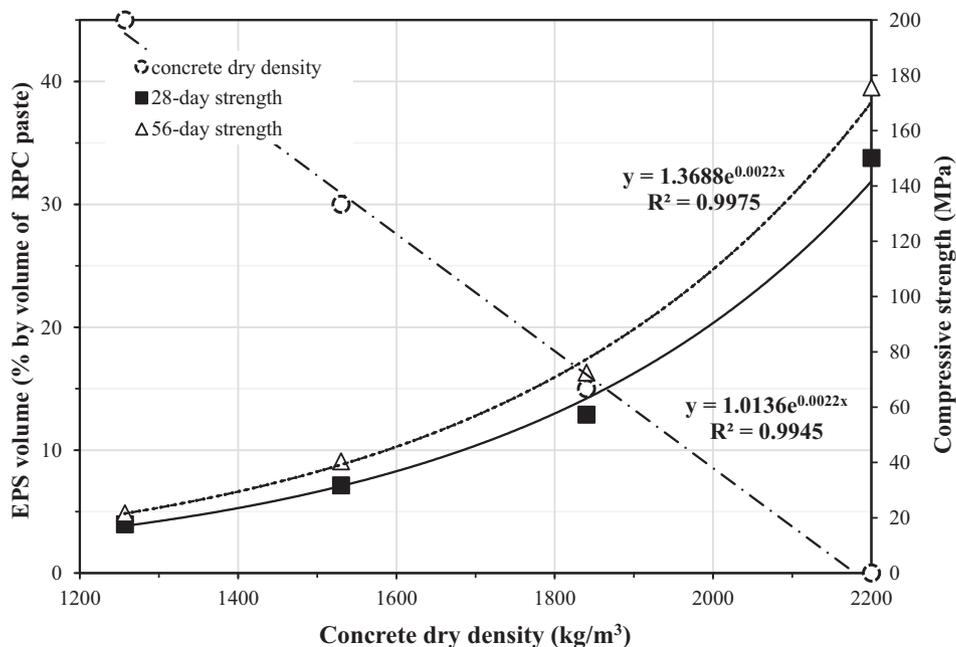


Fig. 7. GLRPC density versus EPS volume.

reduction in concrete dry density to achieve different dry density values of 1840, 1530 and 1257 kg/m³, with corresponding reduced 28-day compressive strengths equal to about 38%, 21%, and 12% of GLRPC0, respectively.

As seen and in contrary to previous works on EPS concrete [17,20], the compressive strength of water-cured GLRPC decreases exponentially with increasing the EPS content of the concrete, so that different classes of mechanical strength and density for different applications can be achieved. The obtained prediction relationships (Eqs. (2) and (3)) between dry density and compressive strength of GLRPC with densities varying from 2200 to 1257 kg/m³ displayed good correlation $R^2 = 0.9945$ and $R^2 = 0.9975$ for 28- and 56-compressive strengths, respectively:

$$f_{1c} = 1.3688 * \exp(0.0022 * d) \quad (2)$$

$$f_{2c} = 1.0136 * \exp(0.0022 * d) \quad (3)$$

where f_{1c} and f_{2c} are 28- and 56-day compressive strengths in MPa, respectively, and d is concrete dry density in kg/m³.

3.2.1. Structural lightweight concrete

In general, complying with ACI 213, concrete with densities between 1120 and 1920 kg/m³ and minimum 28-day compressive strength of 17 MPa can be considered in structural lightweight-aggregate concrete class. This concrete class includes application of both lightweight aggregate and binary compositions of lightweight and normal-density aggregates.

Therefore GLRPC30 and GLRPC45 mixtures with densities of 1530 and 1257 kg/m³ and 28-day compressive strengths of 31.1 and 17.5 MPa, respectively can be categorized in this class. In other words, structural lightweight concrete can be achieved by replacing RPC paste volume with EPS beads by 30% and 45%.

3.2.2. high-strength lightweight concrete

Conforming to ACI 213, structural lightweight concrete with a 28-day compressive strength of 40 MPa or greater can be considered as high-strength lightweight concrete class. Therefore, according to the obtained results, the GLRPC15 mixture exhibiting compressive strength 57.3 MPa after 28 days of standard water curing can undoubtedly be categorized in this group.

3.2.3. Cost-effectiveness and environmental sustainability

The green and environmentally friendly promises were given in comparison to reactive powder concrete (RPC) for special very high strength applications and of course not in comparison to normal concrete for normal applications. RPC requires significant amounts of quartz powder and quartz sand (generally over 1000–1300 kg/m³),

in addition to its very high Portland cement content (between 800 and 1000 kg/m³) for exhibiting very high compressive strengths. Use of such high amounts of quartz powder, quartz sand, and Portland cement makes the RPC a not environmentally friendly concrete. It has also been proven that for the production of commercially available concrete after Portland cement, aggregate is the largest source of CO₂ emission, 13–20% of total CO₂ emissions is related to this materials. It is clear that total replacement of quartz powder and quartz sand along with partial replacement of Portland cement contents of RPC with a high volume of a suitable industrial waste material (GGBFS as a supplementary cementing material) is a feasible solution to this problem. This well-known solution can effectively reduce resource depletion and potential pollution problems [24,25]. In the present work, GLRPC0 is the control RPC mixture, in which quartz powder and quartz sand were totally replaced with GGBFS. In addition, in lightweight RPC mixtures (namely GLRPC15, GLRPC30 and GLRPC45), significant volumes of the binder paste comprising of Portland cement, silica fume and GGBFS were replaced with ESP beads. For example in GLRPC45 mixture, 45 vol% of Portland cement, silica fume and GGBFS was replaced with EPS beads. It must also be noted that EPS beads can also be prepared from recycled EPS. The developed lightweight RPC mixtures are, therefore, green and environmentally friendly compared to normal RPC.

In order to compare the cost-effectiveness of GLRPC to the available lightweight concretes, the total cost of 1 m³ of different lightweight concretes at equal density (1800–1900 kg/m³) was calculated and presented in Table 5. The market prices for the concrete constituents were taken from Iran Mercantile Exchange on March 22, 2018. For a precise comparison, the 28-day compressive strength of the concretes has also been taken into account and the specific cost defined as total cost of 1 m³ of concrete per 28-day compressive strength was calculated. As expected, the total cost of 1 m³ of GLRPC15 is higher than the available lightweight concretes based on Scoria, oil palm shell, and expanded clay aggregate and noticeably lower than lightweight concrete based on Perlite. However, the high 28-day compressive strength level of GLRPC15 reduces its specific cost significantly. The GLRPC, therefore, could be a cost-effective lightweight concrete compared to many available lightweight concretes considering its high compressive strength.

3.3. Effects of heat curing on compressive strength

Fig. 8 represents the results of compressive strength measurement for heat curing regimes applied at 100, 150 and 200 °C as well as 28-day standard water curing at 20 °C as control. Heat

Table 5
Constituent prices (\$/kg), total cost (\$/1 m³) and specific cost (\$/MPa/m³) for different lightweight concretes (based on Iran Mercantile Exchange prices on March 22, 2018).

Material	GLRPC15	Lightweight concrete based on Scoria [26]	Lightweight concrete based on Perlite [27]	Lightweight concrete based on oil palm shell [25]	Lightweight concrete based on expanded clay aggregate [28]
Cement	17.36	12.75	8.92	8.92	11.47
Silica fume	17.32	–	–	–	–
GGBFS	15.28	–	–	2.55	–
Sand	–	–	–	4.47	1.45
Gravel	–	–	–	–	1.89
Superplasticizer	34.68	–	–	8.5	5.35
Scoria	–	38.47	–	–	–
Perlite	–	–	154.32	–	–
Oil palm shell	–	–	–	33.6	–
Expanded clay aggregate	–	–	–	–	11.96
Sum total (\$/m ³)	84.64	51.22	163.24	58.31	32.12
28- compressive strength (MPa)	57.2	27.5	23.5	38.5	48.6
Specific cost (\$/MPa/m ³)	1.47	1.86	6.94	1.51	0.66

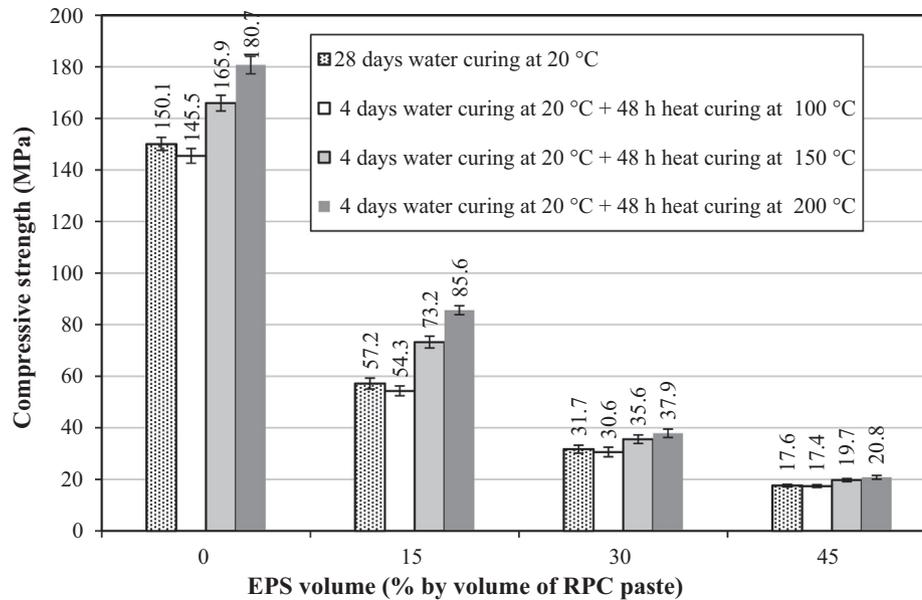


Fig. 8. Variation of compressive strength under different curing regimes.

curing might be feasible when time saving and/or higher compressive strengths are of concern. As seen in Fig. 8, 48 h of heat curing after 4 days of standard water curing at 20 °C can save a time period of 22 days at the expense of some thermal energy for GLRPC mixtures to achieve almost the same or even higher compressive strengths. The higher, the heat curing temperature, the higher the final compressive strength. Also the effectiveness of the heat curing temperature on compressive strength enhancement significantly decreases at higher replacement levels. This is a logic behavior due to the significant paste volume decrease at higher replacement levels. In fact, the considerable decrease in the binder content (PC, SF and GGBFS) at higher replacement levels significantly affects the strength and the strength development with heat curing. On the other hand, loss of integrity in matrix significantly prevents development through heat curing. The maximum compressive strength enhancement, therefore, belongs to GLRPC15 that shows almost 49% increase compared to its control mixture.

The compressive strength enhancement under heat curing regimes is clearly due to quick progression of hydration of cement grains and acceleration of the pozzolanic reactions of both silica fume and GGBFS. It was proved that heat curing at temperatures between 150 °C and 200 °C causes the formation of calcium silicate hydrate of longer chains in the form of coarser and denser tobermorite crystals, which can increase the concrete compressive strength and improve its microstructure [1,3,7,8].

As seen, heat curing at 100 °C resulted in a little bit lower compressive strengths compared to other curing regimes including 28 days of standard water curing at 20 °C. This shows that 48 h of heat curing at 100 °C results in lower degrees of hydration compared to other curing regimes. Since GGBFS is the less reactive component of the mixture compared to Portland cement and silica fume, the relatively slow pozzolanic reactions of GGBFS were not probably accelerated at 100 °C. In addition, application of heat treatment in oven is accompanied with moisture removal, which causes unsaturated condition in surface regions of concrete cubes. Clearly, reducing the water consumption in surface regions leads to lower hydration degrees in the same regions and undoubtedly significant reductions in compressive strength [29]. This is confirmed by XRD patterns of GLRPC0 mixture hardened under heat curing regimes applied at 100 °C, 200 °C and also 28-day standard water curing showed in Fig. 9. As seen, under all curing conditions, the material

is mainly amorphous with few crystalline phases including calcite, Portlandite, and tiny amount of residual unhydrated calcium-silicates (alite and belite) originating from Portland cement. A comparison of the patterns clearly shows that the intensity of alite and belite peaks for heat curing condition at 100 °C is higher than 28-day standard water curing. This shows that the heat curing time at 100 °C was relatively short and resulted in a relatively lower degree of hydration and hence lower compressive strength compared to standard water curing. Also, as seen, for heat curing condition at 200 °C, the reduced intensity of alite, belite and Portlandite peaks compared to both standard water and heat curing at 100 °C confirms higher hydration degrees achieved for both Portland cement phases and pozzolanic hydration reactions between GGBFS and Portlandite.

3.4. Water absorption

The water absorption values of GLRPC (% by weight of GLRPC concrete cubes) hardened under different curing conditions were determined and the obtained results are represented in Fig. 10. It can be seen that the amount of water absorption depends not only on the EPS volume, but also on the curing conditions applied. By increasing the EPS volume, the amount of water absorption tends to increase, while the rate of increase (the slope of water absorption/EPS volume curve) strongly depends on the type of curing conditions applied.

The least values of water absorption and the least increase in the amount of water absorption with replacement level belongs to GLRPC hardened under standard water curing conditions. The minimum water absorption value, therefore, belongs to GLRPC0 under standard water curing and GLRPC45 mixture shows only about 0.2% increase in water absorption compared to GLRPC0. This relatively small increase in water absorption may be related to the slightly higher air voids resulted by the incorporation of EPS beads into GLRPC [21]. On the contrary, application of heat curing at 200 °C leads to higher values of water absorption so that GLRPC45 hardened under heat curing condition at 200 °C exhibited the maximum value of about 3.5%. This can be related to the reduction of EPS volume under heat curing conditions, which can strongly influence the amount of porosity in GLRPC. When EPS-containing GLRPC mixtures are being heated, EPS beads start shrinking at

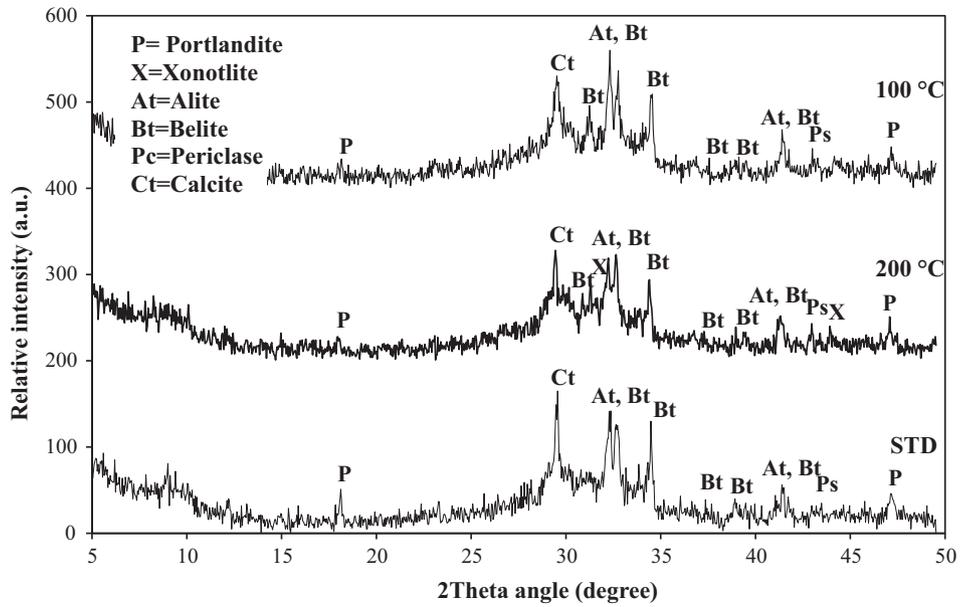


Fig. 9. XRD pattern of GLRPC under different curing regimes.

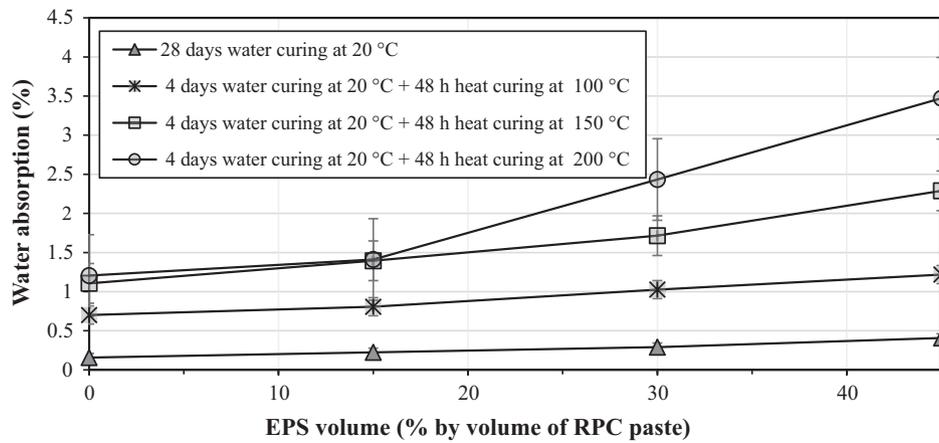


Fig. 10. Variation of water absorption under different curing regimes.

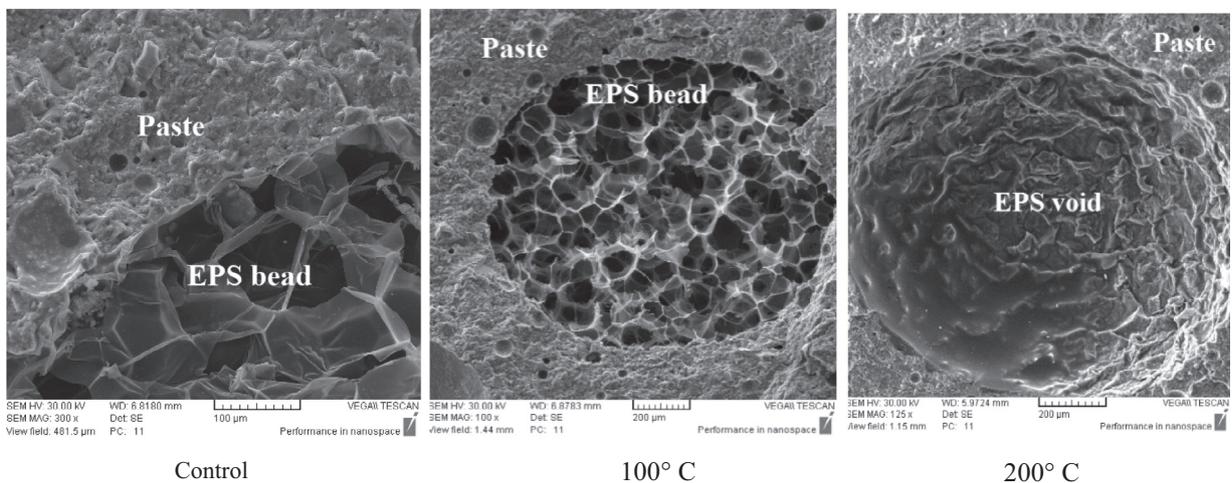


Fig. 11. SEM micrographs of interfacial bonding between EPS and matrix.

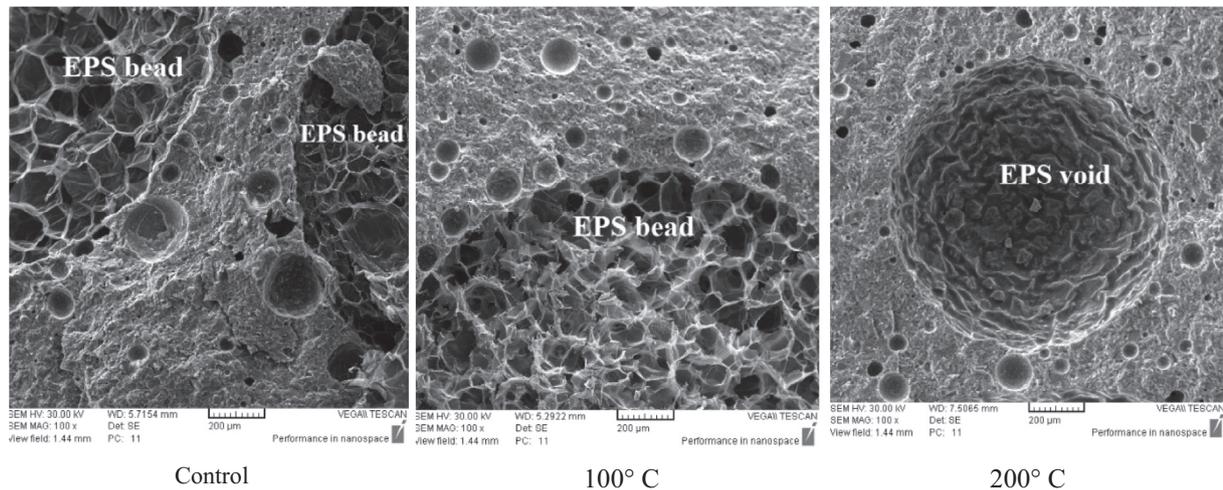


Fig. 12. SEM micrographs of GLRPC microstructure.

about 110–120 °C and melt at 160 °C [30]. The reduction in EPS volume causes creation of additional pores in GLRPC and therefore increases water absorption [31].

3.5. Microstructural studies

The SEM microphotographs of EPS and the EPS/GLRPC interface under different curing conditions of standard water curing, heat curing at 100 °C and heat curing at 200 °C from left to right, respectively, are shown in Fig. 11.

As can be seen, under standard water curing conditions and heat curing at 100 °C, despite the hydrophobic property of EPS, the interfacial bonding between EPS beads and GLRPC matrix is tight and compact and no transition zone of high porosity can be observed in this region. It has been proved that incorporation of silica fume and rice hush ash as supplementary cementitious materials remarkably enhances the interfacial bonding between EPS and matrix [21,23]. In the case of heat curing at 200 °C, since the curing temperature exceeds the EPS melting point of about 160 °C, the EPS beads start shrinking and melting during the heat curing regime leaving voids of almost the same sizes in the matrix. As seen in Fig. 11, the EPS melt spreads on the void surface and creates a ripple-surfaced EPS film. Formation of EPS voids in the GLRPC matrix results in significant increase in the amount of water absorption as observed in Fig. 10 for heat curing regime applied at 200 °C.

Generally RPC is characterized by very dense and homogeneous microstructure with very low macro and micro porosity and such a closely packed structure causes an increase in internal integrity and thus resulting in higher compressive strengths [32]. SEM observations confirmed that incorporation of EPS beads into RPC mixture can introduce more and larger macro air voids into the matrix as shown in Fig. 12. These macro defects can significantly affect the properties of the GLRPC including compressive strengths and water absorption and any effort to avoid these air voids can result in significant improvements. In addition, it is observed that standard water curing resulted in relatively larger pores as compared to the heat curing conditions and pores get considerably smaller by increasing the heat curing temperature. This is because increasing curing temperature leads to a higher degree of hydration along with formation of some crystallized hydration products which result in microstructure densification and smaller pore sizes [3].

4. Conclusions

A new class of green lightweight reactive powder concrete with different densities ranging from 1257 to 1840 kg/m³ and compressive strengths ranging from 20.8 to 85.6 MPa were successfully developed by using GGBFS to totally replace the quartz powder and incorporating EPS beads at different replacement levels of 15%, 30% and 45% (by volume of binder paste). The obtained results show that incorporation of EPS beads into RPC and increasing its volume results in significant reduction in compressive strength due to loss of integrity (because of non-uniform distribution of EPS beads in the matrix), weak mechanical nature of the EPS beads, lower density and inefficient compaction. It was also found that water absorption of the lightweight RPC increases as the EPS volume and the heat curing temperature are increased. This is due to increase in the matrix air voids introduced by EPS beads and also internal porosity caused by shrinkage and melting of EPS beads at curing temperatures close to and higher than 160 °C. Microstructural studies by SEM confirmed a tight and compact interfacial bonding between EPS and RPC matrix. As a concluding remark, the developed green lightweight reactive powder concrete mixtures in this work have certain advantages compared to the available lightweight reactive powder concrete; such as eco-friendly, superlative mechanical behavior at the late ages, and low production cost.

Conflict of interest

No conflict of interest.

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