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RESEARCH

Durability of Structural Lightweight Concrete Containing Expanded Perlite Aggregate

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Abstract

This study focuses on the development of durable structural lightweight concrete (LWC) by incorporating expanded perlite aggregate (EPA) in the range of 0 to 20% by weight. In order to ensure its durability when exposed to chloride environment, concrete was produced with low water-to-cement ratio and ordinary Portland cement (OPC) was replaced with 50% and 7% ground granulated blast furnace slag (GGBFS) and silica fume (SF), respectively. The mechanical properties and durability of concrete were assessed by determining the unit weight, compressive strength, flexural strength, drying shrinkage, chloride permeability and migration, as well as resistance of concrete to corrosion of reinforcing steel. Very importantly, thermal insulation properties were determined using a hot guarded plate. In addition, a finite element model (FEM) was prepared to study the behavior of EPA-modified concrete under seismic loading. The results showed that the unit weight of concrete was reduced by 20% to 30% when compared with the normal weight concrete (NWC). The compressive strength of the developed LWC was sufficient to be used as structural concrete, particularly of those mixtures containing 10% and 15% perlite aggregate. The durability of LWC was comparable to NWC in terms of chloride diffusion and resistance of concrete to corrosion of reinforcing steel. The tangible outcomes also include the superior thermal insulation properties of LWC compared to NWC. The greater incorporation of EPA in the concrete resulted in better behavior under seismic loading.

Keywords: expanded perlite aggregate, lightweight concrete, compressive strength, durability, chloride diffusion, thermal conductivity

1 Introduction

To conserve energy and mitigate greenhouse gas emissions, which is believed to be the primary cause of global warming, there has been increase in research in the area of developing lightweight concrete (LWC) due to its notable benefits such as exceptional heat and sound insulation characteristics. However, when the unit weight of concrete is reduced by incorporating lightweight aggregates, it is believed that the mechanical properties and durability of such a concrete is compromised. Hence, the LWC need to be designed not only for superior mechanical performance, but also for ensuring long-term durability in order it to function satisfactorily when exposed to harsh environmental conditions.

It is estimated that about 77.7% of the electrical energy generated is consumed to power buildings, while in hot and arid regions about 73% of the total building energy is used for air-conditioning (Annual Report 2016; Elhadidy et al. 2001). With the global energy consumption and its cost is expected to rise steadily in the future, enhancing the energy efficiency of the building materials and systems is essential. As the normal weight concrete (NWC) has relatively higher thermal conductivity, lightweight concrete (LWC) is preferred in the construction industry

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due its multiple advantages including; reduction in the selfweight of structure due to reduced sizes of structural elements which consequently reduces the consumption of cement and reinforcing steel, reduction in the transportation and lifting equipment expenses, exceptional heat and sound insulating characteristics (Abdelrahman et al. 1993; Ahmad and Hadhrami 2009). A key constituent material that significantly influences the density of concrete is type of aggregate in the mixture. Therefore, utilization of good quality lightweight aggregate in the concrete mix may well reduce the unit weight of concrete without compromising the mechanical properties and durability. However, it is very difficult to obtain a concrete mix design having lesser unit weight yet possessing superior mechanical properties and durability.

In general, LWC is produced either by using natural or synthetic lightweight aggregates or by adding additives which produces air voids in the hardened concrete (Cheng et al. 2012). However, lightweight concrete for structural applications have been produced by utilizing natural or synthetic aggregates in the past (Felicetti et al. 2013; Yang and Zhang 2012). The different types of aggregates utilized to produce LWC previously and its durability and mechanical performance are summerized in the following sections.

Kan and Demirboga (2009), were able to produce a semi-structural LWC by using modified waste expanded polystyrene (MEPS) aggregates in concrete. In their research, the natural aggregates were fully or partially (25%, 50%, and 75%) replaced with MEPS aggregates. For comparison purposes, a mix with no replacement of natural aggregates was prepared. The density of the LWC produced was in the range of 900–1700 kg/m³ while the compressive strength in the range of 13–23.5 MPa (Kan and Demirboğa 2009). (Kou et al. 2009), studied the properties of fresh and hardened concrete. In their study, river sand was partially replaced with poly-vinyl chloride (PVC) plastic granules, in the range of 0–45% by volume. By using such replacements, they produced a concrete that was lighter, shrinks less, more ductile, and less permeable to chloride ions, than NWC. However, lower compressive, tensile and splitting strengths were reported (Kou et al. 2009). A comprehensive study was conducted earlier in which number of flooring systems were modeled in a FEM analysis (del Díaz et al. 2010). The constituent materials such as clay along with conventional and lightweight concrete was used. Even the geometry of the blocks was also varied with different openings and investigated the influence of change in geometry on the thermal transmittance of building envelop. The results presented revealed that the thermal efficiency significantly depends on the number of horizontal and vertical bulkheads in a block and by varying these the thermal

transmittance can be varied. Elsewhere, based on the results of a research study LWC having density and moisture content in the range of 900 to 1400 kg/m³ and 0 to 0.25 kg/kg was proposed to be used to improve the thermal efficiency of concrete prepared with expanded clay aggregate (del Díaz et al. 2013). Another study in this regard focused on the experimental and numerical analysis of a one square meter wall fabricated using light concrete hollow blocks fully instrumented to study the moisture transport along with the heat transfer (del Díaz et al. 2014). In a numerical analysis using finite element model, a steady and transient states were applied. The outcomes have shown that there was excellent correlation between the experimental and numerical analysis results in this study.

The effect of the dry environment on shrinkage properties of high-strength lightweight concrete (HSLWC) was investigated by (Zhang et al. 2005). The LWC was prepared using normal sand as fine aggregate and expanded clay as coarse aggregate. For comparison, NWC was prepared using normal sand and granite as coarse aggregate. It was reported that the shrinkage was more in the NWC than in the LWC, during the first 6 months of exposure. The shrinkage in the LWC decreased as the density of aggregates reduced and it increased with increase in the porosity of aggregates and water absorption. It was also reported that the shrinkage in the NWC slightly less than that of LWC after a year of exposure. The addition of up to 1.5% by volume of fiber and 5% of silica fume, as a replacement of the binder, produced a LWC that was less susceptive to shrinkage (Zhang et al. 2005). The volcanic pumice (VP) is a material that can be used to produce LWC. Hossain (2004) conducted a study on partial replacement of cement (0–25%) by weight and coarse aggregates (0–100%) by volume with VP to produce LWC. The results from their study showed that VP can be used to produce a structural lightweight concrete with reasonable strength and density. A low modulus of elasticity, high water permeability and initial surface absorption, were reported (Hossain 2004).

Basaltic pumice, also known as scoria, was used as lightweight aggregates in a study by (Kılıç et al. 2003), to produce a structural lightweight high strength concrete (SLWHSC). The mixtures were designed with and without mineral admixtures such as fly ash and silica fume as replacement of ordinary Portland cement (OPC). A control mix was prepared using scoria as aggregates and OPC as the binder. The control mix was modified using 10% silica fume and 20% fly ash to replace the cement binder in the mix. In addition, a ternary mix containing 20% fly ash, 10% silica fume and 70% Portland cement, respectively, was also prepared. For the purpose of comparison two NWCs mixes were prepared. All concrete

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specimens were cured at 20˚C and a relative humidity of 65%. The workability and unit weights of all the fresh mixes were also recorded (Kılıç et al. 2003). Results from the study showed that scoria aggregates can be used to produce structural lightweight concrete. In addition, a structural lightweight high strength concrete (SLWHSC) can be produced when ternary concrete was used in the mix design. This was attributed to its strength development with time (Kılıç et al. 2003).

Chia and Zhang (2002) conducted a study on the durability aspect of LWC, by measuring the chloride and water permeability of HSLWC. The results were compared with those of high strength NWC and conventional concrete having compressive strength between 30 MPa and 40 MPa. The results of the study showed that the water permeability of LWC was lower than that of the NWC. The high strength LWC and NWC both showed similar water permeability results. Similar results were also reported on the ability of LWC and high strength NWC to resist chloride ion penetration. It was also reported that there was no correlation between the water penetration depth and the chloride ion penetration in the concrete. However, there was a correlation between the chloride permeability values and chloride ion penetration due to the fact that the permeability values increased with depth of chloride penetration (Chia and Zhang 2002).

Keeping in view of global warming concerns, there is a urgent need to limit greenhouse gas emissions by conserving energy. Among several measures, energy efficient building materials and systems can be developed which will not only reduce the energy consumption of building envelop but also having added advantages as mentioned above. These desired features of building materials can be achieved when the normal weight concrete (NWC) is replaced with lightweight concrete (LWC). Therefore, developing a concrete which has lower density, yet having the required structural strength is needed which render huge economic benefit to the construction industry. Due to these notable benefits of LWC there has been renewed attempt to develop LWC materials. However, reducing the density of concrete might compromise the durability aspect of it that has not been fully elucidated in the past. Hence, this study focuses on the development of LWC by partially replacing aggregate with expanded perlite aggregate (EPA). The current study was not only concentrated on the engineering properties of the developed concrete but also its durability under chloride laden environment.

2 Materials and Methods
2.1 Materials
In order to reduce the unit weight of concrete, lime stone coarse aggregate was partially replaced with

Fig. 1 Expanded perlite aggregate.

Table 1 Physical properties of various aggregates.

Aggregate type	Specific gravity, gr/cc	Absorption,%
Expanded perlite	0.356	71
Lime stone	2.6	1.1
Dune sand	2.55	0.58

expanded perlite aggregate (EPA). The perlite aggregate is naturally available in the form of glassy volcanic rock. After crushing it to required sizes, it is subjected to heat treatment close to softening point of about 870˚C. This process increases its volume by 4 to 20 times compared to the initial volume. The heating process creates air voids in the aggregate there by makes it lighter. Since the majority (more than 80%) of the expanded perlite aggregate was retained on #8 sieve (2.36 mm opening), lime stone aggregate of similar size was partially replaced with it along with a portion of fine aggregate. The expanded perlite aggregate acquired from the local market is shown in Fig. 1. Table 1 displays the physical properties of various aggregates used in the study. The ordinary Portland cement (OPC) was also partially replaced with 50% and 7% ground granulated blast furnace slag (GGBFS) and silica fume (SF), respectively. The chemical composition of GGBFS and SF are given in Table 2. A high-range superplasticizer based on polycarboxylate was used to improve and extend the workability of concrete. It was used in the range of 0.5 to 1.5% to obtain a slump between 80 and 100 mm.

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Table 2 Elemental composition of GGBFS and SF.

Oxides, %	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	P_2O_5	LOI
GGBFS	33.32	11.82	1.045	44.57	2.45	0.77	0.35	–	1.36
SF	92.7	0.82	0.76	0.51	1.06	0.82	0.39	–	1.41

2.2 Experimental Design

The expanded perlite aggregate used was in the range of 0 to 20% by weight of aggregate. The concrete mixes were prepared with a coarse aggregate to total aggregate ratio and fine aggregate to total aggregate ratio of 0.65 and 0.35, respectively. The quantity of constituent materials used for preparing concrete mixes with varying quantity of expanded perlite aggregate is given in Table 3.

2.3 Methods

2.3.1 Unit Weight and Compressive Strength

The unit weight and compressive strength of concrete were determined in accordance with ASTM C138 (2010) and ASTM C39 (2010), respectively. The compressive strength was determined as early as 1 day of curing until 90 days. Three specimens were utilized at each period and average values are reported.

2.3.2 Flexural Strength

A third point loading was used in accordance with ASTM C78 (2010) to determine the flexural strength of concrete on the prismatic specimens of size $40 \times 40 \times 160$ mm. It was determined after 28 and 90 days of curing. To ensure the accuracy of results, three specimens at each period were prepared and tested.

2.3.3 Water Absorption

The water absorption of concrete was determined using Ø75 mm and 150-mm-long cylindrical specimen. It was conducted according to ASTM C642 (2010) after 28 and 90 days of curing.

2.3.4 Drying Shrinkage

Prismatic specimens of size $50 \times 50 \times 250$ mm were utilized to monitor drying shrinkage of concrete in accordance with ASTM C341 (2010). After an initial 28 days of curing, the specimens were retrieved and stored in a laboratory which was maintained at 23 ± 2 °C temperature and a relative humidity of $50 \pm 5\%$. Subsequently, at regular intervals change in length was monitored using a LVDT fixed to a steel frame.

2.3.5 Chloride Permeability and Migration

The rapid chloride permeability of concrete was measured inccordance with ASTM C1202 (2010) using 50 mm thick Ø100 mm cylindrical specimens after 28 and 90 days of curing. A non-steady-state chloride migration coefficient was determined using Nordtest NT BUILT 492 (NT BUILD 2010). The test specimens were obtained by cutting Ø100 mm having 50 mm thickness from a 200 mm high Ø100 mm cylindrical specimen. It was computed utilizing Eq. 1, after 28 and 90 days of curing.

$$D_{nssm} = \frac{0.0239(273 + T)L}{(U - t)t}\left(x_d - 0.0238\sqrt{\left\{\frac{(273 + T)Lx_d}{U - 2}\right\}}\right), \quad (1)$$

where

$D_{nssm} =$ non-steady-state migration coefficient, $\times 10^{-12}$ m²/s.

$U =$ absolute value of the applied voltage;

$T =$ average value of initial and final temperatures in anolyte solution, °C;

$L =$ thickness of the specimen, mm;

$x_d =$ average value of the penetration depths, mm;

$t =$ test duration, hour.

2.3.6 Corrosion of Reinforcing Steel

The resistance of concrete to corrosion of reinforcing steel was assessed by measuring half-cell corrosion potentials and corrosion current density on steel that was

Table 3 Constituent materials used for preparing concrete containing perlite aggregate.

Mix #	Perlite Agg., %	Water/cement	OPC kg/m³	GGBFS kg/m³	SF kg/m³	Coarse Agg. kg/m³	Fine Agg. kg/m³	Perlite Agg. kg/m³
M0	0	0.25	198	230	32	1218	655	0
M10	10	0.25	198	230	32	674	336	112
M15	15	0.25	198	230	32	560	233	140
M20	20	0.25	198	230	32	482	160	160

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centrally placed in a concrete cylinder of Ø75 mm and 150 mm high in occordance with ASTM C876 (2010). The corrosion potentials were measured at regular intervals after partially immersing the specimens in 5% NaCl solution utilizing saturated calomel reference electrode (SCE). The corrosion current density (I_{corr}) on reinforcing steel was evaluated by the linear polarization resistance method (LPRM). The polarization resistance (Rp) was determined by conducting a linear polarization scan in the range of ± 10 mV of the measured corrosion potential. A scan rate of 10 mV/m was used. The corrosion current density (I_{corr}) was determined using the Stern and Geary formula (Stern and Geary 1957).

2.3.7 Thermal Conductivity

The concrete slab specimens prepared with and without expanded perlite aggregate (EPA) were tested for thermal conductivity using a Dynatech guarded hot plate that conforms to ASTM Standard C 177 (2010) under steady-state heat flow conditions. The guarded hotplate equipment, shown in Fig. 2, is suitable for testing of concrete block, clay brick, solid concrete, pozzolan, gypsum, composites, etc., and thermal insulation materials such as the extruded polystyrene, rock wool, perlite, vermiculite, rubber, plastic, etc. The accuracy of the guarded hotplate equipment is about ± 4% of the true value of the thermal conductivity. The guarded hotplate is designed to carry two specimens of maximum 15 cm thickness. A thin calibrated expanded polystyrene dummy specimen was used on the upper side of the plate and the concrete mixtures slab test specimens were placed on the lower side of the plate.

The types of concrete slab specimen tested are shown in Fig. 3. The four types of specimens of dimensions

Fig. 3 Test specimens for evaluation of the thermal conductivity of concrete.

35 cm × 35 cm × 5 cm (thickness) were prepared in the laboratory as described in the Sect. 2.1. The equipment requires specimens of 61 cm × 61 cm to cover the main heater and the guard heater. The main heater is 30 cm × 30 cm in size, which needs to be covered by the test specimen. Due to the smaller specimen size, the insulated frame of outside dimensions 61 cm × 61 cm was used as displayed in Fig. 4 to place the test specimen inside the frame to cover the main heater and the guard heater. The hot and cold plate surfaces of the equipment must be in proper contact with the test specimen surfaces to minimize the surface contact resistance. During casting of the test specimens in the laboratory, it was observed that the specimen surfaces were not smooth and flat. The rough surface of the test specimen would
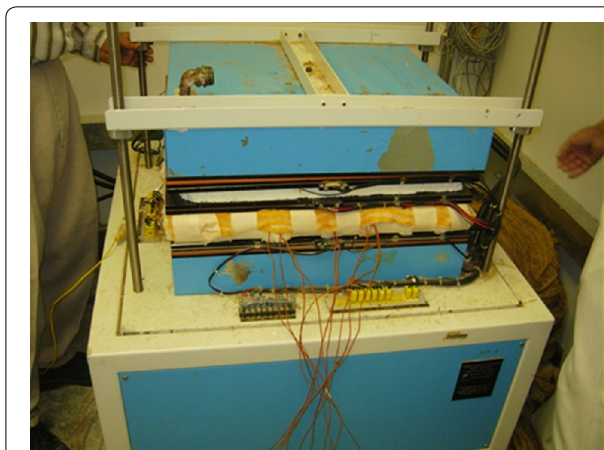

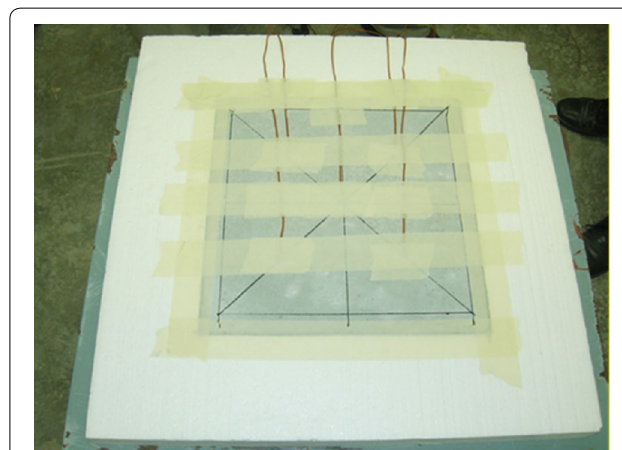**Fig. 2** Guarded hot plate for measuring the thermal conductivity of the concrete.

Fig. 4 Specimens with thermocouple wires fixed on the concrete slab surfaces for measuring temperatures.

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result in a significant temperature difference between the guarded hotplate and the corresponding test specimen surfaces. In order to reduce the contact resistance between the surfaces, the T-type thermocouples were fixed on both sides of the test specimen and the specimens were covered with a blanket on both sides to have smooth contact with the plate surfaces. A Campbell data logger was used to monitor the surface temperatures at every 60-min intervals till steady-state conditions were attained.

The thermal conductivity, *k*, for the test specimen was calculated by the following equation (Eq. 2):

$$k = \frac{Qd}{A(T_h - T_c)},$$

(2)

where Q [Watts] is the heat flow through the test specimen, d (m)—the thickness of the test specimen, T_h and T_c (℃)—the hot side and cold side test specimen temperatures, respectively, and A (m^2)—the area of the main heater.

3 Results and Discussion
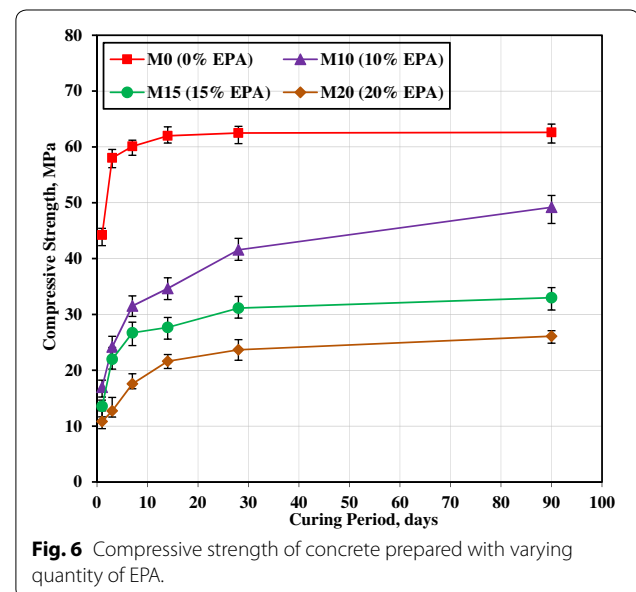
3.1 Unit Weight and Compressive Strength

A key factor which influences the unit weight of concrete is the specific gravity of aggregate used in the production of concrete as it is the major proportion in the entire concrete mixture. The unit weight of concrete was reduced progressively as the quantity of EPA was increased in the concrete mix as noted in Fig. 5. It was in the range of 2497 to 1729 kg/m^3, lowest in the mixture prepared with 20% EPA and the highest in the mix prepared without it. There was about 20 to 30% reduction in the unit weight of concrete prepared with EPA compared to the
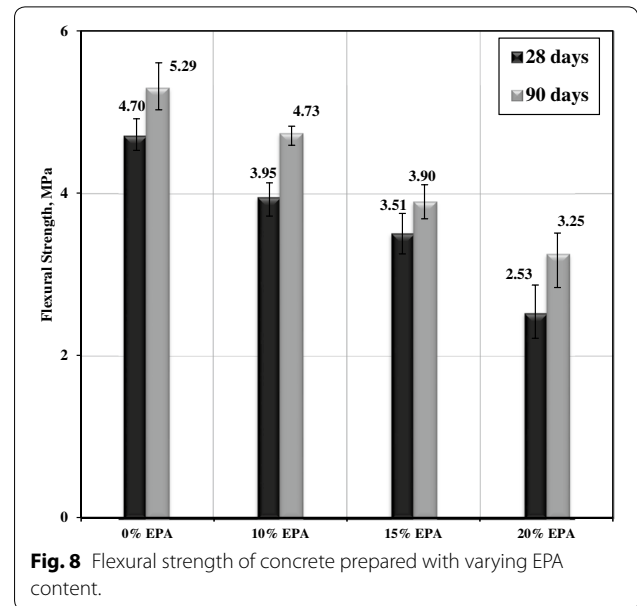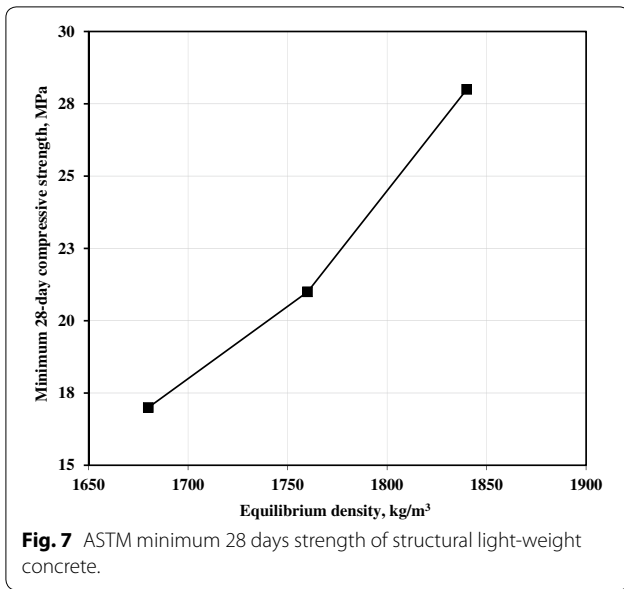
conventional concrete. According to the ACI 318 (ACI 318–10 2010) classification, the concrete produced with 15% and 20% EPA may well be classified as lightweight concrete.

Figure 6 displays the compressive strength development in the concrete. As expected, the compressive strength was high in the concrete prepared without EPA. After 1 day of curing the compressive strength was 44.22, 16.97, 13.56 and 10.84 MPa in the concrete containing 0, 10, 15 and 20% of EPA, respectively. However, as the curing continued, the strength gain in the concrete containing EPA was good and at 28 days, it was 41.58, 31.13 and 23.69 MPa in the concrete mixes containing 10, 15 and 20% EPA, respectively. According to the ASTM C330 (2010) standard classification of structural lightweight concrete as presented in Fig. 7, the concrete having equilibrium density of 1760 kg/m^3 should have a minimum 28-day compressive strength of 21 MPa, whereas, a minimum strength of 28 MPa is required for a density of 1840 kg/m^3. Hence, the concrete prepared in this study with 15 and 20% EPA may well be classified as structural lightweight concrete. The strength of EPA-concrete was marginally higher than the standard specification defining the structural lightweight concrete.

A similar study conducted by Kan and Demirboğa (Kan and Demirboğa 2009) used modified waste expanded polystyrene aggregate to produce concrete. The density of the LWC developed was in the range of 900–1700 kg/m^3, while, the corresponding compressive strength was between 13 and 23.5 MPa. In couple of other studies, volcanic pumice was used as partial replacement of coarse aggregate which enabled to produce structural

Fig. 5 Unit weight of concrete containing varying quantity of EPA.

Fig. 6 Compressive strength of concrete prepared with varying quantity of EPA.

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Fig. 7 ASTM minimum 28 days strength of structural light-weight concrete.

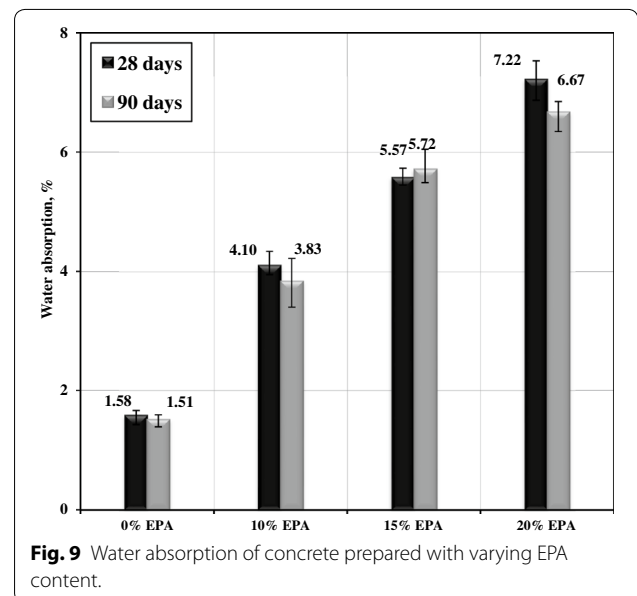**Fig. 8** Flexural strength of concrete prepared with varying EPA content.

lightweight concrete with reasonable strength and density (Hossain 2004; Kılıç et al. 2003). The lower compressive strength of concrete produced with aggregates such as, expanded polystyrene beads, volcanic pumice as well as EPA may well be attributed to the lower strength and high volume of these aggregates which results in insufficient cement paste to bind them. In addition, the porous nature of the aggregate as well as the increased amount of air entrapped in the concrete mixture results in the weakening of cementitious matrix which eventually reduces the strength of concrete.

3.2 Flexural Strength

Figure 8 illustrates the flexural strength of concrete produced with varying EPA content after subjecting prismatic specimens to three-point loading. It was noted that the failure of EPA-modified concrete was to some extent ductile compared to the conventional concrete. The flexural strength results followed the similar trend as that of compressive strength. A maximum flexural strength of 4.70 and 5.29 MPa was obtained after 28 and 90 days of curing, respectively, in the control mixture, whereas, it was lowest in the concrete prepared with 20% EPA. There was gradual reduction in the flexural strength as the EPA content was increased in the concrete mixture which was about 10.6, 26.3 and 38.6% in the concrete prepared with 10, 15 and 20% EPA, respectively, compared to the control mix after 28 days of curing. The reduction in flexural strength of concrete produced with EPA may well be attributed to the weaker bond between the adjacent aggregates resulting in the weaker planes.

3.3 Water Absorption

The water absorption is one of the basic characteristic of concrete which determines the durability aspect of it. A conventional concrete of normal weight generally results about 5% of water absorption which is considered as good (Ali et al. 2018). The water absorption of 28 days cured concrete produced in this study ranged between 1.58 to 7.22%, while, it was about 1.51 to 6.67% in the specimens cured for 90 days as displayed in Fig. 9. It was lowest in the conventional concrete and highest in the 20% EPA-modified concrete. The higher water absorption of

Fig. 9 Water absorption of concrete prepared with varying EPA content.

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EPA-modified concrete was due to the excessive air voids in the concrete and aggregate which makes it aborptive in nature. However, less than 6% of water absorption as in case of 10 and 15% EPA-modified concrete is also considered to be very good. Generally, the water absorption of lightweight concrete was reported to be between 6 to 12% (Ali et al. 2018; Andi Prasetiyo Wibowo 2017; Bajare et al. 2013).

The water absorption in the range of 4.10 to 7.22% after 28 days of curing in the EPA-modified concrete could be considered as moderate comparing the results of previous studies. This type of performance of developed concrete was possible due to the fact that it was produced with lower water to cement ratio in addition to the partial replacement of OPC with GGBFS as well as SF. The water absorption of control mixture was less than 2% due to the same reason.
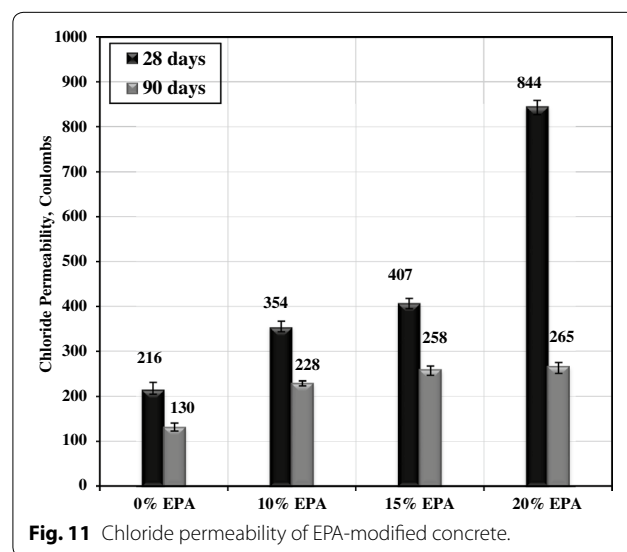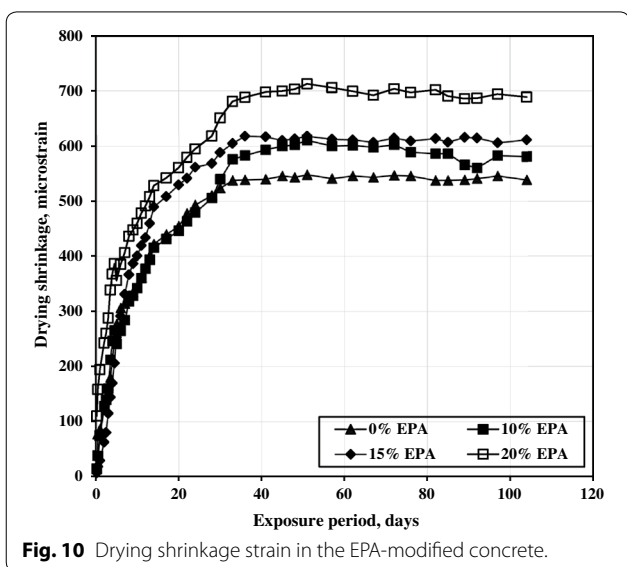
3.4 Drying Shrinkage

The drying shrinkage strain was measured utilizing prismatic concrete specimens. The frequency of shrinkage measurement was more at the initial stages of exposure compared to the latter. As expected, the shrinkage was rapid during the first stage of exposure, subsequently, it was reduced as illustrated in Fig. 10. The drying shrinkage strain was maximum in the 20% EPA-modified concrete of the order 712 microstrain, while, it was the lowest in the control mixture of about 548 microstrain. The primary factor which influences the shrinkage charateristic of concrete is the rate of evaporation of water from the surface of concrete, it was higher in the case of concrete prepared with 20% EPA. The absorptive nature of the aggregate also results in higher shrinkage of concrete and
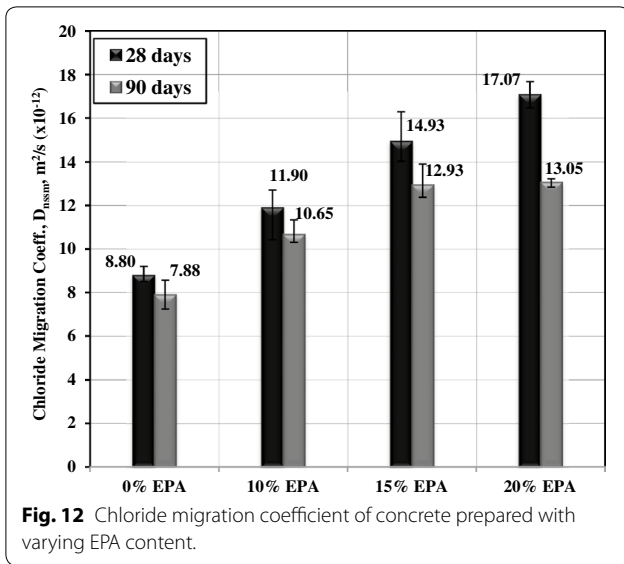
as the amount of such type of aggregate increases so does the shrinkage (2010).

In a previously conducted study, the effect of dry environment on shrinkage properties of high-strength lightweight concrete (HSLWC) was investigated by Zhang et al. (2010). The LWC was prepared using normal sand as fine aggregates and expanded clay as coarse aggregates. For comparison, NWC was prepared using normal sand and granite as coarse aggregate. The shrinkage in the LWC decreased as the density of aggregates decreased and it increased with increase in the porosity of aggregates and water absorption. The addition of up to 1.5% by volume of fiber and 5% of silica fume, as a replacement of the binder, produced a LWC that was less susceptive to shrinkage (2010). In another study, where LWC was developed using prickly pear fiber, there was about 18% increase in shrinkage due to the incorporation of 15 kg/m^3 such fiber compared to control mixture (Kammoun and Trabelsi 2019).

3.5 Chloride Permeability and Migration

Figures 11 and 12 show the rapid chloride permeability and chloride migration coefficient of concrete prepared with and without EPA, respectively. The rapid chloride permeability fairly gives the indication of durability of concrete exposed to chloride environment. Also, the migration coefficient determined based on the non-steady state using Nordtest NT BUILT 492 can be utilized to predict the initiation of corrosion of reinforcing steel embedded in the concrete. The chloride permeability in the concrete mixes prepared with 0, 10, 15 and 20% EPA was 216, 354, 407 and 844 Coulombs, respectively, after 28 days of curing. As the curing extended to 90 days, these values

Fig. 10 Drying shrinkage strain in the EPA-modified concrete.

Fig. 11 Chloride permeability of EPA-modified concrete.

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Fig. 12 Chloride migration coefficient of concrete prepared with varying EPA content.

significantly reduced which were in the range of 130 to 265 Coulombs. Based on the ASTM C1202, the concrete produced in this study can be classified as very low penetrability. The chloride migration coefficient of different concrete mixes followed similar trend as that of chloride permeability. It was maximum in the concrete prepared with 20% EPA and lowest in the control mixture. The magnitude of chloride migration coefficient was in the range of 8.80 to 17.07 (x10^{-12}) m^2/s at 28 days of curing. However, it reduced marginally as the curing extended to 90 days.

A review of literature indicated that there were fewer studies conducted to investigate the durability aspect of LWC, particularly the performance of such a concrete in chloride-laden environment. Among few of them, Chia and Zhang (Chia and Zhang 2002), conducted a study on the durability properties of LWC, by measuring the chloride and water permeability of HSLWC. The results were compared with those of high-strength NWC and conventional concrete having compressive strength between 30 MPa and 40 MPa. The results displayed that the water permeability of the LWC was lower than that of the NWC. The high strength LWC and NWC both showed similar water permeability results. Similar results were also reported on the ability of LWC and high strength NWC to resist chloride ion penetration. It was also reported that there was no correlation between the water penetration depth and the chloride ion penetration in the concrete. There appears to be a correlation between the chloride permeability and chloride ion penetration due to the fact that the permeability values increased with depth of chloride penetration (Chia and Zhang 2002).

3.6 Corrosion of Reinforcing Steel

The half-cell corrosion potentials and corrosion current density on steel embedded in concrete prepared with varying EPA content are shown in Figs. 13 and 14, respectively. The cylindrical concrete specimens prepared with and without EPA having centrally placed 12-mm diameter rebar were exposed to 5% NaCl solution over a period of more than 600 days. The corrosion rate measurements were carried out throughout the expsoure period. At the onset of exposure, the corrosion potentials on steel were in the range of -100 to -300, more negative
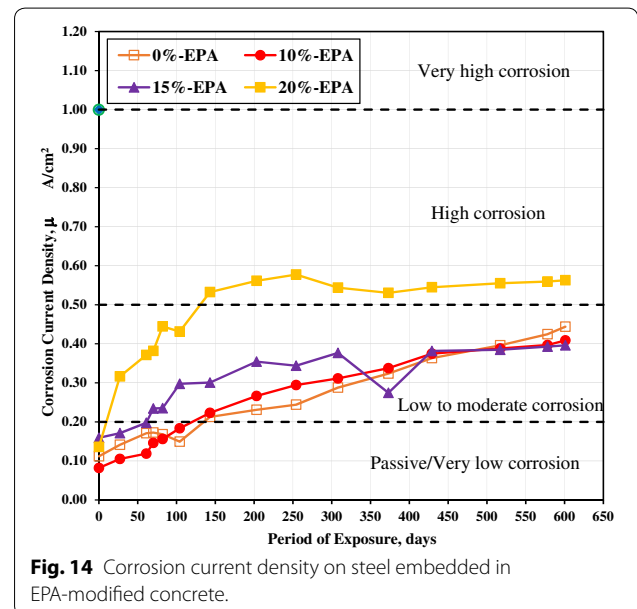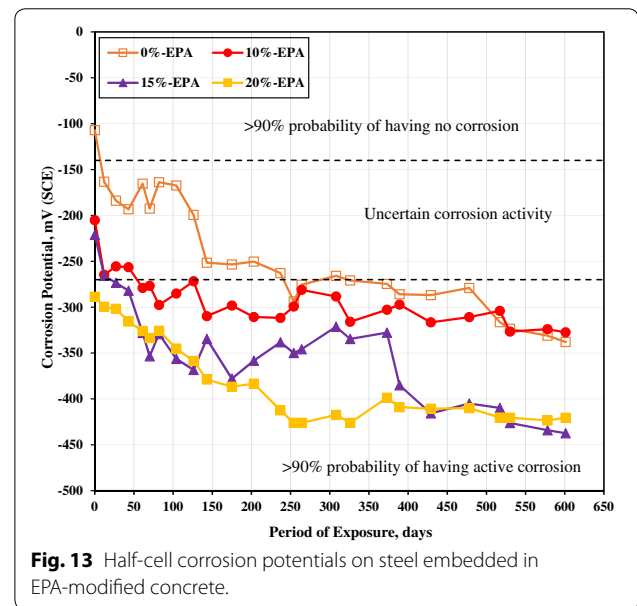

Fig. 13 Half-cell corrosion potentials on steel embedded in EPA-modified concrete.

Fig. 14 Corrosion current density on steel embedded in EPA-modified concrete.

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Table 4 State of corrosion on steel bar based on corrosion current density (Millard 2003).

Corrosion status of reinforcing bar	Corrosion current density I_{corr}, (μA/cm^2)
Passive/very low	Up to 0.2
Low/moderate	0.2 to 0.5
Mod/high	0.5 to 1.0
Very high	>1.0

in the concrete specimens prepared with EPA. These values became more negative gradually as the exposure continued. The magnitude of corrosion potential on steel embedded in concrete prepared with 0, 10, 15 and 20% EPA was − 338, − 327, − 437 − 420 mV, respectively, after about 600 days of exposure. These values indicate that there was a > 90% probability that the rebar was in a state of active corrosion. However, the values measured for 0 and 10% EPA-modified concrete was less negative than the ones for 15% and 20% EPA.

The state of corrosion on steel based on the magnitude of corrosion current density as classified by Millard S., (Millard 2003) is given in Table 4. The corrosion current desnsity on steel in all the mixes prepared in this study was very low at the onset of exposure. It started to increase significantly for the concrete mix prepared with 20% EPA and after a period of about 150 days, the corrosion rate could be classified as high in this particular mix. However, in the other mixes namely, 0, 10 and 15% EPA, the corrosion current density was between very low to moderate throughout the exposure. After about 600 days of continuous exposure to 5% NaCl solution, the corrosion current density on steel in the concrete prepared with 0, 10, 15 and 20% EPA was 0.44, 0.41, 0.39 and 0.56 $\mu m/cm^2$, respectively.

As mentioned earlier, the durability aspect of LWC was not investigated in detail in the previous studies. In particular, the data on corrosion of reinforcing steel embedded in LWC were limited. In view of potential exposure of such a concrete to chloride-laden environment, the aspect of corrosion of reinforcing steel is essential. A study carried out earlier in which LWC was developed utilizing polyethylene beads and scoria aggregate aspect of corrosion of reinforcing steel was studied (Ali et al. 2018). In that study, however, the corrosion potentials on steel were more negative than -600 mV and corrosion current density was as high as 0.7 $\mu m/cm^2$ in some of the concrete mixes proposed. This was attributed to the porous nature of the aggregate utilized in producing such a concrete, particularly, scoria. In the current study, the performance of LWC developed by utilizing EPA was better compared to the previous study. The enhanced

performance of concrete was due to the low water-to-cement ratio and addition of supplimentary cementitious materials.

3.7 Thermal Performance

The test results of the thermal conductivity for all the four types of concrete specimens prepared without and with different percentage of expanded perlite aggregate (EPA) varying from 0 to 20% are presented numerically in Table 5. The data show that there was reduction in the thermal conductivity for the EPA-modified concrete specimens compared to the normal concrete (without EPA). The thermal conductivity for the normal concrete (without EPA) was 1.138 W/m.k, which has the highest value compared with the other concrete (with EPA) specimens. The thermal conductivity of the concrete specimens with, 10, 15, and 20% EPA was much lower than the normal concrete specimen by about 49.3, 58.7 and 65.6%, respectively. The reduction in thermal conductivity of the EPA concrete specimens is attributed to the insulating nature of the aggregate and as the quantity of such type of aggregate was increased in the work there was less heat conduction. The data obtained in this study were comparable to the results of earlier studies conducted where various types of aggregates were utilized to produce lightweight concrete (Ali et al. 2018).

Generally, the thermal conductivity of LWC ranges between 0.1 and 0.7 W/mK for a range of 600-1600 kg/m^3 of density of concrete (Jones and McCarthy 2005). This value reduces as the density decreases. The thermal insulating properties of concrete are generally inversely proportional to the density (Shrivastava 1977). In general, it was observed that a 100 kg/m^3 reduction in the unit weight of concrete results in 0.04 W/mK reduction in the thermal conductivity (Weigler and Karl 1980; Van Deijk 1991). Further, it was reported elsewhere that usage of foam in the concrete could result in lowering the unit weight between 1000 and 1200 kg/m^3 with a corresponding thermal conductivity in the range of 0.2 and 0.4 W/mK (Jones and McCarthy 2006). The results obtained

Table 5 Thermal performance data of the concrete specimens.

Type of concrete	Thermal conductivity	Reduction in Thermal conductivity
	W/m.k	
0% EPA concrete	1.138	–
10% EPA concrete	0.577	49.3
15% EPA concrete	0.470	58.7
20% EPA concrete	0.392	65.6

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in the current study showed similar results. The main reason of reduction in the thermal conductivity of EPA-modified concrete in this study was due to increased heat flow path because of the cellular nature of perlite aggregate.

3.8 Structural Modeling and Behavior

A finite element model (FEM) was developed in ABAQUS to study the behavior of proposed concrete material under seismic loading. In order to make sure the validity of model, the multi-story framed FEM model was extracted from the study conducted by Vlad Inculet (Inculet 2016). Initially the model was prepared and replicated the results obtained from the original study and later it was modified to intended material used in this study. The prepared model and discretization are shown in Fig. 15a, b, respectively. As shown in Fig. 15b, a very finer mesh was chosen to obtain better stress–strain behavior of the structure. The seismic load was applied to the structure along the z-direction, the analysis was carried out for a real earthquake load. The loading spectrum was extracted from Vlad Inculet's (Inculet 2016), which represents the earthquake incident that occurred in Romania at 1977. The load spectrum is shown in Fig. 16. The model was analyzed for concrete material and the properties of material was defined from the experimental findings of M0, M10, M15 and M20 EPA-modified concrete mixes.

The comparison of stress distribution at base of the column and plastic drift at each story level were calculated from the ABAQUS results. The story drift along the z-axis was calculated using the equation given in Eq. 3, where u_{top} and u_{bottom} are represented lateral displacement (along z-direction in this case) of story at the top
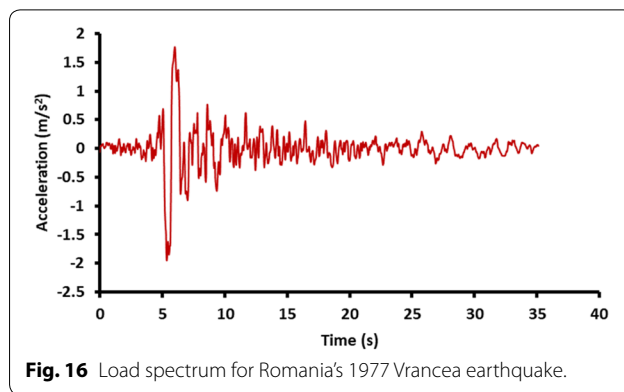

Fig. 16 Load spectrum for Romania's 1977 Vrancea earthquake.

and bottom level, respectively, and H is height of the considered story.

$$d_s = \frac{u_{top} - u_{bottom}}{H} \qquad (3)$$

Figure 17: The variation of time with story drift: (a) M0 (b) M10 (c) M15 (d) M20.17(a) to 17(d) represents the variation in story drift at each time limit of loading spectrum for M0, M10, M15 and M20 EPA-modified concrete, respectively. In all cases maximum drift was observed at first story level, the corresponding values are 6.30, 6.78, 5.18, 4.78 for M0, M10, M15 and M20, respectively, as shown in Fig. 17: The variation of time with story drift: (a) M0 (b) M10 (c) M15 (d) M20.17 (a) to 17(d). It shows that, lesser story drift was observed when 20% of EPA (M20) was used. This is a better observation in terms of serviceability requirement of the structure compared to other mixes.

Similarly, the stress variation of column at the ground floor level was investigated using the FEM findings as shown in Fig. 18a–d for M0, M10, M15 and M20, respectively. It shows in case of normal concrete (M0) the structure reaches the plastic region and the maximum stresses are 5.57 MPa in compression and 4.74 MPa in tension (see Fig. 18a). These values show better agreement with the experimental findings, because the compressive and flexural strength of M0 concrete are 62.49 MPa and 4.70 MPa, respectively (see Figs. 6, 8). Therefore, flexural crack can be observed in columns, consequently the structure shows the inelastic behavior in successive load cycles.

On the other hand, when the concrete of $M10, M15$ and $M20$ are used the structure is still in the elastic region as shown in Fig. 18b–d, respectively. As shown in Fig. 18b, the maximum stresses are 4.34 MPa in compression and 3.34 MPa in tension in the case of $M10$ concrete, however, these values are 2.17 MPa & 1.67 MPa, 1.54 MPa & 0.93 MPa, respectively, when $M15$ and $M20$ concrete are used. These values are less than the characteristic
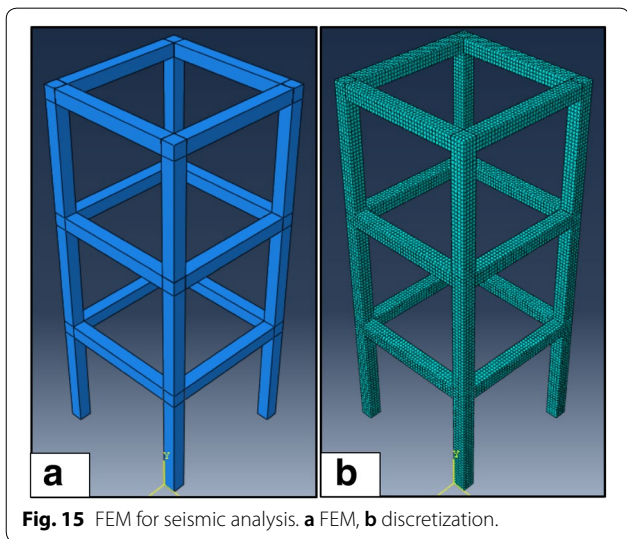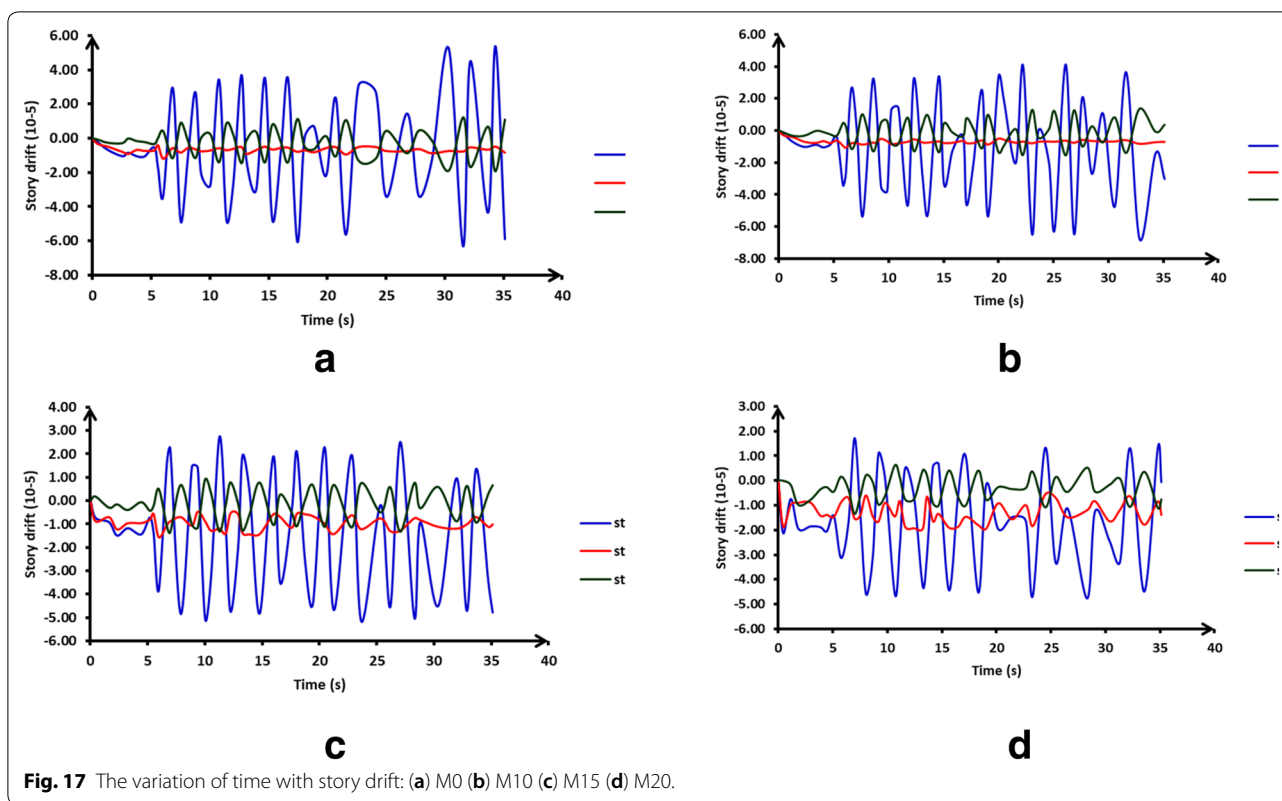

Fig. 15 FEM for seismic analysis. **a** FEM, **b** discretization.

Fig. 17 The variation of time with story drift: (**a**) M0 (**b**) M10 (**c**) M15 (**d**) M20.

compressive flexural strength of these concrete. Therefore, M20 concrete shows the better behavior under seismic loading because of its flexible nature and reduced density.

4 Conclusions

The objective of the current study was to develop LWC with superior mechanical properties and enhanced durability. In order to obtain such characteristics, concrete was produced by utilizing very low water-to-cement ratio and OPC was partially replaced with supplementary cementitious materials. The weight of concrete was reduced by partially replacing aggregate with 0% to 20% EPA. The following conclusions were drawn based on the data obtained in the study:

- The unit weight of concrete prepared with 10 to 20% EPA was in the range of 1729 to 2008 kg/m³ and the strength after 28 days of curing was between 23.69 and 41.58 MPa. The concrete mixes produced with 10% and 15% EPA could be classified as structural lightweight concrete based on ASTM classification. The flexural strength of EPA-modified concrete was fairly good and the failure under three-point loading was to some extent ductile in nature.

- As expected, the durability performance of concrete prepared with 0% EPA was excellent due to the fact that it was produced using low water-to-cement ratio and supplementary cementitious materials. Generally, the durability of concrete prepared with EPA was reasonably good. The water absorption, chloride permeability and chloride migration coefficient was in the range of 4.10% to 7.22%, 354 to 844 coulombs and 11.90 to 17.07 ($\times 10^{-12}$) m²/s, respectively. The drying shrinkage in the 20% EPA-modified concrete was higher, however, it was comparable to the NWC in the mixes prepared with 10% and 15% EPA. The resistance of EPA-modified concrete was moderate in most of the mixes prepared in this study.

- Thermal performance of the concrete is considerably improved with the increase in content of the expanded perlite aggregate (EPA) in the concrete.

- The incorporation of EPA in concrete shows the better behavior under seismic loading compared with normal concrete because of its flexible nature and reduced unit weight. The higher percentage of replacement is advantageous in terms of seismic loading.

Overall, it can be stated that the developed concrete utilizing lightweight EPA achieved good mechanical strength
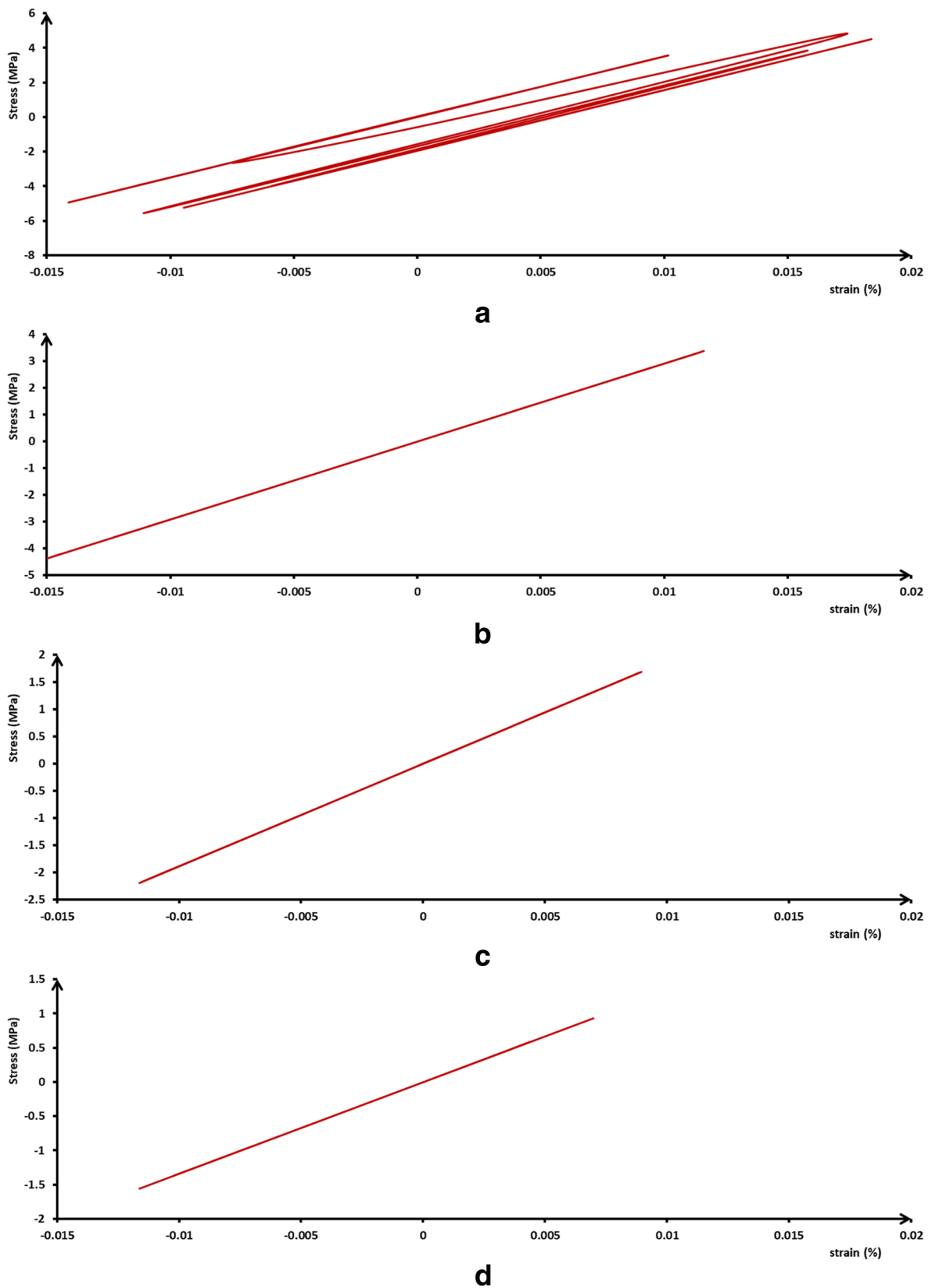
Fig. 18 The variation of strain with stresses at ground floor level of the column: (**a**) M0 (**b**) M10 (**c**) M15 (**d**) M20.

and performed well in terms of durability. Therefore, it can be used as cast in place concrete or in the precast industry as the initial compressive strength of concrete was good. The material is suitable to be used in the structural elements such as, slabs, beams and walls. The extensive thermal properties and the effect of moisture content can be studied as future research in this area. Also, a detailed structural modeling and the behavior of the structure subjected to various loading conditions can be the topic of future research.

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Authors' contributions
Corresponding author, MI and co-author MSB conducted experimental work, analyzed and prepared results. Partially prepared manuscript. Co-author, AA proposed mix design and conducted thermal properties of concrete mixes prepared in the study. Partially prepared manuscript. Co-author, LMA proposed concrete mix composition and analyzed thermal properties of produced concrete. Also, reviewed manuscript. Co-author, MSAC developed structural model to study the effect of EPA incorporation in the concrete on the behaviors of structure when seismic loading is applied. All the authors read and approved the final manuscript.

Availability of data and materials
All data are provided in the results section.

Ethics approval and consent to participate
Not applicable.

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Competing interests
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References
Abdelrahman, M. A., Said, S. A. M., & Ahmad, A. (1993). A Comparison of energy consumption and cost-effectiveness of four masonry materials in Saudi Arabia. *Energy The International Journal, 18*(11), 1181–1186.

ACI 318–10. (2010). *Building code requirement for structure concrete practice and commentary*. Indianapolis: American Concrete Institute.

Ahmad, A., & Hadhrami, L. M. (2009). Thermal performance and economic assessment of masonry bricks. *Thermal Science, 13*(4), 221–232.

Ali, M. R., Maslehuddin, M., Shameem, M., & Barry, M. S. (2018). Thermal-resistant lightweight concrete with polyethylene beads as coarse aggregates. *Construction and Building Materials, 164*, 739–749.

Andi Prasetiyo Wibowo. (2017). Water absorption of styrofoam concrete. *ARPN Journal of Engineering and Applied Sciences, 12*(16), 4782–4785.

Annual Report. (2016). "Annual Statistical Booklet for Electricity and Seawater Desalination Industries." Electricity and Cogeneration Regulatory Authority, www.ecra.gov.sa, Riyadh, Kingdom of Saudi Arabia.

ASTM C1202–10. (2010). *Standard test method for electrical indication of concrete's ability to resist chloride ion penetration*. West Conshohocken: ASTM International.

ASTM C138–10. (2010). *Standard test method for density (Unit Weight), yield, and air content (Gravimetric) of concrete*. West Conshohocken: ASTM International.

ASTM C177–10. (2010). *Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the guarded-hot-plate apparatus*. West Conshohocken: ASTM International.

ASTM C330–10. (2010). *Standard specification for lightweight aggregates for structural concrete*. West Conshohocken: ASTM International.

ASTM C341–10. (2010). *Standard practice for length change of cast, drilled, or sawed specimens of hydraulic-cement mortar and concrete*. West Conshohocken: ASTM International.

ASTM C39–10. (2010). *Standard test method for compressive strength of cylindrical concrete specimens*. West Conshohocken: ASTM International.

ASTM C642–10. (2010). *Standard test method for density, absorption, and voids in hardened concrete*. West Conshohocken: ASTM International.

ASTM C78–10. (2010). *Standard test method for flexural strength of concrete (using simple beam with third-point loading)*. West Conshohocken: ASTM International.

ASTM C876. (2010). *Standard test method for half-cell potentials of uncoated reinforcing steel in concrete, annual book of ASTM standards* (Vol. 402). West Conshohocken: American Society for Testing and Materials.

Bajare, Diana, Kazjonovs, Janis, & Korjakins, Aleksandrs. (2013). Lightweight concrete with aggregates made by using industrial waste. *Journal of Sustainable Architecture and Civil Engineering, 4*(5), 67–73.

Cheng, C. M., Su, D., He, J., & Jiao, C. (2012). Compressive strength of organic lightweight aggregate concrete. *Adv Mater Res, 374–377,* 1531–1536.

Chia, K. S., & Zhang, M. H. (2002). Water permeability and chloride penetrability of high strength lightweight aggregate concrete. *Cement and Concrete Research, 32*(4), 639–645.

del Díaz, J. J. C., Álvarez Rabanal, F. P., García Nieto, P. J., Hernández, J. D., Soria, B. R., & Pérez-Bella, J. M. (2013). Hygrothermal properties of lightweight concrete: experiments and numerical fitting study. *Construction and Building Materials, 40,* 543–555.

del Díaz, J. J. C., Álvarez-Rabanal, F. P., Gencel, O., García Nieto, P. J., Alonso-Martínez, M., Navarro-Manso, A., et al. (2014). Hygrothermal study of lightweight concrete hollow bricks: a new proposed experimental–numerical method. *Energy and Buildings, 70,* 194–206.

del Díaz, J. J. C., García Nieto, P. J., Domínguez Hernández, J., & Álvarez Rabanal, F. P. (2010). A FEM comparative analysis of the thermal efficiency among floors made up of clay, concrete and lightweight concrete hollow blocks. *Applied Thermal Engineering, 30,* 2822–2826.

Elhadidy, M.A., Ul-Haq, M., and Ahmad, A. (2001). "Electric energy consumption in selected residential buildings at KFUPM, Dhahran, Saudi Arabia." Proc., Mediterranean Conference for Environment and Solar., Beirut, Lebanon, Nov. 16–18, COMPLES 2000, IEEE, Vol. EX493.

Felicetti, R., Gambarova, P. G., & Bamonte, P. (2013). Thermal and mechanical properties of light-weight concrete exposed to high temperature. *Fire Mater, 37*(3), 200–216.

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Hossain, K. M. A. (2004). Properties of volcanic pumice based cement and lightweight concrete. *Cement and Concrete Research., 34*(2), 283–291.

Inculet V. (2016). Nonlinear analysis of earthquake-induced vibrations Master of Science Final Project, Master Sci. Thesis Proj. Aalborg Univ.

Jones, M. R., & McCarthy, A. (2005). Behaviour and assessment of foamed concrete for construction applications. In R. K. Dhir, M. D. Newlands, & A. McCarthy (Eds.), *Use of foamed concrete in construction* (pp. 61–88). London: Thomas Telford.

Jones, M. R., & McCarthy, A. (2006). Heat of hydration in foamed concrete: effect of mix constituents and plastic density. *Cement and Concrete Research, 36*(6), 1032–1041.

Kammoun, Z., & Trabelsi, A. (2019). Development of lightweight concrete using prickly pear fibres. *Construction and Building Materials., 210,* 269–277.

Kan, A., & Demirboğa, R. (2009). A novel material for lightweight concrete production. *Cement and Concrete Composites, 31*(7), 489–495.

Kılıç, A., Atiş, C. D., Yaşar, E., & Özcan, F. (2003). High-strength lightweight concrete made with scoria aggregate containing mineral admixtures. *Cement and Concrete Research., 33*(10), 1595–1599.

Kou, S. C., Lee, G., Poon, C. S., & Lai, W. L. (2009). Properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes. *Waste Management (Oxford), 29*(2), 621–628.

Millard, S. (2003). Measuring the corrosion rate of reinforced concrete using linear polarization resistance. DTI DME Consortium, Good Practice Guide No 132. Concrete, 36–38.

NT BUILD 492. (2010). Concrete, mortar and cement-based repair materials: chloride migration coefficient from non-steady-state migration experiments, NORDTEST, Espoo, Finland

Shrivastava, O. P. (1977). Lightweight aerated concrete—a review. *Indian Concrete Journal, 51,* 10–23.

Stern, M., & Geary, A. L. (1957). A theoretical analysis of the slope of the polarization curves. *Journal of Electrochemical Society, 104,* 56.

Van Deijk S. (1991). Foam concrete Concrete. pp. 49–53.

Weigler, H., & Karl, S. (1980). Structural lightweight aggregate concrete with reduced density—lightweight aggregate foamed concrete. *International Journal Lightweight Concrete, 2,* 101–104.

Yang, Y., & Zhang, H. (2012). Experimental study on flexural behaviors of all-lightweight aggregate concrete slabs. *Advance Material Research, 535–537,* 1918–1922.

Zhang, M. H., Li, L., & Paramasivam, P. (2005). Shrinkage of high-strength lightweight aggregate concrete exposed to dry environment. *ACI Materials Journal, 102*(2), 86–92.

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