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A novel material for lightweight concrete production

Abdulkadir Kan [a,*], Ramazan Demirboğa [b]

[a] Vocational College of Erzurum, Construction Program, Ataturk University, 25240 Erzurum, Turkey
[b] Department of Civil Engineering, Faculty of Engineering, Ataturk University, 25240 Erzurum, Turkey

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ABSTRACT

This paper presents the results of an experimental study on the effects of using recycled waste expanded polystyrene foam (EPS), as a potential aggregate in lightweight concrete. In this study, thermally modified waste EPS foams have been used as aggregate. Modified waste expanded polystyrene aggregates (MEPS) were obtained by heat treatment method by keeping waste EPS foams in a hot air oven at 130 °C for 15 min. Effects of MEPS aggregate on several properties of concrete were investigated. For this purpose, six series of concrete samples were prepared. MEPS aggregate was used as a replacement of natural aggregate, at the levels of 0%, 25%, 50%, 75%, and 100% by volume. The density of MEPS is much less than that of natural aggregate; MEPS concrete becomes a lightweight concrete with a density of about 900–1700 kg/m^3. The 28-d compressive strengths of MEPS concrete range from 12.58 MPa to 23.34 MPa, which satisfies the strength requirement of semi-structural lightweight concrete.

1. Introduction

In many countries, due to the increasing cost of raw materials and the continuous reduction of natural resources, the use of waste materials is a potential alternative in the construction industry. Waste materials, when properly processed, have shown to be effective as construction materials and readily meet the design specifications. The continued and expanding extraction of natural aggregate is accompanied by serious environmental problems. Often it leads to irremediable deterioration of rural areas, since quarrying of aggregates alters land topography and causes other potential problems, such as erosion. The artificial aggregates from industrial and post-consumer wastes are not only adding extra aggregate sources, but also reduce environmental pollution.

Lightweight concrete can be produced by introducing: (i) gassing agents such as aluminum powder or foaming agents, (ii) lightweight mineral aggregate such as perlite, vermiculite, pumice, expanded shale, slate, and clay, or (iii) plastic granules as aggregate, e.g., expanded polystyrene foam (EPS), polyurethane or other polymer materials [1]. There are many publications considering different wastes as a source of raw materials for the manufacturing of lightweight concrete. Nevertheless, the application of the different types of waste, produced either within a single industry or by several industries located within a small region, can represent a complex problem for their reutilization.

Original EPS beads can be easily incorporated with different contents in concrete to produce lightweight concrete with a wide range of densities. However, EPS lightweight concrete has not been used for structural concrete because of its generally low strength. The strength of concrete is influenced by the strength of the aggregate and it is known that the EPS beads have almost zero strength. Their low strength and weak performances in both concrete and mortar was clearly demonstrated by Kan and Demirboğa [2]. A new technique has been developed to achieve the recycling of waste EPS foams, with the aim of reusing the thermally modified waste EPS foams (MEPS) as aggregate in concrete. The MEPS aggregates developed by Kan and Demirboğa [3] from waste EPS foams show higher strength values than the unmodified EPS material.

The main objective of this paper is to provide some basic information on mechanical properties of structural concrete using artificial MEPS aggregates. MEPS aggregate concrete mixtures were obtained by partially replacing natural aggregate with the MEPS aggregates. In addition, the effects of the MEPS aggregate on compressive strength, splitting-tensile strength, modulus of elasticity, and freeze–thaw resistance were investigated.

2. Experimental details

Several experimental studies have been carried out on MEPS concrete specimens according to Turkish and ASTM codes. The properties of the materials used in these concrete mixtures are given below.

2.1. Materials

The following materials were used in the preparation of the concrete specimens. MEPS aggregate were obtained modified from waste EPS foams by using a thermal treatment method in the

* Corresponding author. Tel.: +90 442 231 2662; fax: +90 442 236 0982.
E-mail address: akan@atauni.edu.tr (A. Kan).

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laboratory [3]. Specific gravity factor (SGF) of fine (0–4 mm) and coarse (4–16 mm) MEPS aggregate was 0.34 and 0.24, respectively. SGF is not a true specific gravity, since its value incorporates compensation for absorption of free water by the MEPS aggregates, but it is used in exactly the same way to calculate volume relationship. The SGF has a different value for fine and coarse aggregate. Specification of MEPS aggregate can be seen from Table 1. The use of MEPS as lightweight aggregate makes it difficult to predict the concrete density. Indeed, MEPS is a compressible material and exhibits high porosity, contrary to natural aggregates such as sand or gravel.

The fine MEPS aggregates consisting of rigid and smooth shape spherical particles have a maximum dimension 4 mm. The fine MEPS aggregate were classified according to their aggregate sizes of 0–0.25 (5%), 0.25–0.5 (12%), 0.5–1.0 (%19), 1.0–2.0 (17%), and 2–4 mm (47%). Coarse MEPS aggregate were classified 4–8 mm (59%) and 8–16 mm (41%).

Maximum aggregate size of MEPS and natural aggregates were 16 mm. The natural sand used is from the Aras River and the coarse aggregate from Daphan. Unit weights of aggregates were sand (0–4 mm) 1850 kg/m^3; coarse aggregate (4–16 mm) 1660 kg/m^3. The specific gravity of aggregates were sand (0–4 mm) 2560 kg/m^3; coarse aggregate (4–16 mm) 2620 kg/m^3.

The cement used in this study was commercial grade ASTM Type I [4] Portland cement, which is produced as CEM I in Turkey. The cement contents for the concrete mixtures were constant at 500 kg/m^3 throughout the study. A polycarboxylate-based superplasticizer was used to produce mixtures of a flowable or highly flexible nature, to suit the adopted hand compaction method.

2.2. Concrete mix design and experimental procedures

Mix preparation is particularly important when using very lightweight aggregates. For the anticipated testing exactly six different mixtures of component materials were produced (they are labeled as series from C1 to C6). MEPS aggregate was used as 0%, 25%, 50%, 75%, and 100% of natural aggregate by volume and three concrete prism specimens were produced for each mixture proportion. For the 100% MEPS concrete, 50% fine MEPS + 50% coarse MEPS aggregate were used (C1). For a second group, 25% of fine MEPS were replaced with natural sand. Thus, 25% fine MEPS + 50% coarse MEPS + 25% natural sand were used (C2). For the third group, 50% coarse MEPS aggregate + 50% natural sand was used (C3). The fourth group was made up of 50% fine MEPS and 50% coarse natural aggregate (C4). The fifth group consisted of 25% fine MEPS + 25% coarse MEPS and 25% natural sand + 25% coarse natural aggregate (C5). Finally, 25% fine MEPS aggregate + 25% natural sand + 50% coarse natural aggregate were used (C6). The complete details of the MEPS aggregate and natural aggregate ratios are presented in Table 2.

For each test 100 mm × 200 mm cylinders were used for the determination of compressive and splitting-tensile strength (at 7, 28 and 90 days) and freezing and thawing tests (300 cycles). ASTM C 39 [5] was the test procedure used to evaluate the compressive strength. UPV measurements are reported for three repeats per cylinder and were conducted in accordance with ASTM C 567-97 [6].

All the concretes were mixed in a planetary mixer of 50 dm^3 capacity in the laboratory. The production and curing of lightweight concrete (LWC) has been described earlier [7–10]. The mixing of materials was done in a specific sequence, by placing a part of the water with superplasticizer in the mixture and adding the dry MEPS aggregates, which was thoroughly mixed for about 5 min to get the aggregates wetted with water and plasticizer similar to the mixtures designed for previous studies. Then, the remaining materials were added to the mixer and the remaining water was gradually added while the mixing was in progress. The mixing was continued until a mix of uniform consistency was achieved. The fresh concrete densities and slump values were measured immediately after mixing for all the concretes. The slump value for all the concretes varied between 25 mm and 50 mm. The test specimens were cast with hand compaction only. The specimens were covered with wet gunny bags 10 h after casting, demolded after 24 h and stored in water for curing until testing.

Properties of freezing and thawing of MEPS aggregate concrete were obtained by a rapid test in water according to the ASTM C 666 procedure B [11]. The cylindrical mould was used to measure the weight loss and the relative dynamic modulus of elasticity (RDME). RDME is the ratio of the dynamic modulus of elasticity value measured after a number of freeze–thaw cycles to the initial value before being subjected to freeze–thaw testing.

$$Pc = \left(n_1^2/n^2\right) \times 100 \quad (1)$$

Pc, denotes relative dynamic modulus of elasticity, after c cycles of freezing and thawing, percent, n, denotes fundamental transverse frequency at 0 cycles of freezing and thawing, and n_1, denotes fundamental transverse frequency *at c* cycles of freezing.

All specimens were removed from the moulds 24 h after casting. Then, they were cured at 20 ± 3 °C and 95% RH for 14 days according to ASTM C 666 [11]. A fraction of the specimens were then immersed in water for 4 days before being exposed to the freezing and thawing cycles; these specimens were put in the freeze–thaw apparatus and were used to measure the compressive strength, weight loss and RDME after 300 freezing and thawing cycles. An automatic environmental cabinet was used to carry out the accelerated freeze–thaw test.

Table 1
Specification of MEPS aggregate [3].

MEPS aggregate			
Origin of aggregate	Waste, expanded polystyrene foams (EPS)		
Method of recycling	At 130 °C for 15 min, thermal treatment method		
Density (kg/m^3)		Loose	Dense
	Fine	191	220
	Coarse	138	162
	Mixed	181	196
Water absorption	By weight	4.1%	
	By volume	0.58%	
Compressive strength at 10% deformation (MPa)	According to density of MEPS aggregate 1.76–8.22 MPa		
Thermal conductivity (W/(m K))	According to density of MEPS aggregate 0.0366–0.0521		
Weight loss of freezing–thawing (10 cycling)	0.31%		
Specific gravity factor (SGF)	Coarse		0.22–0.24
	Fine		0.31–0.34

3. Results and discussion

3.1. Workability and density

It is well known that the workability of fresh concrete and bonding between aggregates and the mortar phase are influenced significantly by physical properties such as shape, roughness and texture of aggregates. The smoothness or roughness of aggregate reflects the surface texture; glassy, smooth, granular, rough, crystalline, porous, and honeycombed textures are the visual properties of the surface. The bond is the development of anchorage and it depends on the roughness and porosity of the surface of the aggregate. Surface texture may help in the development of good bonds by the absorption of the paste into pores.

Table 2
Mixing details of MEPS aggregate concrete.

Mix type	MEPS/NA[a] (%) (F+CA)/(F+CA[*])	cement (kg)	MEPS (kg)		NA[b](kg)		SP[c] (kg)	w/c	Fresh density (kg/m3)	Slump values (mm)
			F	CA	F	CA				
C1	50% + 50%/0%	500	108	77	–	–	2.5	0.38	876	25
C2	25% + 50%/25% + 0%	500	53	75	402	–	2.5	0.39	1229	30
C3	0%+50%/50% + 0%	500	–	74	786	–	2.5	0.42	1572	30
C4	50% + 0%/0% + 50%	500	104	–	–	804	2.5	0.42	1621	30
C5	25% + 25%/25% + 25%	500	52	37	393	402	2.5	0.42	1596	40
C6	25% + 0%/25% + 50%	500	52	–	390	797	2.5	0.43	1956	50

[a] NA: natural aggregate.
[b] F+CA: fine and coarse aggregates.
[c] SP: super plasticizer.

Replacement of the natural aggregate with MEPS aggregate reduced the workability of the concrete mixtures because of the increased surface area of the aggregates. This was due to the fact that coarse MEPS aggregate surfaces have a large number of pores. This was more pronounced in the C1, C2, and C3 mixtures, due to their higher MEPS aggregate content (50%), resulting in a lower degree of compaction in the test specimens, which partly contributed to the reduction in strength. It was observed that when the MEPS aggregate content was increased, the fresh concrete mix became rubbery, harsh, and difficult to place and compact. Therefore, the use of a superplasticizer was found to be essential for the concrete mixtures with 100% MEPS (C1) and 75% MEPS (C2) aggregate replacements of natural aggregate. In addition, fine MEPS aggregates in mixtures without superplasticizer tend to float to the top surface during setting, increasing the risk of poor mix distribution and segregation. The fine MEPS aggregate improved the workability of the concrete mixture due to its 'shape effect'.

Slump tests were carried out to determine the consistency of the fresh concretes. The results of slump tests belonging to six series of concrete are given in Table 2. The measured slump values ranged between 25 mm and 50 mm. It can be seen that the slump values of the fresh concretes were decreased with an increasing MEPS ratio of the concretes.

Density is one of the important parameters, which can control many physical properties in lightweight concrete and it is mainly controlled by the amount and density of lightweight aggregate. Previous studies indicate that the density of EPS concrete decreases with an increase in volume of EPS aggregate and hence results in a decrease in compressive strength of the concrete [2,7,12,13]. By incorporating the MEPS aggregate at different volume percentages in a concrete, mortar or in the cement paste, a wide range of concrete densities can be produced. The fresh density of C1 concrete was 876 kg/m^3 compared to 1956 kg/m^3 for the C6 concrete. Thus the fresh density of the C1 concrete was 45% of the C6 (Table 2).

3.2. Compressive strength

A comprehensive summary of density, UPV, compressive and splitting-tensile strength of MEPS aggregate concrete is presented in Table 3.

Fig. 1 shows the relationship between the density of MEPS concrete and the 7, 28 and 90 days compressive strength. Apparently, the rates of strength development of all MEPS concretes have a similar trend. All MEPS concretes were able to develop more than approximately 80% of their corresponding 28-day strength at 7 days and 90% of their corresponding 90-day strength at 28 days, except for the C2 and C6 mixtures. As the MEPS aggregate decreased in the mixtures, the strength of the concrete increased. This may be due to the lower density and weakness of the MEPS aggregate. Higher MEPS aggregate ratio concrete (C1) developed 83% of its 90- day strength after 7 d, while the lowest MEPS aggregate concrete (C6) developed only 69%. The probable reason for this may be the lower specific thermal capacity of the MEPS aggregate resulting in a reduced heat loss from the concrete, thereby increasing the heat of hydration. Thus, the earlier strength gaining was higher when compared to the lower MEPS content concrete mixture.

The strength of C3 was lower than that of C4 and C5 even though their MEPS aggregate contents were all 50% by volume. However, 50% MEPS aggregate of the C3 was coarse MEPS aggregate while for the others (C4 and C5), 50% MEPS were fine aggregate. It can be said that the coarser aggregate is brittle and weaker because of their higher porosity structure. Similar results are observed for conventional lightweight concrete where replacement of coarse aggregate with LWA decreases strength more substantially than does replacement of fine aggregate with LWA.

The relation between the compressive strength and density for the MEPS concretes (having hardened densities ranging from 980 kg/m^3 to 2025 kg/m^3 and strengths ranging from 12.58 MPa to 23.34 MPa) were similar to those of previous studies using unmodified EPS aggregates [2,7,14]. Moreover, for equal concrete densities, MEPS aggregate concrete have exhibited 40% higher compressive strength than vermiculite or perlite aggregate concrete and these were found to be freezing–thaw resistant and hence used as a good thermal insulation material in building construction. The relationship between hardened concrete density and compressive strength, based on the results of MEPS concretes with densities ranging from 980 kg/m^3 to 2025 kg/m^3 can be proposed as

Table 3
Density, UPV, compressive and splitting-tensile strength of MEPS aggregate concrete.

Mix type	Density (kg/m^3)	UPV (m/s)			Splitting-tensile str. (MPa) f_{ct}			Comp. Str (MPa) f_c		
		7 days	28 days	90 days	7 days	28 days	90 days	7 days	28 days	90 days
C1	980	1980	2190	2270	1.70	1.82	1.85	11.17	12.58	13.39
C2	1377	2500	2620	2750	2.23	2.34	2.40	12.55	13.08	15.62
C3	1692	2940	3060	3190	1.72	2.07	2.15	11.37	13.93	14.31
C4	1734	2820	3010	3180	2.13	2.38	2.39	13.44	17.65	18.92
C5	1741	3020	3150	3230	1.75	2.16	2.56	12.75	17.85	19.14
C6	2025	3420	3600	3670	2.47	3.00	3.01	19.22	23.34	27.78

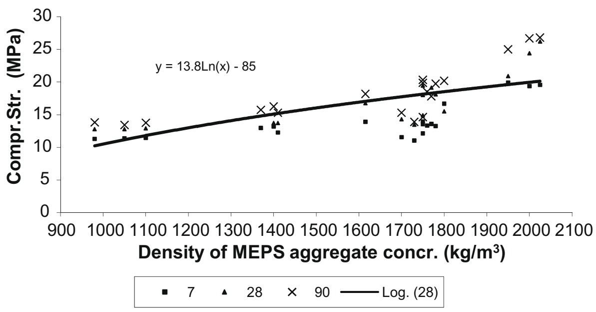

Fig. 1. The relationship between MEPS aggregate concrete density and compressive strength.

$$f_c = 13.8\text{Ln}(\gamma) - 85 \quad (2)$$

where f_c is the compressive strength (MPa) and γ is the hardened density (kg/m^3) of the MEPS aggregate concrete.

Lots of studies can be found on the mechanical properties of lightweight concrete mixtures made of polystyrene aggregates (PAC). Tang et al. [15], developed a class of structural grade PAC with a wide range of concrete densities between 1400 kg/m^3 and 2100 kg/m^3 through partial replacement of coarse aggregate with EPS aggregate. Their results show that the concrete density and concrete strength decrease with an increase of EPS aggregate content in the mixture. Perry et al. [12] also studied the mechanical properties of PAC over a density range from 850 kg/m^3 to 1250 kg/m^3 and stated that the mechanical behavior of PAC should be considered similar to that of cellular concrete as the EPS aggre-

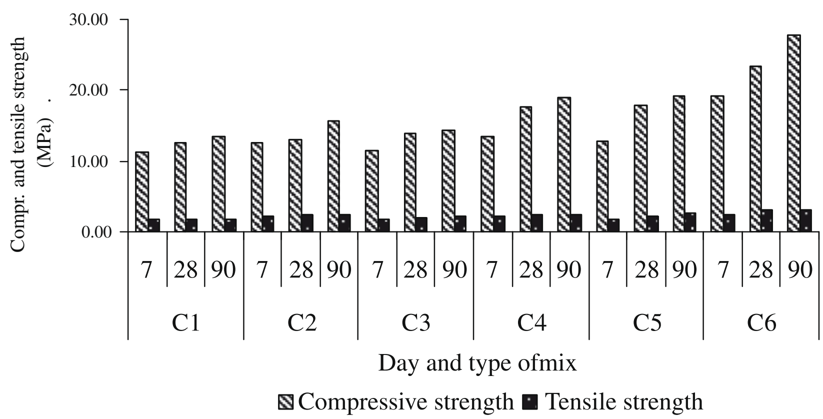

Fig. 2. The relationship between MEPS aggregate concrete 7, 28 and 90 day compressive strength and tensile strength.

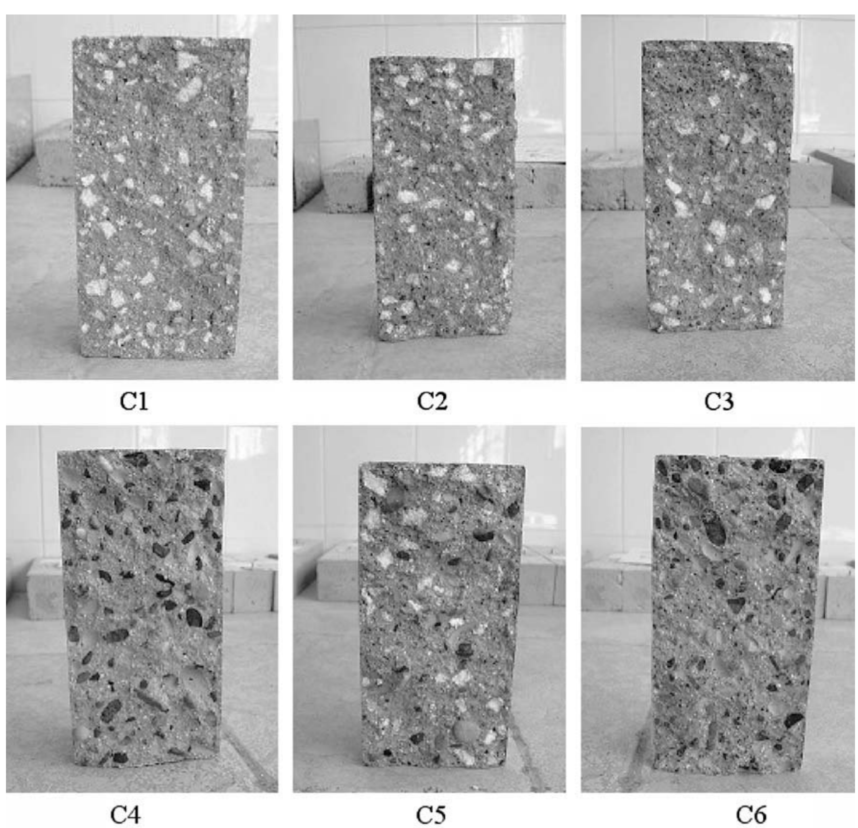

Fig. 3. Splitting failure mode of the concrete specimens containing MEPS aggregates.

Table 4
Comparison of unmodified EPS with MEPS aggregate concretes.

References	Concrete mix	Density (kg/m^3)	Compressive strength (MPa)		Splitting-tensile strength (MPa)
			7 days	28 days	
Kan and Demirboğa [2]	EPS+C	464–1370	–	0.11–8.53	–
Babu and Babu [8]	EPS+FA+S+C	582–984		1.10–3.83	–
Babu et al. [9]	EPS+C+S+FA	582	0.62	1.1	–
Park and Chisholm [13]	EPS+ S+C	820	3.2	3.8	–
Chen and Liu [16]	EPS+NA+C	876	7.6	10.6	1.32
Babu and Babu [17]	EPS+NA+SF+C	1552	7.6–14	10.2–21.4	1.53–2.16
Miled et al. [19]	EPS+S+C	1810		7.6–8.5	–
Muravljov [20]	EPS+S+PP+C	1130–1484	6.4–10.84	7.73–14.62	–
Laukaitis et al. [21]	EPS+C	149–275	–	–	0.25
Sabaa and Ravindrarajah [22]	EPS+C+NA	1600–2000		8.8–21.3	–
Ravindrarajah et al. [23]	EPS+C+NA	1100–1920		8.5–37.5	0.92–4.05
Present study	MEPS+C (C1)	980	**11.17**	**12.58**	1.82
	MEPS+C+NA (C4)	1734	**13.44**	**17.65**	2.38

EPS; unmodified expanded polystyrene.
C; cement.
NA; natural aggregate.
FA; fly ash.
S; natural sand.
PP; polypropylene.
SF; silica fume.

gate consists essentially of air. Similarly, Chen and Liu [16] investigated the strength properties of PAC at a constant water/binder ratio (i.e., 0.37) producing a series of PAC with compressive strengths of 10–25 MPa over a density range between 800 kg/m^3 and 1800 kg/m^3. Recently, Babu and Babu [8,17] have studied the strength and durability of PAC containing mineral admixtures with concrete densities varying from 550 kg/m^3 to 2200 kg/m^3 and the corresponding strength results were found to vary from 1 MPa to 21 MPa. It seems that most studies reported to date have been essentially related to PAC of lower strength. To better use the advantages of PAC for both structural and functional requirements, a series of structural grade PAC of 1400–2100 kg/m^3 densities with corresponding strengths of about 17 MPa minimum were designed and studied [18].

3.3. UPV of MEPS aggregate concrete

UPV of MEPS aggregate concrete is influenced by many factors, such as density, age, moisture content, porosity, the physical and chemical characteristics of component materials and mixture proportions. Hence, it is desirable to keep the mixture proportions, type of cement and ratio of MEPS aggregate/natural aggregate as well as the method of production constant. A relationship exists between the UPV and density, and also between UPV and compressive strength. Any change to the factors mentioned above could vary that relationship quite markedly. The results indicate that the UPV values increase as the strength of the concrete increases. UPV also decreased with the increase of the MEPS content. The variation of UPV is given in Table 3.

3.4. Splitting-tensile strength

The splitting-tensile strengths and density of MEPS aggregate concretes are summarized in Table 3. The variation of splitting-tensile strength with the compressive strength is given in Fig. 2. Similar to compressive strength, the splitting-tensile strength of MEPS aggregate concrete also increased with a decrease in the MEPS aggregate ratio. It can be seen that the tensile strength increased with an increase in compressive strength. All test specimens exhibited linear-elastic behavior until cracking. As seen in the Fig. 3, the splitting failure mode of the concrete specimens containing MEPS aggregates also exhibited the typical brittle failure normally observed in conventional concrete in splitting tensile tests.

Splitting-tensile strength of concretes containing only MEPS aggregate is lower than that of those partially containing natural aggregate. The differences are greater at lower water to cement ratios. Substitution of sand for the fines of MEPS aggregates does not result in improved strength. Concrete using fines from MEPS aggregate requires a higher water to cement ratio. This is expected because of the presence of higher amounts of porosity.

The literature in the field of EPS concrete is mostly devoted to characterizing the mechanical properties of these materials. It is shown that these properties can be significantly improved by adding polypropylene fibers (PP) or silica fume (SF) in the concrete matrix or by decreasing EPS beads size. This phenomenon has been proved by Babu and Babu [17] with structural EPS concretes of higher densities and with two EPS beads sizes: 6.3 mm and 4.75 mm.

Comparisons of density, compressive strength and splitting-tensile strength of the unmodified EPS concretes and MEPS aggregate concretes are given in Table 4. This comparison was made only for concretes containing unmodified EPS aggregates and similar cement contents as in the present study.

3.5. Freezing and thaw resistance

An automatic environmental cabinet was used to carry out the accelerated freeze–thaw test. The ASTM Standard test lasted for 5 h. The cylinders were kept in lime saturated water until the date of the test. Performance results of C1–C6 in the accelerated freeze–

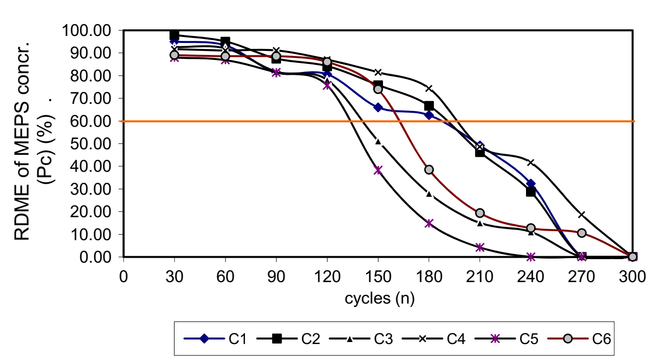

Fig. 4. RDME of MEPS aggregate concrete during freezing and thawing cycles.

Table 5
Relative dynamic modulus of elasticity of MEPS aggregate concrete (%).

Freeze–thaw cycles	Relative dynamic elasticity module (RDME)					
	C1	C2	C3	C4	C5	C6
30	**94.94**	**97.85**	92.58	91.62	87.96	89.00
60	**93.28**	**95.03**	92.03	91.04	86.85	88.49
90	**81.31**	**87.47**	81.73	91.04	81.43	88.49
120	**80.54**	**84.14**	78.10	87.00	75.66	85.97
150	**65.93**	**75.78**	51.14	81.39	38.23	73.93
180	**62.50**	**66.67**	27.99	74.37	14.79	38.43
210	**49.12**	**46.22**	14.95	48.62	4.17	19.30
240	**32.31**	**28.73**	10.98	41.64	0.00	12.66
270	**0.00**	**0.00**	0.00	18.59	0.00	10.46
300	**0.00**	**0.00**	0.00	0.00	0.00	0.00
Weight loss (%)	**2.36**	**0.15**	6.25	0.79	4.62	1.70
Compressive strength before 300 cycles (MPa), f_{c28}	12.58	13.08	13.93	17.65	17.85	23.34
Compressive strength after 300 cycles	4.14	6.31	5.14	7.34	5.63	7.96
DF	38	40	26	45	30	37

thaw cycling tests are given in Fig. 4 and Table 5. In addition, Table 5 contains the relative dynamic modulus of elasticity (RDME), compressive strength before and after freezing–thawing cycles, durability factor (DF) and loss in weight of MEPS aggregate concrete as the evaluation indicators. As is well known, lightweight concrete exhibits a higher frost resistance due to the existence of 20–50% voids in the lightweight aggregates. Hence, C1, C2, and C4 without any anti-frost treatment (air entrainment) can still fulfill the normal anti-frost requirements, 60% RDME, up to 180 cycles of freeze–thaw tests. However, C3 and C5 fell below 60% RDME at 150 cycles and C6 at 180 cycles. The highest performance was observed, up to 240 cycles, for mixture C4. RDME of C4 was over 40% at 240 cycles. The performance of C3 was lower than that of C4 even though both of them have the same percentage (50%) of MEPS aggregate. This can be attributed to the coarser part of MEPS aggregate size of C3. As can be seen from the Table 2, all 50% of MEPS aggregate of the C3 mixtures was coarse aggregate, while in C4 it was fine. Thus, coarse lightweight MEPS aggregate is more suscep-

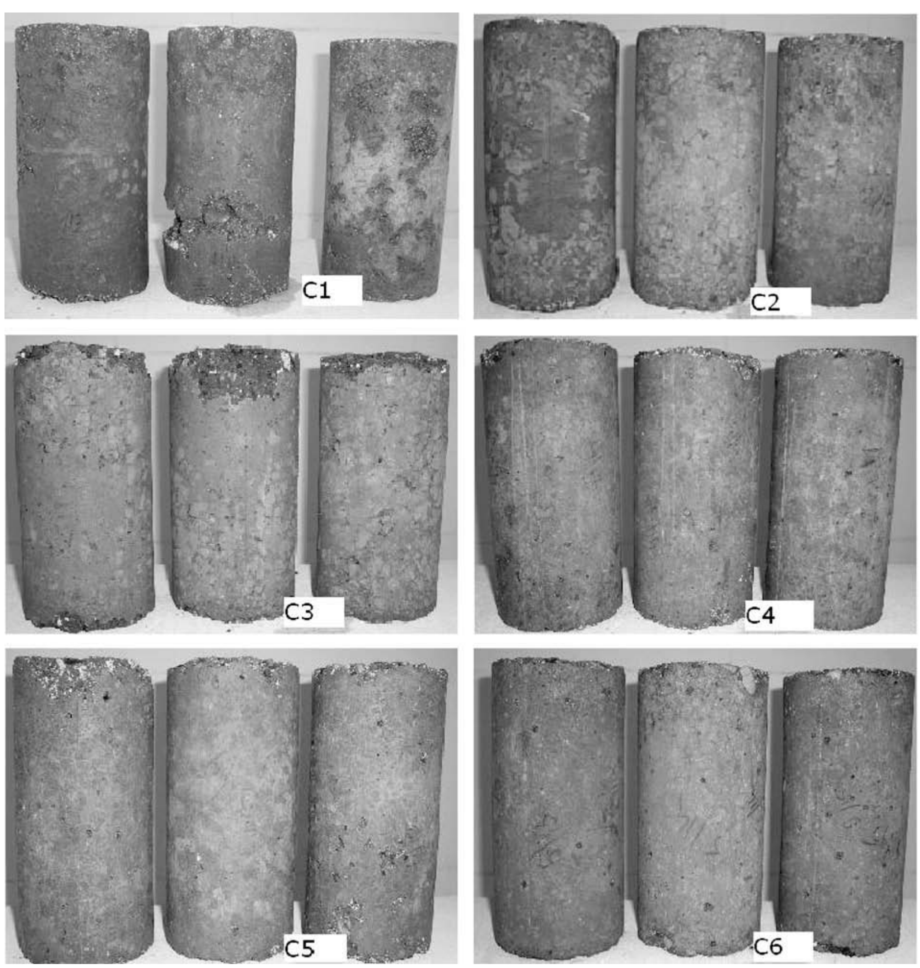

Fig. 5. MEPS concrete samples after 300 cycles of freezing–thawing.

tible to the freeze–thaw cycles when compared to the fine lightweight aggregate. All mixtures failed before 300 freeze–thaw cycles with regards to RDME; in general, none of them fulfills the basic requirements of durability. This explains that lightweight concrete is also subject to deterioration due to freeze–thaw cycling. However, increasing the MEPS aggregate ratio in mixtures, the concrete can be expected to exhibit a higher frost resistance and bear a higher durability (Fig. 5).

All freeze–thaw specimens were in saturated surface dry condition during mechanical tests. The compressive strength losses after 300 freeze–thaw cycles were 67%, 52%, 63%, 58%, 68%, and 67% from C1 to C6, respectively.

The highest DF was observed for C4. Both C2 and C4 fulfill the minimum requirements of ASTM C 666 [11] with respect to the DF. The lowest DF value was observed for C3.

4. Conclusions

The aim of this study was to evaluate the usability of MEPS as an aggregate for concrete and other secondary construction materials. A basic experimental study on the physical and mechanical properties of concretes containing MEPS as an aggregate provided the following results.

All the MEPS concretes without any special bonding agents show good workability and could be easily compacted and finished except for mixture C1. Experience with MEPS aggregate concrete indicated that care must be exercised while mixing, pouring and compacting the fresh concrete to minimize segregation of the concrete mixture. It was noticed that a fairly uniform concrete may be achieved by limiting the amount of vibration to the period when the fine MEPS aggregates just start to accumulate at the top of the mould. But in order to achieve a good compaction at the same time, it was found necessary to add a superplasticizer to the concrete mixture to improve its workability. The addition of MEPS aggregate reduced the workability of the concrete, an effect that may have been caused by the thermal treatment method applied to the MEPS aggregate particles. Research has shown that fine MEPS aggregate particles (0–2 mm) increase the bond between the paste and the coarse aggregate. The smooth and plane surface of the some coarse MEPS particles can significantly weaken the bond between the cement paste and aggregate particles.

The rate of strength development of the concretes increased with increasing percentage of natural aggregate. The strength of MEPS concretes was found to be directly proportional to the concrete density. The strength of MEPS concrete marginally increased as the aggregate size decreased, and increased as the natural coarse aggregate size increased. This increase in strength was greater in leaner mixes compared to the richer mixes. The proposed equation for the relation between compressive strength and hardened density of different MEPS concretes with densities ranging from 980 kg/m^3 to 2025 kg/m^3 is given by $f_c = 13{,}8\text{Ln}(\gamma) - 85$.

Both compressive strength and UPV were very low for all concrete mixtures during the early-age curing period, especially for samples containing high volumes of MEPS. However, with the increase of the curing period, both compressive strength and UPV of all samples increased. MEPS also caused the reduction of compressive strength and UPV at all curing periods.

The increase of splitting-tensile strengths with increasing MEPS concrete density was about 31%, reaching up to 64% when natural aggregates were used.

The density of concrete significantly affects hardened concrete properties of MEPS aggregate concrete and compressive strength is more sensitive to the density compared to tensile strength and RDME. The split tensile strength increased with an increase in the compressive strength. The compressive and splitting failures of the concrete specimens containing MEPS aggregates show a large compressibility of the material.

While using MEPS in the concrete as aggregate improves some of the concrete properties, it also negatively affects some others. A high amount of MEPS as aggregate is known to decrease the concrete density. As the amount of the MEPS added into the concrete increases, compressive strength decreases on the grounds that adherence cannot be achieved fully between the MEPS and cement paste and that the MEPS particles themselves are quite weak.

Use of MEPS in concrete is important from an environmental perspective. If waste EPS aggregates were reused as lightweight aggregates for concrete, positive effects are expected on the recycling of waste resources and the protection of the environment. MEPS aggregates offer a potentially sustainable construction material and simultaneously solve the environmental problem of reduction in solid waste. This will have the double advantage of reduction in the cost of construction materials and also cost of waste disposal.

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