Construction and Building Materials 35 (2012) 730–734

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Thermal conductivity and shrinkage properties of modified waste polystyrene aggregate concretes

Ramazan Demirboga [a,b], Abdulkadir Kan [c,*]

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

HIGHLIGHTS

- MEPS aggregate reduced thermal conductivity (TC) of concrete up to 70%.
- TC is more sensitive to the change in the density than the shrinkage.
- MEPS concrete's shrinkage increased with the increase of MEPS aggregate ratio.
- Shrinkage of MEPS aggregate concrete is smaller than that of normal concrete.
- The artificial MEPS aggregate offers as a potential construction material.

ARTICLE INFO

Article history:
Received 20 December 2010
Received in revised form 13 April 2012
Accepted 29 April 2012

Keywords:
Shrinkage
Environmental waste
Artificial aggregate
Modified polystyrene
Thermal conductivity

ABSTRACT

Using artificial aggregate in replacement of natural aggregate in production of concrete has a tendency to increase by the future in order to provide greater sustainability in construction industry. This study investigates the effectiveness of thermal modified waste expanded polystyrene (MEPS) on the workability, density, thermal conductivity and shrinkage of concrete. MEPS aggregate was used as lightweight aggregate in concrete by 25%, 50%, 75%, and 100% in replacement of natural aggregate. The thermal conductivity of samples decreased with increasing of MEPS aggregate and their values were 1.990, 1.518, 1.000, and 0.600 W/mK for 25%, 50%, 75%, and 100% MEPS aggregate in replacement of natural aggregate, respectively. Maximum reduction in the thermal conductivity was observed at the samples that made up of 100% MEPS aggregates and the reduction percentage was around 70%. The average drying shrinkage after 210-day of ambient curing condition was 2.59×10^{-3} for samples of 25% natural aggregate, while it was 5.08×10^{-3} for 100% MEPS aggregate samples.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Artificial lightweight aggregate produced from environmental waste, like waste expanded polystyrene (EPS) foams, is a viable new source of structural aggregate material. The use of lightweight concrete permits greater design flexibility and substantial cost savings, reducing dead load, improved cyclic loading structural response, longer spans, thinner sections, smaller size structural members, and lower foundation costs.

With increasing concern over the excessive exploitation of natural aggregates, artificial lightweight aggregate produced from environmental waste is a viable new source of structural aggregate material. EPS beads are often used as the basis for packaging materials. This leads to a large amount of waste material that is not biodegradable. This material can be modified by heat treatment method, and it can be used as a lightweight aggregate for concrete. Thermal modified waste expanded polystyrene (MEPS) aggregate is made by heat treatment method from the waste EPS [1,2]. Depending on the temperature and time of modification used, the waste EPS can be 20 times smaller than the unmodified one. The reduction of energy consumption in construction, production of thermal-insulation materials, and being a solution for environmental problems by recycling industrial and domestic waste are becoming greater problems. There are many lightweight composites that contain recycled fillers and aggregate, including waste glass and recycled aggregate [3], natural pasa [4], expanded perlite [5,6], fly ash [7,8], waste EPS aggregate [9,10], waste-oil palm shell [11], lightweight crushed bricks [12,13], waste rubber [14]. In addition, EPS foams and its waste are used for various purposes [15–17].

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

0950-0618/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2012.04.105

Shrinkage is an important parameter among others such as ductility, self-compacting ability, strength, high modulus or wear resistance. Shrinkage is a time-dependant decrease in concrete volume compared with the original placement volume of concrete. Shrinkage results from physical and chemical changes that occur in the paste fraction of concrete. The two principal types of shrinkage are plastic and drying shrinkage. Plastic shrinkage occurs while concrete is in plastic state. Drying shrinkage occurs after concrete has reached initial set. Technically, drying shrinkage will continue through the life of the concrete, but most shrinkage will occur within the first 90 days after placement. The duration of shrinkage is dependent on the size and shape of concrete since they control the rate of moisture loss. In addition, Wittmann [18] reported that drying shrinkage reaches critical values after some 100 days depending on the dimensions of the drying specimen. The size and shape are often considered together as the volume-to-surface area ratio. Larger specimens will shrink after longer periods but the ultimate magnitude may be lower. When a hardened concrete, cured in water, is allowed to dry, it first loses water from its voids and capillary pores and only starts to shrink during further drying when water is drawn out of its cement gel. This known as drying shrinkage and in some concretes it can be greater than 1500×10^{-6}, but a value in excess of 800×10^{-6} is usually considered undesirable for most structural applications [19].

The drying process in concrete is very slow. Hygral gradients exist for a long time in drying concrete elements with usual dimensions. Measured shrinkage, is in fact the response of a concrete specimen to strains and stresses generated by the drying process. If the water loss of a specimen with known geometry is measured, the Hygral diffusion coefficient can be determined by inverse analysis [20].

Shrinkage is important in applications such as large slabs on grade, containment structures, and reinforced concrete exposed to deicing chemicals. Shrinkage of concrete on drying frequently leads to cracking; this is recognized in concrete design and construction practice, especially concerning pavements, floors, and relatively thin structural members. To counteract this problem shrinkage-compensating concrete containing expansive cements or expansive admixtures has been employed successfully for the last 20 years [21].

Thermal conductivity (TC) gives the heat flux transmitted through a unit area of a material under a unit temperature gradient. The TC of concrete is influenced by the mineralogical characteristics of aggregate, and by the moisture content, density, and temperature of concrete. TC of concrete depends also on curing and compacting condition. Unal et al. [22] carried out a study on TC of low-strength lightweight aggregate concrete (LWC) produced with diatomite in different ratios and cement content.

A review of earlier studies reveals that Mineralogical character of the aggregate would greatly influence the TC of concrete [23]. Aggregate with less TC produce the less conductive concrete whereas the more conductive aggregates produce more conductive concrete [24,25]. Thus, aggregate type can cause nearly twice an increase in TC of concrete and this is depend on not only aggregate composition but also depend on its degree of crystallization. Aggregate with crystalline structure shows higher heat conduction than amorphous and vitreous aggregate of the same composition [26,27]. Porosity and moister content are another important factors that effecting on the TC of concrete [24,25,27].

According to Costa et al. [28] when compared to normal weight concrete, different studies proved that shrinkage in lightweight aggregate concretes (LWA) is usually lower. This happens when saturated LWA are used, since an efficient internal curing is promoted by an uninterrupted hydration of the binding paste, as a result of a continuous flow of LWA moisture stored in its alveolar internal structure, avoiding self-desiccation This gives rise to expansive autogenous deformations and thus to reduced total shrinkage. Also improved transition zone between the LWA and the binding matrix is observed, reducing its permeability [28].

In this study, it was concerned with the effect of MEPS aggregate on shrinkage and TC properties of concrete. Because of this reason MEPS aggregate was used as a coarse aggregate in production of concrete for possible application of low-strength concrete such as masonry units and semi-structural purposes.

2. Experimental program

2.1. Materials

The MEPS, one of the artificial lightweight aggregates, was used in the production of lightweight concrete. MEPS aggregate were obtained from waste EPS foams by using thermal treatment method in the laboratory [1]. Mechanical properties of MEPS aggregate concretes have been determined earlier by Kan and Demirboğa [2]. Properties of MEPS aggregate were given in Table 1. Maximum aggregate size of MEPS and natural aggregates were 16 mm. ASTM Type I Portland cement was used in the study. The cement contents for the concrete mixtures were 500 kg/m^3 and constant throughout the study. A polycarboxylate-based super plasticizer was used to improve workability of the concretes. Consolidation of concrete was done by hand compaction. The details of the MEPS aggregate concrete mix proportions were given in Table 2.

2.2. Method

2.2.1. Mixing, curing and testing of MEPS aggregate concretes

MEPS aggregate was used as 0%, 25%, 50%, 75%, 100% of natural aggregate and three concrete prism specimens were produced for each mixture proportions (Table 2). Mix preparation is particularly important when using very lightweight aggregates. For the anticipated testing exactly six various mixtures of component materials are produced (they are labeled as series from C1–C6).

All the concretes were mixed in a planetary mixer of 50 l capacity in the laboratory. Several standard test specimens of different sizes were chosen to investigate the various parameters. Prisms of $40 \times 110 \times 160$ mm and $70 \times 70 \times 240$ mm were cast for the determination of thermal conductivity and drying shrinkage of MEPS concretes, respectively. For each test, three specimens were cast. The mixing of materials was done in a specific sequence, by placing a part of the water with super plasticizer 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 mixes designed for previous studies [7,15,16]. Then the remaining materials were added to the mixer and the remaining water was gradually added while the mixing was in progress. The fresh concrete densities and slump values were measured immediately after mixing for all the concretes. The test specimens were consolidated with hand compaction. The curing of concrete adopted for TC has been described earlier [7,8,17]. The specimens were covered with wet gunny bags 10 h after casting, then the specimens were removed and cured in water (25 ± 2 °C) until the time of testing.

A quick thermal conductivity meter (QTM 500) based on ASTM C 1113-90 [29] was used. Measurement range is 0.0116–6 W/mK. The QTM 500 system is a rapid, non-destructive easy to use TC system. Based on the modified hot-wire technique, users can expect accurate and repeatable results.

Table 1
Specification of MEPS aggregate.

MEPS aggregate			
Origin of aggregate	Crushed 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)	1.76–8.22 MPa		
Thermal conductivity (W/mK)	0.0521, 0.0415, 0.0366		
Weight loss of freezing–thawing (10 cycling)	0.31%		
Specific gravity factor (SGF)	Coarse	0.22–0.24	
	Fine	0.31–0.34	

Table 2
Details of MEPS concrete mixes containing natural aggregate.

Mix type	MEPS/NA[a] (%) (F + CA)/(F + CA[b])	Cement (kg)	MEPS (kg)		NA[a] (kg)		SP[c] (kg)	*w/c*	Fresh density (kg/m^3)	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.

The effects of different volume contents of MEPS on the shrinkage were investigated as well. Mitutoyo Digimatic Calipers trademarked was used to determine drying shrinkage (measuring range: 0–300 mm (0–12″), accuracy: 0.03 mm (0.001″), (>100–200 mm)). Drying shrinkage specimens were exposed to ambient air conditions (t = 20 °C and RH 40%) alongside the TC specimens. After the water on the surface of each specimen was wiped off with a damp cloth, the length change was measured and the shrinkage strain was calculated according to ASTM C490–93a [30].

3. Results and discussion

Studied parameters in this paper are discussed. Open structure of MEPS aggregate concretes have shown in Fig. 1. After the experiments conducted on series of hardened concrete, properties for shrinkage and thermal properties were determined. Changes in these properties were examined in relation with the MEPS /natural aggregate volume ratio and the results were given below.

3.1. Concrete workability

Consistency tests of mix were run based on Abram's Cone procedure [5,6,8]. At this point it is worth to mention that when the MEPS aggregate content was increased the fresh concrete mix became rubbery, harsh, and difficult to place and compact. This may be due to the shape of crashed and thermally modified MEPS aggregate. After the thermally modification process the surface texture of the MEPS aggregate was gotten more rough. The roughness of the surface of MEPS might be due to the melting. The workability of MEPS aggregate concrete was different from that of tradition light weight aggregate concrete because the tradition light weight aggregates suck water from the mixes because of their higher porous structure. However voids of MEPS aggregate surface was closed and filled with melted materials. In addition, MEPS aggregate is hydrophobic material. With increase of MEPS ratio in the mixes, the reduction in slump increased and at 50% and 75% of MEPS replacement, the slumps was not being able to measure. Thus, superplasticizer was essentially added to solve the problem associated with the hydrophobic nature of the MEPS aggregates and to improve the cohesiveness of the mix. The average slump for w/c = 0.38 was 25 mm and for w/c = 0.43 was 50 mm, as shown in Table 2. Apart from the amount of natural aggregate replaced, the workability was kept approximately constant for 0.42 w/c ratio, confirming the efficiency of the adopted mixing procedure in maintaining the workability of concrete.

Another reason of the low slump of MEPS aggregate mixes may be due to the lower density of the MEPS. Because of lower MEPS aggregate density, structural low-density concrete does not show slump as much as normal density concrete with the same workability [31,32].

3.2. Drying shrinkage of MEPS concrete

Shrinkage is affected mainly by the quantity of cement paste in the mix, the quality of the cement paste, and the type of aggregate used. Gravel concrete with its hard dense aggregate usually shows relatively small shrinkage, the movements due to the cement being restrained in a large scale by the rigidity of the aggregate. In case of LWC, however, where weaker and less rigid aggregates are used, much less, restraint is imposed on the cement paste, and this is reflected in the higher drying shrinkage in these concretes-generally about twice that observed in heavy aggregate concrete [33].

Two of the most significant factors affecting the shrinkage of concrete are the degree of restraint by the aggregate, that is, its elastic properties and the volumetric proportion of the paste in the mix. The MEPS aggregates offer little hindrance to the shrinkage of the paste.

The importance and effects of drying shrinkage in concrete structures cannot be over emphasized [34]. The conventional test was conducted to investigate the effect of the drying period and

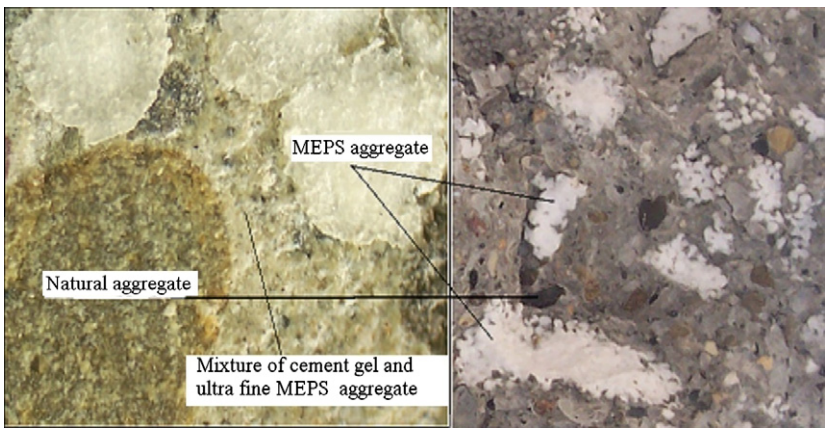


Fig. 1. Open structure of MEPS Aggregate concretes (on the left X100).

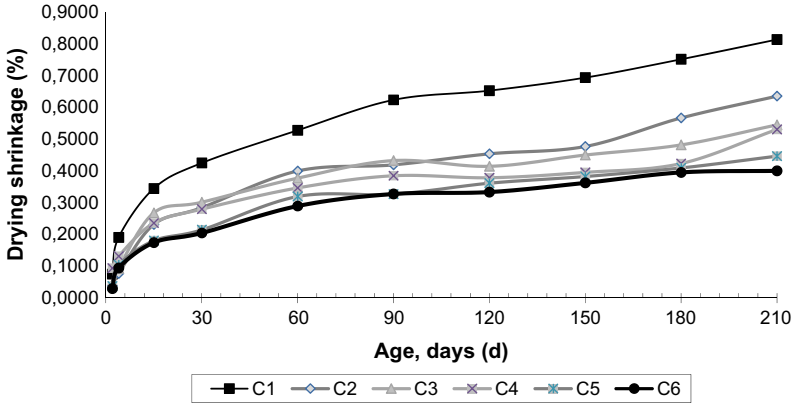


Fig. 2. Shrinkage of MEPS aggregate concrete.

the MEPS aggregate percent on the shrinkage of concrete. Fig. 2 shows that the MEPS aggregate ratios have a significant effect on the shrinkage of concrete. It is apparent that a drying period of 4 days and more is very important to ensure that the concrete has a higher shrinkage. Drying shrinkage of the C1 type concretes; included 100% MEPS aggregate, more than that of the other mixes for 210 day curing ambient condition. Drying shrinkage was decreased with decreasing of MEPS aggregate content.

For the C1 concrete shrinkage is almost 2.35 times higher than that of C6 concretes. At 90 days, the drying shrinkage of C1 and C6 samples were 6.2×10^{-3} and 3.4×10^{-3}, respectively. For 100% MEPS concrete, C1 samples, the drying shrinkage at 210 days was 8.131×10^{-3}, which indicates the disadvantage in the application of MEPS when compared to the control sample. It can be concluded that MEPS aggregate drastically increases the drying shrinkage of MEPS concrete. Even for 25% MEPS aggregate concrete samples, (C6), the drying shrinkage at 210 days was 3.989×10^{-3} and it was higher than that of normal concrete. Neville [35] has indicated that lightweight aggregate usually results in higher shrinkage values mainly because of the lower modulus of elasticity of the aggregate. According to Jackson and Dhir [19], in normal concretes shrinkage can be greater than 1.5×10^{-3}, but a value in excess of 8×10^{-4} is usually considered to be undesirable for most structural applications.

Furthermore, the drying shrinkage of the 75% natural aggregate +25% MEPS aggregate concretes (C6) was more less than that of MEPS concrete specimens (C1) and their values were 2.59×10^{-3} and 5.08×10^{-3} for 210 days ambient curing condition, respectively.

Fig. 2 shows clearly that natural aggregate concrete (C6) presents up to 30 days a delayed shrinkage compared to MEPS aggregates concrete; this is followed by an abrupt increase of up to 30% at 90 days of curing duration. For the MEPS concrete (C1 and C2), shrinkage at early age is almost higher than that of the natural aggregates concrete (C6) and continues with the same rate of increase up to 210 days. On the other hand, when both coarse and fine MEPS are used together as aggregates, the shrinkage of the MEPS concrete (C1) is stabilized at early age (up to 7 days) and becomes comparable with that of the C6 concrete. At later age, shrinkage of MEPS aggregates concrete (C1) is again higher than those of partially replaced natural aggregate concrete (C3–C5). The incorporation of MEPS aggregates significantly increases the shrinkage of the mixes.

3.3. Thermal conductivity of MEPS concrete

Figs. 3 and 4 show the variation in TC with MPES ratios. The effect of MPES that replaced normal aggregate at 25%, 50%, 75%, and

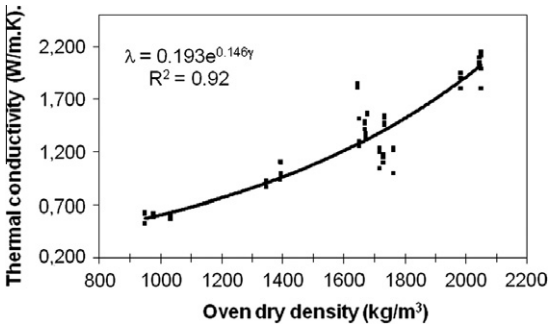


Fig. 3. Relationship between oven dry density and thermal conductivity of MEPS concrete.

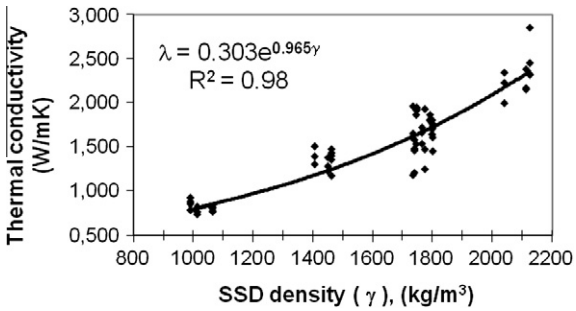


Fig. 4. Relationship between SSD density and thermal conductivity of MEPS concrete.

100% by volume on thermal conductivity is approximately 24%, 26%, 50% and 70%, respectively. TC is a function of density. The TC values of MEPS concretes was found to be directly proportional to the concrete dry density, the saturated surface dry density and MEPS aggregate contents. By increasing dry density of MEPS concrete from 980 to 2025 kg/m^3, TC coefficients have varied from 0.600 to 1.99 W/mK. The TC values of MEPS concrete marginally increased as the natural aggregate ratio increased, and decreased as the MEPS aggregate ratio increased. The TC values of MEPS concretes at dry conditions, according to MEPS aggregate ratio, was minimum, 0.600 W/mK, and maximum, 1.990 W/mK, at 100% and 0% MEPS, respectively. This is can be attributed to the lower density of MEPS [36]. Results are compatible with the previous studies. Demirboga and Gül [5] reported that EPA reduced the thermal conductivity of samples up to 43.5%. In this study the maximum reduction due to the MEPS was 70%, this is may be due to the lower density of MEPS concrete when compared to their study.

Demirboga and Gül [5], Karakoc and Demirboga [36], Lu-shu et al. [37], and Uysal et al. [38] reported the relationship between TC and the density of lightweight concrete. They derived a correlation between the density and TC for lightweight concrete experimentally and also reported that TC has a strong relationship to the density. They experimentally formulated a correlation between the TC and the Density and reported that TC increased with increasing density (see Figs. 3 and 4).

ACI Committee 213R-03 [39] has also recommended an equation to obtain TC of structural LWC related with its dry density (γ) as follows:

$$\lambda = 0.0864e^{0.00125\gamma} \quad (1)$$

The curves were obtained for experimental and ACI 213R-03 depending on density and saturated surface dry density, and they are shown in Figs. 3 and 4. As it can be seen from these figures, there is a little difference between both curves. These differences may be due to the surface structure of MEPS aggregate. There was a good relationship between TC (λ) and density (γ) of experimental results (R^2 = 0.91 and 0.98). For the moderate TC of MEPS concrete, the following equations can be proposed:

$$\lambda = 0.193e^{0.146\gamma} \quad (2)$$

$$\lambda = 0.303e^{0.965\gamma} \quad (3)$$

TC of concrete is influenced by the mineralogical characteristics of aggregate, and by the moisture content, density, and temperature of concrete. TC of concrete depends also on curing and compacting condition.

4. Conclusion

Partial replacement of MEPS aggregate changed the properties of concrete such as workability, the density, TC and shrinkage of concrete. The change in the quantity of the properties was depending on the level of replacement. Thus, below results can be drawn from the study:

- MEPS aggregate content decreased the workability of mixtures.
- Dry densities of the concrete decreased from 2025 to 980 kg/m^3 with the increase of MEPS aggregate ratio in the mix.
- TC of concrete was drastically decreased with increase of MEPS aggregate and the reduction value was 70%.
- MEPS aggregate increased the shrinkage of concrete drastically. When the MEPS aggregate content was 25% (C6 type) drying shrinkage was 2.35 times less than that of the C1 type (having 100% MEPS aggregate) for 210 days of ambient curing duration.
- TC is more sensitive to the change in the density than the shrinkage.

It can be concluded that workability, density, drying shrinkage and TC of concrete were depend on the percentage replacement of MEPS aggregate in the mixes. As a result, the artificial MEPS aggregate offers can be a potential construction material and simultaneously solve the environmental problem by recycling solid waste.

References

[1] Kan A, Demirboğa R. A new technique of processing for waste – expanded polystyrene foams as aggregates. J Mater Process Technol 2009;206:2994–3000.
[2] Kan A, Demirboğa R. A novel material for lightweight concrete production. Cem Concr Compos 2009;31:489–95.
[3] Park SB, Lee BC, Kim JH. Studies on mechanical properties of concrete containing waste glass aggregate. Cem Concr Res 2004;34:2181–9.
[4] Tosunoğlu V, Demirboga R, Boncukçuoğlu R, Anaplı Ö, Öztepe Ç. Pozzolanic properties of natural pasa. Energy Edu Sci Technol 2002;8(2):77–84.
[5] Demirboğa R, Gül R. Thermal conductivity and compressive strength of expanded perlite aggregate concrete with mineral admixtures. Energy Build 2003;35:1155–9.
[6] Demirboğa R, Örüng İ, Gül R. Effects of expanded perlite aggregate and mineral admixtures on the compressive strength of low-density concretes. Cem Concr Res 2001;31:1627–32.
[7] Babu DS, Babu KG, Wee TH. Properties of lightweight expanded polystyrene aggregate concretes containing fly ash. Cem Concr Res 2005;35:1218–23.
[8] Babu KG, Babu DS. Performance of fly ash concretes containing lightweight EPS aggregates. Cem Concr Compos 2004;26:605–11.
[9] Choi NW, Ohama Y. Development and testing of polystyrene mortars using waste EPS solution-based binders. Constr Build Mater 2004;18:235–41.
[10] Gaggino R. Light and insulant plates for housing external closure. Constr Build Mater 2006;20:917–28.
[11] Mannan MA, Ganapaty C. Concrete from an agricultural waste-oil palm shell (OPS). Build Environ 2004;39:441–8.
[12] Farid D, Said K. The use of coarse and fine crushed bricks as aggregate in concrete. Constr Build Mater 2008;22:886–93.
[13] Cachim PB. Mechanical properties of brick aggregate concrete. Constr Build Mater 2009;23:1292–7.
[14] Topcu İB, Avcular N. Collision behaviors of rubberized concrete. Cem Concr Res 1997;27:1893–8.
[15] Kan A, Demirboğa R. Effect of cement and EPS beads ratios on compressive strength and density of lightweight concrete. Indian J Eng Mater Sci 2007;14:158–62.
[16] Chen B, Liu J. Properties of lightweight expanded polystyrene concrete reinforced with steel fiber. Cem Concr Res 2004;34:1259–63.
[17] Babu KG, Babu DS. Behaviour of lightweight expanded polystyrene concrete containing silica fume. Cem Concr Res 2003;33:755–62.
[18] Wittmann FH. Crack formation and fracture energy of normal and high strength concrete. Acad Proc Eng Sci 2002;27:413–23.
[19] Jackson N, Dhir KR. Civil engineering materials. 5th ed. Newyork: Mc. Millan; 1996.
[20] Wittmann XH, Sadouki H, Wittmann FH. Numerical evaluation of drying test data. In: Transaction 10th Conf on Struct Mech in Reactor Technology; 1983. p. 71–9.
[21] Mehta PK, Monteiro JM. Concrete: microstructure, properties, and materials. 3rd ed. New York: The McGraw-Hill; 2006.
[22] Unal O, Uygunoglu T, Yildiz A. Investigation of properties of low strength lightweight concrete for thermal insulation. Build Environ 2007;42:584–90.
[23] Khan MI. Factors affecting the thermal properties of concrete and applicability of its prediction models. Build Environ 2002;37:607–14.
[24] USBR. Boulder Canyon project report. Thermal properties of concrete. Bulletin No. 1, Part VII; 1940.
[25] Campbell Allen D, Thorne CP. The thermal conductivity of concrete. Mag Concr Res 1963;15(43):39–48.
[26] Zoldners NG. Thermal properties of concrete under sustained elevated temperatures (SP25). ACI Spec Pub 1971; 1–31.
[27] Harmathy TZ. Thermal properties of concrete at elevated temperatures. J Mater 1970;5:47–74.
[28] Costa H, Júlio E, Lourenço J. New approach for shrinkage prediction of high-strength lightweight aggregate concrete. Constr Build Mater 2012;35:84–91.
[29] ASTM. Test method for thermal conductivity of refractories by hot wire (platinum resistance thermometer technique). ASTM C 1113–90; 1990.
[30] ASTM. Standard practice for use of apparatus for the determination of length change of hardened cement paste, mortar and concrete. ASTM C490–93a; 1993.
[31] Hossain KMA. Properties of volcanic pumice based cement and lightweight concrete. Cem Concr Res 2004;34:283–91.
[32] Gunduz L. The effects of pumice aggregate/cement ratios on the low-strength concrete properties. Constr Build Mater 2008;22:721–8.
[33] Short A, Kinniburgh W. Lightweight concrete. 3rd ed. London: A Sci. Publishers Ltd.; 1978.
[34] Kayali O, Haque MN. A new generation of lightweight concrete. In: Malhotra VM, editor. Advances in concrete technology. Detroit: ACI SP-171; 1997. p. 569–88.
[35] Neville AM. Properties of concrete. 4th ed. Essex (England): Addison Wesley Longman; 1997.
[36] Karakoç MB, Demirboga R. HSC with expanded perlite aggregate at wet and dry curing conditions. ASCE J Mater Civil Eng 2010;22(12):1252–9.
[37] Lu-shu K, Man-qing S, Xing-Sheng D, Yun-xiu L. Research on several physico-mechanical properties of lightweight aggregate concrete. Int J Lightweight Concr 1980;2(4):185–91.
[38] Uysal H, Demirboga R, Sahin R, Gul R. The effects of different cement dosages, slumps, and pumice aggregate ratios on the thermal conductivity and density of concrete. Cem Concr Res 2004;34:845–8.
[39] ACI Committee 213R–03. Guide for structural lightweight aggregate concrete. 2003; 26, 22–23. ACI 213R–03. Farmington Hills: American Concrete Institute; 1992.