Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 172 (2017) 937 – 944

Procedia Engineering

www.elsevier.com/locate/procedia

Modern Building Materials, Structures and Techniques, MBMST 2016

Comparison of material properties of lightweight concrete with recycled polyethylene and expanded clay aggregates

Deividas Rumšys[a]*, Darius Bačinskas[a], Edmundas Spudulis[a,b], Adas Meškėnas[a,c]

[a]*Department of Bridges and Special Structures, Vilnius Gediminas Technical University, Sauletekio av. 11, Vilnius LT–10223, Lithuania*
[b]*Scientific Institute of Thermal Insulation, Vilnius Gediminas Technical University, Linkmenu st. 28, Vilnius LT-08217, Lithuania*
[c]*Linkmenu Fabrikas, Vilnius Gediminas Technical University, Linkmenu st. 28, Vilnius LT-08217, Lithuania*

Abstract

The article discusses the possibility of using high and low density polyethylene waste as aggregate in lightweight concrete with high strength cement mortar. Research is dedicated to experimental investigation and comparison of material properties of concrete made of polyethylene waste and expanded clay aggregates. Hydration kinetics studies of concrete specimens with different aggregates are performed using measurements of ultrasonic pulse velocity. For the experimental investigation high and low density polyethylene plastic waste aggregates with low water absorption and hydrophobic surface were used. It is stated that concrete with low water absorption plastic waste aggregates after 7 days of curing showed significant decrease in strength growth rate. The specimens had a density of 1950 – 2050 kg/m^3 with a compressive strength of at least 40 MPa. Using pre-wetted expanded clay aggregate with similar mix composition, concrete density was 1900 kg/m^3 with a compressive strength up to 70.2 MPa. Although having similar mechanical properties as the waste plastic aggregate, pre-wetted expanded clay allows better cement hydration process, resulting in lower water absorption of lightweight concrete.

Peer-review under responsibility of the organizing committee of MBMST 2016

Keywords: lightweight aggregate; concrete; plastic waste; polyethylene; expanded clay.

---

* Corresponding author. Tel.: +3-705-274-5246; fax: +3-705-270-0122
E-mail address: Deividas.Rumsys@vgtu.lt

Peer-review under responsibility of the organizing committee of MBMST 2016
doi:10.1016/j.proeng.2017.02.105

1. Introduction

For the production of lightweight concrete various fillers with smaller density than a conventional gravel and crushed stone are used. Lightweight aggregates (LWA) differ in density, strength, water absorption, surface characteristics and shape. All these differences affect the mechanical and durability properties of the concrete. One of the problems in the production of lightweight concrete with porous LWA is that the rheological properties depend on sorption properties of such aggregates. Performed research of sorption properties of 14 expanded shale and expanded clay aggregates showed that 24h water absorption is from 6.0% to 30.5% [1]. If the aggregates are not pre-wetted, a lot of water can be lost through absorption during mixing and under the pressure of pumping concrete can lose workability. Meanwhile water absorption of most plastics is very small and these materials meet the requirements of density for production of lightweight concrete.

The possible application of recycled plastic waste aggregates in concrete has been studied by many researchers [2,3]. State-of-the-art review in this area is presented by Siddigue [4]. It is stated that in Europe largest component of plastic waste is low density polyethylene (LDPE) at about 23% followed by 18.5% of polypropylene (PP), 17.3% of high density polyethylene (HDPE), 12.3% of polystyrene (PS/expanded PS), 10.7% polyvinyl chloride (PVC), 8.5% polyethylene terephtalate (PET) and 9.7% other types. About 40% of plastic waste is LDPE and HDPE, however most of the research is focused on use of polyethylene terephtalate (PET) waste [5] and low-density expanded polystyrene (EPS) beads [6].

Higher compressive strength lightweight concrete with EPS beads and cenospheres can be obtained using geopolymeric binder from fly ash, metakaoline, sodium hydrokside and sodium silicate solution. Geopolymeric binder materials applied with different aggregates, could result in low density concrete [7]. It was indicated that while the cenospheres has a tendency to absorb water almost as much as its own weight and conversely, EPS beads is hydrophobic and its water absorption is zero, water absorption of both concrete specimens is large and similar [7]. In order to increase cement mortar and plastic adhesion, surfaces of aggregates, produced from waste PET bottles and sand or ground blast furnace slag, were modified [8,9].

The use of polyethylene (PE) aggregates in concrete is not widely investigated. Ismail and AL-Hashmi [10] carried out a study on public plastic utilities which were made of 80% of polyethylene and 20% of polystyrene. Substituting 20% of sand by these waste resulted in significantly lower compressive strength in comparison with ordinary concrete. This could be explained by the decrease in adhesive strength between the surface of plastic waste and the cement paste.

The present research focuses on investigation of the various shape of HDPE and LDPE plastic waste impact on the mechanical properties of concrete. The attained results are compared to the concrete with the same volumetric amount of expanded clay LWA. It is defined how the water absorption of the aggregates influence the water absorption of the concrete specimens.

2. Materials

The materials used in this study are as follows:

Cement: “Aalborg” white cement CEM I 52.5 R was used in all types of mixtures: density – 3.063 g/cm^3, fineness (Blaine) – 308 m^2/kg, 28 days age compressive strength – 73 MPa.

Fine aggregate: for the fine aggregate washed sand fraction 0/4 from “Gariūnai” deposit and expanded clay Leca-S fraction 2/4 were used.

Microfillers: ground quartz sand from JSC “Anykščiai“ deposit with maximum grain size less than 100 μm and silica fume “RW –Füller“ from “RW silicium GmbH“ were used.

Superplasticizer: For low water to solid ratio (W/S) of cement mortar two superplasticizers based on poly-carboxylate ester (No 1) and on poly-ethylene glycol (No 2) were used.

Waste plastic: Waste plastic were collected from plastic manufacturing company JSC “Plasta”.

Table 1 presents the physical and mechanical properties of used plastic and expanded clay aggregates. Density and water absorption properties of the materials are determined in accordance with EN 1097-6:2013 [11], crushing resistance obtained according to EN 13055-1:2003 [12]. As can be seen from the data (Table 1) all aggregates have almost equal apparent particle density, however, depending on the shape, bulk densities are different. Measured water absorption of plastic is negligible low, contrary to that, expanded clay absorption is quite large. Crushing resistance of aggregates depends on their shape and mechanical properties of materials. HDPE MFI 2.51 specimen has the identical particles with a diameter of about 6 mm and thickness of 3 mm. After crushing resistance experiment HDPE MFI 2.51 specimen particles, due to their elastic properties, were not damaged, while expanded clay particles exhibit the brittle failure.

Granulometry of all used aggregates, cement and microfillers is presented in Fig.1. Shapes of all aggregates are presented in Fig. 2.

A part of HDPE MFI 2.51 plastic aggregates was treated mechanically in order to roughen the surface of the particles. Plastic and 0/4 fraction sand with a ratio 2:1 by weight was mixed in a mixer “Eirich R02E” for 5 minutes period. After mixing plastic was separated by sieving. Primary and mechanically threated particles are shown in Fig. 3. It can be seen that this form of treatment can modify HDPE aggregates surface.

Table 1. Physical and mechanical properties of used plastic and expanded clay aggregates.

No.	Material	Bulk density, kg/m^3	Apparent particle density, kg/m^3	Saturated and surface-dried particle density, kg/m^3	Water absorption after immersion for 24 h, %	Crushing resistance, MPa
1	Expanded clay	488	804	1002	24.5	3.49
2	HDPE MFI 2.51	540	935	935	0.040	5.29
3	HDPE MFI 0.3	436	945	945	0.016	2.30
4	LDPE crumbs	286	781	781	0.290	0.62
5	HDPE crumbs	418	931	931	0.016	2.44

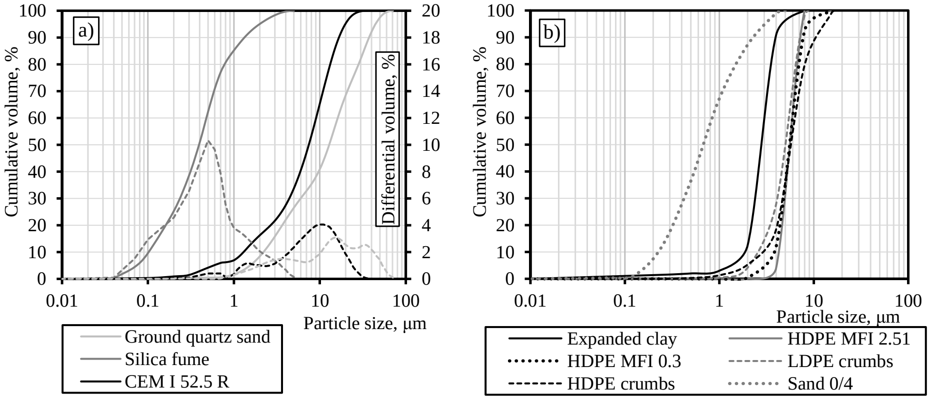

Fig. 1. Granulometry of used materials: (a) obtained by particle size analyzer “Cilas 1090“, (b) obtained by vibrating sieve “Haver EML 200 digital T“.

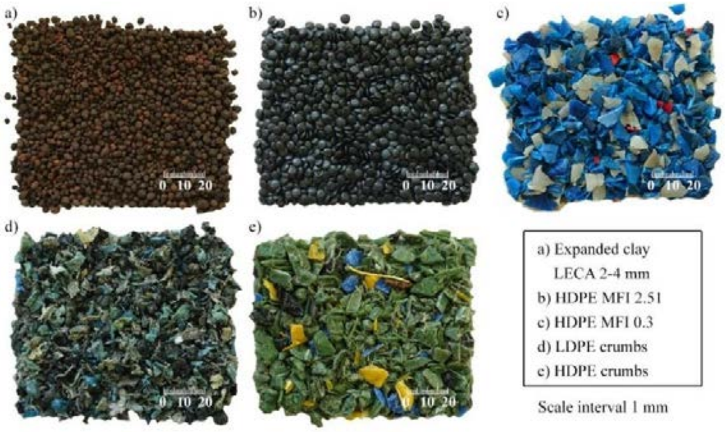

Fig. 2. Shapes of aggregates.

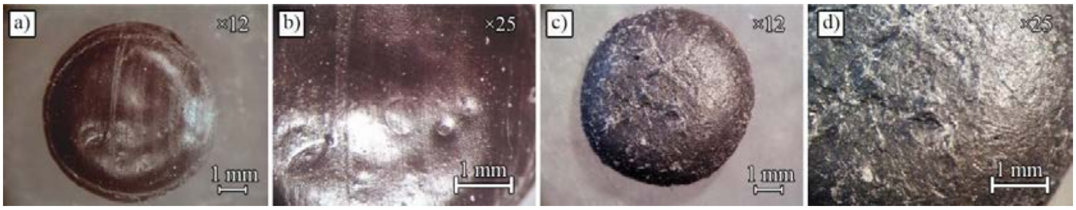

Fig. 3. Microscopic view of HDPE MFI 2.51 primary (a), (b) and mechanically treated HDPE MFI 2.51* (c), (d) (obtained by microscope “MOTIC K-400 L” with video camera “Pixera VSC”).

3. Mixture proportioning

Plastic waste and expanded clay concrete mixtures D1 – D12 are presented in Table 2. Cement mortar composition in all cases was the same, however different microfiller – ground quartz sand or silica fume was used. The aggregate percentage amount by weight (over the total weight of cement mortar) slightly varied for each of the specimens depending on the apparent particle density.

Table 2. Concrete mixtures proportions.

No.	Material	Code of specimens/ Quantity by weight, %											
		D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12
1	Sand	60											
2	Cement	36											
3	Ground quartz sand	4	-	4	-	4	-	4	-	4	-	4	-
4	Silica fume	-	4	-	4	-	4	-	4	-	4	-	4
	Total	100											
5	Expanded clay	15.0		-	-	-	-	-	-	-	-	-	-
6	HDPE MFI 2.51	-	-	17.4		-	-	-	-	-	-	-	-
7	HDPE MFI 2.51*	-	-	-	-	17.4		-	-	-	-	-	-
8	HDPE MFI 0.3	-	-	-	-	-	-	17.6		-	-	-	-
9	LDPE crumbs	-	-	-	-	-	-	-	-	14.6		-	-
10	HDPE crumbs	-	-	-	-	-	-	-	-	-	-	17.4	

11	Superplasticizer No. 1	3 % from cement weight
12	Superplasticizer No. 2	0.5 % from cement weight
13	W/S (aggregates not included)	0.0914

4. Experimental program

4.1. Mixing procedure

Concrete mixing was carried out in 20l Hobart type planetary mixer adding the aggregates to the mixed cement mortar. Expanded clay aggregate was additionally pre-wetted with 10 % (by the weight) of water in a separate container for 1 h before the mixing. All other aggregates were used dry.

4.2. Strength test

Concrete specimens were cast in (70.7×70.7×70.7) mm steel molds without additional mechanical impact. The specimens were cured in molds for 2 days and the rest of the time (up to 28 days) at 20 °C ± 1 °C and a relative humidity of 95 %. After 2, 7, 14 and 28 days the ultrasonic pulse velocity (UPV) test was performed by "PUNDIT 7" device. Average values obtained from the measurements of the three specimens are presented (Fig. 4). The compressive strength after 7 and 28 days is presented as the average value obtained from six specimens (Fig. 5b).

4.3. Density test

Density of the samples is the average value obtained by testing three samples after 28 days of curing. Oven-dry density determined after drying samples at 80 °C to constant mass. Volume of the samples was calculated according to their dimensions.

4.4. Water absorption test

Water absorption of the specimens was determined after 28 days in accordance with EN 1097-6:2013 [11]. Surfaces of the specimens were not protected with a resin. Additional water absorption in vacuum was carried out. While keeping the specimens under the water the vacuum of 0.027 MPa was formed in the container within 5 minutes, retained for 20 minutes at the constant value, and within 5 minutes reduced to ambient pressure. For full saturation of specimens 3 cycles were used.

4.5. Tensile splitting test

Tensile splitting test was carried out with (70.7×70.7×70.7) mm size specimens after water absorption test by vacuum. The test was carried out according to EN 12390-6:2009 [13].

5. Results and discussion

Ultrasonic pulse velocity (UPV) test is a nondestructive testing method, which allows assessing the changes of concrete structure during cement hydration. The velocity of sound in a solid material is a function of its dynamic modulus of elasticity and its density. Knowing the modulus of elasticity of the concrete, other mechanical properties can be easily estimated from empirical correlation, that is the basic idea of the UPV test [14].

Relationship between UPV and curing periods of concrete containing plastic aggregate and expanded clay aggregates are shown in Fig. 4. After 2 days of curing highest UPV value was obtained for D12 series with HDPE crumbs and silica fume. Minimum value of UPV was measured for specimen series D4 and it remained low after 7 days of curing. After 7 days of curing, a fairly uniform increase of UPV is observed, but the largest increase is for specimens with the ground quartz sand microfiller. After 28 days a minimal influence of microfillers to the UPV is observed: UPV of D1 and D2 specimen series with expanded clay aggregate is the largest. Meanwhile, UPV of most samples with plastic aggregate is lower by 300 m/s. Since UPV increase is associated with the variation of the mechanical properties of cement mortar during the hydration process, it can be observed that specimens with plastic aggregates had worse conditions of cement hydration than specimens with expanded clay aggregate. These differences can be observed after 7 days of curing, and are significant after 14 days of curing, while for specimens with plastic aggregates UPV value remains almost the same.

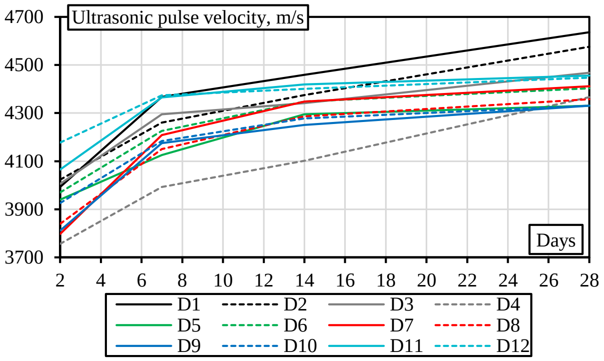

Fig. 4. Ultrasonic pulse velocity of specimens changing after 2, 7, 14 and 28 days.

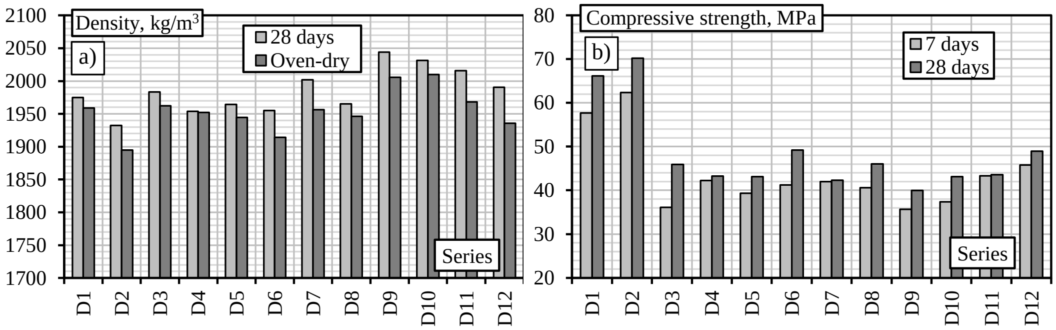

Fig. 5. (a) Density of series of specimens after 28 days curing and oven-dried; (b) Compressive strength of series of specimens.

The velocity of ultrasound in a solid material is also dependent on the density of material. Densities of the specimens after 28 days of curing and after oven drying are shown in Fig. 5a.

It should be noted that the series of specimens with silica fume filler (D2, D4, D6, D8, D10, D12) have lower density. This is due to the fact that at the same W/S ratio of cement mortar with silica fume is more viscous and entrained air during mixing is not escaping. The highest density after 28 days was observed for the samples with LDPE crumbs (D9 – 2044 kg/m^3, D10 – 2031 kg/m^3), while the lowest density of specimens was obtained with expanded clay aggregate (D1 – 1975 kg/m^3, D2 – 1932 kg/m^3).

Relationship between compressive strength and curing periods of concrete specimen are shown in Fig. 5b. Structural lightweight concrete is defined by RILEM as having a density in range of 1600 – 2000 kg/m^3 and a compressive strength of more than 15 MPa [15]. It was found that compressive strength of all concrete specimens series after 28 days of curing exceeded 40 MPa, and almost every series of specimens had density less than 2000 kg/m^3, so it can be identified as a structural lightweight concrete. Compressive strength of the samples with plastic aggregate is less than 50 MPa, while series of specimens with expanded clay and silica fume microfiller – 70.2 MPa and specimen with ground quartz sand microfiller – 66.1 MPa. Specimen D6 with mechanically treated HDPE MFI 2.51 aggregates and silica fume microfiller showed the highest compressive strength among other specimens with plastic aggregates, resulting in 49.2 MPa. Similar result was obtained for concrete with HDPE crumbs: specimen series D12 had a compressive strength of 49 MPa. At the time of crushing, the samples with plastic aggregates exhibited non-rigid failure and retained their original shape. To assess the factors, which influence the compressive strength of concrete, water absorption and tensile splitting tests after water absorption under vacuum were carried out. Obtained results are presented in Table 3.

Table 3. Water absorption and tensile splitting strength data.

No.	Specimen	Water absorption, %	Water absorption after vacuuming, %	Increase of water absorption, %	Tensile splitting strength, MPa
1	D1	1.76	1.81	0.05	5.38
2	D2	1.48	1.49	0.01	4.84
3	D3	3.00	3.51	0.51	3.18
4	D4	3.13	3.87	0.74	2.31
5	D5	3.77	4.51	0.74	2.51
6	D6	3.14	3.91	0.77	3.28
7	D7	3.23	3.91	0.68	3.61
8	D8	2.67	3.31	0.64	3.48
9	D9	2.70	3.84	1.14	3.77
10	D10	2.14	3.39	1.25	3.41
11	D11	3.56	4.19	0.63	3.97
12	D12	2.90	3.60	0.70	4.07

Obtained data of water absorption test is unusual. The water absorption of the specimens with porous, water-absorbing expanded clay aggregate is 2 times lower than for the specimens with plastic aggregates, which water absorption is negligible low. It was found that water absorption of specimens also depends on the used microfiller and in most cases, it is lower when using silica fume. Exceptional case are specimen D3 with ground quartz sand microfiller, resulting in lower water absorption. Water absorption by vacuuming showed even greater difference between samples with expanded clay and plastic aggregates. Water absorption of D1 and D2 series increased 0.05% and 0.1%, respectively, while for series range D3 – D12 from 0.51% to 1.25%. Among the samples with plastic aggregate, maximum water absorption increase was observed for the higher density specimens D9 and D10 with LDPE crumbs aggregate.

Performed splitting test allows the assessment of aggregate and cement mortar adhesion properties. Series D1 and D2 with expanded clay aggregate had brittle failure, with a splitting plane passing through the aggregate. Expanded clay particles did not separate from cement mortar and, therefore, highest tensile splitting strength was obtained. For D1 series specimens with ground quartz sand microfiller 5.38 MPa was obtained. After splitting test in specimens water penetration depth was clearly visible, resulting in ~8 mm from each side of the specimen and ~16 mm at the edges.

Meanwhile, specimens of series D3 and D4 with plastic aggregates were equally soaked. Aggregates were undamaged during splitting test and easily debonded from the cement mortar. Specimens with HDPE MFI 2.51 aggregates showed the lowest splitting tensile strength values.

Water absorption of specimen with expanded clay aggregate showed that cement mortar structure differs significantly from specimens with plastic aggregate and is less permeable to water.

The tendency of concrete to self-desiccacion and autogenous shrinkage leads to a reduction in its internal relative humidity. This causes early-age cracking and influences the hydration process of cement [16,17,18]. In order to avoid this, aggregate pre-wetting prior to mixing is done. Additional water will also promote a maximization of the hydration of the cement in the mixture. Enhanced hydration densifies the pore structure of the material. This approach is called internal curing [19,20].

6. Concluding remarks

- It was found that UPV methodology allows to observe cement hydration process peculiarities of concrete with different water absorption aggregates. After 7 days of curing concrete with plastic waste aggregates (which have a very low water absorption), a significant decrease in growth of strength properties is observed in comparison to concrete with pre-wetted expanded clay aggregate.
- Concrete composition having a density of 1950 to 2050 kg/m^3 with plastic waste aggregates HDPE and LPDE has 28 days compressive strength higher than 40 MPa. Using pre-wetted expanded clay aggregate with same cement mortar resulted in the density of 1900 kg/m^3 with a compressive strength up to 70.2 MPa.
- Although having similar mechanical properties as the waste plastic aggregate, higher porosity pre-wetted expanded clay aggregate creates optimal conditions for cement hydration, which results two times lower water absorption.
- Additional mechanical treatment of HDPE beads did not influence compressive strength and water absorption of concrete.
- It was found that the application of silica fume microfillers in concrete mixture at the same W/S ratio gives higher compressive strength and lower water absorption in comparison to ground quartz microfiller.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the Research Council of Lithuania (Research project No. MIP-093/2015). The authors also wish to thank JSC “Plasta” for providing recycled polyethylene aggregates.

References

[1] J. Castro, L. Keiser, M. Golias and J. Weiss. Absorption and desorption properties of fine lightweight aggregate for application to internally cured concrete mixtures. Cem. Concr. Compos. 33 (10), (2011) 1001-1008.
[2] Y. Senhadji, G. Escadeillas, A.S. Benosman, M. Mouli, H. Khelafi, S. Ould Kaci, Effect of incorporating PVC waste as aggregate on the physical, mechanical, and chloride ion penetration behavior of concrete, J. Adhes. Sci. Technol. 29 (2015) 625–640.
[3] K. Senthil Kumar, K. Baskar, Recycling of E-plastic waste as a construction material in developing countries, J. Mater. Cycles Waste Manag. 17 (2015) 718–724.
[4] R. Siddique, J. Khatib, I. Kaur, Use of recycled plastic in concrete: A review, Waste Manag. 28 (2008) 1835–1852.
[5] B.-W. Jo, S.-K. Park, J.-C. Park, Mechanical properties of polymer concrete made with recycled PET and recycled concrete aggregates, Constr. Build. Mater. 22 (2008) 2281–2291.
[6] K.G. Babu, D.S. Babu, Behaviour of lightweight expanded polystyrene concrete containing silica fume, Cem. Concr. Res. 33 (2003) 755–762.
[7] H.C. Wu, P. Sun, New building materials from fly ash-based lightweight inorganic polymer, Constr. Build. Mater. 21 (2007) 211–217.
[8] Y.W. Choi, D.J. Moon, J.S. Chung, S.K. Cho, Effects of waste PET bottles aggregate on the properties of concrete, Cem. Concr. Res. 35 (2005) 776–781.
[9] Y.W. Choi, D.J. Moon, Y.J. Kim, M. Lachemi, Characteristics of mortar and concrete containing fine aggregate manufactured from recycled waste polyethylene terephthalate bottles, Constr. Build. Mater. 23 (2009) 2829–2835.
[10] Z.Z. Ismail, E.A. AL-Hashmi, Use of waste plastic in concrete mixture as aggregate replacement, Waste Manag. 28 (2008) 2041–2047.
[11] EN 1097-6:2013. Tests for mechanical and physical properties of aggregates - Part 6: Determination of particle density and water absorption. 2013.
[12] EN 13055-1:2003. Lightweight aggregates - Part 1: Lightweight aggregates for concrete, mortar and grout. 2003.
[13] EN 12390-6:2009. Testing hardened concrete - Part 6: Tensile splitting strength of test specimens. 2009.
[14] E. Proverbio, V. Venturi, S.A. Messina, Reliability of nondestructive tests for on site concrete strength assessment, Situ. (2005) 0–7.
[15] Newman J, Choo BS, editors. Advanced concrete technology constituent materials. Elsevier Ltd. 2003.
[16] D.P. Bentz, K.A. Snyder, Protected paste volume in concrete: Extension to internal curing using saturated lightweight fine aggregate, Cem. Concr. Res. 29 (1999) 1863–1867.
[17] M. Golias, J. Castro, J. Weiss, The influence of the initial moisture content of lightweight aggregate on internal curing, Constr. Build. Mater. 35 (2012) 52–62.
[18] D. Cusson, T. Hoogeveen, Internal curing of high-performance concrete with pre-soaked fine lightweight aggregate for prevention of autogenous shrinkage cracking, Cem. Concr. Res. 38 (2008) 757–765.
[19] S. Zhutovsky, K. Kovler, Effect of internal curing on durability-related properties of high performance concrete, Cem. Concr. Res. 42 (2012) 20–26.
[20] D.P. Bentz, W.J. Weiss, Internal Curing : A 2010 State-of-the- Art Review, Civ. Eng. (2011).