Case Studies in Construction Materials 16 (2022) e00919

Contents lists available at ScienceDirect

Case Studies in Construction Materials

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

Drying shrinkage properties of expanded polystyrene (EPS) lightweight aggregate concrete: A review

Mehdi Maghfouri [a,*], Vahid Alimohammadi [b,*], Rishi Gupta [c], Mohammad Saberian [d], Pejman Azarsa [c], Mohammad Hashemi [e], Iman Asadi [f], Rajeev Roychand [g]

[a] *Department of Civil Engineering, University of Ottawa, 161 Louis-Pasteur Private, Ottawa, ON K1N 6N5, Canada*
[b] *Department of Civil Engineering, Faculty of Engineering, Arak Branch, Azad University, 3836119131 Arak, Iran*
[c] *Department of Civil Engineering, University of Victoria, 3800 Finnerty Rd., Victoria, BC, Canada*
[d] *Vice-Chancellor's Postdoctoral Fellow, School of Engineering, RMIT University, Melbourne, Victoria, Australia*
[e] *College of Civil Engineering, Hunan University, Changsha 410082, Hunan, China*
[f] *Department of Structural Engineering, Norwegian University of Science and Technology, NO-7491, Trondheim, Norway*
[g] *School of Engineering, RMIT University, Melbourne, Victoria, Australia*

ARTICLE INFO

Keywords:
Expanded polystyrene (EPS)
Lightweight aggregate, Lightweight aggregate concrete
Drying shrinkage

ABSTRACT

Expanded polystyrene (EPS) is currently being utilized in sustainable materials owing to its ultra-low density and superior thermal performance. It can be incorporated in concrete mixtures to replace coarse aggregate to produce lightweight aggregate concrete (LWAC). Concerning the high shrinkage development in LWAC, the present study reviews the available published articles regarding the drying shrinkage of lightweight concretes containing expanded polystyrene. According to the previous studies, the drying shrinkage development in expanded polystyrene concrete (EPSC) has been reported to be greater than that in conventional concrete, which must be considered for its application in the construction industry. It is mainly attributed to the low elastic modulus and mechanical properties of the EPS. However, incorporating additives and fibers can improve its shrinkage resistance properties. A comprehensive comparison of drying shrinkage magnitude between various LWAC showed that the drying shrinkage strain of EPSC is not generally higher than other types of LWAC; however, the density of EPSC was measured lower than that in other types of lightweight aggregate concretes.

1. Introduction

Concrete is considered one of the most consumed materials in the construction industry, offering strength, durability, reflectivity, and versatility. The density of normal-weight concrete can be changed depending upon its application. In this regard, the selection of the raw materials, particularly aggregates, that form the skeleton of the concrete plays a significant role in adjusting the weight of concrete. Using lightweight aggregates for the fine and coarse aggregates substitution in concrete is the common method to produce lightweight aggregate concrete (LWAC) [1,2]. However, by applying an air-entraining agent in the concrete mixture, low-density concrete can be produced. Technically, concrete with a density less than 2000 kg/m^3 and aggregates with a bulk density of less

---

* Corresponding authors.
E-mail addresses: m.maghfouri@gmail.com, mmagh009@uottawa.ca (M. Maghfouri), vahid.almh@gmail.com (V. Alimohammadi).

https://doi.org/10.1016/j.cscm.2022.e00919
Received 28 September 2021; Received in revised form 13 January 2022; Accepted 24 January 2022

Nomenclature

EPS	Expanded Polystyrene
EPSC	Expanded Polystyrene Concrete
LWAC	Lightweight Aggregate Concrete
LWC	Lightweight Concrete
LWAs	Lightweight Aggregates
OPS	Oil Palm Shell
OPBC	Oil Palm Boiler Clinker
LECA	Expanded Clay
W/C	Water per Cement
PAC	Polystyrene aggregate concrete
MPC	Mgnesia Phosphate Cement
OPC	Ordinary Portland cement
PP	Polypropylene Fibers
RH	Rice Husk Ash
SF	Silica Fume
SPS	Stabilized Polystyrene
ACI	American Concrete Institute

than 1120 kg/m^3 are categorized as lightweight concrete (LWC) and lightweight aggregates (LWA), respectively [3]. LWAs vary in origins, such as natural aggregates of volcanic origin, artificial aggregates produced by the processing of industrial by-products, and factory-made artificial aggregates. However, the most LWAs used in concrete are lightweight expanded clay aggregate (bulk density: 200–1000 kg/m^3), pumice (bulk density: 500–900 kg/m^3), and expanded shale aggregates (bulk density: 600–1000 kg/m^3).

With increased emphasis on improving energy efficiency in buildings and enhancing thermal resistance and a less total deadweight of structures, precast concrete wall panels or façade panels could be the main target to apply LWAC. In the construction industry, the LWAC is being used with numerous advantages such as significant reduction in structure's dead load (due to less density) with a reduction in the costs of both superstructures and foundation, high strength to weight ratio, improved thermal and sound insulation properties, and frost and fire resistance. In addition, its application may significantly reduce the energy consumption in buildings. The advantages of using LWA on mortar and concrete thermal properties and energy saving in buildings were discussed in available literature [4–9]. The thermal conductivity of LWA concrete is lower than the thermal conductivity of normal-weight concrete due to its higher porosity. Thus, the total heat transfer coefficient of a LWA concrete envelop is lower than the regular weight concrete due to the higher thermal resistance in LWA concrete.

However, there are some drawbacks such as relatively low mechanical properties, requiring more cement content in the mixtures to achieve the same strength as conventional concrete, and pre-stressing loss in pre-tension structures. Meanwhile, time-dependent deformations due to creep and shrinkage are significant drawbacks of such concrete, resulted in the volumetric changes and subsequently crack generation on the restrained concrete members affecting durability performance in short-term and long-term ages [1, 10–12]. Shrinkage in hardened concrete is categorized as autogenous shrinkage and drying shrinkage, which can be regarded as water loss due to the self-desiccation or dry environment. The Japan Concrete Institute (JCI) defines the autogenous shrinkage as the macroscopic volume reduction of cementitious materials under sealed conditions after the initial setting [13]. While, the drying shrinkage refers to the volume change caused by the evaporation of internal water from the matrix due to the difference in humidity between the internal and external of the cement-based material [14]. They are mainly caused by the loss of water in C–S–H and the change in internal moisture during the drying process of concrete [15,16]. Drying shrinkage, which mainly occurs during the hardening state and restrained concrete members, is one of the most important causes of the crack generation [17]. According to ASTM C157 [16], shrinkage tests must start 24 h after casting. It is important to assess the drying shrinkage as early as possible because it is responsible for early age cracking that occurs when the concrete does not have much strength [18]. In addition to adverse effects on the appearance of concrete, cracks may reduce the strength and durability by increasing the permeability of concrete and facilitating the entry of aggressive agents into it [17]. This exposes vulnerabilities to corrosion and deterioration of the reinforcement bar, particularly in concrete structural applications. Specifying the dry shrinkage of concrete in long-term performance is highly required [19].

One of the main important factor affecting drying shrinkage of concrete is the degree of restraint by the aggregate – the higher the elastic modulus of aggregates, the higher the restraint and the volumetric proportion of the paste in the concrete mixture [20]. However, concrete curing and its duration also impact the drying shrinkage magnitudes as the longer sealed curing allowed a better hydration of cement and reduced long-term water loss [21]. Among various types of aggregate, the LWA with a lower modulus of elasticity offers less restraint on the potential shrinkage of cement paste. As a result, an immense drying shrinkage strain is expected – it is mainly affected by the properties and the amount of aggregates [22]. Generally, for the normal-weight concrete, the ultimate drying shrinkage ranges from 200 to 800 με [23,24], while that value for LWC could be greater up to a double amount [25]. The magnitude of drying shrinkage in LWC shows the importance of this phenomenon, particularly in concrete products and structures using LWC. Although various prediction models can predict the shrinkage development, the actual rate should be examined before using concrete in any structures or building elements [24,26].

Based on the available literature, expanded polystyrene (EPS) is considered one of the common materials used instead of aggregates to reduce the weight and concrete's thermal conductivity. EPS is a kind of stable foam with low density, consisting of discrete air voids in a polymer matrix. As a lightweight artificial aggregate, EPS is commercially available and can be incorporated in mortar or concrete to produce lightweight insulating concrete [27,28]. From the engineering point of view, the advantage of using EPS among different types of LWAs is the lesser water absorption due to its less porosity [29]. In addition, the low thermal conductivity of EPS (0.03–0.04 W/m.K) is one of the main reasons for its use in the construction industry – particularly for insulting purposes [30]. Previous researches have promoted the applications of EPSC in construction and building products. Currently, EPS lightweight concrete is used in various structural and non-structural elements such as precast concrete panels, cladding panels, composite flooring systems, subbase materials in pavements, floating marine structures, and insulating building elements [31]. However, replacing the normal-weight aggregate with EPS lightweight aggregate increases drying shrinkage strain. By increasing the drying shrinkage magnitude, the possibility of having time-dependent deformations and as a result drying shrinkage cracking in the structure would be higher which may yield the formation of surface crack patterns and impact the durability of the concrete structure [32,33]. Therefore, the current review article presents an overview of drying shrinkage in EPS lightweight concrete.

An extensive literature search was carried out using appropriate keywords, including lightweight concrete, lightweight aggregate, EPS, and drying shrinkage in the databases including Scopus, Elsevier, Springer, Wiley, Taylor & Francis, and other scientific and engineering resources to retrieve the relevant articles. Ultimately, about 75 articles were found and reviewed. However, not many publications exactly focus on drying the EPS lightweight concrete shrinkage and how it may affect negatively on the properties of EPSC structures. This comprehensive review helps the research community to give an overview of EPS lightweight concrete shrinkage behavior in short-term and long-term ages. This review paper eventually helped to glean much information on the way forward and reveals areas of necessary studies towards controlling and minimizing the shrinkage strain in EPS lightweight concrete.

2. Expanded polystyrene lightweight concrete

Polystyrene is produced using styrene (vinyl benzene), which originates from the crude oil refinery. It is in liquid form at normal ambient temperature, but increasing the temperature up to 100 °C, the granulated bead polystyrene. Besides using this product for food packaging and protective devices, its profound impact in the construction industry with its ultra-lightweight and superior thermal properties is undeniable. Table 1 shows various types of EPS and their densities following ASTM C 578-95 [34]. It is worth mentioning that EPS with the size of 1–8 mm and density ranging from 12 to 46 kg/m^3 (0.7–2.82 lb/ft^3) is categorized as a lightweight material; hence, in the construction industry, it can be used by partially or fully substitution of the normal-weight aggregate in concrete technology – depending upon the requirements of density and strength.

EPS is a non-natural ultra-lightweight aggregate with closed-cell membranes and a non-absorbent which can be simply mixed with cement, sand, natural aggregate, and chemical admixture if required for the production of lightweight aggregate concrete with various densities from 800 to 2000 kg/m^3 [23,24,35-37] The low-density feature of products made from EPS such as lightweight wall panel that can be used very effectively for load-bearing walls of single storey houses and non-loadbearing walls of multi-storey buildings, encourages engineers to consider the EPSC structural and non-structural elements in their technical proposals and designs. In addition, the LWC-derived structure is lighter; thus, catastrophic earthquake forces and inertia forces that impact the structures could be reduced since the earthquake forces are linearly dependant on the structure's weight [38-41]. Fig. 1, prepared by the author, shows the size and shape of expanded polystyrene grain to produce the EPS lightweight concrete.

The study on using EPS in concrete is traced back to 1973, when the EPS was first used as aggregate in a concrete mixture [42]. Numerous studies and experimental works have been conducted to explore the properties of EPSC and predict its characteristic in short and long-term ages [37, 43-45]. Fig. 2 is a schematic of a lightweight non-load-bearing wall panel using the cement fiberboard for outer layers of the wall (on both sides) and EPSC as infill and insulating material. The heat insulation of such a combination is approximately twice that of conventional concrete, which is remarkably impactful in the global agenda of reducing CO$_2$ emissions and energy consumption in buildings.

Generally, the mix proportion, casting, molding, curing, setting time, and demolding of EPSC are similar to conventional concrete. The mix design for lightweight aggregates concrete such as EPSC is being carried out in accordance with various internationally recognized standards and specifications. However, the mix proportion and aggregate replacement level can be adjusted to meet concrete's workability and mechanical properties. Because of the ultra-light feature of EPS aggregates and their hydrophobic properties, they might float during the mixing process and integrate poorly with the cement matrix. Therefore, various treatment techniques such as the addition of bonding agents (epoxy resin or water-emulsified epoxies) or different mineral admixtures such as fly ash

Table 1
Various types of expanded polystyrene (EPS) [31]

Type	Density (kg/m^3)
XI	12
I	15
VIII	18
II	22
IX	29
XIV	38
XV	46

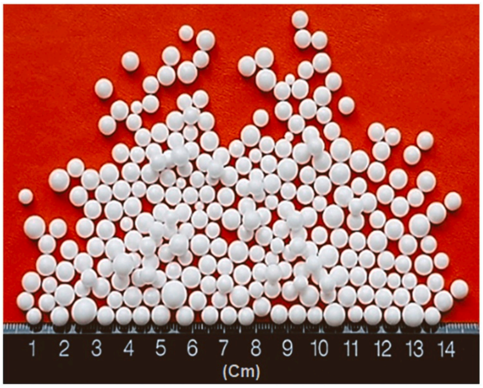
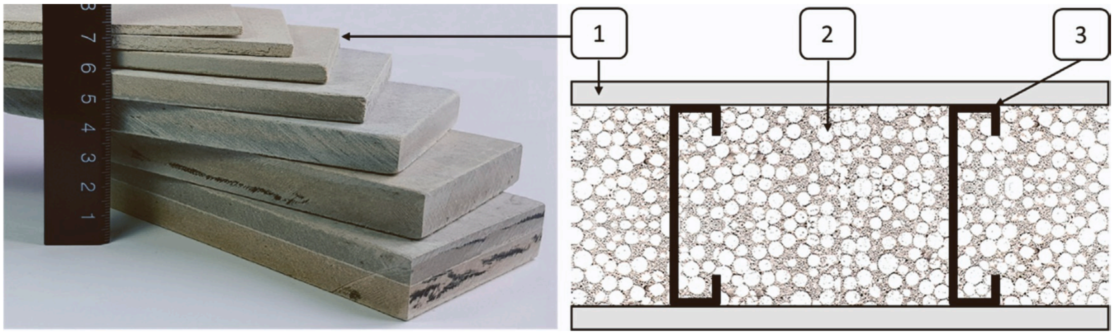


Fig. 1. Expanded polystyrene grain for lightweight concrete.



1. Cellulose cement fibreboard in different sizes
2. EPS lightweight concrete infill
3. 0.50-1.15mm light gauge galvanized steel frame or equivalent @ 305mm c/c max

Fig. 2. Schematic of the lightweight solid wall using expanded polystyrene concrete and cement fiber board. 1. Cellulose cement fiberboard in different sizes 2. EPS lightweight concrete infill 3. 0.50–1.15 mm light gauge galvanized steel frame or equivalent @ 305 mm c/c max.

or micro silica can improve the bonding of the mixtures and prevent segregation in fresh concrete [46]. EPSC has proven better corrosion and chemical resistance than those of conventional concrete due to its inert characteristic [47]. Fig. 3 shows the mixing process of the EPS lightweight concrete, which the author of this study carried out.

The workability decreases when EPS is incorporated into the concrete. Adeala and Soyemi [48] investigated the structural use of expanded polystyrene concrete. They replaced normal aggregate with 5–30% EPS (5% interval) to compare the workability and

Fig. 3. The mixing of EPS lightweight aggregate concrete.

mechanical properties of the concrete with different levels of EPS as aggregate. They reported that the workability of the concrete decreases as the EPS replacement level increases in the concrete. According to the test results, it was observed that the inclusion of 30% EPS induced a remarkable reduction in the slump value by about 85%. Therefore, higher contents of EPS in concrete would reduce the workability of concrete. Meanwhile, a similar trend was reported for the compressive strength, whereby a 66% reduction was recorded for 28-day compressive strength at 30% EPS replacement. It can be concluded that the compressive strength of EPSC is governed by the volume of EPS in the concrete mixture – the higher the dosage of EPS, the lower the compressive strength of concrete can be expected. However, the mechanical properties of EPSC can be significantly improved with the addition of supplementary cementitious materials such as silica fume, fly ash, or bonding additives to the concrete mixtures by 15% [31, 49]. The enhancement of the mechanical properties is mainly attributed to the better bonding between EPS and the cement paste, microstructural changes and improvement of the weak interfacial transition zone region through using the supplementary cementitious materials [50-52].

The effects of EPS particles on fire resistance, thermal conductivity, and compressive strength of foamed concrete – with an EPS volume range of 0–82.22% – were studied by Sayadi et al. [47]. Their test results concluded that a higher fire endurance is obtained for concrete mixtures with low EPS volume and high cement content, which is due to the amorphous silica in the cement paste contributed to higher fire resistance. However, by increasing EPS volume, a lower fire endurance and thermal conductivity were recorded, which is attributed to satisfactory thermal properties of EPS aggregate with 98% air. Concrete with 82% and 28% EPS had a thermal conductivity of 0.0848 and 0.212 W/mK, respectively.

3. Drying shrinkage of lightweight aggregate concrete

Shrinkage is mainly caused by moisture transfer in concrete. It is a complicated time-dependent process taking place in cementitious materials, leading to a volumetric contraction and crack formation within concrete materials. Generally, the variety and stiffness of fine and coarse aggregates in concrete considerably influence the magnitude of shrinkage and the ultimate shrinkage strain value [53]. Aggregates impact the deformation properties of concrete through a combination of the effects of the interaction between cement paste and aggregates, water absorption and aggregate stiffness [54]. Hence, concrete with higher aggregate content exhibits a lower rate of shrinkage. In addition, concrete with aggregates of higher elastic modulus or rougher surfaces is more resistant to the shrinkage phenomenon; therefore, a smaller drying shrinkage strain could be expected [55].The amount of shrinkage in conventional concrete can be calculated as follows [56]:

$$\varepsilon_{nc} = \varepsilon_b (1 - V_{ag})^n \tag{1}$$

Where ε_{nc} is shrinkage of concrete, $\varepsilon_b$is shrinkage of binder, V_{ag} is the aggregate volume, and n is a constant between 1.2 and 1.7.

In the case of lightweight aggregate concrete, the low elastic modulus of aggregates and great water absorption rate – due to the texture and porous nature of the LWA – are caused a large rate of drying shrinkage. Extreme concrete drying shrinkage may lead to micro-cracks development and further crack propagation, which facilitate the penetration of harmful substances into the concrete, inducing the corrosion of reinforcement and reducing concrete durability and bearing capacity [57,58]. Maghfouri et al. [1] reported a range of surface cracks, from fine to visible, on LWC containing agro-waste lightweight aggregate. They confirmed that the complete replacement of normal-weight aggregates with lightweight aggregates leads to a remarkable increase in drying shrinkage and subsequently surface cracks. Moreover, LWC shrinkage heavily affects pre-stress loss measurement and diminishes dimensional stability at a large scale. The ACI Committee (2003) [59] suggested the potential adverse impact of drying shrinkage on concrete crack growth and propagation. It was reported that drying shrinkage could deteriorate pre-stress forces, reduce the effective tensile strength, and induce structural deformation [60] As a long-term phenomenon, drying shrinkage is influenced by several factors, including the free evaporation of water from capillaries and pores exposed to the air, the absorption of water into aggregates, hydration rate, the water-cement ratio, water content, shape, cement composition, relative humidity, strength, and starting age [61, 62]. Saturated LWAs can transfer water into the cement at early drying ages, increasing weight loss and shrinkage [63]. Additionally, LWAs of lower strength caus a minor restraining contribution to cement paste shrinkage, resulting in more significant shrinkage than conventional concretes. According to Demirboga and Kan [64], aggregate elasticity and paste volume fraction are the major factors that influence concrete shrinkage.

3.1. Drying shrinkage of expanded polystyrene (EPS) concrete

EPS lightweight concrete is characterized by a considerably lower density and higher structural efficiency than conventional concrete. Basically, when the bead content increases, both the density and strength are significantly reduced. Chen and Liu [31] reported a range of 10–25 MPa for compressive strength and 800–1800 kg/m^3 for density of concretes produced with expanded polystyrene beads used as partial substitutes for aggregates. Apart from the compressive strength, drying shrinkage is of increasing concern when focusing on maintaining durable structures. Generally, EPSC possesses a higher drying shrinkage than conventional concrete [65]. Over time, this high magnitude shrinkage induces cracking which would negatively impact the concrete durability.

3.1.1. Impact of aggregate type on drying shrinkage of EPS lightweight concrete

Several factors affect the drying shrinkage of the hardened concrete, but aggregates similar to EPS have a more substantial impact on the high rate of LWC's drying shrinkage in short-term and long-term ages. This is mainly attributed to the low mechanical properties, higher surface smoothness, and insignificant elastic modulus of EPS, which result in very little restraint to the shrinkage of cement paste and, subsequently, the concrete mixtures [10, 36] In an investigation on the properties of lightweight expanded polystyrene concrete, EPS with different volumes of 25%, 40%, and 55% was used to replace sand and aggregate. It was observed that drying shrinkage strain of control concrete mix (without EPS) at the age of 90-day was remarkably lower than EPS concrete mixes by about 33%, 42%, and 78% when the volume content of EPS in concrete mixtures was 25%, 40%, and 55% respectively [31]. The previous results and significant increase in creep and drying shrinkage of LWC containing a high volume of EPS were also confirmed by Sabaa and Ravindrarajah [66] and Elsalah, J., et al. [67].

Additionally, Herki and Khatib [60] applied a novel coating technique with a binder consisting of clay and cement for the EPS beads to produce stabilized polystyrene (SPS) aggregates and minimize the segregation of EPS particles in concrete mixtures. Their study investigated the impact of SPS incorporation with different volumes (0%, 30%, 60%, and 100%) on mechanical properties and drying shrinkage (up to 720-day). Although the coating technique was applied, the increasing drying shrinkage development was recorded. It was reported that the drying shrinkage of such concrete drastically increased, primarily for the mixture containing 100% SPS, which was due to the paste volume of mixtures and very little restraint imposed by SPS on the cement paste. Similar findings were reported by Chen and Liu [31],Tang et al. [65], and Demirboga and Kan [54]. Table 2, recreated from the original source [62], represents six concrete mixtures (C1-C6 mixes) containing different percentages of fine and coarse MEPS as a replacement for natural aggregate. The first impact of MEPS inclusion on the concrete mixtures was a significant reduction in density where the C1 mix containing 100% MEPS aggregate possessed the lowest density by 876 kg/m^3.

The results of drying shrinkage value up to the age of 210-day have been indicated for C1 to C6 mixes in Fig. 4. It clearly shows the direct correlation between drying shrinkage value and MEPS volume in concrete mixtures, as the mixes containing higher volumes of MPES experienced greater rates of drying shrinkage strain in both early and long-term ages. For instance, the C1 mix showed the highest rate of shrinkage among other mixes under 210 days ambient curing conditions. In contrast, the lowest shrinkage was recorded for the C6 mix containing 25% MEPS aggregate and 75% natural aggregate.

Drying shrinkage value of C1 mixture containing 100% MPES increased considerably by 820 με, while drying shrinkage magnitude of 25% MEPS aggregate and 75% natural aggregate (C6 mix) shows a slow development from 100 to 360 με up to the age of 210-day. The drying shrinkage value of 75% MPES and 25% natural aggregate concrete specimens (C2) experienced a considerable increase by almost 530 με, the second-highest growth among the concrete samples. Similarly, the C3 mix containing 50% MPES as coarse aggregate and 50% natural aggregate as fine aggregate also shows an upward trend in the drying shrinkage during the curing condition, reaching 460 με at 210-day curing condition. While the drying shrinkage development of other samples (C4 and C5) containing 50% MPES moderately increases by almost 290 and 300 με, respectively, during 210-day curing age, it is almost stable after 120 curing days [64].

Overall, the higher recorded rate of drying shrinkage strain shows the disadvantage of MPES compared to the control concrete mix, meaning that MPES aggregate considerably increases the drying shrinkage of concrete.

Generally, it is expected that by increasing the EPS volume in concrete mixtures, the shrinkage would increase, as shown in Table 3. In this table, the drying shrinkage of 90-day reference concrete was 610 με. On the other hand, when the number of EPS in the concrete sample was 20%, the drying shrinkage at the age of 90-day drastically increased to 1000 με, revealing the effect of the EPS on the ultimate magnitude of drying shrinkage [68].

3.1.2. *Impact of curing condition on drying shrinkage of EPS lightweight concrete*

Basically, the purpose of concrete curing is to maintain adequate moisture and temperature to effectively develop the microstructure and strength. There are different types of curing conditions which could have different effects on mechanical properties and shrinkage behavior of concrete [24]. In construction industry, various curing conditions could be proposed as effective factors to control or minimize drying shrinkage and its subsequent effects such as shrinkage cracking and durability issues in concrete structures. Many studies focusing on the effect of curing are available which show the significance of this factor [11,16,26,65]. Therefore in this section, the impact of water curing (with different curing duration) as the common method of curing, on drying shrinkage of EPS lightweight concrete will be discussed.

In this regard, Table 3 presents the EPSC's drying shrinkage strains versus drying time and control concrete mix in various conditions of water curing and continuous curing (sample was cured under 90-day water curing until the age of testing), 7 days and 28 days. The results show that drying shrinkage decreases gradually with elapsed time for all concrete mixes under different curing conditions. Though, the rates of drying shrinkage strain of EPSC and control concrete mix vary at earlier ages [65]. As presented in the table, drying shrinkage in PAC grows with increasing the EPS content compared to the reference concrete during water curing

Table 2
Details of MEPS concrete mixes containing natural aggregate [58].

Mix code	MEPS/NA (%) (FA + CA)/ (FA + CA)	Cement (kg)	MEPS (kg)		NA (kg)		SP (kg)	w/c	Fresh density (kg/m^3)	Slump value (mm)
			FA	CA	FA	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

NA: natural aggregate; FA + CA: fine and coarse aggregates; SP: superplasticizer.

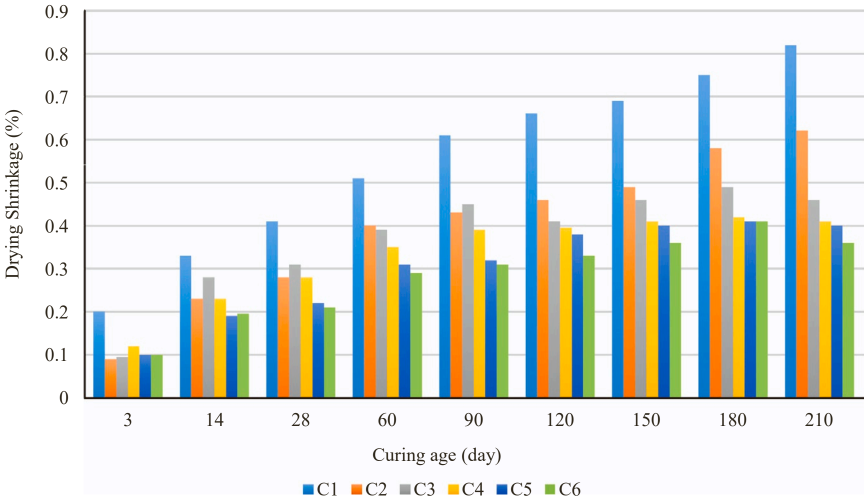


Fig. 4. The effect of various percentages of MEPS on the drying shrinkage of concrete [64].

Table 3
Drying shrinkage results of the polystyrene aggregate (PA) under various water curing conditions.

Mix codes	Drying shrinkage (με)						Curing condition	Ref.
	Short-term ages				Long-term ages			
	3 days	7 days	14 days	28 days	60 days	90 days		
PA (0)	–	200	320	475	630	630	Continuous curing	[31]
PA (0)	–	200	290	430	520	610	Continuous curing	[68]
PA (20)	70	230	320	390	480	530	28-day water curing	[65]
PA (20)	150	240	380	430	570	595	7-day water curing	
PA (20)	–	250	400	670	940	1000	Continuous curing	[68]
PA (20)	160	270	410	600	700	720	Continuous curing	[69]
PA (25)	–	225	430	640	870	990	Continuous curing	[31]
PA (40)	–	300	480	685	930	1020	Continuous curing	
PA (40)	198	305	400	440	570	630	28-day water curing	[65]
PA (40)	160	320	470	510	630	670	7- day water curing	
PA (40)	190	310	450	640	720	740	Continuous curing	[69]
PA (45)	–	485	590	800	1060	1100	Continuous curing	[68]
PA (55)	–	430	600	830	1080	1120	Continuous curing	[31]
PA (60)	210	350	480	650	740	770	Continuous curing	[69]
PA (60)	250	380	510	580	720	780	28-day water curing	[65]
PA (60)	250	340	510	630	750	810	7- day water curing	
PA (80)	320	505	690	760	850	910	28-day water curing	
PA (80)	400	520	770	880	970	1070	7-day water curing	

conditions. Furthermore, LWC with different percentages of polystyrene aggregate (PA) under continuous curing shows a higher drying shrinkage value than 7- and 28-day water curings. Usually, the drying shrinkage values of the expanded polystyrene concrete made of Portland cement and 20–80% PA are reported to be between 70 and 1120 με at the age of 3–90 days [69].

3.1.3. *Impact of additives on drying shrinkage of EPS lightweight concrete*

Many researchers have reported that by increasing the volumetric proportion of the EPS in concrete mixtures, the rate of shrinkage would increase significantly. It is mainly attributed to the low elastic modulus of the EPS ranging from 4 to 10 MPa [31,43,65]. However, incorporating steel fibers remarkably improves the shrinkage resistance properties and provide some exceptional control of long-term drying shrinkage cracking. Chen and Liu [31] presented steel fibers to EPSC with a density up to 1800 kg/m^3 and revealed that the steel fibers could significantly enhance the tensile and compressive strengths and improve the drying shrinkage of the EPSC specimens [10]. Past investigations also confirmed that EPSC reinforced by steel fibers possesses a better control in a drying shrinkage development [68,70]. Technically, the three-dimensional distribution of steel fibers in concrete provides a frame constraining the shrinkage deformation of concrete. This positive impact on drying shrinkage would be stronger with the increasing volume fraction of steel fiber due to the better net structure bridged among steel fibers [62].

Furthermore, the inclusion of silica fume in LWC mixtures could mitigate the adverse effects of drying shrinkage. It has been highlighted by Zhang et al. [71] that shrinkage of LWC is reduced by the addition of 5% silica fume and up to 1.5% steel fibers. Beng et al. [31] tested 14 different EPS-based concrete mixtures on investigating the impact of silica fume and steel fiber on mechanical and shrinkage properties of EPSC. They reported that drying shrinkage of normal concrete at the age of 90-day was about 630 με, while that value for the EPSC with volume contents of EPS at 25%, 40%, and 55% (at the same age) was up to 950, 995, and 1121 με, respectively. Additinally, they found out that steel fiber greatly decreases the drying shrinkage of EPS concrete. Even for EPS concrete with 55% of the volume content of EPS and 1.5% of steel fibers, the drying shrinkage at 90 days was 610 microstrain, which was less than that of normal concrete (630 με) and EPSC made with 55% EPS without steel fiber content (1121 microstrain).

Moreover, researchers have demonstrated that drying shrinkage would be changed by changing the property of EPS. For instance, adding different additives such as rice husk ash and polypropylene fiber into the EPSC could increase drying shrinkage [72,73] Another study investigated the quality of the interfacial transition zone between the cement and expanded polystyrene beads. It was highlighted that the inclusion of silica fume in the EPSC mixtures improved the bonding between the EPS and C-H-S, and as a result, the compressive strength was enhanced [70] Additionally, previous studies reported that, by inclusion of 10 mm basalt aggregate and silica fume (SF), the rate of drying shrinkage of the EPSC can be reduced in short-term and long-term ages. The shrinkage value of EPSC containing SF (400 kg cement + 40 kg SF) was reported by 730 με at 84 days, whereas that value for EPSC containing SF as cement replacement (360 kg cement + 40 kg SF) – with lesser binder compare to the previous mix – was 655 με [36]. It shows how EPS in concrete mixtures can significantly increase, which is mainly due to the low stiffness of the polystyrene beads providing very little restraint to the shrinkage of cement paste.

Fig. 5 shows the drying shrinkage of certain expanded polystyrene concretes with polypropylene fibers (PP) and rice husk ash (RH) under various curing ages. The drying shrinkage of each sample is compared with It can be concluded from the figure that using 0.3% and 0.5% of PP remarkably increases the drying shrinkage value of the EPSC. At the same time, the inclusion of silica fume results in a reduction of drying shrinkage development. Additionally, similar results can be observed and concluded for the concrete containing rice husk ash (RH) [47]. EPSC containing 0.5% PP has the highest value of drying shrinkage, as opposed to the EPSC made with 15% EPS and 10% SF, which has the least amount. Concretes containing 15% EPS with the addition of 0.30% PP and 20% RH experienced an increasing trend of drying shrinkage, compared with normal-weight concretes (E0) and concretes made with 15% EPS, which the last ones show higher drying shrinkage values than the first ones. It can be found out that increasing curing age significantly increases the drying shrinkage value in NWC and certain EPS concrete with different additives.

Fig. 6 demonstrates the influence of another additive, named magnesia phosphate cement (MPC), on the drying shrinkage strain of the EPSC. Similar to the concrete mixtures by ordinary Portland cement (OPC), the shrinkage strain of MPC-EPSC increased by increasing the volume of EPS in the mixture [69] Furthermore, the shrinkage strain of the reference magnesia phosphate cement sample was constant after 28 days, but the shrinkage of MPC-EPSC samples extended after 28 days. At the age of 60 and 90 days, the drying shrinkage of MPC-EPSC samples was lower than 800 με, and the drying shrinkage of reference EPSC was only about 315 με. Overall, the drying shrinkage of MPC containing various percentages of EPS showed a more upward trend in the increment of drying shrinkage value after 14 days compared to the curing age up to 7 days. This is mainly due to the higher moisture of aggregates due to the continuous curing condition and higher strength of concrete, as well as the low stiffness and high compressibility of polystyrene aggregates which offer little restraint to the shrinkage process.

3.1.4. Impact of additives on drying shrinkage of various LWCs versus EPSC

Comparison of the EPSC with other lightweight aggregate concretes gives a broad perspective on the characteristic of such concrete with a particular focus on shrinkage properties. In this regard, Table 4 compares properties of several types of lightweight aggregate concretes such as drying shrinkage, compressive strength, and density with 50% and 100% of lightweight aggregates including, EPS, MEPS, oil palm shell (OPS), oil palm boiler clinker (OPBC), expanded clay (LECA), pumice, expanded perlite and sintered fly ash aggregate (Lytag). From the summarized information in the table, normal-weight concrete made with granite aggregates has almost the lowest drying shrinkage strain value compared to other types of lightweight concretes. Additionally, it can be observed that

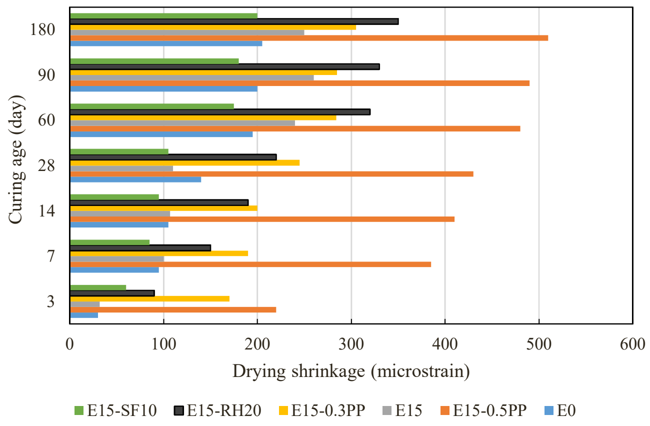


Fig. 5. Drying shrinkage of EPS concretes with different additives including 0% Expanded Polystyrene (E), 15% Expanded Polystyrene (E) with 10% Silica Fume (SF), 15% Expanded Polystyrene (E) with 20% rice husk ash (RH), 15% Expanded Polystyrene (E), 15% Expanded Polystyrene (E) with 0.5% polypropylene fibers (PP) and 15% Expanded Polystyrene (E) with 0.3% polypropylene fibers (PP) [47].

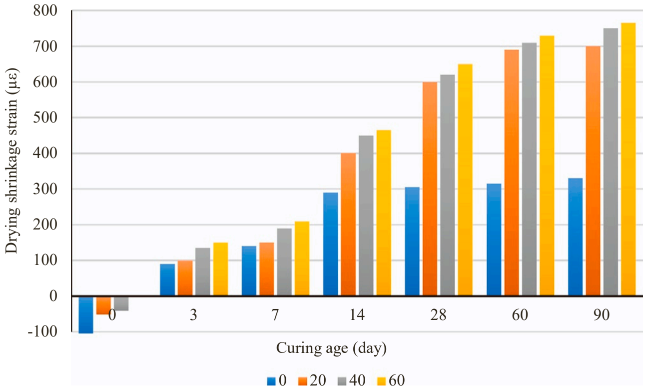


Fig. 6. Effect of EPS content (0%, 20%, 40% and 60%) on drying shrinkage strain of MPC–EPS concrete [69].

lightweight concretes containing EPS or MEPS have the lowest density and compressive strength. In contrast, this type of concrete does not possess the lowest drying shrinkage strain value, among others. Furthermore, the importance of drying shrinkage in concretes made with complete substitution of lightweight aggregates are greater than those mixtures containing 50% or lower replacements. According to the table, the ultimate drying shrinkage of lightweight concrete containing 50% EPS without cementitious materials under 28-day water curing conditions is almost two times higher than that of the lightweight concrete made with modified EPS at an early age (28 days of curing). However, the drying shrinkage of LWC containing EPS with MPC at the age of 90-day is approximately 7% greater than that of the EPS-LWC without MPC. LWC made with pumice aggregate, pre-soaked for 24 h, has a higher drying shrinkage value than that under one-hour pre-soaking. While LWC containing OPS and various percentages of OPBC experienced higher drying shrinkage values than LWC made with cement at W/C 0.39. Using 50% OPBC in OPS-LWC at W/C 0.29 resulted in a lower drying shrinkage by at least 23%.

Similarly, the addition of other additives and various curing conditions directly affects the drying shrinkage of different LWC, made with a 100% substitution level of lightweight aggregates. EPS-LWC indicates a higher ultimate drying shrinkage than MPS-LWC. Lytag concrete, as another type of LWC, shows a lower drying shrinkage when using 1.7% steel fiber compared to using 1% polypropylene fibers. Additionally, LWC made with 100% pumice aggregates with one-hour pre-soaking curing condition has a higher drying shrinkage value than that cured under 24-hour pre-soaking condition, as opposed to LWC containing 50% replacement pumice aggregates under the same curing condition. Therefore, the types of conditions and the addition of various cementitious materials and coarse aggregates considerably impact the drying shrinkage value.

Comparing the rate of drying shrinkage development, although lightweight concrete containing 100% Lytag aggregates experienced the highest drying shrinkage development at long-term age, this type of concrete has higher compressive strength and density than EPS concretes. The compressive strength of concrete directly impacts the rate of drying shrinkage. The higher the compressive strength, the lower the drying shrinkage strain. Generally, it can be concluded that EPS or MEPS has a significant effect on the mechanical properties of LWCs, which should not be underestimated.

4. Conclusion

This review paper investigates the drying shrinkage behavior of lightweight concrete made with expanded polystyrene (EPS) and various types of additives. Based on the existing published articles, drying shrinkage is an important factor affecting the behavior of EPS lightweight concrete in the hardened state. From the preceding, the following conclusions can result:

1. Lightweight concrete containing EPS has a larger drying shrinkage than normal-weight concretes since EPS aggregates have lower mechanical properties and lower stiffness.
2. Polystyrene aggregate concrete (PAC) showed a more significant drying shrinkage strain at higher polystyrene aggregate fractions. While early-age shrinkage is important at higher polystyrene contents, the PAC and control specimens showed no considerable drying shrinkage differences at higher ages. Drying shrinkage values in PAC increased by increasing EPS aggregate content compared to the conventional concrete during the same water curing condition. The main reason is polystyrene aggregates' low stiffness and high compressibility, which offer little restraint to the shrinkage process.
3. Lightweight concrete made with various lightweight aggregates, especially PAC, under continuous curing conditions showed a lower drying shrinkage value than those under 7- and 28-day water curing conditions. This may be due to higher moisture of aggregates resulted from the continuous curing condition, as well as higher strength of concrete. Other types of lightweight aggregates such as Lytag, OPS, pumice, expanded perlite, and expanded clay possess different drying shrinkage values when various cementitious materials are added under different curing conditions. In 50% aggregate replacement level, concrete containing expanded perlite under constant relative humidity showed the highest ultimate drying shrinkage strain, while in 100% aggregate replacement level, the highest rate of drying shrinkage was recorded for the EPS lightweight concrete under 28 days water curing condition. This difference mainly results from the various stiffness and mechanical properties of the aggregates.

Table 4
Different rates of shrinkage for various lightweight aggregates at 50% and 100% aggregate replacements.

Aggregate		Concrete				Ref.	Remark
		Density (Kg/m^3)	Compressive strength 28-day (MPa)	Drying shrinkage (με)			
Type	Replacement level (%)			90-day	Ultimate[a]		
Granite	–	2357	74.4	215	271	[11]	Control aggregate for control mix (for comparison)
Expanded perlite 1	< 50	2302	NG	410	900	[73]	100% constant relative humidity was applied for curing
EPS 1	50	1765	23.1	705	840	[65]	28-day water curing was applied
Pumice 1	50	2350	60.6	490	630	[75]	Pumice was pre-soaked in water for 24-hr
OPS+OPBC 1	< 50	1808	37	560	570	[76]	OPS replaced with OPBC at 10% by volume (w/c = 0.36)
OPS 1	50	2053	46.3	411	544	[1]	Cement + 20% fly ash
OPS 2	50	2011	44.5	430	540	[77]	w/c = 0.29
OPS+OPBC 2	< 50	1833	43.5	510	525	[76]	OPS replaced with OPBC at 30% by volume (w/c = 0.36)
OPS+OPBC 3	50	1904	41	490	515	[78]	OPS replaced with OPBC at 50% by volume (w/c = 0.36)
Pumice 2	50	2359	61.7	415	510	[75]	Pumice was pre-soaked for 1-hr
OPS 3	50	2141	52	317	471	[1]	Only cement was used as a binder
MEPS 1	50	1572	NG	410	460	[64]	50% (modified expanded polystyrene as coarse aggregates) + 50% (natural fine aggregates)
Expanded Clay 1[b]	50	1809	30.8	315	430	[77]	Expanded clay with a nominal size of 8 mm
MEPS 2	50	1596	NG	320	420	[64]	50% (modified expanded polystyrene as coarse and fine aggregates) + 50% (natural coarse and fine aggregates)
MEPS 3	50	1621	NG	390	410	[64]	50% (modified expanded polystyrene as fine aggregates) + 50% (natural coarse aggregates)
OPS+OPBC 4	50	1940	51.1	380	395	[78]	OPS replaced with OPBC at 50% by volume (w/c = 0.29)
Expanded perlite 2	< 50	2302	NG	70	130	[74]	Lime-saturated water was applied
EPS 2	50	1036	12.9	1087	–	[31]	Underwater curing condition without silica fume and steel fiber
MPC-EPS	50	990	17	750	–	[69]	EPSC containing Portland cement with magnesia phosphate cement (MPC)
EPS 1	100	1170	8	1040	1210	[65]	28-day water curing
Lytag 1[c]	100	1890	64.8	800	1060	[79]	Plain Lytag concrete
Lytag 2	100	1860	57.9	630	995	[79]	LWP3 Reinforced with polypropylene fibers 1%
OPS 4	100	1753	33.1	701	935	[1]	Cement + 20% fly ash
Lytag 3	100	1940	61.2	655	925	[80]	LWS3 Reinforced with steel fibers 1.7%
OPS 5	100	1909	40.5	593	826	[1]	Only cement was used as a binder
MEPS 4	100	876	NG	610	820	[64]	100% modified expanded polystyrene as coarse and fine aggregates
Pumice 3	100	2208	47.1	650	770		Pumice was pre-soaked in water for 1-hr
Pumice 4	100	2246	50.5	625	720	[75]	Pumice was pre-soaked in water for 24-hr
Expanded clay 2	100	1880	25	415	420	[80]	14 mm LECA with density of 760 kg/m^3 (w/c = 0.40)
OPBC 1	100	NG	–	335	395	[81]	10 mm POC as both coarse and fine aggregates + 90% OPC + 10% fly ash
OPBC 2	100	NG	–	260	330	[81]	20 mm OPBC as both coarse and fine aggregates + 90% OPC + 10% fly ash
Expanded clay 1	100	1950	35	280	330	[80]	14 mm LECA with density of 970 kg/m3 (w/c = 0.40)

[a] The maximum recorded shrinkage in research.
[b] Expanded clay aggregate is also known as LECA.
[c] Sintered fly ash aggregate known as Lytag.

4. Adding various types of additives such as rice husk ash, silica fume, and polypropylene fiber into the expanded polystyrene concretes can impact the rate of drying shrinkage. The inclusion of silica fume and rice husk ash leads to an increase in the drying shrinkage at lower extents. Whereas the addition of steel fibers to EPS concrete significantly improves the shrinkage resistance properties and provides exceptional control of long-term drying shrinkage cracking. This is mainly due to the improvement of bonding between EPS and the cement paste.

Although this review studied the drying shrinkage phenomena in EPS concrete, there are still research gaps in the area. For future studies, reviewing and comparing the available published articles related to the drying shrinkage values in various lightweight aggregate concretes in comparison with EPSCs would be useful since there is a lack of comprehensive information regarding this subject. Furthermore, investigating the effects of different additives and nanotechnology on the drying shrinkage of EPS concretes would be interesting. Finally, investigating the relationship between the financial aspect and EPSCs facing drying shrinkage is also recommended.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] M. Maghfouri, V. Alimohammadi, P. Azarsa, I. Asadi, Y. Doroudi, B. Balakrishnan, Impact of fly ash on time-dependent properties of agro-waste lightweight aggregate concrete, J. Compos. Sci. 5 (6) (2021) 156.
[2] S. Chandra, L. Berntsson, Lightweight Aggregate Concrete, Elsevier, 2002.
[3] T.A. Holm, J.P. Ries, Lightweight concrete and aggregates. Significance of Tests and Properties of Concrete and Concrete-making Materials, ASTM International, 2006.
[4] R.M. Ferraro, A. Nanni, Effect of off-white rice husk ash on strength, porosity, conductivity and corrosion resistance of white concrete, Constr. Build. Mater. 31 (2012) 220–225.
[5] O. Gencel, J.J. del Coz Díaz, M. Sutcu, F. Kocyigit, F.Á. Rabanal, M. Alonso-Martínez, G.M. Barrera, Thermal performance optimization of lightweight concrete/EPS layered composite building blocks, Int. J. Thermophys. 42 (4) (2021) 1–14.
[6] X. Ni, Z. Wu, W. Zhang, K. Lu, Y. Ding, S. Mao, Energy utilization of building insulation waste expanded polystyrene: pyrolysis kinetic estimation by a new comprehensive method, Polymers 12 (8) (2020) 1744.
[7] P. Shafigh, I. Asadi, N.B. Mahyuddin, Concrete as a thermal mass material for building applications-a review, J. Build. Eng. 19 (2018) 14–25.
[8] Y. Zaetang, A. Wongsa, V. Sata, P. Chindaprasirt, Use of lightweight aggregates in pervious concrete, Constr. Build. Mater. 48 (2013) 585–591.
[9] H. Zhang, J. Yang, H. Wu, P. Fu, Y. Liu, W. Yang, Dynamic thermal performance of ultra-light and thermal-insulative aerogel foamed concrete for building energy efficiency, Sol. Energy 204 (2020) 569–576.
[10] A. Babavalian, A.H. Ranjbaran, S. Shahbeyk, Uniaxial and triaxial failure strength of fiber reinforced EPS concrete, Constr. Build. Mater. 247 (2020), 118617.
[11] M. Maghfouri, P. Shafigh, M. Aslam, Optimum oil palm shell content as coarse aggregate in concrete based on mechanical and durability properties, Adv. Mater. Sci. Eng. (2018), 2018.
[12] M. Zareh, Comparative study of lightweight and normal weight concrete in flexure, 1971.
[13] K. Kovler, S. Zhutovsky, Overview and future trends of shrinkage research, Mater. Struct. 39 (9) (2006) 827–847.
[14] Y. Mao, J. Liu, C. Shi, Autogenous shrinkage and drying shrinkage of recycled aggregate concrete: a review, J. Clean. Prod. (2021), 126435.
[15] W. Wongkeo, P. Thongsanitgarn, A. Chaipanich, Compressive strength and drying shrinkage of fly ash-bottom ash-silica fume multi-blended cement mortars, Mater. Des. 36 (2012) 655–662.
[16] C157, A., Standard test method for length change of hardened hydraulic-cement mortar and concrete, in: Annual Book of ASTM Standards, 2006. 4, pp. 96–101.
[17] F. Azarhomayun, M. Haji, M. Kioumarsi, M. Shekarchi, Effect of calcium stearate and aluminum powder on free and restrained drying shrinkage, crack characteristic and mechanical properties of concrete, Cem. Concr. Compos. 125 (2022), 104276.
[18] A. Castel, S.J. Foster, T. Ng, J.G. Sanjayan, R.I. Gilbert, Creep and drying shrinkage of a blended slag and low calcium fly ash geopolymer Concrete, Mater. Struct. 49 (5) (2016) 1619–1628.
[19] S. Ismail, M. Ramli, Mechanical strength and drying shrinkage properties of concrete containing treated coarse recycled concrete aggregates, Constr. Build. Mater. 68 (2014) 726–739.
[20] P. Bischoff, K. Yamura, S. Perry, Polystyrene aggregate concrete subjected to hard impact, Proc. Inst. Civ. Eng. 89(2) (1990) 225–239.
[21] H. Samouh, E. Rozière, V. Wisniewski, A. Loukili, Consequences of longer sealed curing on drying shrinkage, cracking and carbonation of concrete, Cem. Concr. Res. 95 (2017) 117–131.
[22] L. Chandra Berntsson, Lightweight Aggregate Concrete Science, Technology and Applications, Noyes Publications, Norwich, NJ, 2003.
[23] P. Zia, S. Ahmad, M. Leming, High-Performance Concretes: A State-of-Art Report (1989–1994) FHWA-RD-97-030, Federal Highway Administration, McLean, Virginia, 1997.
[24] M. Maghfouri, P. Shafigh, V. Alimohammadi, Y. Doroudi, M. Aslam, Appropriate drying shrinkage prediction models for lightweight concrete containing coarse agro-waste aggregate, J. Build. Eng. 29 (2020), 101148.
[25] J. Clarke, Structural lightweight aggregate concrete.
[26] M. Maghfouri, Drying shrinkage strain development of agro-waste oil palm shell lightweight aggregate concrete by using the experimental result, ACI and eurocode prediction models, Int. J. Integr. Eng. 11 (9) (2019) 255–263.
[27] D.S. Babu, K.G. Babu, W. Tiong-Huan, Effect of polystyrene aggregate size on strength and moisture migration characteristics of lightweight concrete, Cem. Concr. Compos. 28 (6) (2006) 520–527.
[28] A. Short, K. Kinniburgh, Lightweight Concrete, CR books, 1963.
[29] S. Vėjelis, S. Vaitkus, Investigation of water absorption by expanded polystyrene slabs, Mater. Sci. 12 (2) (2006) 134–137.
[30] I. Asadi, P. Shafigh, Z.F.B.A. Hassan, N.B. Mahyuddin, Thermal conductivity of concrete–a review, J. Build. Eng. 20 (2018) 81–93.
[31] B. Chen, J. Liu, Properties of lightweight expanded polystyrene concrete reinforced with steel fiber, Cem. Concr. Res. 34 (7) (2004) 1259–1263.
[32] H. Colina, S. Roux, Experimental model of cracking induced by drying shrinkage, Eur. Phys. J. E 1 (2) (2000) 189–194.
[33] G.W. Scherer, Drying, shrinkage, and cracking of cementitious materials, Transp. Porous Media 110 (2) (2015) 311–331, 2015.
[34] ASTM, C., C578-Standard Specification for Preformed. Cellular Polystyrene Thermal Insulation.
[35] D.S. Babu, K.G. Babu, T. Wee, Properties of lightweight expanded polystyrene aggregate concretes containing fly ash, Cem. Concr. Res. 35 (6) (2005) 1218–1223.
[36] R.S. Ravindrarajah, A. Tuck, Properties of hardened concrete containing treated expanded polystyrene beads, Cem. Concr. Compos. 16 (4) (1994) 273–277.
[37] N. Liu, B. Chen, Experimental study of the influence of EPS particle size on the mechanical properties of EPS lightweight concrete, Constr. Build. Mater. 68 (2014) 227–232.
[38] D.C.L. Teo, M.A. Mannan, V.J. Kurian, Structural concrete using oil palm shell (OPS) as lightweight aggregate, Turk. J. Eng. Environ. Sci. 30 (4) (2006) 251–257.
[39] S. Akçaözoğlu, C.D. Atiş, K. Akçaözoğlu, An investigation on the use of shredded waste PET bottles as aggregate in lightweight concrete, Waste Manag. 30 (2) (2010) 285–290.
[40] K. Aghaee, M. Foroughi, Construction of lightweight concrete partitions using textile waste, in: ICSDEC 2012: Developing the Frontier of Sustainable Design, Engineering, and Construction, 2013, pp. 793–800.
[41] E. Yaşar, C.D. Atiş, A. Kiliç, High strength lightweight concrete made with ternary mixtures of cement-fly ash-silica fume and scoria as aggregate, Turk. J. Eng. Environ. Sci. 28 (2) (2004) 95–100.

[42] D.J. Cook, Expanded Polystyrene Beads as Lightweight Aggregate for Concrete, School of Civil Engineering, University of New South Wales, 1972.
[43] D. Bouvard, et al., Characterization and simulation of microstructure and properties of EPS lightweight concrete, Cem. Concr. Res. 37 (12) (2007) 1666–1673.
[44] K. Miled, K. Sab, R. Le Roy, Particle size effect on EPS lightweight concrete compressive strength: experimental investigation and modelling, Mech. Mater. 39 (3) (2007) 222–240.
[45] K. Miled, R. Le Roy, K. Sab, C. Boulay, Compressive behavior of an idealized EPS lightweight concrete: size effects and failure mode, Mech. Mater. 36 (11) (2004) 1031–1046.
[46] A. Sadrmomtazi, J. Sobhani, M.A. Mirgozar, M. Najimi, Properties of multi-strength grade EPS concrete containing silica fume and rice husk ash, Constr. Build. Mater. 35 (2012) 211–219.
[47] A.A. Sayadi, J.V. Tapia, T.R. Neitzert, G.C. Clifton, Effects of expanded polystyrene (EPS) particles on fire resistance, thermal conductivity and compressive strength of foamed concrete, Constr. Build. Mater. 112 (2016) 716–724.
[48] A.J. Adeala, O.B. Soyemi, Structural use of expanded polystyrene concrete, Int. J. Innov. Sci. Res. Technol. 5(6) 1131–1138.
[49] B. Chen, J. Liu, Mechanical properties of polymer-modified concretes containing expanded polystyrene beads, Constr. Build. Mater. 21 (1) (2007) 7–11.
[50] B.A. Akinyemi, J. Ojediran, O. Olawale, S. Ayanwola, Efficacy of expanded polystyrene as fine aggregate in cement mortars modified with latex paint as an alternative to polymer admixture, J. Mech. Behav. Mater. 29 (1) (2020) 163–168.
[51] Babu, K. Ganesh, D. Saradhi Babu, Behaviour of lightweight expanded polystyrene concrete containing silica fume, Cem. Concr. Res. 33 (5) (2003) 755–762.
[52] R. Le Roy, E. Parant, C. Boulay, Taking into account the inclusions' size in lightweight concrete compressive strength prediction, Cem. Concr. Res. 35 (4) (2005) 770–775.
[53] I. Adam, K. Sakata, T. Ayano, Influence of coarse aggregate on the shrinkage of normal and high-strength concretes, 岡山大学環境理工学部研究報告 6 (1) (2001) 41–45.
[54] M.G. Alexander, Aggregates and the deformation properties of concrete, Mater. J. 93 (6) (1996) 569–577.
[55] D. Hobbs, Influence of aggregate restraint on the shrinkage of concrete, J. Proc. (1974).
[56] A.M. Neville, Properties of Concrete, vol. 4, Longman, London, 1995.
[57] Z.P. Bažant, J.-K. Kim, L. Panula, Improved prediction model for time-dependent deformations of concrete: part 1-Shrinkage, Mater. Struct. 24 (5) (1991) 327–345.
[58] J.F. Lamond, J. Pielert, Significance of Tests and Properties of Concrete and Concrete-making Materials, ASTM, West Conshohocken, PA, 2006.
[59] D.J. Akers, R.D. Gruber, B.W. Ramme, M.J. Boyle, J.G. Grygar, S.K. Rowe, T.W. Bremner, E.S. Kluckowski, S.R. Sheetz, R.G. Burg, M.J. Kowalsky, Guide for Structural Lightweight-aggregate Concrete. ACI 213R-03, American Concrete Institute (ACI), Michigan, 2003.
[60] J. Khatib, B. Herki, A. Elkordi, Characteristics of concrete containing EPS, in: Use of Recycled Plastics in Eco-efficient Concrete, 2019, pp. 137–165.
[61] N. Kabay, F. Aköz, Effect of prewetting methods on some fresh and hardened properties of concrete with pumice aggregate, Cem. Concr. Compos. 34 (4) (2012) 503–507.
[62] S. Zhao, C. Li, M. Zhao, X. Zhang, Experimental study on autogenous and drying shrinkage of steel fiber reinforced lightweight-aggregate concrete, Adv. Mater. Sci. Eng. (2016), 2016.
[63] K.H. Mo, S.H. Goh, U.J. Alengaram, P. Visintin, M.Z. Jumaat, Mechanical, toughness, bond and durability-related properties of lightweight concrete reinforced with steel fibres, Mater. Struct. 50 (1) (2017) 1–14.
[64] R. Demirboga, A. Kan, Thermal conductivity and shrinkage properties of modified waste polystyrene aggregate concretes, Constr. Build. Mater. 35 (2012) 730–734.
[65] W. Tang, Y. Lo, A. Nadeem, Mechanical and drying shrinkage properties of structural-graded polystyrene aggregate concrete, Cem. Concr. Compos. 30 (5) (2008) 403–409.
[66] B. Sabaa, R.S. Ravindrarajah, Engineering properties of lightweight concrete containing crushed expanded polystyrene waste, in: Proceedings of the Symposium MM: Advances in Materials for Cementitious Composites, Boston, MA, USA, 1997.
[67] J. Elsalah, Y. Al-Sahli, A. Akish, O. Saad, A. Hakemi, The influence of recycled expanded polystyrene (EPS) on concrete properties: influence on flexural strength, water absorption and shrinkage. AIP Conference Proceedings, American Institute of Physics, 2013.
[68] A. Haghi, G. Zaikov, Effects of EPS size on Engineering Properties of Concrete, in: Polymers for Advanced Technologies: Processing, Characterization and Applications, 2013, p. 229.
[69] Y. Li, N. Liu, B. Chen, Properties of lightweight concrete composed of magnesia phosphate cement and expanded polystyrene aggregates, Mater. Struct. 48 (1) (2015) 269–276.
[70] H.S. Abed, Production of lightweight concrete by using construction lightweight wastes, Eng. Technol. J. 37 (2019), 1 Part (A) Engineering.
[71] M.-H. Zhang, L. Li, P. Paramasivam, Shrinkage of high-strength lightweight aggregate concrete exposed to dry environment, Mater. J. 102 (2) (2005) 86–92.
[72] A.M. Rodriguez, C.A. Gomez, Flexural Behaviour of Lightweight Ferrocement Fencing Panels. EPS (litres), 758(703) 707.
[73] A. Sadrmomtazi, J. Sobhani, M.A. Mirgozar, M. Najimi, Properties of multi-strength grade EPS concrete containing silica fume and rice husk ash, Constr. Build. Mater. 35 (2012) 211–219.
[74] İ. Turkmen, A. Kantarci, Effects of expanded perlite aggregate and different curing conditions on the drying shrinkage of self-compacting concrete, 2006.
[75] N. Kabay, A.B. Kizilkanat, M.M. Tüfekçi, Effect of prewetted pumice aggregate addition on concrete properties under different curing conditions, Period. Polytech. Civ. Eng. 60 (1) (2016) 89–95.
[76] M. Aslam, P. Shafigh, M.Z. Jumaat, Drying shrinkage strain of palm-oil by-products lightweight concrete: a comparison between experimental and prediction models, KSCE J. Civ. Eng. 22 (12) (2018) 4997–5008.
[77] P. Shafigh, H. Ghafari, H.B. Mahmud, M.Z. Jumaat, A comparison study of the mechanical properties and drying shrinkage of oil palm shell and expanded clay lightweight aggregate concretes, Mater. Des. 60 (2014) 320–327.
[78] M. Aslam, P. Shafigh, M.Z. Jumaat, Drying shrinkage behaviour of structural lightweight aggregate concrete containing blended oil palm bio-products, J. Clean. Prod. 127 (2016) 183–194.
[79] O. Kayali, M. Haque, B. Zhu, Drying shrinkage of fibre-reinforced lightweight aggregate concrete containing fly ash, Cem. Concr. Res. 29 (11) (1999) 1835–1840.
[80] T.Y. Lo, F.C. Sham, H.Z. Cui, W.C.P. Tang, Study of short term shrinkage and creep of lightweight concrete, Mater. Res. Innov. 12 (3) (2008) 151–154.
[81] M.H. Ahmad et al., Shrinkage of Malaysian palm oil clinker concrete, in: Proceedings of the International Conference on Civil Engineering Practice (ICCE08), Kuantan, Pahang, 2008.