



Chloride diffusivity of lightweight expanded clay aggregate concretes under compressive stress

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ARTICLE INFO

Keywords:

Lightweight concrete
Lightweight expanded clay aggregate
Keramzit aggregate
Chloride diffusivity
Compressive stress
Permeability

ABSTRACT

The lightweight concrete (LWC), whose aggregate is the keramzit (i.e. expanded clay), presents as a potential material for construction in marine environments. However, only a few studies have dealt with the durability of the lightweight expanded clay aggregate concrete and in particular, the chloride diffusion coefficient of this material under service mechanical loading has not been assessed yet. This study aims at investigating experimentally the chloride diffusivity of a LWC under different compressive stresses. The LWC mix has 30.0 MPa compressive strength after 28 days of curing of the cylinder, i.e., the grade of concrete is C30. Rapid Chloride Permeability Testing (RCPT) is used to measure the LWC chloride diffusivity. Chloride migration tests were carried out on cylindrical cores under different stress levels σ varying from 0 % to 75 % of the uniaxial compressive strength σ_c . The test indicates that the chloride diffusion coefficient firstly decreases by about 15 % when the σ reaches about 20 % σ_c , and then increases up to about 40 % compared to the initial value when σ increases to 75 % σ_c . An analysis was performed to have an idea about the water permeability and the gas permeability of the LWC under compressive loading from existing measurements on the ordinary and high-performance concretes. Linear relations between the water permeability, the gas permeability and the chloride diffusivity are resulted from this analysis. The experimental result of this study is significant and useful for the durability assessment of the structures made of LWC and exposed to aggressive environments.

1. Introduction

Lightweight concretes (LWC) have been used for several thousand years in many famous constructions (e.g. towns of Mohenjo-Daro and Harappa in Pakistan, Babylon in Iraq, St. Sofia Cathedral in Turkey, the aqueduct Pont du Gard in France, Pantheon and Colosseum in Italy, etc). LWC has become an important construction material due to its basic advantage in low density, which reduces the dead load and provides thermal and sound insulating properties [1–3]. Currently, LWC is available in a wide range of density, size, and strength. This makes it possible to design concrete with a very wide spectrum, a concrete of very low density for insulation and, at the same time, a high strength

concrete, more than 80.0 MPa of 15 cm cube compressive strength, for structural purposes. According to the method of manufacturing, LWC can be classified into three main group: (1) LWC is produced by using porous lightweight aggregate with low weight with respect to the normal weight aggregate; (2) Aerated concrete is produced by introducing larger voids within the concrete or mortar; (3) no fine concrete is produced by omitting the fine aggregate, which results in the large number of interstitial voids. However, the LWC is often made by using the lightweight aggregate (LWA).

According to its origin, LWA is classified into two main types: natural LWA (e.g. Pumice, Diatomite, Scoria, Volcanic cinders, Saw dust, Rice husk, etc) and artificial LWA (e.g. Artificial cinders, Coke breeze,

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<https://doi.org/10.1016/j.mtcomm.2023.105917>

Received 16 December 2022; Received in revised form 2 March 2023; Accepted 30 March 2023

Available online 31 March 2023

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Table 1Mixture proportion for 1 m³ and mechanical properties of LWC concrete.

Mixture ID	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Water (kg)	Silica fume (kg)	Super-plasticizer (l)	w/c
LWC	430	885	350	185	48	4	0.43

Foamed slag, Bloated clay, Expanded shale's and slate, Sintered fly ash, Expanded perlite, Thermocole beads, Exfoliated vermiculite, organic aggregate like polystyrene beads, etc). An overall picture of LWC and LWA (historical background, production of aggregate and concrete, application in structure, physico-chemical properties, durability, microstructure development, economic aspect, etc) is well documented by Chandra and Berntsson [11].

Lightweight expanded clay aggregate (LECA) is resulted from expanding natural clay in a rotary kiln at 1100–1300 °C. LECA is a porous ceramic with potato or round shape due to the kiln circular movement. The pore structure of LECA is uniform, which makes it lightweight, thermal and sound insulation features. A review of LECA as a building material carried out by Rashad [4] states that the incorporation of LECA into the concrete mixture leads to an increase in workability, water absorption, sound insulation, thermal insulation and fire resistance; and decrease in density, strength, and freeze/thaw resistance. However, the durability of lightweight concrete made of LECA has been rarely studied. To the best of the authors' knowledge, it does not exist any studies on the variation in the transport properties (i.e. chloride diffusion coefficient, water permeability, gas permeability) of this material under serviceable loading.

The chloride diffusivity is a key parameter for determining the serviceability of reinforced concrete (RC) structure exposed to coastal and marine environments based on the durability criterion [5–10]. Interconnected porosity and micro-crack are two main factors controlling the chloride diffusivity. The water/cement ratio, the hydration degree, and the compaction monitor the porosity network, while the presence of micro-crack is primarily due to the stress. Five main transport mechanisms, namely migration, migration, diffusion, capillary suction, and convection make the chloride ingress within the concrete structure [11].

Several test methods have been proposed to determine the chloride diffusivity of the concrete specimen in the laboratory tests, such as: non steady-state diffusion test (NT BUILD 443 [14], NT BUILD 492 [13]); electrical migration test; ponding test (AASHTO T259 [15]); Rapid Chloride Permeability Test (RCPT) (AASHTO T277 [12]). RCPT is the most popular and efficient technique for the sample scale. Temperature variation [16], Fick and Nernst-Planck equations [17], binding isotherms [18] and moisture movement [19] are basic theory to develop laboratory measurement devices. Therefore, they can measure either instantaneous or apparent chloride diffusivity, or rapid chloride permeability (RCP). Relations exist between these three coefficients [20, 21]. Besides, in-situ tests based on either destructive or non-destructive methods have been also developed to monitor the chloride ingress within concrete structures [22].

This study investigates experimentally the effect of microcracks on chloride diffusivity of a lightweight concrete (LWC) made of LECA. Microcracks occurs during the test due to the uniaxial compressive stress. The LWC mixture has 30.0 MPa of uniaxial compressive strength. The uniaxial compressive strength is measured on the sample of size diameter x height = 0.15 × 0.30 m. The laboratory device developed by Wang et al. [23] is used to evaluate the rapid chloride diffusion coefficient. In such a method, a bespoke test setup was used to measure the rapid chloride permeability of a concrete sample under compressive stress (NT BUILD 492 [13]). The chloride diffusion coefficient is then resulted from the rapid chloride permeability via empirical formulation [24]. Uniaxial stress exceeding ~ 20–40 % of the compressive strength

Table 2

Main properties of the LECA considered in this study.

Physical properties	Value
Aggregate size (mm)	5 – 20
Bulk density (kg/m ³)	730
Density of aggregate (kg/m ³)	1360
Crushing value (ACV) (MPa)	1.8
Water absorption 24 h (%)	23

induces the occurrence, growth, and coalescence of microcracks within the concrete sample. The presence of microcracks significantly affects the transport properties of the material [26–29]. Several stress levels from 0 to 0.75 of the stress at ultimate load were considered during chloride diffusion tests. Once the chloride diffusivity is known, water and gas permeability of considered LWC are also estimated from data on ordinary concretes (OC) and high performance concrete (HPC) [26,30]. Therefore, three main transport properties, including chloride diffusivity, gas permeability and water permeability, were evaluated in this work for a LWC, which provides the basic information to assess the durability of structure made by considered LWC under service loading and aggressive environment.

2. Materials

In this study, the LWC is made of lightweight expanded clay aggregate (coarse aggregate), sand (fine aggregate), cement, silica fume, superplasticizer, and water. The mixture proportion of this concrete is shown in Table 1. As a reminder, the mixture is designed to have grade C30 (i.e. uniaxial compressive strength of cylindrical sample with the dimension diameter (D) × height (H) = 150 × 300 mm²) according to ASTM C39 [33].

ViscoCrete®-3000-20M, a polymer based high performance superplasticizer, is used for an extremely high-water reduction and producing very soft consistent, and high flowability. Moreover, this superplasticizer contains neither chlorides nor other corrosion-substances. The superplasticizer bulk density is 1060 kg/m³.

Sikacrete was used as the concrete additive, which is made based on silica fume technology.

Portland cement is made according to ASTM C150 [34]. The coarse aggregate is keramzit, or expanded clay aggregate. The main physical properties of this lightweight aggregate are given in Table 2. The fine aggregate is natural river sand.

3. Chloride rapid penetration test

The laboratory measurement technique developed by Wang et al. [23] is used in this study to measure the Rapid Chloride Permeability (RCP) of a concrete sample under compressive stress. Then, the empirical formulation proposed by Berke and Hicks [24] results in the chloride diffusion coefficient (*D*) from the RCP value.

Concrete samples with the size height (*h*) x diameter (*d*) = 200 × 100 mm were made and cured for 4 weeks (28 days). From the central position of each sample, a concrete disc of 50 ± 0.1 mm of thickness was cut off by a water-cooled diamond saw. One dimensional chloride flow during the test is ensured by sealing the concrete disc lateral surface with two epoxy resin coats. The saturation of concrete discs was done by

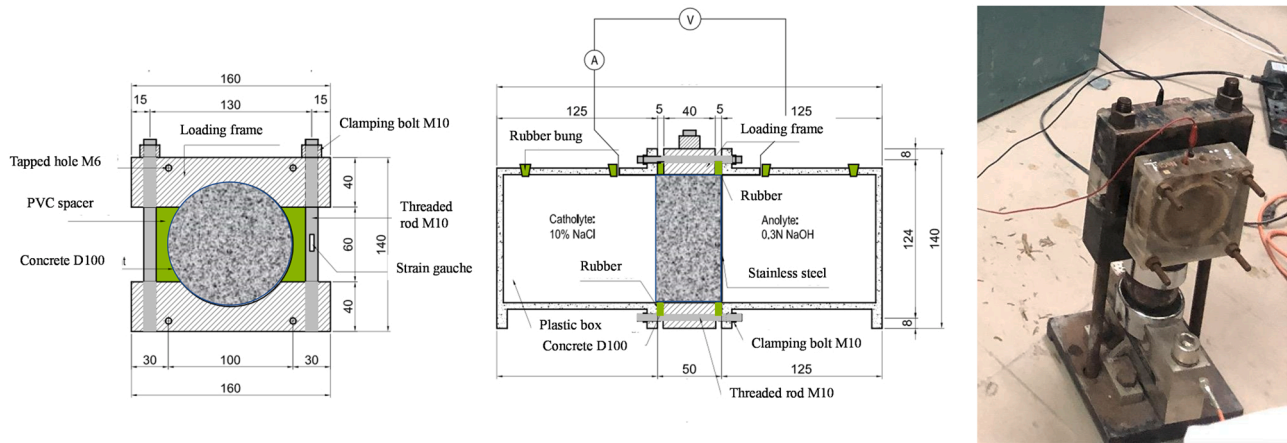


Fig. 1. Laboratory test device for RCP measurement under compressive load.

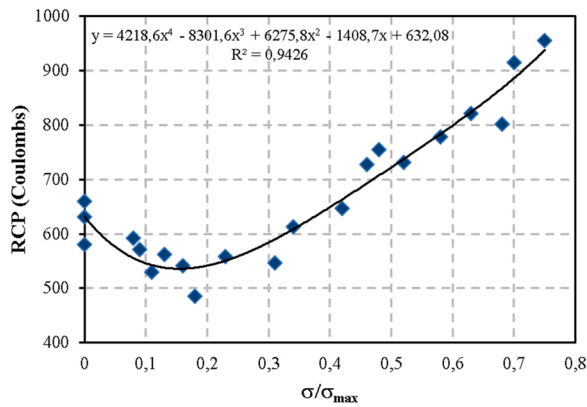


Fig. 2. Measurement of RCP versus uniaxial loading.

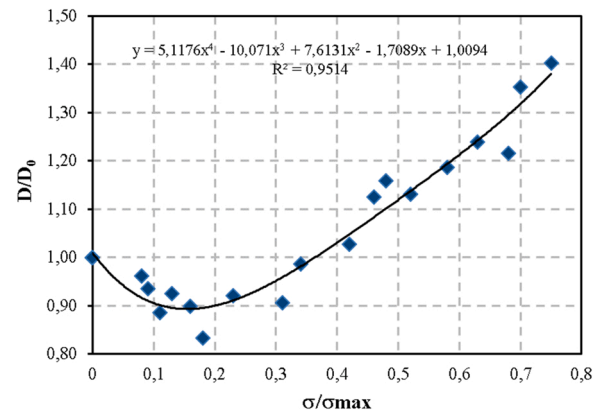


Fig. 3. Chloride diffusivity as a function of loading level.

placing them in a vacuum container. The pressure of the vacuum was decreased to less than 1 mmHg for four hours. Then, water was introduced into the container to immerse the specimen for 18 ± 2 h. Finally, the concrete disc was retrieved and placed into the test device.

To assess the ultimate stress σ_{\max} (or σ_c) of the LWC disc, we increase the load applying on the specimen at a constant rate of 1.23 ± 0.1 kN/s until the failure. We take the average load at the failure of three samples as the maximum load for the LWC σ_{\max} (or σ_c). As seen in Fig. 1, a downforce from bolts and a load cell for adjusting the stress are used to generate a stress state of direct compression. Once the load reaches the target, we installed two cells filled by two solutions NaCl (10 %) and NaOH (0.3 mol/l), respectively. The cells were connected to a 60-V power source. Electrical energy transmitted through the sample was recorded and computed automatically via a computer system connected to the device. The current was recorded for 6 h. RCP value is the total amount of energy passed through the concrete disc, which is calculated by integrating the current over time. 21 values of σ/σ_{\max} from 0 to 0.75 were applied to LWC samples, in which the test at $\sigma/\sigma_{\max} = 0$ is repeated 3 times.

Then, the chloride diffusion coefficient (D) is estimated from the RCP value via Berke and Hicks [24]'s equation.

$$D = 0.0103 (\text{RCP})^{0.84} (10^{-12} \text{ m}^2/\text{s}) \quad (1)$$

As a reminder, Berke and Hicks [24]'s empirical formulation was resulted from tests on samples without loading. However, the device developed by Wang et al. [23] allows a quasi-uniform stress state inside the sample. Thus, the rapid chloride permeation should be uniform within the concrete disc as the case without loading.

4. Results and discussion

4.1. Chloride diffusion coefficient

A recapitulation of measured RCP values and chloride diffusion coefficients (D) estimated from Eq. (1) for the considered LWC is given in Table 3 of the Appendix. Fig. 2 and Fig. 3 plot the variation of RCP and that of the diffusivity D/D_0 as a function of loading level σ/σ_c . Experimental results show an unavoidable dispersion of the chloride diffusivity due to the heterogeneity of concrete materials and different distribution of aggregates between samples. However, a clear tendency can be identified. The chloride diffusivity firstly decreases when the loading σ/σ_c increases from 0 to 0.2, due to the closure of microcracks and porosity under low loading. D reduces about 10–15 % compared to initial value D_0 when $\sigma = 0.2\sigma_c$. Then, the chloride diffusion coefficient (D) increases when uniaxial stress σ increases from $\sim 0.2\sigma_c$ to $0.75\sigma_c$. D recovers initial value D_0 when $\sigma = \sim (0.3\text{--}0.4)\sigma_c$ and increases about 40 % compared to initial value D_0 when $\sigma = 0.75\sigma_c$. A polynomial function is approximated fairly well the variation of the chloride diffusivity versus the loading σ/σ_c .

The observed tendency for LWC considered in this study is similar to that of ordinary concretes (OC) [25,26]. However, the chloride diffusivity of LWC is lower than that of ordinary concrete with $w/c = 0.43$ and uniaxial compressive strength of 30.0 MPa obtained by Tran et al. [26]. This is due to the presence of silica fume in the LWC. Indeed, Lizarazo-Marriaga and López Yépez [27] and Yazıcı [28] showed that the addition of silica fume in concrete results in a reduction in chloride penetration. This is also the case when adding fly ash into the concrete mix [29].

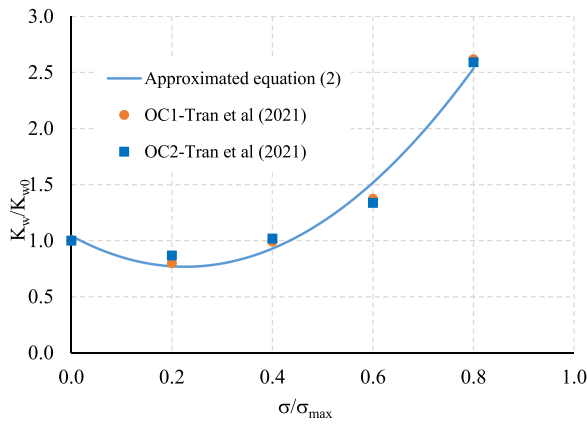


Fig. 4. Water permeability as a function of loading level of two concretes OC1 and OC2 [26].

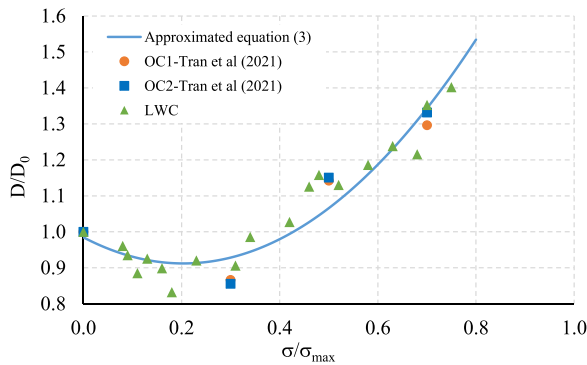


Fig. 5. Chloride diffusivity as a function of loading level of two concretes OC1 and OC2 [26] and of LWC considered in this study.

4.2. Water permeability

Tran et al. [26] presented the raw data of chloride diffusion coefficient and water permeability under compressive stress for 2 ordinary concretes (OC1 and OC2). OC1 and OC2 were designed to reach ~40.0 and 50.0 MPa of uniaxial compressive strength. A similar technique was used by Tran et al. [26] to measure the chloride diffusivity under stress. They measured the water permeability on the hollow cylindrical sample in which the water diffuses in the radial direction through the sample thickness from the outer to inner surfaces under a pressure gradient. In their study, the water permeability K_w was measured at five stress levels $\sigma/\sigma_c = 0, 0.2, 0.4, 0.6$ and 0.8 . Whereas, the chloride diffusivity D was measured at $\sigma/\sigma_c = 0, 0.25, 0.5$, and 0.75 . We treated these data in this section to propose a useful relationship between K_w and D .

Fig. 4 shows the variation of normalized water permeability K_w/K_{w0} . Fig. 5 shows chloride diffusivity D/D_0 as a function of loading level σ/σ_{max} for those two concretes OC1 and OC2, as well as for the LWC considered in this study. K_{w0} and D_0 are the water permeability and the chloride diffusivity without loading ($\sigma/\sigma_{max} = 0$). Obviously, three materials (OC1, OC2 and LWC) have different absolute values of the chloride diffusivity at each loading level. OC1 and OC2 also have different absolute value of the water permeability. However, it is interesting to note that measured data of K_w/K_{w0} versus σ/σ_{max} , as well as D/D_0 versus σ/σ_{max} of two ordinary concretes OC1 and OC2 are very close together. More surprisingly, the measured data of D/D_0 versus σ/σ_{max} of the LWC in this work is also close to those of OC1 and OC2. A second order polynomial equation can be used to approximate the relation between K_w/K_{w0} versus σ/σ_{max} for both OC1 and OC2.

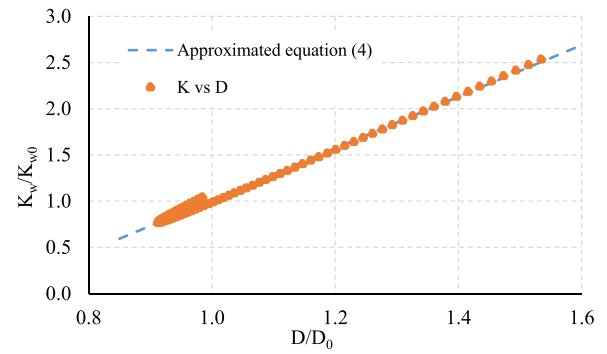


Fig. 6. Relation between K_w and D for two OC1 and OC2.

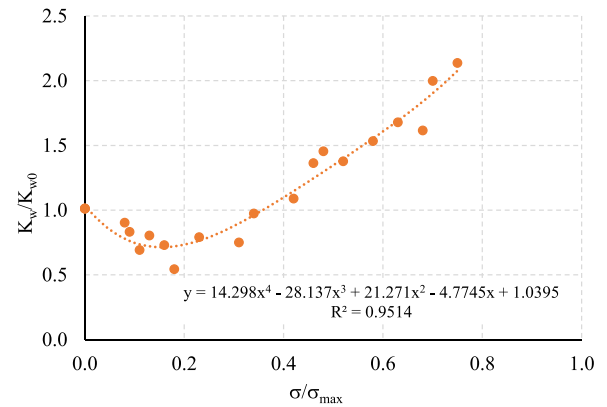


Fig. 7. Estimated water permeability as a function of loading level of considered LWC.

$$\frac{K_w}{K_{w0}} = 5.37585 \left(\frac{\sigma}{\sigma_c} \right)^2 - 2.43656 \left(\frac{\sigma}{\sigma_c} \right) + 1.04347 \quad (2)$$

Similarly, only one second-order polynomial equation can perfectly fit three data of D/D_0 versus σ/σ_{max} for OC1, OC2, and LWC.

$$\frac{D}{D_0} = 1.74923 \left(\frac{\sigma}{\sigma_c} \right)^2 - 0.71238 \left(\frac{\sigma}{\sigma_c} \right) + 0.98462 \quad (3)$$

Thank to the close results in D/D_0 versus σ/σ_{max} between OC1, OC2 and LWC, we assume that the variation in K_w/K_{w0} versus σ/σ_{max} of the LWC may be described by Eq. (2) for two ordinary concretes OC1 and OC2.

From approximated Eqs. (2) and (3), the variation of $\frac{K_w}{K_{w0}}$ as a function of $\frac{D}{D_0}$ for the loading range $0 \leq \frac{\sigma}{\sigma_c} \leq 0.8$ can be plotted in Fig. 6. A linear relation between $\frac{K_w}{K_{w0}}$ and $\frac{D}{D_0}$ can be obtained

$$\frac{K_w}{K_{w0}} = 2.79399 \left(\frac{D}{D_0} \right) - 1.78077 \quad (4)$$

As mentioned above, we assume that Eq. (4) can be also used for the LWC considered in this study, which results in the water permeability of this material as a function of the loading level σ/σ_c as plotted in Fig. 7 or presented in Table 3. It should be noted that the prediction is only correct if $D/D_0 > 1.78077/2.79399 = \sim 0.64$. As shown in Fig. 7, the water permeability data can be fitted fairly well by a polynomial equation of 4th order.

4.3. Gas permeability

To estimate the gas permeability of the considered LWC, we used the data measured and treated by Djerbi Tegguer et al. [30]. As a reminder,

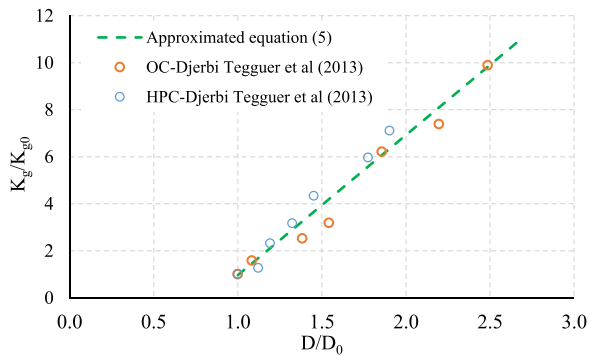


Fig. 8. Relation between K_g and D estimated from the data obtained by Djerbi Tegger et al. [30].

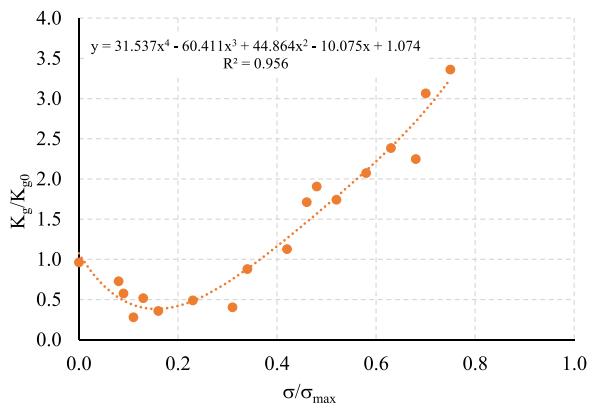


Fig. 9. Estimated gas permeability as a function of loading level of considered LWC.

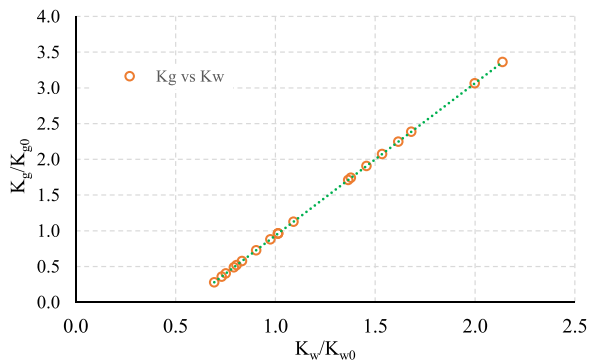


Fig. 10. Linear relation between gas permeability and water permeability of considered LWC.

Djerbi Tegger et al. [30] experimentally investigated the chloride diffusion coefficient and the gas permeability of an OC and a High-Performance Concrete (HPC) under compressive loading. They used the Cembureau permeameter to measure the gas permeability [31] and the steady-state migration test to measure the chloride diffusion coefficient [32]. They also measured the damage variable by using the ultrasound pulse velocity to estimate the stiffness degradation under uniaxial compressive stress ($0.6 \leq \frac{\sigma}{\sigma_c} \leq 0.9$). They proposed relationships between the gas permeability and the chloride diffusivity from the damage variable.

Based on the data of Djerbi Tegger et al. [30] plotted in Fig. 8, we propose a simple and universal linear relation between the gas permeability K_g/K_{g0} and the chloride diffusivity D/D_0 for both OC and HPC.

$$\frac{K_g}{K_{g0}} = 5.96394 \left(\frac{D}{D_0} \right) - 5.00191 \quad (5)$$

This prediction has physic meaning if $D/D_0 > 5.00191/5.96394 = \sim 0.84$. By eliminating the negative value, Eq. (5) gives estimated gas permeability as a function of the loading level σ/σ_c in Table 3 or in Fig. 9. Similar to the chloride diffusivity and the water permeability, a 4th order polynomial equation can be fairly well fitted the data of gas permeability.

A combination of Eqs. (4) and (5) yields the following relations between gas permeability and water permeability. Fig. 10 presents graphically this linear relation for the considered LWC.

$$\frac{K_g}{K_{g0}} = 2.13456 \frac{K_w}{K_{w0}} - 1.20076 \quad (6)$$

5. Conclusions

This study presented an experimental investigation of chloride diffusivity of lightweight concrete samples under compressive stresses varying from 0 % to 75 % of the uniaxial compressive strength. The lightweight property of this concrete is obtained using expanded clay aggregate as coarse granular materials. Rapid Chloride Permeability (RCP) was measured and the chloride diffusion coefficient is calculated from the RCP using an empirical correlation. Data from the literature for conventional concretes and a high-performance concrete were considered to propose relationships between the water permeability and the chloride diffusivity, the gas permeability and the chloride diffusivity, as well as gas permeability and water permeability. The main results can be highlighted for the transport properties of the considered LWC under compressive stress in the range of 0–0.75 of compressive strength.

- The chloride diffusivity decreases when the stress is still lower than about 20 % of ultimate stress due to the closure of microcracks; then increases due to the stress-induced microcracks;
- Compared to the value without loading, the chloride diffusivity is about 15 % less when $\sigma = 0.2\sigma_c$; and about 40 % more when $\sigma = 0.75\sigma_c$;
- 4th order polynomial equations are fairly well fitted to the data of transport properties (chloride diffusivity, water permeability and gas permeability) as a function of the loading level.
- Three linear relations were proposed for the water permeability versus the chloride diffusivity; the gas permeability versus the chloride diffusivity; as well as the gas permeability versus the water permeability.

The last result is essential, which allows giving an ideal about other transport properties when one property is available. Investigation on the measurement of the water permeability and the gas permeability of the LWC under compressive stress should be performed to validate and adjust the proposed relations between them and the chloride diffusivity. This experimental work provides interesting results to assess the durability of concrete structure made of expanded clay aggregate concrete under aggressive environment.

CRedit authorship contribution statement

P.L Dao: Conception and design of study, Acquisition of data, analysis and/or interpretation of data, revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published. **K.C Thai:** Conception and design of study, Acquisition of data, revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published. **D.T Pham:** Conception and design of study, Acquisition of data, revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published. **Q.V. Le:**

Table 3

Measured RCP values; chloride diffusion coefficients (D); estimated water and gas permeabilities for the LWC.

No.	σ/σ_c	RCP (Coulombs)	$D \times 10^{-12}$ (m ² /s)	D/D ₀	K _w /K _{w0}	K _g /K _{g0}
1	0	632	1,66	1,00	1,00	1,00
2	0	660	1,72	1,00	1,00	1,00
3	0	581	1,56	1,00	1,00	1,00
4	0,08	592	1,58	0,96	0,90	0,73
5	0,09	571	1,54	0,94	0,83	0,58
6	0,11	530	1,46	0,89	0,69	0,28
7	0,13	563	1,53	0,93	0,81	0,52
8	0,16	541	1,48	0,90	0,73	0,36
9	0,18	486	1,37	0,83	0,54	–
10	0,23	559	1,52	0,92	0,79	0,49
11	0,31	547	1,49	0,91	0,75	0,40
12	0,34	613	1,63	0,99	0,97	0,88
13	0,42	647	1,69	1,03	1,09	1,13
14	0,48	755	1,91	1,16	1,46	1,91
15	0,46	728	1,86	1,13	1,36	1,71
16	0,52	732	1,86	1,13	1,38	1,74
17	0,58	778	1,96	1,19	1,53	2,07
18	0,63	821	2,04	1,24	1,68	2,38
19	0,68	802	2,00	1,22	1,62	2,25
20	0,70	915	2,23	1,35	2,00	3,06
21	0,75	956	2,31	1,40	2,14	3,36

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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.

Data Availability

Data have been already included in the manuscript.

Appendix

This appendix provides the measured values of RCP, the chloride diffusion coefficient (D) resulted from Eq. (1), as well as the water permeability and gas permeability estimated from the chloride diffusivity via Eqs. (4) and (5) (see Table 3).

See. Table 3.

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