PUMICE AGGREGATE BASED LIGHTWEIGHT CONCRETES UNDER SULFURIC ACID ENVIRONMENT

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In this study, volcanic pumice aggregate incorporated different lightweight concretes (LWC) were investigated under a 5% sulfuric acid environment. For this purpose; OPC, OPC-FA, OPC-S, OPC-FA+S with 0%, 50%, and 100% pumice incorporations were manufactured considering cement efficiency factors for fly ash (FA) and slag (S) given in the TS13515 and EN 206-1 to evaluate the applicability of cement efficiency factors in the water and sulfuric acid environments. The visual appearance, weight change, and compressive strength tests were executed, and strength gain index and strength loss index parameters were utilized for the evaluation. The results indicated that the cement efficiency factors for the fly ash and slag were found appropriate for the pumice aggregate replacements up to 100% for the LWC incorporating only fly ash or slag. However, when the fly ash and slag were used together, the cement efficiency factors should be reduced from 0.4 to 0.35 for FA and from 0.8 to 0.75 for slag materials.

Keywords: *volcanic pumice aggregate, lightweight concrete, cement efficiency factor, durability, sulfuric acid resistance*

1. Introduction

Concrete has been widely utilized as a construction material due to its ease of shape, availability, local accessibility, and economy. More than 26.8 billion tonnes of concretes are produced per year in the world [1]. The huge amount of concrete consumption will cause the gradual depletion of natural resources, especially of aggregates, which comprise approximately 60% of concrete, as well as the accessibility of aggregates, will be difficult in the upcoming years. Meanwhile, global warming has been a significant issue recently, and the released CO_2 during cement production is accountable for approximately 7% of the world's CO_2 emissions [2]. Therefore, alternative sustainable construction materials become necessary for the Portland cement and aggregates to overcome environmental and economic drawbacks. One of the solutions is to utilize alternative cementitious materials (ground granulated blast furnace slag and fly ash) as a partial replacement of Portland cement [3], and the other one is to use lightweight aggregates (LWA) instead of normal aggregates for the concrete production. Due to a large amount of energy requirement and high CO_2 emission during the recycling process of aggregates as well as stock, crushing, pre-sizing, sorting, screening, and contaminant elimination, which needs additional investment costs, it is almost impossible to recycle all the waste materials [4, 5]. Therefore, the utilization of LWA becomes a feasible solution for concrete manufacture.

Lightweight concrete (LWC) is generally manufactured by replacing the normal-weight aggregates with light-weight aggregates. LWC has been thoroughly utilized in the construction industry for low density, acoustic, and thermal insulation. The oven-dry density of LWC should be in the range of 800 kg/m^3 to 2000 kg/m^3 in accordance with EN 206-1 standard [6]. The LWC has better properties than normal weight concrete when the same strength classes are obtained; high thermal insulation and sound absorption, the possibility of longer spans and smaller structural column/beam sections due to low weight, low autogenous shrinkage and better durability [7]. In general, LWC is produced using porous aggregates, such as natural aggregate (pumice, volcanic binder, diatomite) and artificial aggregate (clay, expanded shale, perlite, sintered fly ash) [8]. Due to its highly porous structure, chemical and physical resistance, pumice is the most preferred aggregate in LWC production [9].

Pumice is a natural lightweight material of volcanic origin produced by the release of gases during the solidification of lava. The cellular structure of pumice is created by the formation of bubbles or air voids when gases contained in the molten lava flowing from volcanoes become trapped on cooling [10]. Thanks to a porous rough and absorptive surface, the interfacial transition zone between pumice and matrix is improved by the formation of reaction products both interface and the inner porous structure [11]. Due to the high absorptive structure, pumice holds water inside the pores so that ongoing hydration reactions occur. For this reason, the utilization of natural pumice based LWC with adequate mechanical strength and durability performance becomes significant for sustainable and eco-friendly constructions. The compressive

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strength should be higher than 15 MPa, and density should be less than 1850 kg/m^3 for the structural LWC, whereas the compressive strength should be above 15 MPa and density should be in the range of 1850 kg/m^3 and 2150 kg/m^3 for the semi-lightweight structural concrete [12]. However, there are various density ranges for LWC in the world. In Japan, there is no density requirement exists, and LWC is acceptable when lightweight coarse and fine aggregates are utilized. In Europe, LWC is classified in accordance with compressive strength and density [13]. In USA, LWC density is in the range of 1440 kg/m^3 and 1840 kg/m^3 [14]. In ACI 213R [15], 28-day compressive strength is higher than 17 MPa, and density is in the range of 1120 kg/m^3 and 1920 kg/m^3 for the structural utilization of LWC.

The reduction in the LWC density yields economic profits for the handling and transportation costs and structural design. In addition, the lightweight aggregate concrete (LWAC) has superior earthquake resistance due to its low weight and insulation properties. For the LWAC production, a high amount of Portland cement is utilized to obtain the required mechanical performance and durability properties, which increase shrinkage and hydration heat [16]. For this reason, several supplementary cementitious materials, especially fly ash and ground granulated blast furnace slag, can be included in LWAC at higher volumes to decrease the cement consumption and carbon footprint and the cost of the production [17]. However, there is a lack of research regarding the utilization of supplementary cementitious materials in pumice based LWAC, and thus further research is required to fully understand the effect of pumice on the mechanical performance and durability of LWAC [18].

Some studies have reported that reduced durability performances such as lower carbonation resistance [19], higher water permeability [20], lower chloride resistance [21], and lower acid resistance [22, 23] were obtained in LWC. On the other hand, other researchers have shown that improved durability performances such as higher chemical resistance and lower alkali-silica expansion [24], lower steel corrosion [25], lower water and chloride ion penetration [26], higher carbonation resistance [27], and higher sulfate and acid resistance [28] were obtained in LWC. However, despite the efforts to enhance the strength/weight ratio and versatility of LWC, further research is required to utilize LWC in structural buildings [29].

The sulfuric acid attack can be hazardous to structural reinforced concrete elements of foundations (sulfuric acid including groundwater, resulting from the oxidization of pyrite in backfill) or outer structural column and beam elements, walls, staircases, and slabs at chemical plants or superstructures (acid rain) [30]. In a previous study, the chemical durability of the specimens investigated under seawater, magnesium sulfate, and sulfuric acid environments and the sulfuric acid attack was found the most hazardous environment [31]. Due to the exposure of structural elements to acidic environments, the durability performance of the LWC under sulfuric acid attack has to be investigated thoroughly for the utilization of LWC for structural buildings. Also, there is a lack of literature regarding the influence of cementitious materials on the performance of LWC in acidic media. This paper compares the mechanical and durability properties of pumice aggregate-based different LWC produced with ground granulated blast furnace slag and fly ash with different ratios under the 5% sulfuric acid environment.

2. Experimental Program

2.1 Materials

For the production of various pumice aggregate-based LWC, pumice aggregate replaced only coarse for 50% and 100%, and also concretes without pumice were also cast as a reference normal weight concrete to evaluate the influence of pumice aggregate under sulfuric acid environment. In most cases, the LWA used in the production of LWC is coarse as it was reported that the replacement volcanic pumice (VP) instead of fine aggregates performed lower impact resistance than the replacement of VP instead of coarse aggregate [32]. Therefore, only coarse aggregates were replaced by volcanic pumice in this study. The ground granulated blast furnace slag (S) and F-type fly ash (FA) were utilized as a partial replacement of an ordinary Portland cement (CEM I 42.5 R), and four different concrete types were produced in the study. The concretes produced with only Portland cement were notated as OPC, and pumice replacements instead of coarse aggregate with three ratios 0% (without pumice), 50%, and 100% were shown as OPC-0, OPC-50, and OPC-100. The OPC-FA-0, OPC-FA-50, and OPC-FA-100 represent F-type fly ash incorporating specimens, the OPC-S-0, OPC-S-50, OPC-S-100 represent the ground granulated blast furnace slag incorporating specimens, and the OPC-FA+S-0, OPC-FA+S-50, and OPC-FA+S-100 represent both fly ash and slag incorporating specimens.

Cement replacement ratios of the fly ash, slag, and fly ash+slag replacement ratios were 33%, 45%, 30%+45%, respectively. Total cementitious content in 1 m^3 of concrete was 400 kg for OPC, 470 kg for OPC-FA, 426 kg for OPC-S, and 473 kg for OPC-FA+S specimens. For the similar strength of various cementitious concretes, the efficiency factor, which measures the relative contribution to strength, was utilized. The cement equivalence factors are given to be 0.4 and 0.8 for the fly ash and slag, respectively, in accordance with TS13515 and EN 206-1. All of the mineral additive concretes had an effective binder (cement + efficiency factor x mineral admixture) of 400 kg/m^3, and the water to effective binder ratio was selected as 0.45. A polycarboxylate ether based superplasticizer with a density of 1.095 g/cm^3 was used to obtain high flowability. The superplasticizer content was adjusted to reach S4 slump class limits given in EN 206-1. The crushed limestone (< 4mm) and natural sand were utilized as fine aggregates, while the crushed limestone and pumice aggregates were used with 8-16 mm and 16-22 mm. The densities of the Portland cement, ground granulated blast furnace slag, F-type fly ash, pumice, coarse limestone, fine limestone, and sand were 3.14 g/cm^3, 2.95 g/cm^3, 2.05 g/cm^3, 1 g/cm^3, 2.7 g/cm^3, 2.7 g/cm^3, and 2.6 g/cm^3, respectively. The water absorptions of 4-8 mm and 8-16 mm limestone aggregates were 0.6% and 0.7%, and the water absorption of the pumice aggregate was 15% for 8-16 mm and 11% for 16-22 mm. The pumice aggregate was obtained from the Nevşehir province of Turkey, and it has a high silica content and shows acidic characterization, which is beneficial for concrete production. Fig. 1 illustrates the pumice aggregate, and Table 1 presents the physical properties and chemical composition of the OPC, fly ash, slag, and pumice aggregate.

Fig. 1- Pumice aggregate used in the production of LWC

Table 1

Physical properties and chemical composition of materials

Component	Cement	Fly Ash	Slag	Pumice
CaO (%)	64.28	2.10	37.25	0.27
SiO_2 (%)	4.91	54.76	38.37	72.63
Al_2O_3 (%)	20.17	25.26	11.89	12.14
Fe_2O_3 (%)	3.41	6.28	1.05	0.99
MgO (%)	1.18	2.08	8.13	0.01
SO_3 (%)	2.84	0.02	0.38	NA
K_2O (%)	0.96	4.04	1.28	5.99
Na_2O (%)	0.13	0.38	0.38	1.62
LOI	1.61	3.30	0.01	0.23
SG	3.14	2.05	2.95	1
BF (m^2/kg)	394	387	432	-

2.2. Mixture Design

After several LWC trial batches, the mixes having the best cohesive and workable concretes were selected as presented in Tables 2.a and 2.b. The densities of the LWC were in the range of 2350-2390 kg/m^3 for those without pumice, 2000-2050 kg/m^3 for 50% pumice, and 1700-1715 kg/m^3 for 100% pumice incorporating specimens. During the mixing period, dry ingredients were added to the mixer and mixed for 2 min. Then, stirred water and half of the SP were added to the mixer and mixed for 2 min. Finally, the remaining SP was added and mixed for 2 min. The obtained mixes were cast to the 150 mm cubic molds, and demolding was realized 48h later due to the slow reaction of the cementitious materials. The water-curing was applied to all specimens during experiments.

Table 2.a

Mix ingredients of OPC, OPC-FA concretes

Materials	Quantity (kg/m^3)					
	OPC-0	OPC-50	OPC-100	OPC-FA-0	OPC-FA-50	OPC -FA-100
Water	180	180	180	180	180	180
Cement	400	400	400	353	353	353
Slag	-	-	-	-	-	-
Fly Ash	-	-	-	117	117	117
Pumice 8-16 mm	-	101	202	-	95	190
Pumice 16-22 mm	-	101	202	-	95	190
Limestone 4-8 mm	546	273	-	512	256	-
Limestone 8-16 mm	546	273	-	512	256	-
Sand	351	351	351	329	329	329
Crushed Sand	351	351	351	329	329	329
SP	8	8	8	8	8	8

Table 2.b

Mix ingredients of OPC-S, OPC-FA+S concretes

Materials	Quantity (kg/m^3)					
	OPC -S-0	OPC-S-50	OPC-S-100	OPC-FA+S-0	OPC-FA+S-50	OPC-FA+S-100
Water	180	180	180	180	180	180
Cement	294	294	294	270	270	270
Slag	132	132	132	122	122	122
Fly Ash	-	-	-	81	81	81
Pumice 8-16 mm	-	100	200	-	95	190
Pumice 16-22 mm	-	100	200	-	95	190
Limestone 4-8 mm	538	269	-	514	257	-
Limestone 8-16 mm	538	269	-	514	257	-
Sand	345	345	345	330	330	330
Crushed Sand	345	345	345	330	330	330
SP	8	8	8	8	8	8

2.3 Sample Preparation and Test Procedure

In the literature, no available testing procedure exists to evaluate the durability of the specimens under chemical environments. ASTM C267 suggests that samples should be left in the water to obtain a water-saturated state before chemical exposure. Hence, the chemical immersion test method was used to assess the sulfuric acid (H_2SO_4) performance of the LWC specimens. Some of the LWC specimens were fully immersed into 5% H_2SO_4 solutions, while others were kept in water for comparison. The 150x150x150 mm cubic samples were utilized, and samples were tested at the ages of 120. days (28+92) and 150. days (28+122) after the initial 28 days of the water curing period. The samples were removed from the acid solutions and left to drying for 24 h. The surface photos of the acid exposed samples were taken for visual inspection, and the weights of the samples were measured to evaluate weight change due to acid exposure. The compressive strength tests were executed according to the ASTM C39 standard, and the variations in the compressive strengths were calculated. The weight change of the samples is also a widely used method to evaluate the deterioration of the samples under sulfuric acid attack [33].

3 Results and Discussions

3.1 Visual Observation

Fig. 2 illustrates the surface photos of the samples at the ages of 150 days after 5% sulfuric acid exposure. The degree of degradation due to acid increased with an increase in acid exposure time. Due to acid attack, the surface erosion, softening, and local particle loss were observed on the specimen surfaces. Especially, loss of cementitious mortar and formation of white deposits can be easily seen on the surfaces, and the amount of surface deteriorations appeared to be similar to each other, except for OPC-S-100 specimens that all of the three specimens were broken into two halves after 5% sulfuric acid attack. It may be due to higher deterioration resulting from high CaO content.

No significant difference was found on the specimen surfaces with/out pumice due to sulfuric acid attack. The spalling in the pumice based LWC may be attributed to the increased vapor pressure resulting from the higher moisture content inside the pumice aggregates [34]. The deterioration due to acid exposure for the OPC-based concretes may be attributed to the C-S-H and N-A-S-H decalcification and the Ca/Si ratio reduction. Due to the high CaO content in OPC, the Ca/Si ratio increases in the pore solution. The sulfate ions in the sulfuric acid (H_2SO_4) solution diffuse into the hydrated cement paste and react with C_3A in the presence of $Ca(OH)_2$ to form gypsum and ettringite, resulting expansion, softening, spalling, and loss of compressive strength [35].

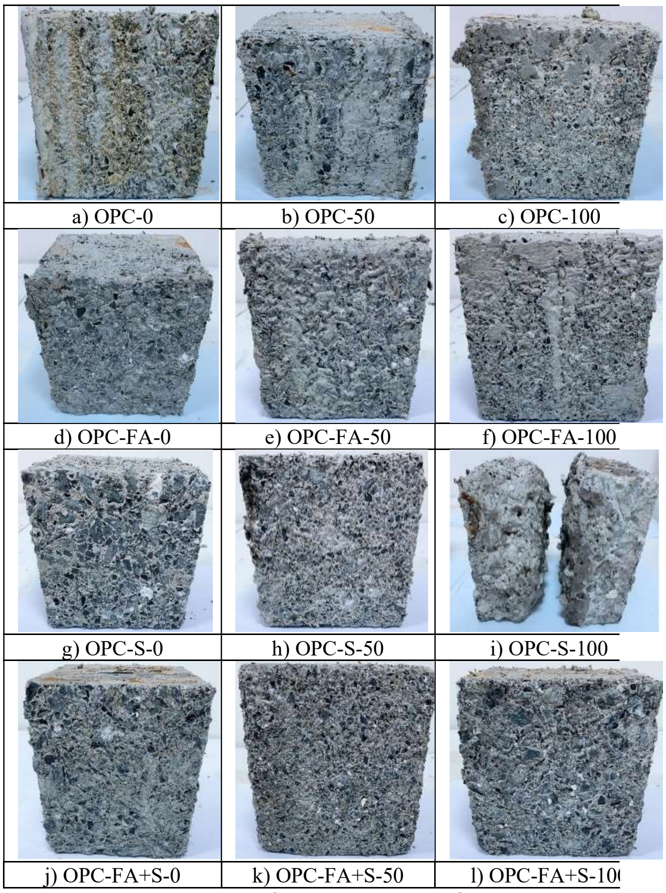
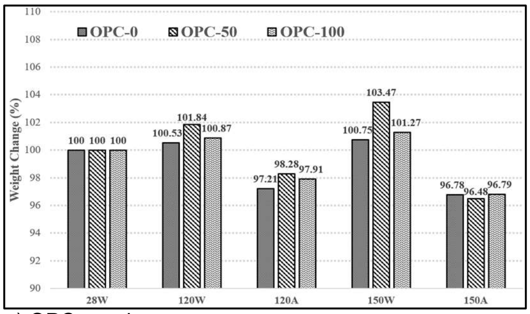


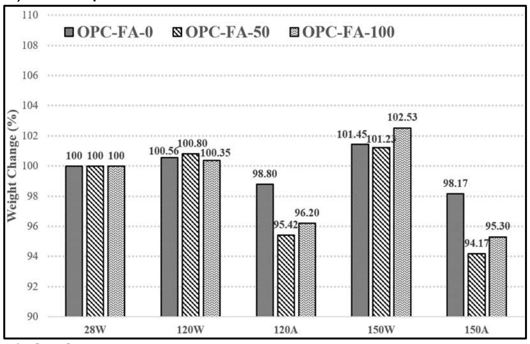
Fig. 2 **-** Visual appearance of samples under sulfuric acid attack

3.2 Weight Change

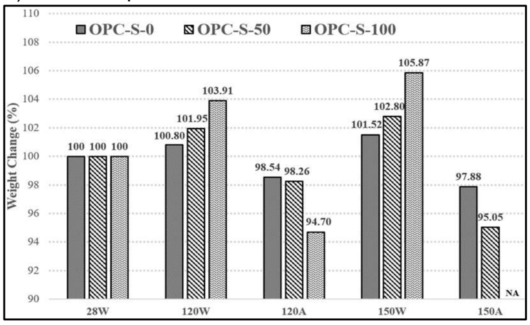
Fig. 3 illustrates the weight variation of the specimens under sulfuric acid and water environments at the ages of 28., 120., and 150. days. The 28W, 120W, and 150W conditions indicate the specimens cured in water at 28,120, and 150 days, respectively. Also, the 120A and 150A refers to the specimens cured in water for 28 days and then exposed to 5% sulfuric acid solutions for 92 and 122 days, respectively. The weight gain was observed on the water cured specimens (120W and 150W) due to water absorption, which increased with time. For the OPC specimens, OPC-50 specimens exhibited slightly higher weight gain than OPC-0 and OPC-100 specimens under water. The OPC-FA-0, OPC-FA-50, and OPC-FA-100 showed almost similar weight gain underwater. For the slag based specimens, OPC-S-100 specimens showed the highest weight gain due to water absorption. For the OPC-FA+S specimens, the highest weight increase was obtained on the OPC-FA+S-50 specimens. The results indicated that the lowest weight increase was observed on the specimens without pumice due to water absorption. This may be attributed to higher porosity inside the pumice aggregates, resulting in more water



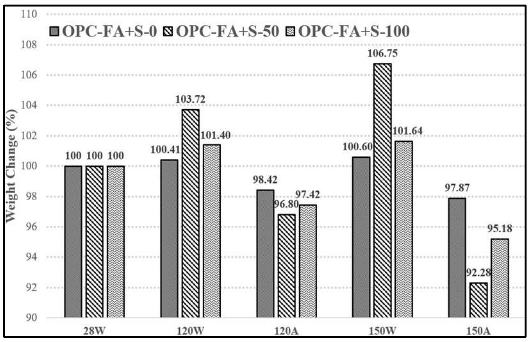
a) OPC specimens



b) OPC-FA specimens



c) OPC-S specimens



d) OPC-FA+S specimens

Fig. 3 - Weight change of the samples

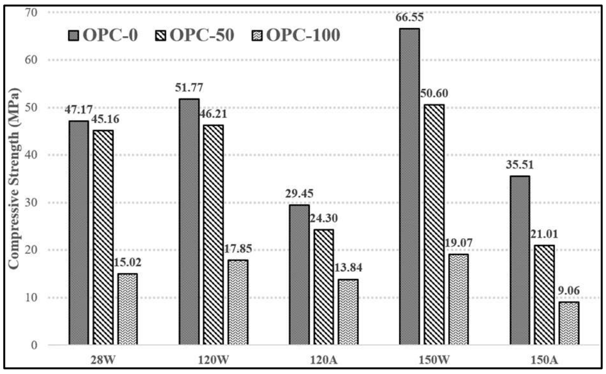
absorption than limestone aggregates. However, the highest weight gain was observed for some of the 50% pumice, including specimens instead of 100% pumice. This may result from the inhomogeneous particle size distribution, shape, roundness, and surface texture, reducing the overall packing density and improving porosity [36].

For the sulfuric acid exposed specimens, weight loss was observed due to the surface erosion (cement paste erosion, Figure 1) and aggregate particle disintegration. The weight loss was found to be more with acid exposure time. For OPC specimens, similar weight losses were observed on the specimens with/out pumice. The OPC-FA-50 specimens showed slightly more weight loss than OPC-FA-0 and OPC-FA-100 specimens. Similarly, the OPC-FA+S-50 specimens showed significantly more weight loss than the OPC-FA+S-0 and OPC-FA+S-100 specimens at 150 days. For the OPC-S specimens, significant weight loss was observed on the OPC-S-50 and OPC-S-100 specimens, especially at 150 days, and tremendous weight loss was observed on 100% pumice including samples. Also, after 150 days of chemical solution, three companion OPC-S-100 specimens were broken into two halves, and one of them was shown in Fig. 2.i. The lowest sulfuric acid resistant binder type was found as OPC-S, while the superior acid resistant binder type was obtained as OPC for the LWC.

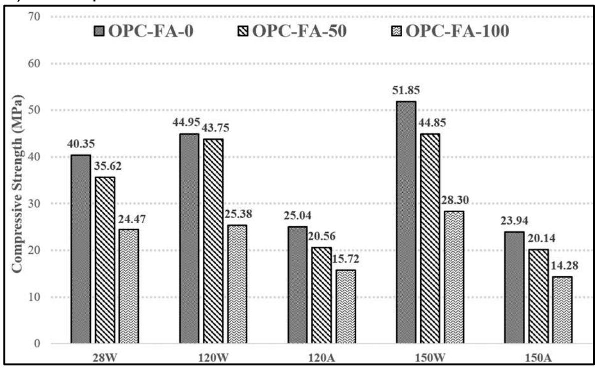
3.3 Compressive Strength Variation

Fig. 4 illustrates the compressive strength results of the specimens, and Table 4 presents the strength loss index (SLI-%) and strength gain index (SGI-%). The strength loss index (SLI-%) is a relative (%) compressive strength variation after a specified acid exposure time with respect to initial compressive strength. The strength gain index (SGI-%) is a relative (%) compressive strength variation after a specified sulfuric acid exposure time with respect to the compressive strengths of the unexposed (reference) specimens in the same period. Due to ongoing hydration reactions of the supplementary cementitious materials, SGI-% should be considered in addition to SLI-% when compared to deterioration amount due to chemical attack. The SGI-% and SLI-% parameters for the compressive strength variations due to chemical attacks were also used in the previous study [37]. The results showed that the compressive strengths increased with time, and the highest compressive strengths were achieved on the specimens at 150 days under water-curing conditions. Similarly, the compressive strengths of the specimens decreased with an increase in the acid exposure time, and the lowest compressive strengths were obtained on the specimens exposed to sulfuric acid solutions at 150 days. The pumice incorporations reduced compressive strengths, and the highest strength reductions were noted on the specimens with 100% pumice incorporations.

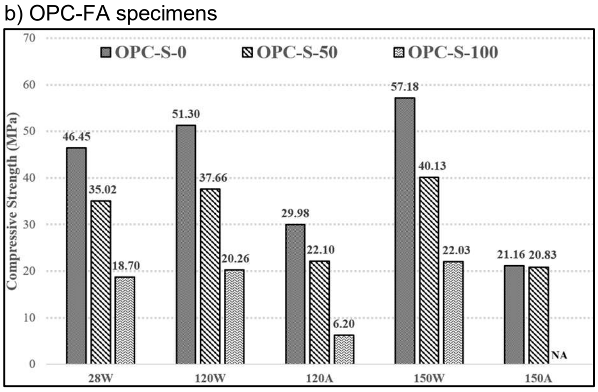
The compressive strength of the 100% pumice incorporating specimens was found to be higher than 15 MPa, and the density (~1700 kg/m^3) was lower than 1850 kg/m^3. Hence, 100% pumice incorporating specimens can be used as lightweight structural concrete. The compressive strengths of 50% pumice including specimens were found higher than 25 MPa (higher than 15 MPa); however, the density was almost 2000 kg/m^3, which is in the range of 1850-2150 kg/m^3. Thus, 50% pumice



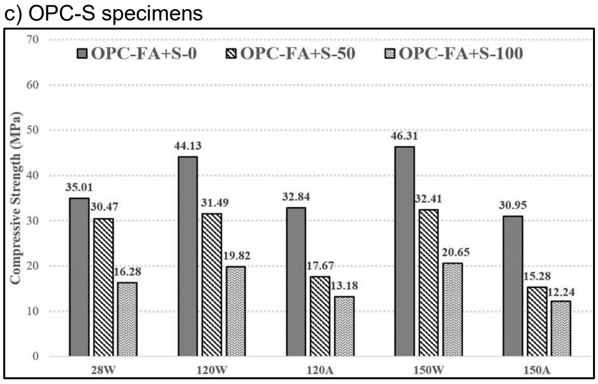
a) OPC specimens



b) OPC-FA specimens



c) OPC-S specimens



d) OPC-FA+S specimens

Fig. 4 - Compressive strengths of specimens

including specimens can be classified as semi-lightweight structural concrete according to the LWC classification [12].

3.3.1. Compressive strengths of OPC concretes

The compressive strength enhancements due to water curing were 10% and 41% for OPC-0, 2% and 12% for OPC-50, and 19% and 27% for OPC-100 specimens at the ages of 120 and 150 days, respectively as compared to 28 days of compressive strengths as shown in Fig. 4.a. The strength loss index (SLI-%) and strength gain index (SGI-%) results were found to be decreased with time due to the acid attack. The lower SLI-% or SGI-% indicates higher deterioration, while higher SLI-% or SGI-% refers to the lower degradations. When 150 days of acid exposure was evaluated, SLI-% and SGI-% were found to be 75.29 and 53.36 for OPC-0, 46.52, and 41.52 for OPC-50, 60.35 and 47.51 for OPC-100 specimens. The results pointed out that SGI-% were found lower than SLI-% due to ongoing hydration reactions; hence, the SGI-% should be the best choice for chemical evaluations. The highest deterioration was observed on OPC-50 specimens, while the minimum damage was found on OPC-0 samples. The higher water absorption for 150W condition and the higher weight loss for 150A conditions was found on the OPC-50 specimens according to weight change results (Fig. 3.a), which support the poor compressive strength resistance. This may be attributed to reduced packing density and improved porosity [36].

3.3.2. Compressive strengths of OPC-FA concretes

Fig. 4.b and Table 4 results indicated that the compressive strength improvements were 11% and 28% for OPC-FA-0, 23% and 26% for OPC-FA-50, and 4% and 16% for OPC-FA-100 specimens at 120 and 150 days, respectively as compared to 28 days of compressive strengths underwater environment. The SLI-% and SGI-% decreased with time and the SGI-% was found less than the SLI-% due to slow hydration reactions of fly ash particles. The SLI-% and SGI-% yielded as 59.32 and 46.17 for OPC-FA-0, 56.64 and 44.90 for OPC-FA-50, 58.37 and 50.47 for OPC-FA-100 specimens under the acid environment at 150 days. The higher deterioration was found on the OPC-FA-50 specimens, whereas less deterioration was noticed on OPC-FA-100 samples. The poor performance of OPC-FA-50 specimens may be attributed to reduced packing density and increased porosity [36]. Meanwhile, the slightly better acid resistance of OPC-FA-100 specimens may be due to unconnected pores. Also, the compressive strength of 100% pumice-based LWC specimens was found to be higher than 24 MPa, which is above the 15 MPa (OPC LWC specimens), indicating that fly ash addition improved both early age strength and durability performance. This may be attributed to the enhanced puzzolanic activity of fly ash due to the additional silica comes from pumice aggregates.

Table 4
SLI-% and SGI-% parameters under acid environment

Days	Strength Loss Index (SLI-%)			Strength Gain Index (SGI-%)		
	OPC-0	OPC-50	OPC-100	OPC-0	OPC-50	OPC-100
28	100.00	100.00	100.00	100.00	100.00	100.00
28+92	62.44	53.82	92.19	56.89	52.60	77.57
28+122	75.29	46.52	60.35	53.36	41.52	47.51
	OPC-FA-0	OPC-FA-50	OPC-FA-100	OPC-FA-0	OPC-FA-50	OPC-FA-100
28	100.00	100.00	100.00	100.00	100.00	100.00
28+92	62.06	57.71	64.25	55.71	46.99	61.94
28+122	59.32	56.64	58.37	46.17	44.90	50.47
	OPC-S-0	OPC-S-50	OPC-S-100	OPC-S-0	OPC-S-50	OPC-S-100
28	100.00	100.00	100.00	100.00	100.00	100.00
28+92	64.53	63.12	33.16	58.43	58.69	30.60
28+122	45.55	59.47	NA	37.00	51.90	NA
	OPC-FA+S-0	OPC-FA+S-50	OPC-FA+S-100	OPC-FA+S-0	OPC-FA+S-50	OPC-FA+S-100
28	100.00	100.00	100.00	100.00	100.00	100.00
28+92	93.80	57.98	80.95	74.40	56.11	66.47
28+122	88.42	50.14	75.17	66.84	47.14	59.25

3.3.3. Compressive strengths of OPC-S concretes

Fig. 4.c and Table 4 results indicated that the compressive strength improvements were 10% and 23% for OPC-S-0, 8% and 15% for OPC-S-50, and 8% and 18% for OPC-S-100 specimens at 120 and 150 days, respectively as compared to 28 days of compressive strengths. The SLI-% and SGI-% were found as 45.55 and 37.00 for OPC-S-0, 59.47 and 51.90 for OPC-S-50 specimens under the acid environment at 150 days. The compressive strength tests for OPC-S-100 specimens could not be performed due to the broken specimens after the acid attack. At 120 days, 70% loss of compressive strength on the OPC-S-100 specimens were observed due to the acid attack. The loss of compressive strength due to the acid attack on the slag incorporated samples may be due to high MgO content in the slag. During the attack, decomposition of C-S-H to M-S-H is realized at later ages, resulting in the softening of the binder and causing loss of mechanical strength [38]. Another reason for the poor acid performance may be due to the high CaO content and unreacted slag particles. Since free calcium deteriorates the binder and yields to the formation of gypsum and ettringite, resulting in the loss of mechanical strength.

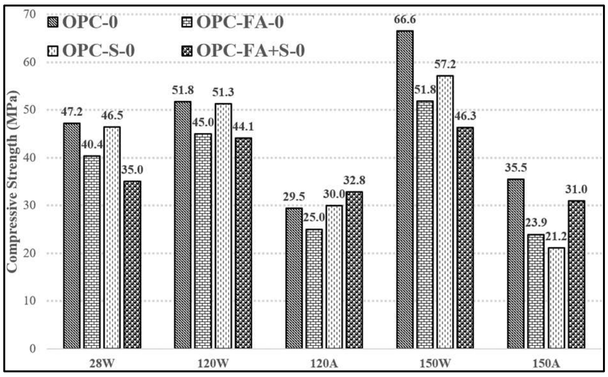
3.3.4. Compressive strengths of OPC-FA+S concretes

Fig. 4.d and Table 4 results pointed out that the enhancements in the compressive strength were 26% and 32% for OPC-FA+S-0, 3% and 6% for OPC-FA+S-50, and 22% and 27% for OPC-FA+S-100 samples at 120 and 150 days, respectively as compared to 28 days of compressive strengths underwater environment. The SLI-% and SGI-% yielded 88.42 and 66.84 for OPC-FA+S-0, 50.14 and 47.14 for OPC-FA+S-50, 66.84 and 59.25 for OPC-FA+S-100 specimens under the acid environment at 150 days. The highest deterioration was found on the OPC-FA+S-50 specimens due to reduced packing density and increased porosity. The OPC-FA+S performed better sulfuric acid resistance than the other concrete types; therefore, the OPC-FA+S concrete type may be the best option for the structural concretes exposed to higher chemical environments. This enhanced performance may be attributed to the lower CaO content and reduced porosity resulting from the increased finer particles (fly ash and slag).

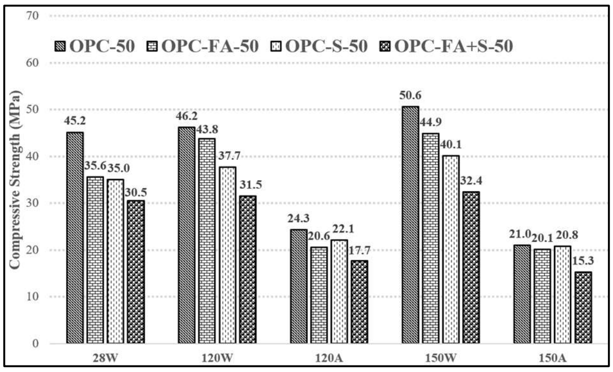
3.3.5. Influence of binder type on compressive strength

Fig. 5 indicates the compressive strength of specimens without pumice (Fig. 5.a), with 50% pumice (Fig. 5.b), and with 100% pumice (Fig. 5.c) and average compressive strength of specimens with/out pumice (Fig. 5.d). The results indicated that pumice incorporation decreased compressive strength significantly. However, the compressive strength difference between specimens without pumice and with 50% pumice was found to be significantly lower than the compressive strength difference between the specimens with 50% pumice and 100% pumice.

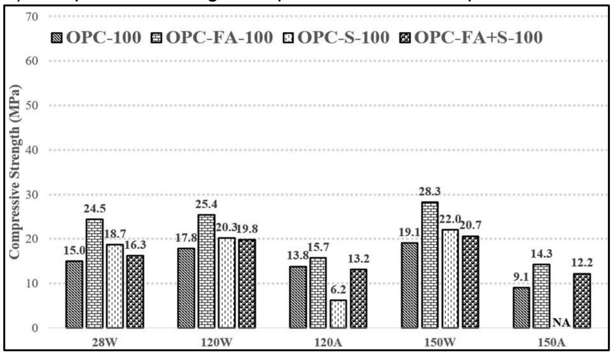
When the average compressive strength was examined (Fig. 5.d), compressive strengths of OPC, OPC-FA, and OPC-S were found close to each other, except for OPC-FA+S specimens, which performed relatively lower compressive strength than the other concrete types. The results pointed out that the efficiency factors of 0.4 for F-type fly ash and 0.8 for slag recommended in the standards were found appropriate for the concretes incorporated only fly ash or slag materials. However, when the fly ash and slag materials were incorporated into OPC together, the efficiency factors should be decreased from 0.4 to 0.35 for fly ash and from 0.8 to 0.75 for slag in TS13515 and EN 206-1 standards to obtain equal compressive strength and durability performance. Also, the efficiency factor (k) coefficients can be utilized in the pumice aggregate incorporated specimens up to 100% replacement ratios. However, further studies are required to support these findings, and microstructural analyses are required for comprehensive evaluations.



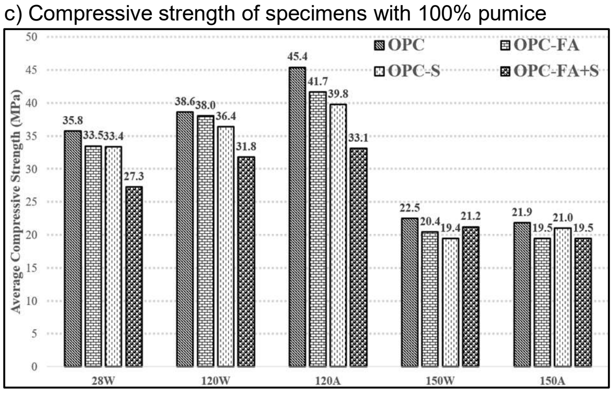
a) Compressive strength of specimens without pumice



b) Compressive strength of specimens with 50% pumice



c) Compressive strength of specimens with 100% pumice



d) Average compressive strength of specimens with/out pumice

Fig. 5 - Influence of binder types on compressive strengths

4. Conclusions

In this study, the mechanical performance and durability properties of the volcanic pumice aggregate incorporated different lightweight concretes (LWC) were investigated cured in 5% sulfuric acid and water environments considering the cement efficiency factors for the fly ash and slag materials recommended in the standards. The applicability of cement efficiency factors in the presence of 50% and 100% pumice replacements instead of coarse aggregate was evaluated underwater and in 5% sulfuric acid environments. In addition, the influence of volcanic pumice aggregates on the chemical resistance of the different LWC was studied. The main findings were summarized as follows:

- Visual inspection results indicated no significant difference was observed on the specimen surfaces with/out pumice due to the sulfuric acid attack. Also, the surface degradation amount for the LWC specimens with different binders appeared to be similar, except for OPC-S-100 specimens that all of the three specimens were broken into two halves after the 5% acid attack at 150 days.
- The weight change results indicated that weight gain was observed on the water cured specimens due to water absorption, and the weight gain increased with time. However, due to surface erosion, weight loss was observed on the sulfuric acid exposed specimens, and the loss progressed with the acid exposure time. The highest weight loss was observed on 50% pumice incorporating LWC specimens due to sulfuric acid attack.
- The compressive strength of the specimens increased with time underwater environment whilst decreased with sulfuric acid exposure time. The 50% pumice incorporation slightly reduced the compressive strength, while 100% pumice replacement significantly decreased the compressive strength of the specimens.
- The strength gain index (SGI-%) and strength loss index (SLI-%) were utilized for the compressive strength evaluation. The SGI-% was found to be the best compressive strength evaluation method under sulfuric acid and water environments due to ongoing hydration reactions, especially for the mineral admixture included specimens.
- The cement efficiency factors of 0.4 for fly ash and 0.8 for slag recommended in the standards were found appropriate for the concretes incorporated only fly ash or slag materials. These coefficients were also found suitable for the pumice aggregate utilization up to 100% replacements. However, when fly ash and slag materials were used together, the cement efficiency factors should be decreased from 0.4 to 0.35 for the fly ash and from 0.8 to 0.75 for the slag to obtain equal compressive strength and durability performance. The coefficient factors were also found applicable up to 33% replacement for the fly ash and 45% replacement for the slag materials.
- The 50% volcanic pumice aggregate replacements should be utilized in structural buildings for superior mechanical strength, durability, and the reduced earthquake force.

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