Journal of Asian Concrete Federation
Vol. 8, No. 2, pp. 23-34, Dec. 2022
ISSN 2465-7964 / eISSN 2465-7972
DOI http://dx.doi.org/10.18702/acf.2022.12.8.2.23

Technical Paper

Ultra-light foamed concrete with recycled sand

Munkhtuvshin Ochirbud, Kyungchan Hong, Suah Kang, Youngho Kim, Sangsu Ha, Donguk Choi*

(Received October 19, 2022; Revised November 22, 2022; Accepted November 23, 2022; Published December 31, 2022)

Abstract: Carbon neutralization and upcycling of recycled resources in concrete and construction industry are key themes of sustainability. In this study, ultra-light foamed concrete (ULFC) was fabricated using high early strength Portland cement, silica fume, fly ash, and recycled fine aggregates. ULFC with dry density as low as 284 kg/m^3 was fabricated by chemical foaming method using hydrogen peroxide (H_2O_2) as the foaming agent and hydroxypropyl methyl cellulose ether (HPMC) as the foam stabilizer. Thermal conductivity of the ULFC was 0.092 W/mK. The potential application of the ULFC fabricated in this study is the inorganic insulating material with low density, low thermal conductivity, and good fire resistance for fabric reinforced cementitious matrix (FRCM) building sandwich panels.

Keywords: ultra-light foamed concrete, recycled fine aggregate, H_2O_2, HPMC.

1. Introduction

During the last decade, researchers have been actively performing research on the ultra-light foamed concrete (ULFC), which is characterized by the mechanical properties such as very low density and thermal conductivity, high flowability, and controlled low strength [1-3].

There are three different approaches that can be taken to fabricate the ULFC: (1) Physical foaming method, (2) mechanical air-entraining method, and (3) chemical foaming method [4]. In the physical foaming method, which is most often used, the preformed foam is mixed together with the cement slurry that is separately prepared [2,5]. In the mechanical air-entraining method, a surfactant such as air-entraining agent is used during conventional mixing [1,6]. The third method, the chemical foaming method, can also be used to fabricate the ULFC [3,7,8]. The chemical foaming method also provides a path for autoclaved lightweight concrete (ALC) with additional treatment by autoclaving.

Constituent materials of the ULFC typically include cement, substitutive cementitious materials, chemical admixtures, water, and filler materials. Different binders such as ordinary Portland cement, rapid hardening Portland cement, high alumina cement, and calcium sulfoaluminate cement have been used [9]. Substitutive cementitious materials such as silica fume, blast furnace slag, and fly ash are often used in addition to the main binder to promote early strength gain and/or control flow. For example, cement was replaced by 5%-15% silica fume (SF) by mass of cement to increase strength of ULFC at early ages by some researchers [10-12]. Other researchers utilized fly ash up to 50% of cement replacement to improve workability of the ULFC fresh mixture [7,13]. Diverse foaming agents such as protein, zinc powders, hydrogen peroxide, and sodium bicarbonate which produce air, hydrogen, oxygen, and carbon dioxide, respectively, have been used to fabricate the ULFC by the chemical foaming method. Another foaming agent often used is aluminium powders. The aluminium reacts with alkali in the cement slurry and generates hydrogen gas. As mixture volume increases rapidly by the hydrogen gas generation and the subsequent micro voids formation, the vertical expansion of the fresh mixture is counter balanced by the self-weight of its own constituent materials. A successful foaming can lead to the volume expansion up to about five times. Foam stabilizer such as calcium stearate and cellulose ether

***Corresponding author Donguk Choi** *is NRF Research Professor, Hankyong National University, Anseong, 17579, South Korea*

Munkhtuvshin Ochirbud *is Researcher at Hankyong National University, Anseong, 17579, South Korea*

Kyungchan Hong *is Researcher at CECM Co. Ltd., 17579, Anseong, South Korea*

Suah Kang *is M.S. Student, Chemical Engineering at Hankyong National University, Anseong, 17579, South Korea*

Youngho Kim *is Professor, Chemical Engineering at Hankyong National University, Anseong, 17579, South Korea*

Sangsu Ha *is Professor, Architectural Engineering at Kangnam University, Yongin 16979, South Korea*

can be used as water-retention agents, thickeners, and film formers [1]. Density of the hardened foamed concrete decreases with efficient foaming. Thermal conductivity of the foamed concrete decreases with decreasing density in general, while the thermal conductivity of the ULFC is also claimed to be proportional to the thermal conductivity of the foaming gas [8].

This study was performed as part of an ongoing research to develop fabric reinforced cementitious matrix (FRCM) building sandwich panels with inorganic insulation material in a form of ULFC. The chemical foaming method was adopted to fabricate the ULFC. The recycled resources such as 5% silica fume, 30% fly ash as well as 100% recycled sand were utilized to fabricate ULFC with reduced environmental footprint. To authors knowledge, this is the first study that tries to utilize recycled sand for the fabrication of ULFC taking advantage of the relatively low density of the aggregates and high alkalinity of the cementitious mixture with recycled aggregates provided by the adhered mortar on the surface of the recycled sand [14].

2. Materials and Fabrication of ULFC and Testing

2.1 Constituent materials

High early strength Portland cement (42.5R grade) was used as the main binder material. Mineral additions utilized were silica fume (SF), which was used to promote early strength gain, and the low-calcium fly ash (Type-F) which was used to improve flow. Table 1 summarizes the chemical composition of cement, silica fume, fly ash, and recycled fine aggregates determined by X-ray fluorescence spectroscopy (XRF). Figure 1 shows particle size distribution of all binder materials determined by laser diffraction analysis. 100% recycled fine aggregate (RFA) with the maximum particle size of 1.25 mm or 0.6 mm was utilized in all batches except the control mix which used 100% natural fine aggregates (NFA) with the maximum particle size of 0.6 mm. The RFA, which conforms to KS F 2573 [15], was produced through crushing and sieving process of the demolished concrete chunks and was provided by a local producer. Figure 2 shows the gradation of the fine aggregates determined by sieve analysis. Mechanical properties of the fine aggregates are shown in Table 2. Two different chemical admixtures were also utilized: Set accelerating admixture ($CaCl_2$) was used as set accelerator and powder type melamine-based superplasticizer (SP) was used to increase flow.

2.2 Foaming agent and foam stabilizer

The foaming agent used in this study was hydrogen peroxide (H_2O_2) in a form of diluted aqueous solution at 35% concentration. When added to the fresh cementitious mixtures, the H_2O_2 became unstable in the alkaline environment and decomposed to water and oxygen. The oxygen gas that was trapped in the fresh mixture formed bubbles which resulted in the micro voids in the hardened concrete. HPMC (hydroxypropyl methylcellulose ether) is a foam stabilizer often used to fabricate the ultra-light foamed concretes and was adopted in this study [1,2]. Table 3 shows the properties of the HPMC.

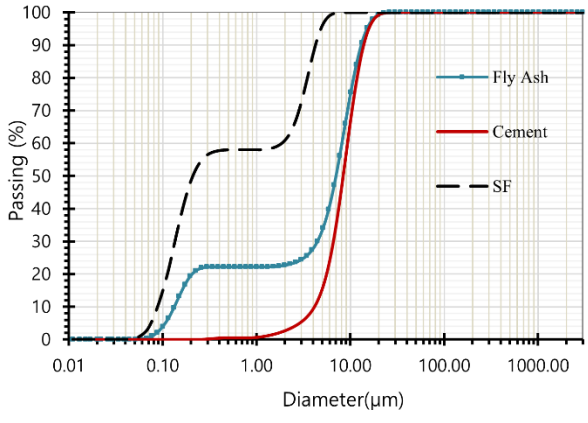


Fig. 1 – Particle size distribution of binder materials

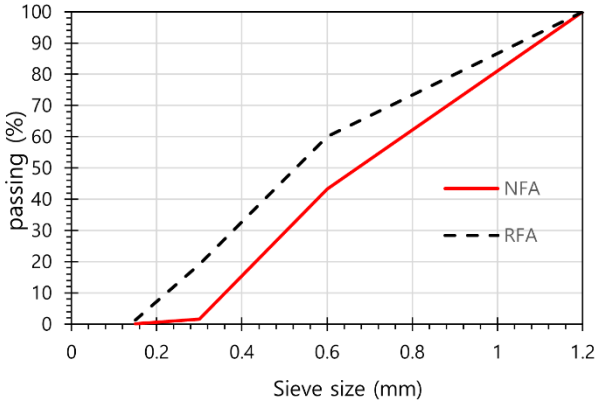


Fig. 2 – Gradation of fine aggregates

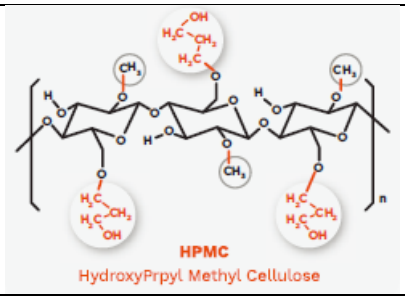
Table 1 - Chemical composition of high early strength cement, SF, fly ash and RFA determined by XRF

	Type-3 Portland cement	Silica fume	Fly ash	Recycled fine aggregate
CaO (%)	71.7	0.952	2.53	21.2
SiO_2 (%)	12.9	92.6	66.2	54.7
Fe_2O_3 (%)	4.81	0.964	4.72	4.27
SO_3 (%)	3.83	0.805	--	0.909
Al_2O_3 (%)	2.13	0.359	20.4	11.0
K_2O (%)	1.71	2.16	0.73	3.17
MgO (%)	1.54	1.03	0.99	1.75
P_2O_5 (%)	0.71	0.154	0.64	0.152
TiO_2 (%)	0.28	--	0.94	0.458
ZnO (%)	0.13	--	0.023	--
MnO (%)	0.13	--	0.082	0.122
LOI (%)	--	--	2.21	--
Na_2O (%)	--	0.643	--	1.91
CI (%)	--	0.192	--	--

Table 2 - Physical properties of fine aggregates

Sand type	Max. particle size (mm)	BSG_{SSD}	BSG_{OD}	Water absorption (%)	F.M.	% passing 0.08-mm sieve	Remarks
RFA	1.2	2.47	2.45	2.34	2.92	1.88	RFA/NFA was sieved from sand < 5 mm
	0.6	2.51	2.46	2.34	1.54	5.33	
NFA	1.2	2.67	2.66	0.46	2.15	0.05	

Table 3 - HPMC properties

Product	
Name: Mecellose Producer: Lotte Fine Chemical, Co., Ltd. Viscosity: 14,900 cps	

2.3 Mix design

Fourteen different mixture designs of light-weight foamed concrete with RFA were planned in two different series as summarized in Table 4. In addition, one mixture was also tested where NFA was used. The aggregate-to-binder ratio was 6:4 by wt. and the effective water-to-binder ratio (W/B) was 0.69 in all mixes.

Series 1 (8 tests) – Test variable was the amount of foaming agent H_2O_2 that changed from 5% to 20% of binder (cement + SF) by wt. in 5% increment. The maximum particle size of RFA was 1.2 mm or 0.6 mm.

Series 2 (6 tests) – Test variable in this series was the amount of foam stabilizer (HPMC), which was either 0.5% or 1.0% of binder by wt. Fly ash partially replaced binder (cement + SF) by 0%, 15%, or 30% by wt.

Control (1 test) – A Control specimen was fabricated using the 100% natural fine aggregates.

2.4 Mixing

A planetary mixer with a 22-liter bowl and the standard paddle, equipped with three different rotating speeds (100 rpm, 180 rpm, and 360 rpm) was used for all batches. The following mixing sequence was employed:

- All powder materials (cement, silica fume, fly ash, SP, HPMC) and fine aggregates were first mixed at low speed (100 rpm) for 2 minutes, where the fine aggregates were supplied in the oven dry condition.
- All batch water with premixed $CaCl_2$ was added and the constituents were mixed for 4 minutes (2 minutes at 100 rpm + 2 minutes at 180 rpm).
  - H_2O_2 was added and the constituents were mixed at high speed (360 rpm) for 30 seconds.

It is noted that, considering the oven dry state of the different fine aggregates (NFA, RFA) and the extra water in the H_2O_2 diluted solution, the water

content was adjusted so that the effective water-to-binder ratio (w/b) = 0.69 in all mixes.

2.5 Casting and fabrication of specimens

For Series 1 tests, the fresh mixture was immediately cast into multiple cylindrical molds (Ø100 mm x 200 mm) upon completion of mixing. The foam generation and subsequent volume expansion, triggered by H_2O_2 added at the last stage of mixing, was completed in about 15 minutes in the molds. The specimens were then cured under PE film for 7 days. After 7 days, all specimens were demolded and cut to the same length (120 mm), and the specimens were continuously wet-cured under water until 28 days. For Series 2 tests, the fresh mix was cast into a slab mold (500 mm x 500 mm x 80 mm) and cured under PE film. After 7 days, the specimens were demolded and were cut to multiple 80 mm x 80 mm x 80 mm cubes, which were continuously cured under water until 28 days. Fig. 3(a), (b) shows a cylindrical specimen and a cube specimen, respectively. All specimens were taken out of water after 28 days, the surface water was removed using dry paper towels, and the surface saturated dry mass (W_{ssd}) was determined. Then the specimens were oven dried until constant mass was reached and the dry mass was determined (W_{dry}). The following equations were used to determine apparent oven dry density (dry density) and water absorption following KS F 2459 [16].

$$\text{Apparent oven dry density} = W_{dry} / V \quad (1)$$

$$\text{Water absorption} = (W_{ssd} - W_{dry}) / W_{ssd} \quad (2)$$

where V is nominal volume of specimen.

(a) S1-5: Series 1

(b) S2-6: Series 2

Fig. 3 – Hardened Series 1 and Series 2 concretes

Table 4 - Mix design (unit: kg for approximately 0.16 m^3 batch)

Series	C	SF	Fly ash	Water	NFA	RFA < 1.25 mm	RFA < 0.6 mm	H_2O_2	SP	$CaCl_2$	HPMC
Series 1	95	5	--	69.8	--	150		5	1	3	--
S1-1				66.5				10			
S1-2				63.3				15			
S1-3				60.0				20			
S1-4				69.8			150	5			
S1-5				66.5				10			
S1-6				63.3				15			
S1-7				60.0				20			
S1-8											
Series 2	95	5	0	69.4	--	--	150	5	2	3	0.5
S2-1	80		15								
S2-2	65		30								
S2-3	95		0								1.0
S2-4	80		15								
S2-5	65		30								
S2-6											
Control N-1	80	5	15	66.9	150	--	--	5	2	3	0.5

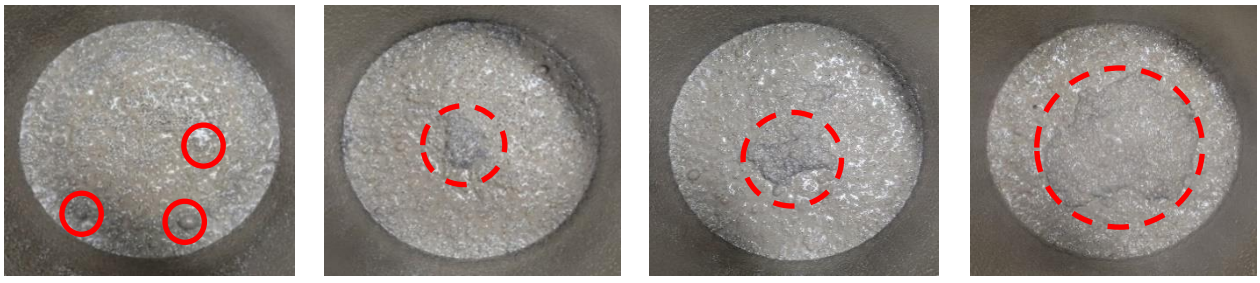
2.6 Compressive strength

The compressive strength was determined 28 days after casting for all specimens: i.e. Cylindrical specimens for Series 1 and cube specimens for Series 2. A compression testing machine with maximum capacity of 30 kN was used under position control at ramp rate of 1 mm/m. Although the aspect ratio was not the same between the cylindrical specimens (Ø100 mm x 120 mm) and the cubic specimens (80 mm x 80 mm x 80 mm), the compressive strengths of the cylindrical specimens and the cubes are reported without any conversion.

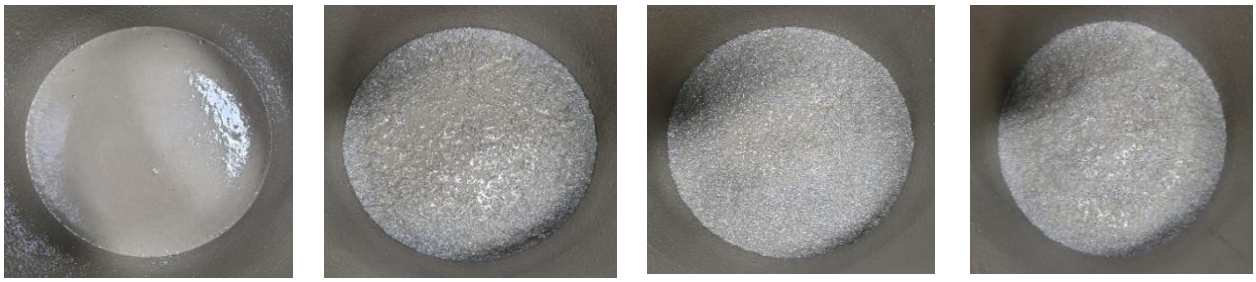
3. Test Results and Discussions

3.1 Series 1

Test variable of Series 1 was the amount of H_2O_2. At the same time, both finer sand (RFA < 0.6 mm) and coarser sand (RFA < 1.2 mm) were used for Series 1 tests. During the final stage of mixing, before the foaming agent (H_2O_2) was added to the fresh mixture, the mixture filled only part (about 1/5th) of the mixing bowl. After H_2O_2 was added, the oxygen bubbles began to form immediately and the volume of the fresh mixture expanded rapidly. The early reaction was often violent, where the top surface of the foamed mixture in the bowl was fast raised, but then the foams collapsed in many mixtures. This process was typically repeated for several times for the mixes with large amount of H_2O_2 (≥ 10%). Figure 4(a) shows several large bubbles on the top surface of S1-1, which often led to large voids in the hardened concrete. In Figure 4(b)-(d), dashed circles indicate that the initial foam formation was rapid but then the foams collapsed leaving extra mortar on the top surface of the fresh mixture (S1-2 through S1-4). On the other hand, in Fig. 4(e)-(h), the top surface of the fresh mixes is relatively free of the large bubbles and the extra mortar. Since S1-5 through S1-8 used finer RFA (particle size < 0.6 mm) than the S1-1 through S1-4 (particle size < 1.2 mm), it was deduced that the finer sands are potentially better suited for the uniform foam formation than the coarser sands.



(a) S1-1 (b) S1-2 (c) S1-3 (d) S1-4



(e) S1-5 (f) S1-6 (g) S1-7 (h) S1-8

Fig. 4 – Fresh mixture after completion of mixing: Series 1

The test results of Series 1 are also shown in Fig. 5 in terms of dry density, water absorption, and compressive strength of the hardened concrete after 28 days. For S1-1 through S1-4 with the coarser sand (i.e. particle size < 1.2 mm), the dry density varies between 812 kg/m3 and 1,158 kg/m3 and the 28d compressive strength ranges between 4.13 MPa and 7.95 MPa in Fig. 4(a) and (c). Both density and strength tend to decrease with increasing amount of H_2O_2 that varies from 5% to 20%. On the other hand, for S1-5 through S1-8 with the finer sand (particle size < 0.6 mm), the dry density is about the same (855-878 kg/m3) while the 28d strength of two mixtures with low amount of H_2O_2 (4.63 MPa and 5.77 MPa for H_2O_2 amount of 5% and 10%, respectively) is higher than two other mixtures with larger amount of H_2O_2 (3.25 MPa and 3.46 MPa for H_2O_2 amount of 15% and 20%, respectively) in Fig.

5(b) and (d). Figure 5(e) shows that the water absorption of S1-1 through 1-4 mixes ranges from 21.7% to 31.4%. In Figure 5(f), the water absorption is 28.2%~30.6% and does not differ much in between the mixes. From the hardened properties such as dry density, water absorption, and 28d compressive strength, it is observed that S1-5 through S1-8 mixes result in more favorable properties for the light-weight concrete despite the decreased strength which is result of the lowered density. Table 5 summarizes dry density, water absorption, and compressive strength of all Series 1 mixes. From Series 1 tests, the mix design of S1-5 with H_2O_2 amount of 5% and 0.6 mm RFA was chosen as a base mix for the Series 2 tests based on overall performance such as dry density, water absorption, and strength as shown in Table 5 and Fig. 5.

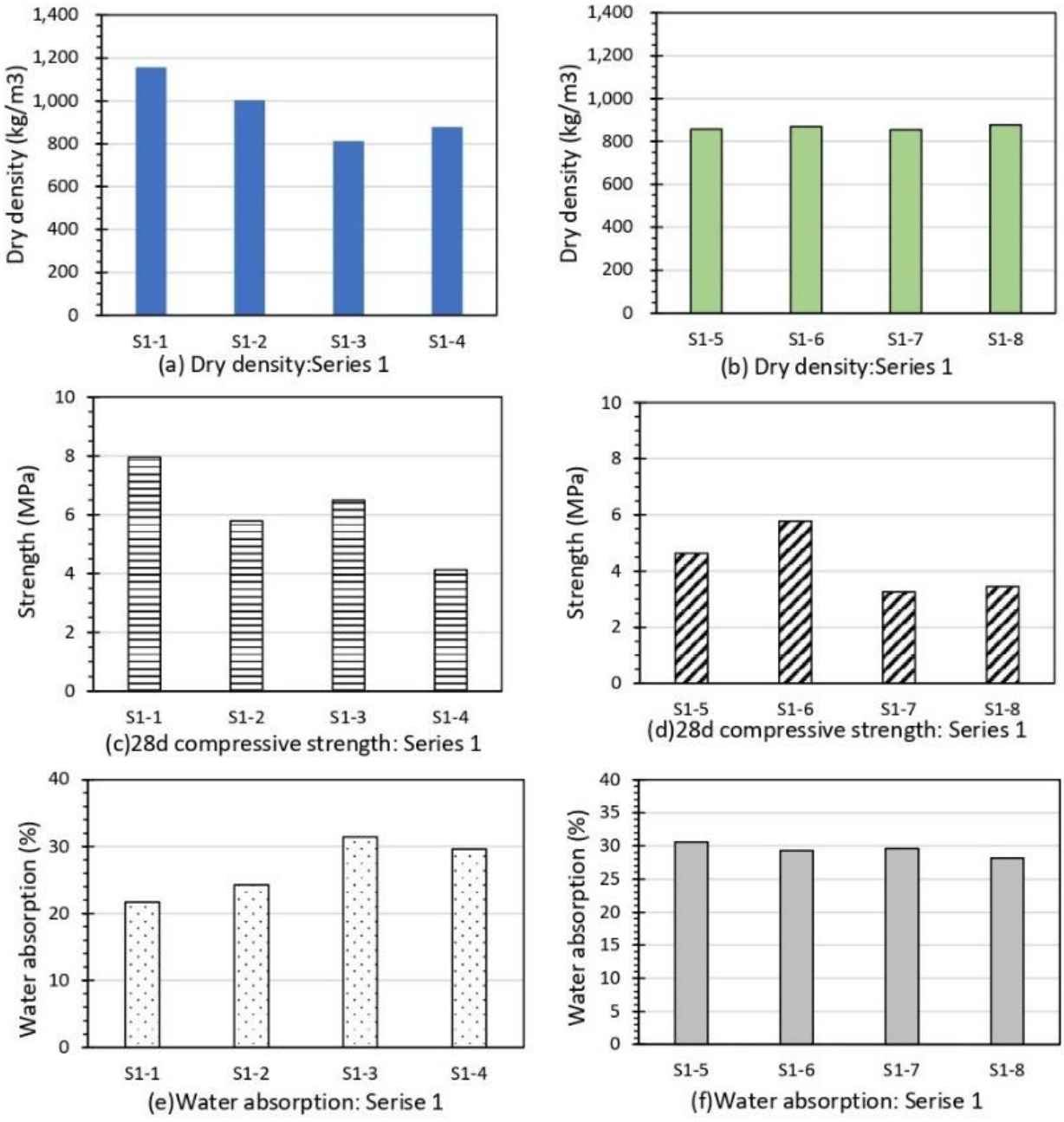


Fig.5 − Density, water absorption and 28d compressive strength: Series 1

3.2 Series 2

Test variable in Series 2 was the amount of foam stabilizer (HPMC), which was either 0.5% or 1.0% of binder by wt. At the same time, fly ash partially replaced binder (cement + SF) by 0%, 15%, or 30% by wt. A total of six mixes was tested (Only results of five mixes are reported due to handling mistake of S2-5. See Note to Table 5). Figure 6 shows test results of Series 2 specimens. Table 5 also summarizes test results in terms of dry density, water absorption, and compressive strength.

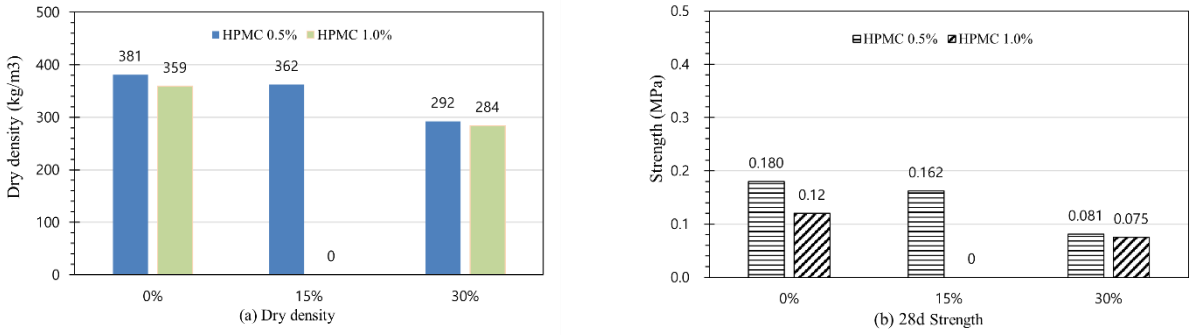
In Figure 6(a), the dry density ranges between 292 kg/m^3 and 381 kg/m^3 when the HPMC amount is 0.5% of the binder and the dry density decreases with increasing replacement ratio of binder by fly ash (0%, 15%, 30% of binder by wt.). The same trend is observed for two specimens with the HPMC amount of 1%, where the dry density decreases from 359 kg/m^3 to 284 kg/m^3 without and with 30% fly ash, respectively. With very low density of the ULFC specimens in Series 2 tests, the compressive strength was also low and ranged between 0.08 MPa and 0.18 MPa as shown in Fig. 6(b) and Table 5. In Figure 6(c), it is seen that the water absorption of Series 2 specimens ranges between 57.2% and 66.8% revealing that the voids, especially continuous voids, takes almost 70% of the specimen volume.

It must be noted that the introduction of the foam stabilizer in this test series had a big impact in lowering the density of the hardened concretes. Dry density was lowered by 2.25-2.9 times from that of S1-5 for three mixes with 0.5% HPMC (without or with 15% or 30% fly ash replacement) for S2-1, S2-2, S2-3. Dry density was lowered by 2.4 and 3.0 times from S1-5 for two mixes with 1.0% HPMC for S2-4 and S2-6, respectively (without or with 30% fly ash replacement).

Table 5 - Test results: Mechanical and thermal properties

Index	Dry density (kg/m^3)	Water absorption (%)	Compressive strength (MPa)	Thermal conductivity (W/mK)
S1-1	1,158	21.7	7.95	
S1-2	1,004	24.3	5.78	
S1-3	812	31.4	6.49	
S1-4	878	29.6	4.13	
S1-5	857	30.6	4.63	
S1-6	869	29.3	5.77	
S1-7	855	29.6	3.25	
S1-8	878	28.2	3.46	
S2-1	381	57.2	0.18	
S2-2	362	58.7	0.16	
S2-3	292	63.7	0.08	
S2-4	359	59.8	0.12	
S2-6	284	66.8	0.08	0.092
N-1	417	49.7	0.07	

NOTE: 1. Foams collapsed during mixing for S2-5 specimen due to mishandling of the specimen during fabrication and therefore the results are not reported; 2. N-1. Mix design is the same as S2-2, but NFA was used instead of RFA.



(a) Dry density (b) 28d strength

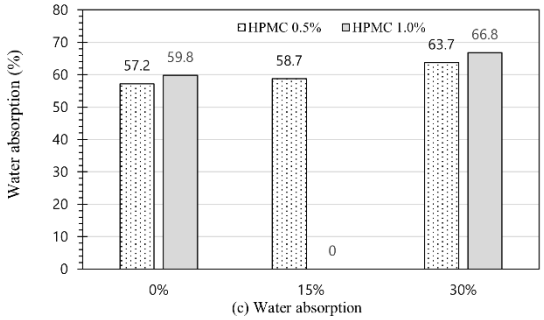
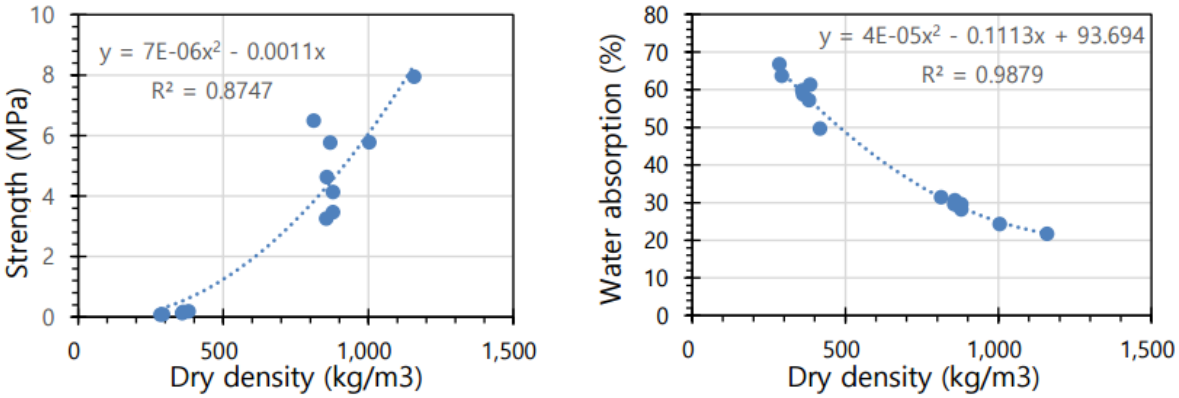


Fig. 6 – Density, water absorption and 28d compressive strength: Series 2

3.3 Discussions of test results

3.3.1 Density, flow and strength of ULFC

ULFC with dry density as low as 284 kg/m^3 was fabricated in this study through fabrication and testing specimens grouped in two different test series. Although the dry density was successfully lowered to below 300 kg/m^3 by the chemical foaming method, the accompanying loss of the compressive strength was significant as shown in Fig. 7. A regression analysis of 14 tests resulted in a polynomial equation as shown. The test data and the regression equation show that the compressive strength will be higher than 8 MPa at dry density of 1,200 kg/m^3 while it will be smaller than 1 MPa at dry density below 400 kg/m^3. The low strengths can be explained as follows: (1) The binder-to-aggregate ratio was fixed at 4:6 in this study in an attempt to fabricate ULFC with low amount of binder, and thus less environmental footprint; (2) fly ash up to 30% of binder by wt. was used in an attempt to increase flow of fresh mixtures. As shown in Fig. 8, the flow increases with increasing amount of fly ash up to 30% replacement while the 28d compressive strength decreases.

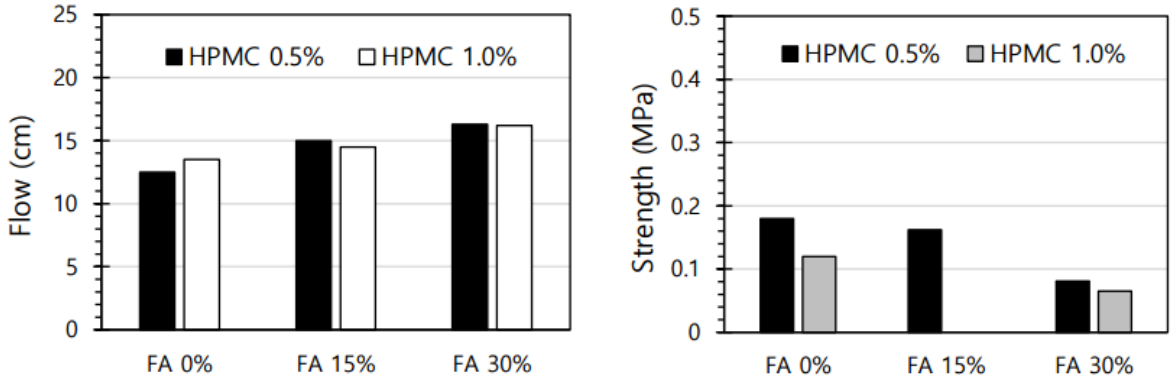


(a) Density vs. strength (b) Density vs. water absorption

Fig. 7 Dry density versus 28d compressive strength and water absorption: Series 1 and Series 2 test results

In this study, the recycled sand was used in all mixes except the Control mix. The Control mix N-1 has the same mix design as that of S2-2 while 100% NFA was used in N-1 and 100% RFA was used for S2-2 (See Table 4). Test results summarized in Table 5 indicate that S2-2 developed lower dry density (362 kg/m^3), higher water absorption (58.7%), and higher strength (0.16 MPa) than the corresponding values of N-1 (dry density = 417 kg/m3, water absorption = 49.7%, strength = 0.07 MPa). Figure 9 shows variation of pH of each mixture during the first 15 minutes when the chemical decomposition of H_2O_2 is most active. In Figure 9, pH of both fresh mixtures continuously increases with time, and pH of S2-2 with RFA is consistently higher than that of N-1. Figure 9 seems to indicate that the condition is more favorable for the decomposition of H_2O_2 (for alkalinity) for S2-2 than it is for N-1. It is well known that the recycled aggregates contain adhered mortar that is attached to natural aggregates in the original concrete which cannot be entirely removed during the manufacturing process of the recycled aggregates. The adhered mortar contains unhydrated cement particles which is available for hydration with water. At the same time, the light adhered mortar causes the RFA density smaller than that of NFA. Therefore,

test results seem corroborate the assumptions taken in the beginning stage of this study that it would be efficient to utilize recycled sand for the fabrication of ULFC taking advantage of the relatively low density of RFA (RFA is lighter than NFA in Table 2) and high alkalinity of the cementitious mixture including RFA (as shown in Fig. 9).



(a) Fly ash replacement ratio vs. flow (b) Fly ash replacement ratio vs. strength

Fig. 8 Fly ash replacement ratio vs. flow and 28d compressive strength: Series 2

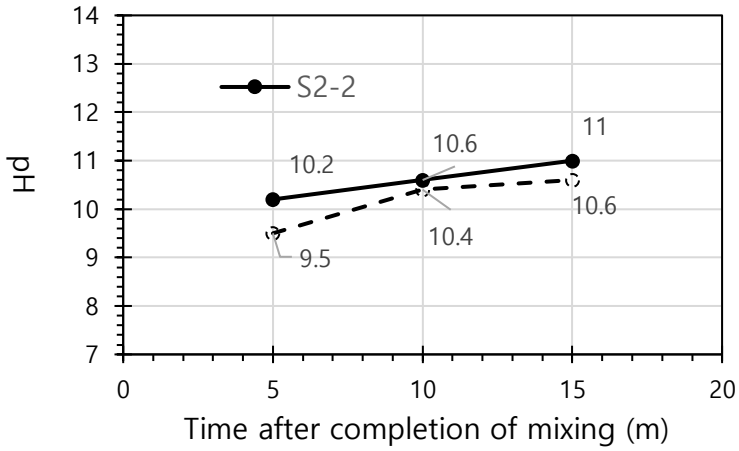


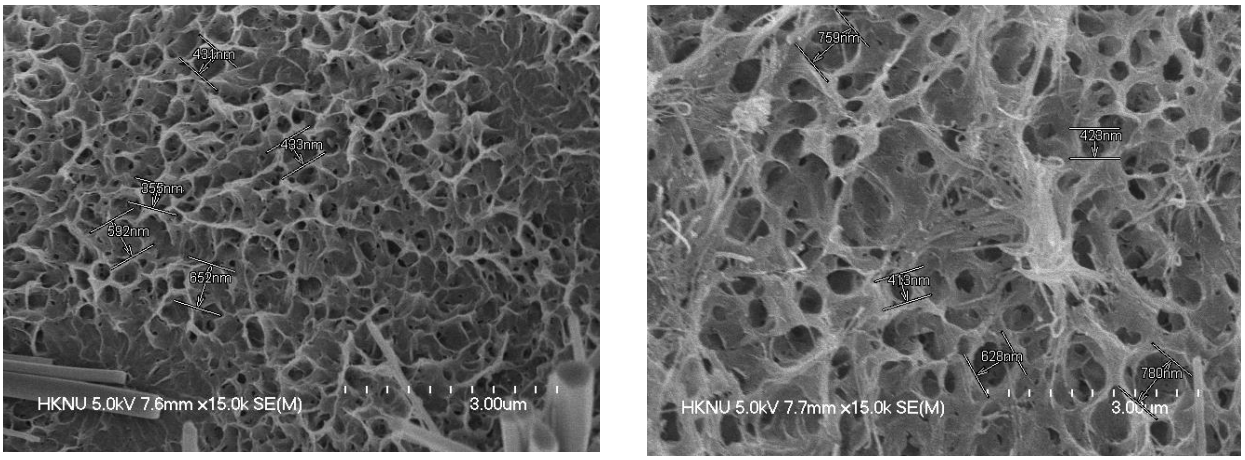
Fig. 9 Variation of pH in two Series 2 fresh mixtures: S2-2 and N-1

3.3.2 Thermal conductivity

The thermal conductivity of one Series 2 mix with the lowest density (S-2-6) was investigated by hot plate method following KS L 9016. Flat ULFC panel of 300 mm * 300 mm * 50 mm was cast, wet cured for 28 days, and then oven dried for 48 hours before testing the thermal conductivity. Test results revealed that the thermal conductivity is 0.092 W/mK.

3.3.3 Micro structural investigation by scanning electron microscopy

The micro structure of the foamed concrete developed in this study, S2-6 and N-1, was investigated by scanning electron microscopy (SEM) using Hitachi S-4700. Figure 10 shows that the cellular structure is formed while the diameter of a cell is smaller than 1 μm.



S2-6 N-1

Fig. 10 — SEM images of ULFC

3.3.4 Others aspects

This study was performed as part of an ongoing research to develop fabric reinforced cementitious matrix (FRCM) building sandwich panels with inorganic insulation material in a form of ULFC using the chemical foaming method. ULFC with low density of 284 kg/m^3 and low thermal conductivity of 0.092 W/mK was fabricated at the cost of very low strength. Further effort is deemed to be needed to further decrease the density, thermal conductivity while improving the strength, especially the flexural strength, by adding short fibers in the future.

It is noted that good quality recycled sand produced by wet processing method was used in this study, which has the bulk specific gravity of 2.47-2.51 and the water absorption of 2.34%. It was assumed by the authors that it would be efficient to utilize recycled sand for the fabrication of ULFC taking advantage of the relatively low density of RFA and high alkalinity of the cementitious mixture including RFA. It is believed that the similar results can be reached by using the recycled sand with even larger amount of adhered mortar: i.e. recycled sand with lower density and higher water absorption.

4. Conclusions

In this study, ULFC with reduced environmental footprint was fabricated using Type 3 Portland cement and cementitious substitutions such as silica fume, fly ash as well as 100% recycled fine aggregates. The results of investigation can be summarized as follows:

1) This study used H_2O_2 as the foaming agent and HPMC as the foam stabilizer. Introduction of the foam stabilizer had a big impact in lowering the density of the hardened concretes;
2) ULFC with dry density as low as 284 kg/m^3 and 0.092 W/mK thermal conductivity was developed by chemical foaming method.
3) Low density in this study was achieved only at the cost of compressive strength. Use of increasing amount of fly ash increased flow of the ULFC, but also decreased strength; and
4) It was efficient to utilize recycled fine aggregates for the fabrication of ULFC taking advantage of the relatively low density of the recycled fine aggregates and high alkalinity of the cementitious mixture including the recycled fine aggregates.

Acknowledgement

This research was supported by Global Infrastructure Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (grant number: 2021K1A3A1A20001722).

References

[1] Sang G., Z.Y., Yang G., Zhang H, (2015). Proportions and characterization of high porosity cement-based foam material, Construction and Building Materials, 91, 133-137.

[2] Zhang, X.Z., Yang, Q., Shi, Y.Y., Zheng, G.F., Li, Q.F., Chen, H., Cheng, X., (2020). Effects of different control methods on the mechanical and thermal properties of ultra-light foamed concrete, Construction and Building Materials, 262.

[3] Jin, L., Chen, S., Zhao, Y., Zeng, Q., Huang, Z.P., Li, M., Shi, Y.J., (2021). Characterizing the foam-shell microstructure of industrial ultra-light foamed concrete cast under different temperatures, Materials Characterization, 173.

[4] KCI, (2022). guideline on lightweight concrete for non-structural use, Korea Concrete Institute.

[5] Falliano, D., Restuccia, L., Ferro, G.A., Gugliandolo, E., (2020). Strategies to increase the compressive strength of ultra-lightweight foamed concrete, 1st Virtual European Conference on Fracture - Vecf1, 28, 1673-1678.

[6] Kim, H.K., Jeon, J.H., Lee, H.K., (2012). Workability, and mechanical, acoustic and thermal properties of lightweight aggregate concrete with a high volume of entrained air, Construction and Building Materials, 29, 193-200.

[7] Aguilar, A.S., Melo, J.P., Olivares, F.H., (2013). Microstructural analysis of aerated cement pastes with fly ash, Metakaolin and Sepiolite additions, Construction and Building Materials, 47, 282-292.

[8] Li, T., Huang, F.M., Zhu, J., Tang, J.H., Liu, J.p., (2020). Effect of foaming gas and cement type on the thermal conductivity of foamed concrete, Construction and Building Materials, 231.

[9] Ramamurthy, K., Nambiar, E.K.K., Ranjani, G.I.S., (2009). A classification of studies on properties of foam concrete, Cement & Concrete Composites, 31, 6, 388-396.

[10] Chen, B., Liu, J.Y., (2008). Experimental application of mineral admixtures in lightweight concrete with high strength and workability, Construction and Building Materials, 22, 6, 1108-1113.

[11] Ahmad, M.R., Chen, B., Shah, S.F.A., (2019). Investigate the influence of expanded clay aggregate and silica fume on the properties of lightweight concrete, Construction and Building Materials, 220, 253-266.

[12] Seker, B.S., Gokce, M., Toklu, K., (2022). Investigation of the effect of silica fume and synthetic foam additive on cell structure in ultra-low density foam concrete, Case Studies in Construction Materials, 16.

[13] Gopalakrishnan, R., Sounthararajan, V.M., Mohan, A., Tholkapiyan, M., (2020). The strength and durability of fly ash and quarry dust light weight foam concrete, Materials Today-Proceedings, 22, 1117-1124.

[14] Chinzorigt, G., Lim, M.K., Yu, M., Lee, H., Enkhbold, O., Choi, D., (2020). Strength, shrinkage and creep and durability aspects of concrete including CO2 treated recycled fine aggregate, Cement and Concrete Research, 136.

[15] KS F 2573, (2014). Recycled aggregates for concrete, KATS.

[16] KS F 2459, (2017). Standard test method for bulk specific gravity, water content, absorption and compressive strength of cellular concrete, KATS.