Korean J. Chem. Eng., 34(5), 1385-1392 (2017)
DOI: 10.1007/s11814-017-0019-z

pISSN: 0256-1115
eISSN: 1975-7220

Performance improvement of local Korean natural hydraulic lime-based mortar using inorganic by-products

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(*Received 18 August 2016 • accepted 6 February 2017*)

Abstract−Our goal was to verify the manufacturing availability of local Korean natural hydraulic lime (K-NHL) using local Korean low-grade limestone and to test the basic physical properties on the basis of EU standards (BS EN 459-1:2015). We also sought to improve the physical properties of natural hydraulic lime by adding inorganic by-products such as blast furnace slag and silica fume. Where the inorganic by-products were not incorporated, properties such as soundness, air content, particle size, and water absorption (excluding compressive strength and setting time) did not show significant differences with the physical properties evaluated based on EU standards. Also, in terms of the composition of hydraulic phase, local Korean NHL A5 and A8 were similar to NHL 2 of EU standards, whereas local Korean NHL HL correlated with NHL 3.5 or NHL 5. When inorganic by-products were added, the compressive strength and setting time were improved.

Keywords: Natural Hydraulic Lime, Mortar, Inorganic By-product, Blast Furnace Slag, Silica Fume

INTRODUCTION

The use of hydraulic lime as a building material declined with the introduction of portland cement. However, with rapid urbanization from the early 20th century, hydraulic lime remained a significant multi-functional and eco-friendly material [1-4]. In countries where hydraulic lime is widespread, it is still regarded as a suitable material for many older buildings using lime. It is also actively used as a building material for modern buildings, as primary material, bonding agents, and interior/exterior materials, and the development of hydraulic lime as an eco-friendly energy efficient material is also being explored [1,5,6].

Natural hydraulic lime (NHL) is the highest grade material among the hydraulic limes complying with EU standards and the most eco-friendly construction material manufactured using low-grade limestone of high SiO_2 content. It is classified as NHL 2, NHL 3.5, and NHL 5 in accordance with the compressive strength at 28 days and the content of hydraulic minerals when manufacturing mortar. To express the specific properties, it was formerly referred to as HL (Hydraulic lime), FL (Formulated lime) etc., for use in mixing with organic/inorganic admixtures [1,2,7,8].

For hydraulic lime, the hardening reactions form a micro-porous structure due to the long-term curing properties. These result in simultaneous non-hydraulic and hydraulic characteristics, and the related structural properties increase the constant temperature and humidity, insulation, and resistance to water and salt; consequently, excellent pliability and permeability are observed [9-12]. The properties are dependent on manufacturing variables such as the mixing ratio of mortar, curing conditions, and types of admixtures [13-16]. Therefore, a wide range of applications can be realized, but not all kinds of limes exhibit useful characteristics and further research is necessary [6,17,18]. In South Korea, the use of lime-based binder has been rare and the awareness of NHL has been low; accordingly, experience with its use and experimental activities released in professional publications and patents are minimal. In this context, the present study verified whether the local Korean natural hydraulic lime (K-NHL) can be manufactured by utilizing the local Korean low-grade limestone, and identified the improved physical properties of NHL when inorganic admixtures are added.

MATERIALS AND METHODS

1. Raw Materials

The NHL was prepared by using three different types of low grade limestone produced in Korea. Table 1 shows the chemical compositions of the low grade limestone. The content of the components contributing to the formation of hydraulic mineral phases was about 7.89%-15.13% SiO_2 and about 41.42%-46.53% CaO, indicating that NHL can be easily prepared from the limestone. For the calcination of the raw materials, the low grade limestone was crushed into pieces of 10 to 20 mm. The calcination was at 1,250 °C, for two hours. Afterwards, hydration, drying, and pulverization were per-

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Table 1. Chemical compositions of the low-grade limestone

Low-grade limestone	Chemical composition (%)				
	SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3
A5	7.89	46.53	1.27	1.96	0.94
A8	13.95	41.58	1.34	2.99	1.12
HL	15.13	41.42	1.19	2.27	0.94

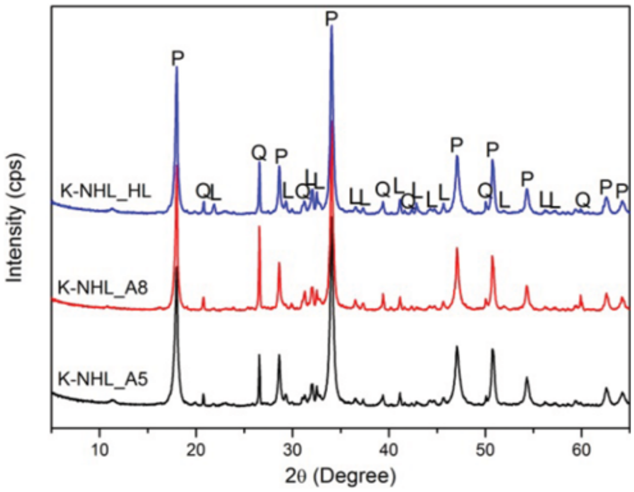


Fig. 1. XRD diffractograms in the 5-65° 2θ angular range of K-NHL. P=portlandite ($Ca(OH)_2$), L=larnite ($2CaO\cdot SiO_2$), Q=quartz (SiO_2).

Table 2. List of the samples according to the type of K-NHL

Type of NHL	Sample name
NHL produced using the local Korean low-grade limestone	K-NHL_A5 K-NHL_A8 K-NHL_HL
K-NHL_A5+BFS 20%	K-NHL_A5_BFS20
K-NHL_A8+BFS 20%	K-NHL_A8_BFS20
K-NHL_HL+BFS 20%	K-NHL_HL_BFS20
K-NHL_A5+SF 20%	K-NHL_A5_SF20
K-NHL_A8+SF 20%	K-NHL_A8_SF20
K-NHL_HL+SF 20%	K-NHL_HL_SF20

formed to produce the final product. Fig. 1 presents the XRD analysis results of K-NHL_A5, K-NHL_A8, and K-NHL_HL utilizing local Korean low-grade limestone. The hydraulic phase is composed of $Ca(OH)_2$, C_2S, and un-reacted SiO_2, where the majority of K-NHL is C_2S and $Ca(OH)_2$, showing a difference in the phases content depending on the types of low-grade limestone. Table 2 presents the name of each sample.

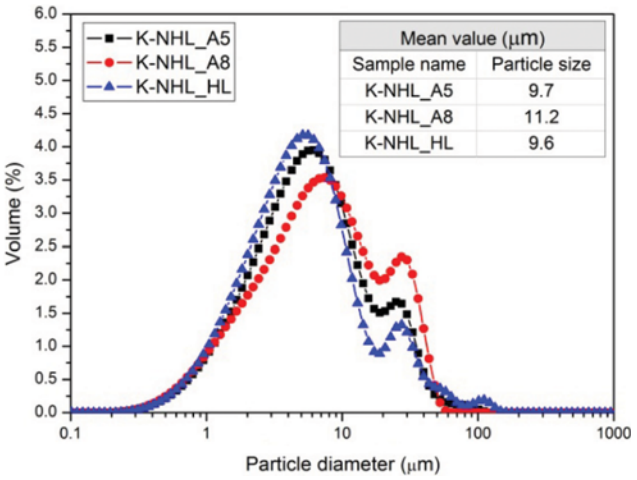


Fig. 2. Particle size and distribution of K-NHL.

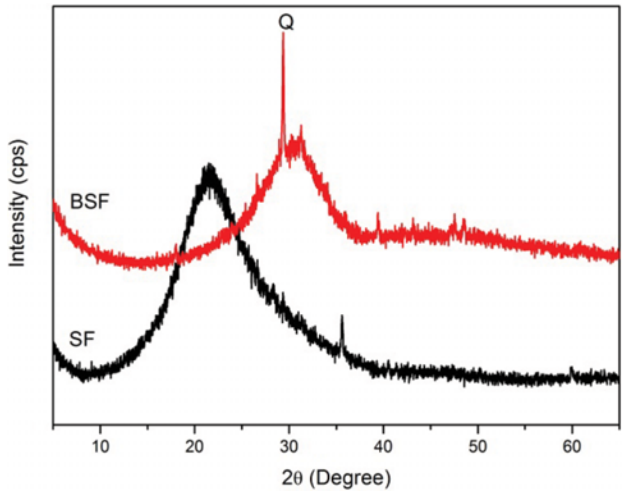


Fig. 3. XRD diffractograms in the 5-65° 2θ angular range of BFS and SF. Q=quartz.

Fig. 2 indicates the results of particle size and distribution of K-NHL. K-NHL was pulverized by utilizing ACM (air classified mill), and the average particle sizes of K-NHL_A5, K-NHL_A8 and K-NHL_HL were 9.7 μm, 11.2 μm, and 9.6 μm, respectively. Table 3 and Fig. 3 provide the chemical analysis results and the mineral phase analysis results on blast furnace slag (BFS) and silica fume (SF). The chemical analysis results of Table 3 show that in the case of BFS, large amounts of CaO, SiO_2, and Al_2O_3 are incorporated: CaO 46.9%, SiO_2 29.6%, and Al_2O_3 13.5%. The main compound of

Table 3. Chemical compositions of inorganic admixture

Inorganic admixture	Chemical composition (%)								
	SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	SO_3	Na_2O	K_2O	Sum
BFS	29.6	46.9	5.52	13.5	0.42	2.01	0.19	0.45	98.59
SF	89.9	5.35	0.73	1.20	0.24	0.09	0.17	1.50	99.18

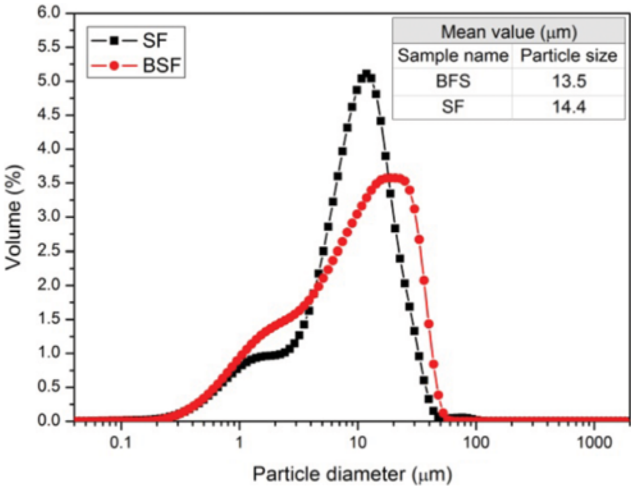


Fig. 4. Particle size and distributions of BFS and SF.

SF was SiO_2 with content of 89.9%. From the mineral phase analysis of Fig. 3, both BFS and SF are amorphous mineral phases. As BFS contains a combination of SiO_2 and Al_2O_3 by hydraulic reaction, calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H) are generated, and it is assumed they will show excellent properties in compressive strength and condensation. However, SF is mainly composed of SiO_2 as its main compound, and it is thought the generation of calcium aluminate hydrate is somewhat minimal. However, it is predicted that, along with C-S-H generation on the surface of particles of SF, the particles will enhance the pore density in a micro-filler role and contribute to an increase in strength [19,20].

Fig. 4 presents the analysis results for the particle size distributions of BFS and SF. Average particle sizes of admixtures are 13.5 μm in the case of BFS, and 14.4 μm in the case of SF, which are not substantially different from K-NHL.

2. Mortar Preparation and Physical Test Methods

Specimen preparation and test methods analyzing the physical properties as per the types of NHL were processed according to BS EN 459-2:2015. Experimental procedures per test item are as follows.

2-1. Compressive Strength

To classify the types of K-NHL, a mortar with a mixture of NHL : sand : water=1 : 3 : 0.5 was manufactured, and to verify the compressive strength properties in accordance with the water/binder ratio (*w/b*) by weight, additional mortars with ratios of *w/b* 0.6 and 0.7 were manufactured. When manufacturing mortars in accordance with *w/b*, flow differences were prominent in relation to the sample properties. To verify the compressive strength properties as per the sample properties when a specific flow was given, mortars were manufactured by fixing the flow (165±3) mm.

To investigate the compressive strength characteristics of NHL with the addition of inorganic admixtures, the compressive strength with mixed amounts (1, 5, 10, and 20%) was examined to check the compressive strength properties of K-NHL. When manufacturing mortars with admixtures, the water ratio of the flow (165±3) mm was applied. Prismatic specimens were made at (40×40×160) mm size and housed into two layers and compacted by utilizing a jolting apparatus. The manufactured specimens were cured at 20 °C and relative humidity 95%. The compressive strength was tested at 28 days, and when measuring the compressive strength, the loading speed was set at 144 kN/min. The compressive strength was calculated in accordance with Eq. (1) by measuring the maximum load of each sample.

$$R_c=\frac{F_c}{1600} \tag{1}$$

Here, R_c is the compressive strength (MPa), F_c (N) represents the maximum load, and 1600 is the square area over which the load is applied.

2-2. Soundness

After manufacturing pastes with NHL (25±0.1) g at a *w/b* of 0.6, samples were made to sizes of 50 mm in diameter and 10 mm in height. Most samples were manufactured as pastes at a *w/b* of 0.6, and the manufactured pastes were cured at 20 °C and relative humidity 95% for 48 hours before the experiment was undertaken. The diameters of all the samples were measured twice to calculate the average diameter (D_i).

Samples were set in steam at 85 to 95 °C for 90 minutes, and after steaming, each sample's diameter (D_e) was calculated. By applying the size changes before and after steaming to Eq. (2), the soundness of each sample was measured.

$$\text{Soundness (mm)}=(D_e-D_i) \tag{2}$$

Here, D_i (mm) presents the average value of the sample diameter before steaming, and D_e (mm) presents the average value of the sample diameter after steaming.

2-3. Air Content

EU criteria stipulate that in the case of NHL 2 and NHL 3.5, the basic *w/b* ratio of mortar should be flow of (165±3) mm for measuring air content, and in the case of NHL 5, which offers excellent hydration properties, it is regulated as a flow of (185±3) mm. We focused on NHL 3.5, and set the *w/b* ratio as flow of (165±3) mm because the types of NHL can be predicted but cannot be clearly classified. Mortars manufactured in accordance with EU criteria at NHL : sand : water=1 : 3 : x (flow (165±3) mm) were measured for air content in an unconsolidated state by utilizing a test device of 0.1 m^3 capacity that was applied by a compressive method. Table 4 shows the *w/b* ratios of each sample.

Table 4. Water/binder ratios of K-NHL mortars with flow (165±3) mm

Sample name	Flow (mm)	Water/binder ratio
K-NHL_A5	165±3	0.80
K-NHL_A8		0.75
K-NHL_HL		0.80
K-NHL_A5_BFS20		0.80
K-NHL_A8_BFS20		0.75
K-NHL_HL_BFS20		0.80
K-NHL_A5_SF20		0.87
K-NHL_A8_SF20		0.88
K-NHL_HL_SF20		0.87

Table 5. Water/binder ratios of K-NHL paste with distance between plunger and needle of (6±2) mm

Sample name	Water/binder ratio
K-NHL_A5	0.60
K-NHL_A8	0.52
K-NHL_HL	0.56
K-NHL_A5_BFS20	0.57
K-NHL_A8-BFS20	0.49
K-NHL_HL-BFS20	0.54
K-NHL_A5-SF20	0.80
K-NHL_A8-SF20	0.76
K-NHL_HL-SF20	0.79

2-4. Setting Time

Paste was set of its *w/b* ratio as the distance between the plunger and the base plate of (6±2) mm, and placed into a mold with a diameter of (75±10) mm and a height of (40±0.2) mm, and after curing at 20 °C and relative humidity 95% for 30 minutes, the initial setting time was assessed. After the initial setting was completed, by turning over the mold, the final setting time was assessed utilizing the base of the specimen. Table 5 presents the water ratios of each sample.

2-5. Water Absorption

After mortar samples with size of (40×40×40) mm were made, they were dried at 105±5 °C for 72±2 hours, and the weights of each sample were measured after drying. Putting the samples into an amount of water that would allow them to be sufficiently soaked in their vessels, the absorption capacity was calculated in accordance with Eq. (3) by measuring the weight changes of the mortar in time intervals of 10, 30, 60, 90, and 120 minutes.

$$\mathrm{WA} = \frac{\mathrm{M}_s - \mathrm{M}_d}{\mathrm{M}_d} \times 100 \tag{3}$$

Here, WA is the absorption (%), M_d is the mass (g) after drying, and M_s is the mass (g) after absorption.

3. Paste Preparation

To investigate the hydration properties of K-NHL paste when adding inorganic admixtures in K-NHL, the hydration properties with mixed amounts (5, 10, and 20%) of BFS and SF were examined to check the hydrates of K-NHL. When manufacturing pastes with admixtures, a water ratio of 60% was applied. NHL has setting and hardening properties when mixed with water and by reaction with carbon dioxide from the air. To show these characteristics, fresh NHL paste was placed on a plastic plate with a thickness of (5-8) mm, and kept at 20 °C and relative humidity of 95% until being analyzed after 28 days. The morphology of these hardened pastes was investigated by means of scanning electron microscopy (SEM, Hitachi, S-4300), and the hydrates that formed were identified using differential scanning calorimetry (DSC, Netzsch, STA449C Jupiter).

RESULTS AND DISCUSSION

1. Compressive Strength

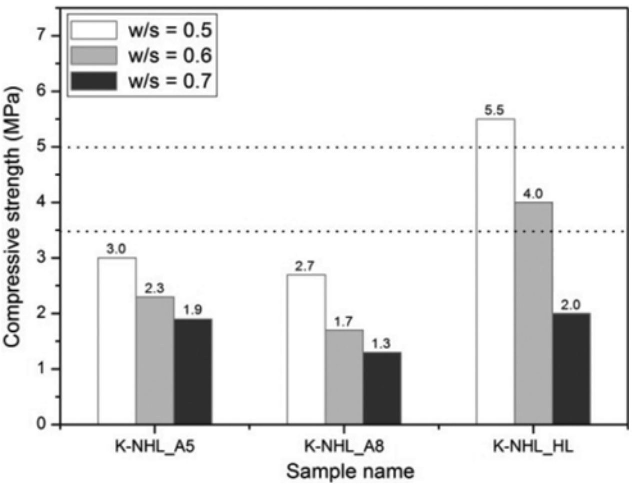


Fig. 5. Compressive strength of K-NHL mortar with water/binder ratio after 28 days. Dotted lines indicate the minimum strength threshold required by EU standards for a NHL 3.5 binder and for a NHL 5 binder.

Fig. 5 shows the assessment results of compressive strength correlated with the *w/b* ratio of K-NHL. The compressive strength properties are excellent, in the order of K-NHL_HL, K-NHL_A5, and K-NHL_A8. At the *w/b* ratio of 0.5, the mortar compressive strength of K-NHL_HL was 5.5 MPa, which represents excellent compressive strength to meet NHL 5 in the EU criteria. And those of K-NHL_A5 and K-NHL_A8 were respectively 3.0 MPa and 2.7 MPa, which represent compressive strength properties that meet NHL 2 in accordance with the properties of the samples themselves.

Overall, as the *w/b* ratios increase, the compressive strength decreases. Water inside the mortar will reduce, and this forms air pores from the cycles of hydrates and evaporation. This is an important factor for the carbonation reaction as it affects the moving path of CO_2, and also leads to improved physical properties. However, if a large amount of water is retained, air pores may not actively form because the water loss rate is slow; on the contrary, the formation of a large amount of air pores may lead to a decrease of durability [21]. Consequently, the optimal selection of the water rate may be important to ensure adequate compressive strength and appropriate workability.

Fig. 6 shows the compressive strength assessment results of K-NHL mortars prepared with the flow set as (165±3) mm. The compressive strength assessment of K-NHL without the addition of inorganic admixtures was K-NHL_A5, K-NHL_A8, and K-NHL_HL, respectively, at 1.2 MPa, 1.3 MPa, and 1.4 MPa. As the mixing rate of both admixtures increased, the compressive strength increased. BFS shows compressive strength of 4.3 MPa when the mixing rate was 10%, and 5.9 MPa at 20%. BFS is a potential hydraulic substance, and its strength may be reduced because of its somewhat low reactivity at the initial curing period. However, after 28 days, it shows properties of a continued increase of strength [22-24]. SF shows better compressive strength properties than those of K-NHL mixed with BFS, reaching a maximum of 4.4 MPa with a 5% mixing rate, and 6.8 MPa with a 10% mixing rate, and 8.8 MPa with a 20% rate. SF is an amorphous substance that performs a pozzolanic reaction. It is composed of very fine particles that cause the

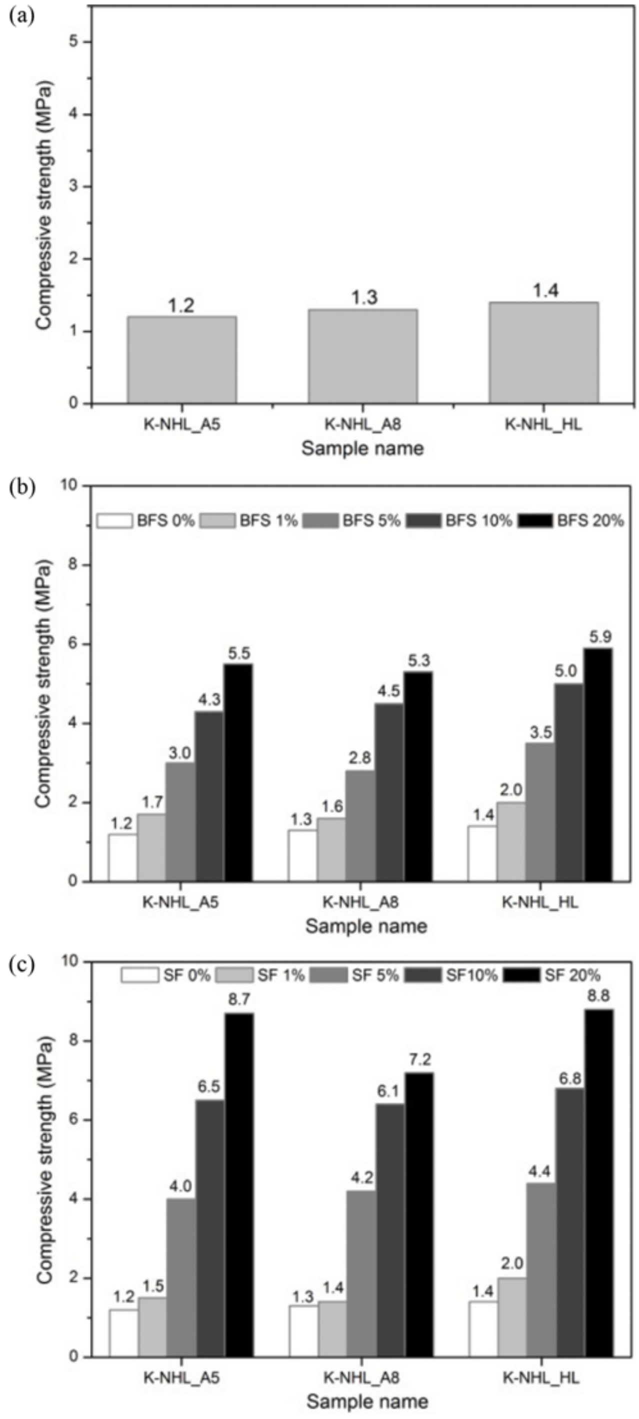


Fig. 6. Compressive strength of K-NHL mortars prepared to set the flow as (165±3) mm after 28 days. (a) Plain mortar, (b) Mortar with BFS, (c) Mortar with SF.

initial hydration reaction to occur quickly, and it plays the role of a micro-filler to fill the inside pores of hydrates, thus lending better development of strength [19,25].

Fig. 7. Photograph of hardened K-NHL_HL_BFS20 and K-NHL_HL_SF20 mortars after 28 days.

Table 6. Setting time of K-NHL pastes

Sample name	Initial setting time (min)	Final setting time (min)
K-NHL_A5	2610	4140
K-NHL_A8	2700	3960
K-NHL_HL	2640	3960
K-NHL_A5_BFS20	730	920
K-NHL_A8-BFS20	245	450
K-NHL_HL-BFS20	415	450
K-NHL_A5-SF20	1250	2120
K-NHL_A8-SF20	940	1100
K-NHL_HL-SF20	870	1065

To examine the color change of the mortar specimen due to the addition of the inorganic admixture, photographs of K-NHL_HL_BFS20 and K-NHL_HL_SF20 mortar after 28 days are shown in Fig. 7. As shown in the figure, it was confirmed that there is no color change of the mortar specimen due to the inorganic admixture.

2. Setting Time and Soundness

Table 6 indicates the setting time measurement results of K-NHL. K-NHL showed properties that do not comply with the EU standards, as the initial setting time is 2,610 min to 2,700 min, and the final setting time is up to 4,140 min. On the other hand, the mixture with BFS showed property values that comply with EU standards by reducing the initial setting time by more than 1,800 min and the final setting time by more than 3,600 min, with records of 415 min for the initial setting time and 450 min for the final setting time of K-NHL_HL than the setting time properties of K-NHL. SF showed the overall setting time by 900 to 1,500 min, but it presented later setting properties than when mixed with BFS, and showed properties that meet EU standards. It is considered that BFS may be suitable for admixtures to shorten the setting time.

Table 7 shows the soundness assessment results of K-NHL. Soundness is parameter to assess the properties of shrinkage and expansion and the long-term durability of the samples. Overall, the deviation rates of both K-NHL specimens were set within ±2 mm to meet EU standards. K-NHL_A8 showed excellent soundness without shrinkage and expansion, and K-NHL_A5 and K-NHL_HL presented excellent soundness properties with 0.5 mm shrinkage.

Adding BFS or SF resulted in expansion in most of the samples. Mixing K-NHL_HL and BFS 20% showed somewhat high expansion of +1.0 mm. However, other samples showed high sound-

Table 7. Soundness of K-NHL mortars

Sample name	1st Test			2nd Test		
	Diameter 1 (mm)	Diameter 2 (mm)	Average (mm)	Diameter 1 (mm)	Diameter 2 (mm)	Average (mm)
K-NHL_A5	0	−1	−0.5	0	0	0
K-NHL_A8	0	0	0	0	0	0
K-NHL_HL	−1	0	−0.5	−1	−1	−1
K-NHL_A5_BFS20	+1	0	+0.5	0	+1	+0.5
K-NHL_A8_BFS20	1	+1	+1	+1	0	+0.5
K-NHL_HL_BFS20	+1	0	+0.5	+1	+1	+1.0
K-NHL_A5_SF20	0	0	0	+1	0	+0.5
K-NHL_A8-SF20	+1	0	+0.5	0	0	0
K-NHL_HL-SF20	0	0	0	0	+1	+0.5

Table 8. Air content of K-NHL mortars

Sample name	Air content (%)
K-NHL_A5	1.4
K-NHL_A8	1.9
K-NHL_HL	2.0
K-NHL_A5_BFS20	2.8
K-NHL_A8_BFS20	2.3
K-NHL_HL_BFS20	2.8
K-NHL_A5_SF20	2.0
K-NHL_A8_SF20	2.9
K-NHL_HL_SF20	2.1

Table 9. Absorption of K-NHL mortars after 28 days

Sample name	Absorption (%)				
	10 min	30 min	60 min	90 min	120 min
K-NHL_A5	13.6	13.7	13.8	14.3	13.6
K-NHL_A8	15.2	15.2	15.3	15.1	15.2
K-NHL_HL	15.2	15.2	15.3	15.1	15.2
K-NHL_A5_BFS20	15.1	15.4	15.2	15.2	15.2
K-NHL_A8_BFS20	13.4	13.9	13.4	13.8	13.8
K-NHL_HL_BFS20	15.4	15.6	15.8	15.9	15.8
K-NHL_A5_SF20	19.2	19.7	19.6	19.6	19.5
K-NHL_A8_SF20	17.1	17.1	17.0	17.2	17.0
K-NHL_HL_SF20	18.7	19.2	19.1	19.1	19.1

ness of +0.5 mm, even though they were produced by mixing inorganic admixtures.

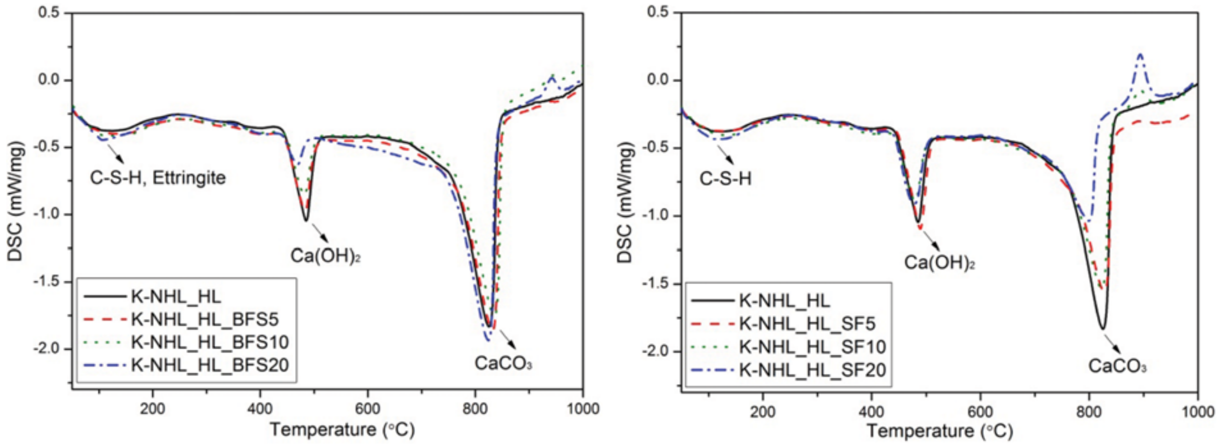
3. Air Content and Water Absorption

Table 8 presents the measurement results of air content for K-NHL. The measurement results of air content showed that all the samples were within 5% air content, thus not complying with the EU standards. Overall, although the differences among individual samples were not great, the lower air content was similar to the samples with lower content of hydraulic phases. Adequate air content can improve workability and durability and reduce drying shrinkage. However, as the particles become finer, and the amount of unit cement becomes larger, air content will decrease [26]. K-NHL_A5 presented relatively low hydration properties and high fineness due to the high content of fine particle $Ca(OH)_2$ (Fig. 2), and this resulted in relatively low air content. On the contrary, it is speculated that because K-NHL_A8 contained more hydraulic phases and had higher specific gravity than K-NHL_A5. In the case of mixing inorganic admixtures into K-NHL, higher air content was present, but it showed properties complying with the standards, with air content of 2.0 to 2.9%. Air content is the result of the fresh mortar, and it is difficult to explain it directly in relation to the development of the long-term strength. This is because hydrates are formed as the hydration time and the pores in hardened mortar change depending on the types and amount of hydrate that are formed.

Table 9 shows the measurement results for the absorption of K-NHL. The adsorption of K-NHL was 13.6 to 15.2%. The difference in absorption has a strong correlation with the inner density of the mortar. As hydration and carbonation occur, $CaCO_3$ particles grow and hydrates such as C-S-H and ettringite are generated, filling the air pores and increasing the inner density, which results in a tendency of lower absorption. In accordance with the addition of inorganic admixtures, similar or higher levels of absorption to other K-NHL mortars were observed. Mixing with BFS showed similar absorption of K-NHL_A8 and K-NHL_HL. Mixing with SF tended to increase absorption as the mixing rate increased, and in the case of mixing K-NHL_A5 and SF 20%, maximum absorption of 19.7% was shown. K-NHL_A5 was the sample with the lowest hydration properties; however, due to later reaction properties than K-NHL_A8 and K-NHL_HL, respectively, the inner humidity loss rate was more pronounced. It is considered that the hydration reaction occurred so slowly that it might show high absorption as the inner ratio of voids was relatively high. The water absorption may be similar between the specimens, but the overall pore size distribution was not similar. For this reason, the relationship between water absorption and strength was not proportional. When the SF was mixed, the water adsorption was larger than in the other specimens, but the strength was higher than that of the other specimens. Therefore, it is considered that the distribution of smaller micropores was larger than that of other specimens.

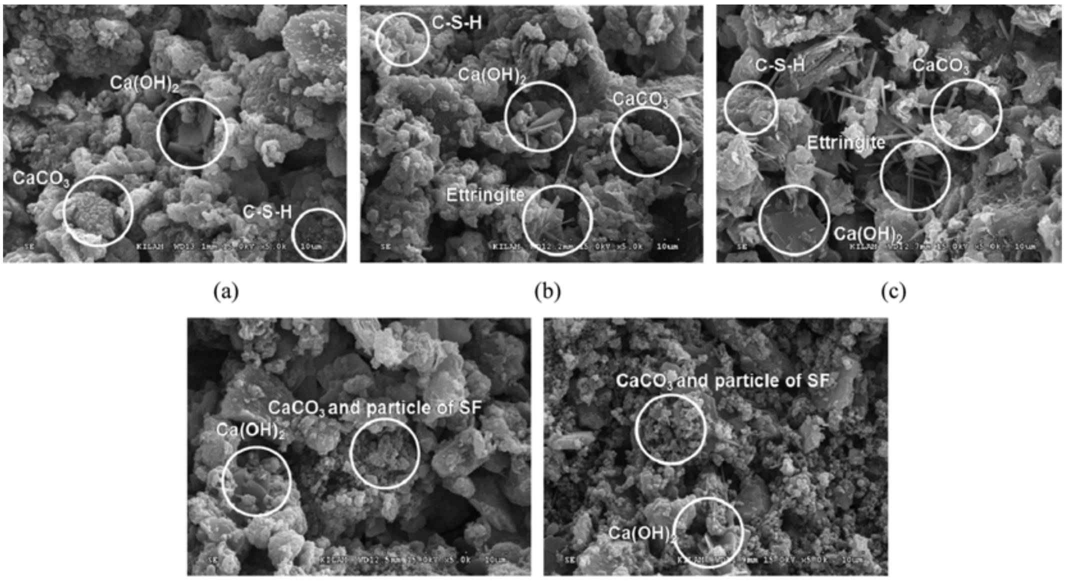
4. Hydration Properties

The results of the DSC analysis conducted for BFS and SF replaced K-NHL_HL pastes after 28 days are presented in Fig. 8.



(a) (b)

Fig. 8. DSC curves of NHL pastes after 28 days. (a) K-NHL_HL mixed with BFS, (b) K-NHL_HL mixed with SF.



(d) (e)

Fig. 9. SEM images of NHL pastes after 28 days. (a) K-NHL_HL, (b) K-NHL_HL_BFS5, (c) K-NHL_HL_BFS20, (d) K-NHL_HL_SF5, (e) K-NHL_HL_SF20.

Since dehydration of capillary water occurs at about 100 °C and an endothermic effect take place at a (100-200) °C temperature range, dehydration developed in hydration products such as the C-S-H gel and ettringite in the hardened NHL pastes. Also, dehydroxylation of $Ca(OH)_2$ was observed in a temperature range of (420-475) °C. The endothermic peaks by the thermal decomposition of $CaCO_3$ were detected at about 800 °C. The endothermic peaks by dehydration of hydrates were increased by the latent hydraulic reaction of BFS and the pozzolanic reaction of SF with an increase of BFS and SF content. Meanwhile, the dehydroxylation of $Ca(OH)_2$ decreased with an increase of inorganic admixtures, and C-S-H formed due to the hydraulic reaction between the Si source in the inorganic admixture and $Ca(OH)_2$ was increased.

The morphology of the hardened K-NHL pastes in the presence of BFS and SF is presented in Fig. 9. In the case of the addition of BFS, needle-like type ettringite and foil-like type C-S-H are created by the latent hydraulic reaction and these phases are presented in Fig. 9(a). These phases play a role in filling pores in the hardened paste, thereby facilitating the development of compressive strength due to the increase of these phases with the addition of BFS. In the case of the addition of SF, the main mineral phase was foil-like type C-S-H. Also, it is composed of very fine particles which act as a micro-filler to fill the inside pores of hydrates. As shown in Fig. 9(b), the paste texture mixed with 20% SF became denser than that of 5% SF due to filling the pores by spherical type SF particles and C-S-H.

CONCLUSION

Major mineral phases of K-NHL manufactured using local Korean low-grade limestone are $Ca(OH)_2$, C_2S, and un-reacted SiO_2. It was revealed that manufacturing K-NHL with compressive strength to comply with NHL 2 (K-NHL_A5: 3.0 MPa, K-NHL_A8: 2.7 MPa) or NHL 5 (K-NHL_HL: 5.5 MPa) based on BS EN 459-1:2015 is possible. Also, considering the significant difference in workability in accordance with water ratios as per the physical properties of each sample, the selection of an appropriate water ratio is expected to be important in practical application.

An assessment of physical properties shows that there was no significant difference among most of the properties. Such differences in properties depended upon whether the mineral phases affecting the initial compressive strength were in the NHL itself. To improve the physical properties of K-NHL, BFS and SF were incorporated. This did not result in any significant difference in the other specific properties that were assessed except the compressive strength and setting time. In the case of BFS, when the mixing rate was 10%, it showed similar compressive strength to NHL 5 in the EU standards, and in the case of silica fume, at a mixing rate 5%, it showed similar compressive strength with that of NHL 5 in the EU standards. In the case of setting time, when mixing BFS at 20%, the initial setting time was shortened by up to 1,800 min, and the final setting time was also reduced by up to 3,600 min, complying with the property values specified in BS EN 459-1:2015. Overall, adding inorganic admixtures could improve the physical properties such as compressive strength and setting time and, furthermore, manufacturing K-NHL to comply with the properties values specified in the EU standards would be possible.

ACKNOWLEDGEMENT

This work was supported by a grant (2013) from the Energy Technology Development Program (2013T100100021) funded by the Ministry of Trade, Industry and Energy of the Republic of Korean Government.

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