pISSN 1598-2033
eISSN 2233-5706

Journal of the Korea Institute of Building Construction, Vol. 13, No. 3
http://dx.doi.org/10.5345/JKIBC.2013.13.3.253

www.jkibc.org

Evaluation of the Performance of the PVA Fiber Reinforced Inorganic Binder and Industrial By-products Building Board

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Abstract

The test on the mix of PVA fiber of low carbon inorganic composite as a cement substitute found it to be satisfactory in terms of flexibility and stiffness. The result of the evaluation of the properties of low carbon inorganic panel revealed that the absorptivity was low at 8 to 9%, which is lower than the KS value of 25%. Also, the test on non-combustibility and gas toxicity found that these factors satisfied the decision criteria. In the test on heavy metals discharges, Pb, Cd, Cr6+, Hg, and As were not detected. Regarding far-Infrared emissivity and formaldehyde emission, the substitute was found to be harmless to the human body. Therefore, if the issue of shrinkage, which is a disadvantage of inorganic composites, is addressed, it is judged that it is possible to develop a low carbon inorganic composite panel with better performance.

Keywords : low carbon, inorganic composite, alkali accelerator, building board

1. Introduction

1.1 Research background and objective

Wall panels, a secondary product in the cement industry, have increasingly been used in masonry or block structures to reduce the construction duration, make a structure lighter or compensate for a lack of professional and skilled construction workers. The korean government has been giving builders incentives to construct rahmen-structured apartments under the housing performance grading system, such as by allowing a higher floor area ratio. For example, for the rahmen structure, lightweight composite panels using EPS and extrusion molding cement complex panels are mainly used, and CRC boards made of cement are employed as the surface material for panels.

The burning process in the production of cement consumes a huge amount of energy, requiring temperatures of 1300℃ or higher, and the greenhouse gas generated in cement production amounts to 37.4 million tons (as of 2005) or 6.3% of the entire greenhouse gas emission in Korea, which means about 0.8 tons of CO_2 is emitted to produce one ton of cement. In fact, cement production creates about 7-8% of the world's greenhouse gases[1,2].

In addition, the construction materials made of cement as a main ingredient have been highlighted as a problem because they include heavy metals and hazardous materials including Pb, Cd, Cr^{6+}, Hg, and As, which can cause health problems for the human body or an unpleasant feeling.

Efforts should be made to reduce CO_2 emissions in the cement industry. For this reason, concrete manufacturers in Korea and overseas have taken a

Received : November 26, 2012
Revision received : March 31, 2013
Accepted : April 5, 2013
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keen interest in eco-friendly cement production, and are making efforts to develop new production technologies to reduce CO_2 emissions and produce safe cement containing less hazardous heavy metals.

Table 1. Heavy metals chemical composition in cement products

(Unit : mg/kg)

구분	Cr	Pb	Cd	Ni	K_2O	Na_2O
A Cement	41.0	105.0	2.0	21.0	1.12	0.07
B Cement	29.0	62.0	2.0	17.0	0.88	0.20
C Cement	33.0	350.0	12.0	15.0	1.11	0.31
D Cement	18.0	330.0	15.0	22.0	1.08	0.10
E Cement	7.0	220.0	4.0	13.0	1.21	0.12

*KOREA TESTING & RESEARCH INSTITUT 2007

The aim of this research is to produce a building board, a secondary product, by replacing cement with industrial by-products: blast furnace slag (BFS), red mud (RM), and silica fume (SF), and to assess the characteristics of the board with reinforced bending strength by mixing PVA fiber to the optimal mix proportion of inorganic binder [3,4,5].

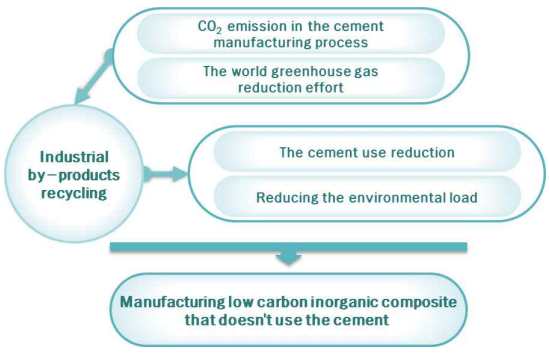

Figure 1. The purpose of study

1.2 The flow of the research

Figure 2 is a flow chart that shows the process of the study. As the basic experiment, reactivity of BFS, SF and RM was tested with five different alkali activators, and the optimal mix proportion was determined in the preliminary experiment by measuring the strength according to changes in Si/Al and CaO content in low-carbonic inorganic binders. As such, the characteristics of the surface material for a low-carbonic inorganic panel were reviewed by adding fiber to the optimal mix proportion of low-carbonic inorganic binder[6].

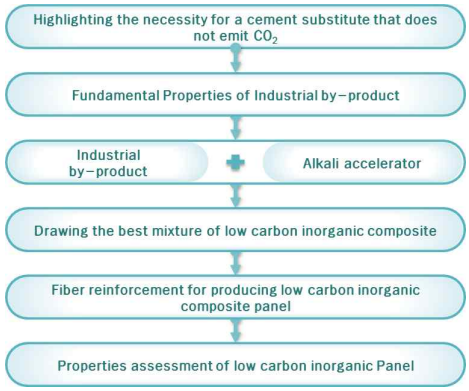

Figure 2. The flow chart of study

2. Basic experimental plan and analysis

The experiment factors and level were set as shown in Table 2, to check the hardened concrete when using BFS, RM, and SF with alkali activator.

To understand the influence of different types of inorganic binders, BFS, RM, and SF were selected from among the industrial byproducts, two liquid types of NaOH and Na_2SiO_3 and three solid types of Na_2SO_4, Na_2CO_3, and K_2SiO_3 were selected as alkali activators, and were added in different levels set at 1, 3, 5, 7, and 10(%).

Table 2. Basic experimental plan

Experimental factor	Experimental level	
Inorganic composite	·Blast Furnace Slag ·Red Mud ·Silica Fume	3
Alkali accelerator	·NaOH, Na_2SiO_3, K_2SiO_3 (Liquid) ·Na_2SO_4, Na_2CO_3 (Solid)	5
Alkali accelerator addition	·1, 3, 5, 7, 10 (%)	5

As illustrated in Figure 3, the specimens with BFS and SF were found to be hardened by all five alkali activators. However, the specimens with SF were hardened slowly compared with the specimens with BFS. On the other hand, the specimens with RM were hardened only by NaOH and Na_2SiO_3. It is believed that RM has an insufficient amount of SiO_2, and Na_2SiO_3 was supplemented for SiO_2, and Na_2O was activated, achieving the result. Therefore, an experiment was planned to derive the optimal mix proportion of the low-carbon inorganic binder by using the liquid alkali activator that was a mix of NaOH and Na_2SiO_3 with the low-carbon inorganic binders that contained BFS, RM, and SF.

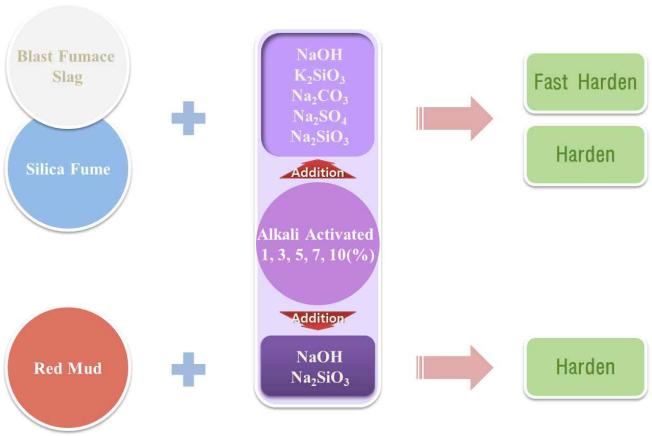

Figure 3. Result of checking the hardening property

3. Preliminary experimental plan for optimal mix proportion and analysis

The preliminary experiment was planned to derive the optimal mix proportion by using liquid alkali activators mixed with NaOH and Na_2SiO_3 of low-carbon inorganic binders that contained BFS, RM, and SF. In addition, the chemical properties of the inorganic binders indicated in Table 3 is a ratio obtained through the process that CaO, SiO_2, and Al_2O_3, the chemical components analyzed by the X-ray florescence analysis(XRF), and the weight of each BFS, RM, and SF within the 400g of the inorganic binder, and then the calculation result was divided by 400g.

Table 3 shows the attempt to understand the strength characteristics based on changes in CaO content and Si/AL of the low-carbon inorganic binder. The Si/Al was set at 4, and then the CaO content was set to be 4 different levels: 20, 25, 30 35(%), after which the CaO content was set at 30% and then Si/Al was set to be 4 different levels: 3,4,5, and 6.

Table 3. Advanced experimental plan

Experimental factor	Experimental level		
Inorganic composite conditions	·CaO content (%)	·20, 25, 30, 35	4
	·Si/Al* ratio	·3, 4, 5, 6	4
Alkali accelerator conditions	·NaOH:Na_2SiO_3 (100 g standard)	·50 g : 50 g	1
	·Amount (binder 400 g standard)	·100	1
Curing conditions	·Relative humidity (60±5) % Temperature (20±2) ℃		1
W/B	·31 %		1
Test item	·Compressive strength, Setting time		1

* Si/Al : SiO_2(molecular weight)/Al_2O_3(molecular weight)

Figure 4 illustrates the compressive strength with changes in CaO content of the low carbon inorganic binder. The higher the CaO content, the faster the alkali activation. As a result, C-S-H gel and sodium hydrates were formed. In addition, the higher the CaO content, the more Ca^+ in the inorganic binder, and all Si was not reacted. More C-S-H gel was formed, and the reaction was accelerated. Therefore, it is believed that the compressive strength improved because of the sodium hydrates, which have low solubility compared to the hydrates generated in ordinary concrete. When the CaO content was 35%, strength development was good, but alkali activator was reacted so quickly that the setting was achieved earlier, which caused a problem in constructability.

When the CaO content was 30%, the strength was developed to be 60MPa or higher, and the hardening time was secured. Therefore, 35% CaO content is believed to be the optimal content for the low-carbon inorganic binder.

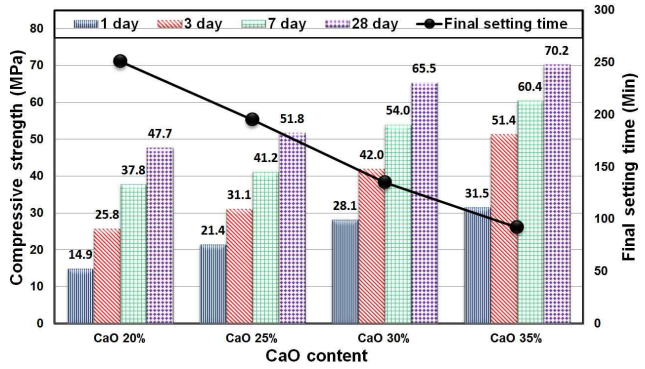

Figure 4. Compressive strength according to CaO content

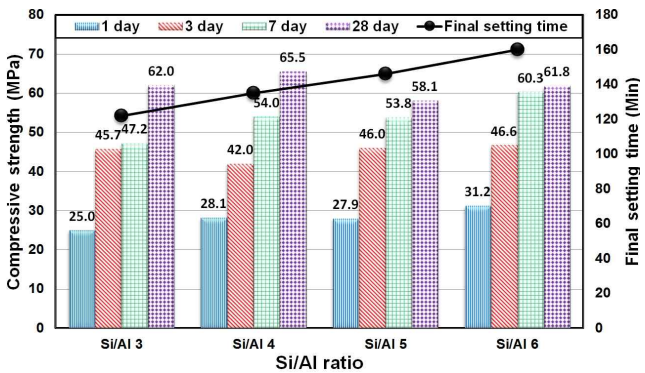

Figure 5. Compressive strength according to Si/Al ratio

In addition, Figure 5 shows the compressive strength with changes in Si/Al. At 28 days, the compressive strength was highest when Si/Al was set at 4, while at 7 days, it was higher than 60MPa when Si/Al was set at 6. On the other hand, the higher the Si/Al ratio, the better the initial strength due to the increase in SiO_2 content within the low carbon inorganic binder. But at 28 days, the compressive strength reached the highest level when Si/Al was set at 4. It is believed that this tendency was found because inorganic binder composition and alkali activation were stable when Si/Al was 4 compared with other levels of Si/Al.

Therefore, Table 4 indicates the optimal mix proportion of the low carbon inorganic binder using the industrial byproducts - BFS, RM, and SF.

Table 4. Best mixture of low carbon inorganic composite

W/B (%)	W* (g)	Alkali accelerator(g)		Experimental level	Inorganic composite chemical component(%)		
		NaOH	Na_2SiO_3		CaO	SiO_3	Al_2O_3
31	60	50	50	CaO 30 % Si/Al 4	29.6	33.5	16.3

* W : mixing water

4. Main experimental plan and analysis

4.1 Main experimental plan and method

Tables 5 and 6 show the experimental plan and mix proportion selected to understand the characteristics of the PVA fiber-reinforced low carbon inorganic binder. In the experiment, the inorganic binder in which BFS, RM, and SF were mixed based on the optimal mix proportion derived in the preliminary experiment was used, along

Table 5. Inorganic composites mixing according to PVA fiber ratio

W/B (%)	W (g)	PVA fiber content (vol.%)	Alkali accelerator (g)		Binder (g)	PVA fiber (g)	Experimental level	Inorganic composite chemical component (%)		
			NaOH	Na_2SiO_3				CaO	SiO_3	Al_2O_3
31	60	0	50	50	400	0	CaO 30 % Si/Al 4	29.6	33.5	16.3
		0.5				0.68				
		1.0				1.37				
		1.5				2.05				
		2.0				2.74				

with the liquid alkali activator mixed with NaOH, and Na_2SiO_3. The PVA fiber was mixed at 5 different levels: 0, 0.5, 1, 1.5, and 2.0(%), and unlike a general secondary product, the high-temperature burning process was not needed as part of the setting condition, because it could be made at room temperature(20±2℃). Ring flow, setting test, compressive and flexural strength, and length change were examined.

Table 6. Experimental plan of the inorganic panel according to PVA fiber ratio

Experimental factor	Experimental level	
Inorganic composite conditions	·CaO content 30 %, Si/Al ratio 4	1
Alkali accelerator conditions	·NaOH : Na_2SiO_3 (100 g standard) ·50 g : 50 g	1
Alkali accelerator conditions	·Amount (binder 400 g standard) ·100 g	1
PVA fiber content	·0, 0.5, 1, 1.5, 2.0 (vol.%)	5
Curing conditions	·Relative humidity (60±5) % Temperature (20±2) ℃	1
W/B	·31 %	1
Test item	·Ring flow, Setting time, Compressive strength, Flexural strength, Length Change	5
Assessment item	·Absorptivity, Moisture content, Far-Infrared emissivity, Non-combustibility, Gas toxicity test, Length change rate by absorption, Heavy metals releases, Formaldehyde emission	8

The assessment and evaluation method of the building board is indicated in Table 7. To examine the changes in the physical properties of the board, PVA fiber was set at two levels: 0 and 1%. Therefore, Plain was compared with 1% PVA fiber-reinforced specimens in terms of absorptivity, moisture content, heavy metals discharge, non-combustibility, gas toxicity, formaldehyde emissivity, and far-infrared emissivity.

Table 7. Assessment and evaluation method of the inorganic panel according to PVA fiber ratio

Assessment	Unit	Evaluation Method
Absorptivity	%	·KS L 5114 : 2008
Moisture content	%	·KS L 5509 : 2007
Far-Infrared emissivity	W/㎡	·KCL-FIR-1005 : 2011
Non-combustibility	%, ℃	·KS F IOS 1182 : 2004
Gas toxicity test	min	·KS F 2271 : 2006
Length change rate by absorption	%	·KS L 5114 : 2008
Heavy metals releases	mg/L	·Notification of the Ministry of Environment(No. 2011-3)
Formaldehyde emission	mg/L	·KS M 1998 : 2009

4.2 Experimental method

18:1 mortar mixer was used for mixing, and BFS, RM and SF were mixed at 20 rpm for 60 seconds. After that, the liquid alkali activator with NaOH and Na_2SiO_3 and water was added and then mixed at 30 rpm for 120 seconds, and PVA fiber was added and mixed at 40 rpm for 120 seconds and then discharged. The mix was performed for a total of 300 seconds[Figure 6].

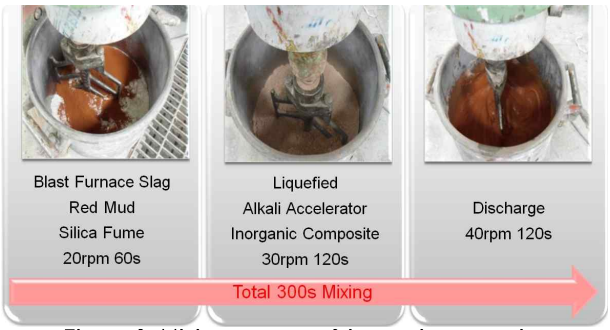

Figure 6. Mixing process of inorganic composite

To examine the fresh paste, the ring flow test was done based on KS F 4041. A PVC pipe with inner diameter of 50 mm was filled with the paste and lifted vertically. The diameter of the pipe was measured in two directions after the paste stopped flowing. The average was determined as the flow value. The setting test was conducted based on KS L 5103(Gillmore needle). To measure the hardened state according to the age, the specimens were

manufactured using a mold with the dimension of 10×10×40㎝ for measurement at the temperature of 20±2℃ and at relative humidity of 60±5%. The specimens were tested for compressive and flexural strength based on KS L ISO 679 and for length change based on the autogenous shrinkage test method of high flow concrete specified by the Japan Concrete Institute(JCI).

4.3 Materials

4.3.1 Blast furnace slag: BFS

BFS used in this study was manufactured by company G in Korea, and had a density of 2.91 g/㎤, and a fineness of 4,464 ㎠/g. The chemical properties of BFS are shown in Table 8, and included a great quantity of SiO_2 and CaO[7].

4.3.2 Red mud: RM

RM used in this study was manufactured by company K in Korea, and had the density of 3.37 g/㎤, and the fineness of 3,483 ㎠/g. The chemical properties of RM are shown in Table 8, and mainly contained Al_2O_3 and Fe_2O_3, and 8.3% of Na_2O[8,9].

4.3.3 Silica fume: SF

SF used in this study was manufactured overseas by company C, and had the density of 2.30 g/㎤, and the fineness of 220,000㎠/g. The chemical properties of SF are shown in Table 8[10].

Table 8. Inorganic composite of chemical component

Using materials	Chemistry components(%)						
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O
BFS*	35.1	13.9	0.5	41.1	3.6	2.4	-
RM**	12.0	25.1	33.3	2.5	0.2	0.3	8.3
SF***	94.0	2.6	1.7	0.3	1.0	0.2	-

4.3.4 Alkali accelerator

A 33% solution of sodium hydroxide and a 1st class, 38.5% sodium silicate were used as alkali activators based on KSM 1415.

4.3.5 PVA fiber (PolyVinyl Alcohol fiber)

PVA fiber was manufactured by company K, and the physical properties of PVA fiber are shown in Table 9.

Table 9. Physical properties of PVA fiber

Diameter (㎛)	Length (mm)	Tensile strength (MPa)	Modulus of elasticity (MPa)	Absorptivity (%)	Density (g/㎥)
40	12	1600	38900	10	1.3

5. Test results and analysis

5.1 Physical properties of the PVA fiber-reinforced paste with inorganic binder

5.1.1 Fluidity and setting test

Figure 7 shows the results of the ring flow and the setting tests. In the ring flow test, Plain with no PVA fiber was shown to have 59mm of fluidity. In addition, the more PVA fiber was mixed, the less the fluidity; however, the difference was very slight. This is believed to indicate that good binding between the PVA fiber and inorganic binder matrix caused friction, deteriorating the fluidity. Through the results of the setting test, the initial setting time was fastest in Plain at 80 minutes, but the final setting time was slowest at 260 minutes. In addition, when PVA fiber was added, the initial setting time was similar to that of Plain, but the final setting time slowed at 1.5% PVA but accelerated at 2% PVA. However, the difference was insignificant. It is believed that OH^- in fiber-combined water accelerated the hardening.

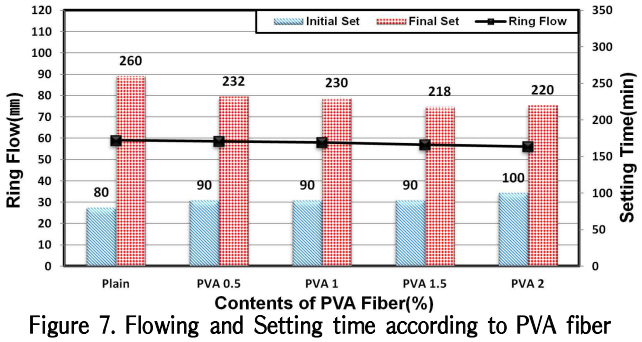

Figure 7. Flowing and Setting time according to PVA fiber ratio

5.1.2 Compressive and flexural strength test

Figure 8 shows the results of the compressive strength test with the increase of PVA fiber-reinforced inorganic binder. When PVA fiber was added, the compressive strength was lower than that of Plain at 1 day, but it was higher than 50MPa from the 3rd days. The compressive strength developed up to 80MPa at 7 days at 2% of PVA fiber. This is believed to indicate that PVA fiber has OH^- and good hydrophilic property, so that the binding was very good when hardened with low carbon inorganic binder, and the strength improved due to low capillary porosity.

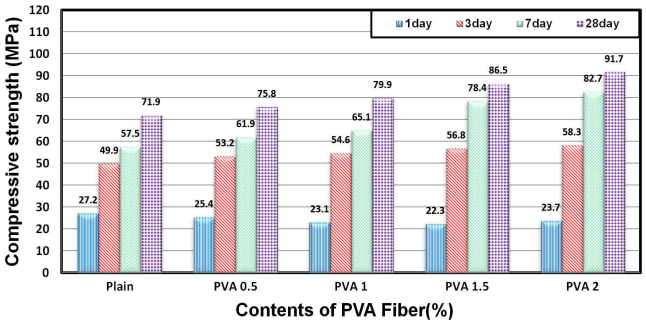

Figure 8. Compressive strength according to PVA fiber ratio

Figure 9 shows the results of the flexural strength test with the increase of PVA fiber-reinforced inorganic binder. When PVA fiber was added, the flexural strength was higher than that of Plain. The more PVA fiber was mixed, the higher the flexural strength became. The rugged surface of PVA fiber played an important role in the combination with inorganic binder matrix, which is believed to exert crack control fully, leading to hairline cracks when the entire fiber was broken, rather than a big crack that could develop into brittle failure, and the strength was improved as a result.

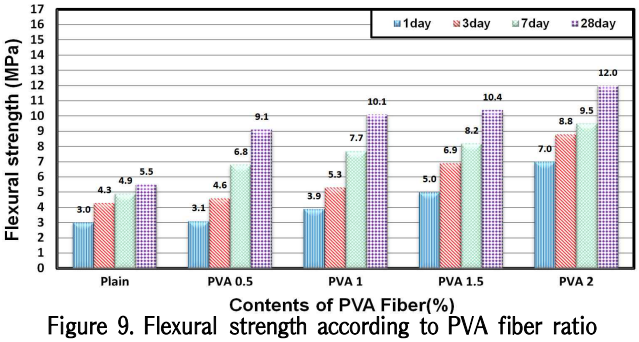

Figure 9. Flexural strength according to PVA fiber ratio

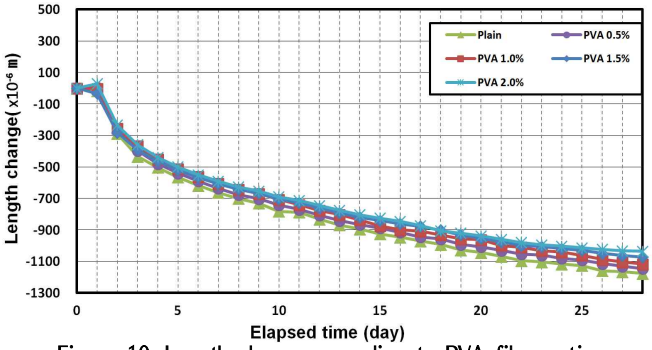

Figure 10. Length change according to PVA fiber ratio

5.1.3 Length change

Figure 10 shows the results of the paste length change test with the increase of PVA fiber-reinforced inorganic binder. The length of the Plain was about -1175×10^{-6} m at 28 days, while the length of PVA fiber-reinforced inorganic binder ranged between -1030×10^{-6}m and -1150×10^{-6}m at 28 days. The low carbon inorganic binder was found to be shrunk from the 1st day, and the PVA fiber-reinforced specimens were shown to be shrunk less than Plain. In addition, the more PVA fiber was mixed, the less a change in length was seen. It is believed that PVA fiber-reinforced specimens shrank less than Plain because the PVA

fiber had hydrophilic fiber consisting of OH^- and a large aspect ratio.

5.2 Properties evaluation of the PVA fiber-reinforced building board

5.2.1 Absorptivity and moisture content

Figure 11 shows the results of the absorptivity test of the building boards, with or without PVA fiber. Plain was shown to be 8.4% while PAV 1% was shown to be 8.9%. When PVA fiber was mixed, absorptivity was improved, and it satisfied the KS requirement for the fiber-reinforced cement plate (less than 28%). It is believed that pores were decreased by the micro-filler effect of SF, an inorganic binder, and it showed lower absorptivity than that stipulated in KS. Absorptivity of the PVA fiber-reinforced specimens were lower than that of Plain because the moisture within the paste was absorbed by the PVA fiber, and the porosity was decreased, reducing the moisture content as a result.

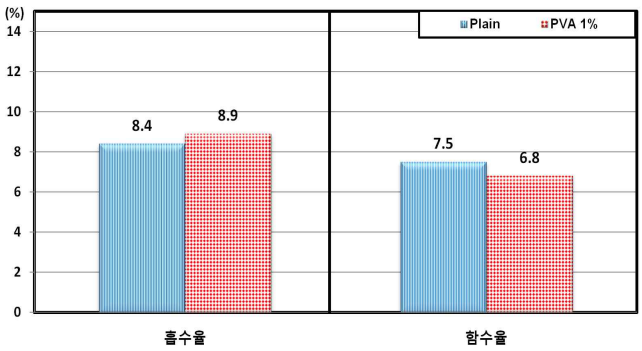

Figure 11. Absorptivity and moisture content of building board

5.2.2 Far-infrared emissivity and actinometry

Table 10 shows the results of far-infrared emissivity and actinometry of building board with or without PVA fiber. The far-infrared emissivity and actinometry of Plain were shown to be 92-92.2%, which is high, and 3.71×10^2 (W/m^2), respectively. In addition, there were insignificant differences between the PVA fiber-reinforced specimens and Plain. Fiber did not have any effect on the far-infrared emissivity and actinometry. The far-infrared ray has effects on the metabolism. More specifically, when the far-infrared ray contacts the human body, it causes the temperature to rise on the skin and in the blood vessels, and the small blood vessels expand, facilitating blood circulation. Therefore, the building board is expected to be widely used in construction projects.

Table 10. Far-Infrared Emissivity and actinometry of building board

Experimental item	Unit	Experimental results	
		Plain	PVA 1%
Far-Infrared emissivity (Thermometry : 40℃, Speech spectrograph : 5㎛~20㎛)	-	0.92	0.92
Far-Infrared actinometry (Thermometry : 40℃, Speech spectrograph : 5㎛~20㎛)	W/m^2	3.71×10^2	3.72×10^2

5.2.3 Non-combustibility and gas toxicity test

Table 11 shows the results of a non-combustibility and gas toxicity test of the building boards with or without PVA fiber. Weight was shown to be reduced by 24.4% in Plain on average, while it was reduced by 23.9% in the 1% PVA-reinforced specimen, and as both were less than 30%, both met the requirement. In addition, the difference between the highest temperature and the final equilibrium temperature was found to be 1.7℃ and 2.8℃, respectively, which did not exceed 20℃. In terms of gas toxicity, non-motion time was measured to be longer than 9:00(s), the minimum requirement. In all the items tested, the board was evaluated to be satisfactory.

Table 11. Non-combustibility and gas toxicity of building board

Experimental level	Non-combustibility		Gas toxicity test
	Mass decreasing rate (%)	A difference between the highest temperature and the final equilibrium temperature (℃)	Non-motion time (min)
Plain	25.0	1.7	13:51
	24.0	1.5	14:45
	24.1	2.0	-
Average	24.4	1.7	-
PVA 1%	23.8	3.0	14:52
	24	2.8	14:54
	24.1	2.5	-
Average	23.9	2.8	-

5.2.4 Length change by absorption

In the length change by absorption of the building boards with or without PVA fiber, the change in Plain was 0.16%, while in PVA 1% it was 0.15%, which satisfied the KS requirement (less than 0.25%). It is believed that the board will have no problems such as deformation and distortion.

5.2.5 Heavy metals elution test

Table 12 shows the results of the heavy metals elution test of the building boards with or without PVA fiber. The test was conducted for Pb, Cd, Cr^{6+}, Hg, and As based on the official wastes test method. None of the chemicals were detected, regardless of fiber mixing. Inorganic binder is considered appropriate to replace cement for the building board.

Table 12. Heavy metals elution test of building board

Experimental level	Experimental item	Unit	Experimental results
Plain	Pb	mg/L	No detection
	Cd	mg/L	No detection
	Cr^{6+}	mg/L	No detection
	Hg	mg/L	No detection
	As	mg/L	No detection
PVA 1%	Pb	mg/L	No detection
	Cd	mg/L	No detection
	Cr^{6+}	mg/L	No detection
	Hg	mg/L	No detection
	As	mg/L	No detection

5.2.6 Formaldehyde emission test

The building boards were tested for formaldehyde emission, with or without PVA fiber. The formaldehyde emission of the boards was shown to be 0.2 mg/L regardless of fiber mixing, and thus the boards were found to be good material with the least harm to human body (less than 0.3 mg/L). Therefore, they can be utilized as the building board considering its formaldehyde emission.

6. Conclusion

In this study, the building boards with PVA fiber were tested to understand physical and chemical characteristics after deducing the optimal mix proportion of the low carbon inorganic binder in replacement of cement with BSF, RM, and SF.

1) In the ring flow test, it was found that the more PVA fiber was mixed, the lower the fluidity became. In the setting test, the initial setting time was fastest in Plain at 80 minutes, while the final setting time was 260 minutes, which was slowest of all. In addition, when PVA fiber was added, the initial setting was similar to that of Plain, but the final setting time was slowed by 218 minutes in the 1.5% PVA-reinforced specimen while it was accelerated in the 2% PVA-reinforced one. However, the differences were very slight.
2) In the compressive strength test, it was found that when PVA fiber was added, the compressive strength was lower than that of Plain, while it was shown to be higher compared with that of Plain from the 3rd day. The more PVA fiber was mixed, the higher the strength became. In the flexural test, the more PVA fiber was mixed, the higher the strength became.
3) In the length change test, the more PVA fiber was mixed, the less the length change was shown.
4) In the absorptivity test, absorptivity of Plain

was shown to be 8.4% on average, while that of the 1% PVA-reinforced specimen was shown to be 8.9%, slightly higher, both of which satisfied the KS requirement (less than 28%). In the far-infrared emission and actinometry test, the far-infrared emission and actinometry were shown to be 92-92.2% and $3.71 \times 10^2 (W/m^2)$, respectively, and fiber mixing had no influence on the results.

5) In the non-combustibility and gas toxicity test, the weight of Plain decreased by 24.4% on average, while that of 1% PVA-reinforced specimen decreased by 23.9%, both of which satisfied the KS requirement (less than 30%). In addition, in the gas toxicity test, non-motion time was longer than 9:00(s), the minimum requirement. In the length change test by absorption, Plain and 1% PVA-reinforced specimen were shown to be 0.15% and 0.2%, respectively, both of which satisfied the requirement (less than 0.2%). For heavy metals elution, no toxic chemicals were detected from the building board, regardless of fiber mixing. In the formaldehyde emission test, the emission was measured to be 0.2 mg/L regardless of fiber mixing, on which basis it was confirmed as a good material with an Eco-friendly Grade of SE0, which means it causes the least harm to the human body. Therefore, considering the formaldehyde emission of the board, it is not hazardous to the human body, and is expected to be utilized as building board.

Acknowledgement

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MEST) (No. 2012-001570)

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