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Original Article

Flame Retardancy of Plywood Treated with Various Water Glass Concentration and Additives[1]

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ABSTRACT

The carbonized length and area of plywood by the various spreading concentration of water glass and the type of additives were measured in accordance with the 45° MecKel's burner method of the fire protection performance standard of the Korean National Fire Agency. As a result of treating water glass with a concentration of 20 to 50 % on plywood, the flame retardancy tended to increase in proportion to the concentration of water glass. However, the optimum concentration of water glass was determined to be 30 % due to the efflorescence and sticky on the surface of plywood treated with high-concentration water glass of more than 30 %. As a result of the experiment by adding different proportions of additives to the water glass with concentration of 30 %, the standard of flame performance standard was satisfied under the conditions with the addition of 15% potassium hydroxide and 1-10% aluminum hydroxide, respectively. On the other hand, there were no significant difference in the flame retardancy by adding magnesium sulfate. These results about the flame retardancy of plywood by water glass and additives were expected to be basic data for improving flame-retardant treated wood.

Keywords: flame retardancy, plywood, potassium hydroxide, aluminium hydroxide, magnesium sulfate

1. INTRODUCTION

Wood has an aesthetic pattern as well as the advantage of being easily processed into various shapes. Due to these characteristics, the use of wood is increasing in interior and exterior materials for buildings and furniture (Park *et al.*, 2005). However, as wood is vulnerable to fire, it is necessary to develop effective flame retardants to reduce human and material damage caused by fire (Park *et al.*, 2019; Kim *et al.*, 2002).

Flame retardants are used in manufacturing of almost all industrial products and there are a wide variety of the retardants depending on its usage (Shin and Baek, 2013). The halogenated flame retardant contains a halogen element, and the highest flame retardancy is found in the order of fluorine (F) < chlorine (Cl) < bromine (Br) < iodine (I) (Cha *et al.*, 2011). Fluorinated flame retardants are not practically used, and as iodinated flame retardants have a disadvantage in that the bond strength between iodine and carbon is too weak that the bond is broken even by low energy, in which leads to loss of the flame retardancy at a temperature below the pyrolysis temperature. With this reason, chlorinated and brominated flame retardants are mainly used

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among halogenated flame retardants. In particular, the brominated flame retardants are widely used around the world due to their high retardancy and low cost (Cho *et al.*, 2002; Lee *et al.*, 2007; Shin *et al.*, 2009). Although the consumption amount of the halogenated flame retardants centered on the brominated flame retardant has continuously increased it was claimed that dioxin is generated during combustion of halogenated flame retarding materials and polymers in Germany. As a result, due to the concerns on the environmental problems, the use of the halogenated flame retardants that emit harmful HCl and HBr gases started to be regulated mostly in developed European countries (Jang and Choi, 2009). Phosphorus flame retardants mainly affect the reaction occurring in the condensed phase, and they are particularly effective for plastics containing oxygen or materials with a high oxygen content such as cellulose and cellulose substituents (Cha *et al.*, 2011). Since inorganic compounds are generally inactive at 150~400 °C, which is a typical pyrolysis temperature for plastics, those that can be used as flame retardants are extremely limited (Choi *et al.*, 2018). However, some inorganic compounds show flame retarding effect when mixed with halogenated flame retardants. For example, inorganic flame retardants containing aluminum hydroxide ($Al(OH)_3$) and boron (B) are most widely used because they affect the combustion reaction through physical processes (Cha *et al.*, 2011). Thus, in this study, we used inorganic compounds as an additive in a basic study for developing eco-friendly flame retardants and examined the flame retardancy.

Sodium silicate is one of the most useful inorganic compounds and it belongs to soluble silicates which are also known as water glass (Medina and Schledjewski, 2009). In general, sodium silicate is a viscous liquid which is composed of 21~34% of SiO_2 and 6~18% of NaO_2. It has been used for a long time in various materials such as paper, wood, and cement to give fire resistance (Medina and Schledjewski, 2009; Lee and Thole, 2018). In particular, water glass is known as an effective material that can improve durability and flame retardancy in the field of fire retardants (Lee and Thole, 2018) and has been applied to noncombustible coatings and paints (Pereyra and Giudice, 2009; Son *et al.*, 2013). Various studies have been conducted previously to improve the bond strength and flame retardancy of sodium silicate. It was revealed that acidic sodium silicate mixed with sulfuric acid, acetic acid (Stark and Wicht, 1998), and boric acid (Obut and Girgin, 2006) can improve the stability of siloxane bonds. Moreover, it was reported that sodium silicate and boron compounds are effective in increasing biological resistance and fire resistance (Furuno and Imamura, 1998; Yamaguchi, 2005).

Therefore, in this study, we analyzed the flame retardancy based on the concentration of water glass and type and ratio of additives in the flame retardant by 45° MecKel's Burner method, as the basic data for improving the flame retardancy using water glass as the main component for a wood flame retardant.

2. MATERIALS and METHOD

2.1. Testing materials

To test the flame retardancy based on the concentration of water glass and additives, we used plywood that satisfies the standards of flame retardant performance of National Fire Agency (NFA). The test specimen was prepared with a 190 mm width × 290 mm length × 5 mm thickness as presented by 45° Meckel's Burner method in the standards of flame retardant performance (NFA Notification No. 2019-2; Korean National Fire Agency, 2019). To measure the flame retardant performance based on the concentration of water glass, water glass of 20, 30, 40, and 50% concentration was used. To measure the flame retardant performance based on the additives, potassium hydroxide (KOH), aluminum hydroxide ($Al(OH)_3$), and magnesium sulfate ($MgSO_4$) were used as additives. The test specimen and nontreated control specimen were prepared in a quantity that can be used in 3 repeated experiments for each water glass concentration and additive. Based on the standards of flame retardant performance, the prepared test specimen was subjected to go through humidity controlling for 24 hours in a thermo-hygrostat with a temperature of 23 °C and humidity of 50% until it reached a constant weight. Then, it was stored in a desiccator with silica gel for 2 hours and used for the experiment. Table 1 shows the concentration and the content of additives for each treatment of the test specimen used in the experiment.

2.2. Water glass and additives treatment

Test specimens were treated with water glass and three additives (KOH, $Al(OH)_3$, $MgSO_4$). The treated amount, treatment method, and number of treatments of flame retardants were determined based on the results of the previous study on commercial flame retardants (Seo *et al.*, 2017). The amount of water glass was determined to be 500 g/m^2. For the treatment method, flame retardants were applied to the test specimens with a brush until the surface of the test specimen was sufficiently wet, then it was dried for 24 hours at a temperature of 23 °C and humidity of 50%. The flame retardant was applied again, and the same process was repeated for 3 times. To analyze the flame retardant performance based on the additives, the concentration of water glass was fixed and the concentration of each additive was determined as follows: 5, 10, and 15% for KOH, 1, 2, 5 and 10 % for $Al(OH)_3$, 0.5 and 1% for $MgSO_4$.

2.3. 45° MecKel's burner method

For the evaluation of flame retardant performance, 45° Meckel's Burner method presented in the standards of flame retardant performance (NFA Notification No. 2019-2) of Article 20, Paragraph 2 of 「Enforcement Decree of the Act on Fire Prevention and Installation, Maintenance, and Safety Control of Fire-Fighting Systems」 was applied. For the fuel used in combustion, butane gas presented in KS M 2150 (Liquefied petroleum gas; Korean Agency for Technology and Standards, 2017) was used. The test specimen was fixed to the pedestal

Table 1. Abbreviation list for specimens used in this study

Abbreviation	Water glass concentration	Additives species and concentration	Treatment method
A	-	-	-
B	20 %	-	
C	30 %	-	spreading
D	40 %	-	
E	50 %	-	
F		Potassium hydroxide 5%	
G		Potassium hydroxide 10%	
H		Potassium hydroxide 15%	
I		Aluminium hydroxide 1%	
J	30 %	Aluminium hydroxide 2%	spreading
K		Aluminium hydroxide 5%	
L		Aluminium hydroxide 10%	
M		Magnesium sulfate 0.5%	
N		Magnesium sulfate 1%	

in the 45° flammability tester, and the flame of the heating device with a length of 65 mm was set to be in contact with the lower part of the center of the test specimen. The heat treatment was proceeded with on each test specimen for 2 minutes, and for the test specimen complexed during the heating process, the heating device was removed 2 second after the complexation occurred. For each test specimen, flame retardant performance was measured in terms of after-glow time (s), after-flame time (s), char length (mm), and char area (mm^2).

3. RESULTS and DISCUSSION

3.1. Flame retardant performance of plywood treated with difference water glass concentration

Table 2 and Fig. 1 show the results of measuring the afterglow time, after-flame time, char length, and char area based on the concentration of the water glass treated on the plywood using 45° Meckel method.

Afterglow and after-flame time were all measured as 0 second regardless of presence of the flame retardant, which satisfied the standard of flame retardant performance. However, as the generation of toxic gases may become a bigger problem than the continuous combustion in the event of a fire (White, 2000), it is considered that a further research on this subject is necessary to be conducted (Kim and Lee, 2016).

The char length of the test specimen without water

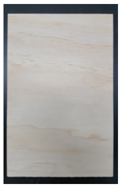
Sample	Specimen before test	Specimen after test
A		
B		
C		
D		
E		

Fig. 1. Result of flame retardancy test for plywood treated with difference spreading concentration of water glass: A: control, B: 20 %, C: 30 %, D: 40 %, E: 50%.

Table 2. Flame retardancy of plywood treated with difference water glass concentration

Sample	Remaining flame time (sec)	Smoldering time (sec)	Carbonized area (mm^2)	Carbonized length (mm)
	less than 10 sec	less than 30 sec	less than 5,000 mm^2	less than 200 mm
A	0	0	16,524	201
B	0	0	14,659	189
C	0	0	8,454	167
D	0	0	8,590	164
E	0	0	2,589	70

glass treatment was measured as 201 mm, which did not satisfy the standard of 200 mm. On the other hand, the char length of the test specimen with water glass treatment was measured in the range of 70~189 mm, which satisfied the standard of flame retardant performance. The char areas of the test specimen without water glass treatment and the test specimen treated with water glass concentration of 20~40 % were measured in the range of 8,590~16,524 mm^2, which did not satisfy the standard of 5,000 mm^2. In contrast, in the case of the test specimen treated with 50 % water glass, the char area was measured as 2,589 mm^2, and it satisfied the standard. These results indicate that the flame retardant performance improves as the concentration of glass water increases, showing a similar trend to the previous study (Lee and Thole, 2018) which reported that the carbonization rate of a particle board decreased as the water glass concentration increased. Meanwhile, Seekamp (1954) claimed that such tendency is due to the inorganic polymer of the water glass, and thus, we assumed that the polymerization of inorganic compounds in glass water was also applied in this study as well. The char length and char area of the test specimens varied according to the concentration of water glass. As the concentration of water glass increased from 20 % to 50 %, the char length and char area decreased from 201 mm and 16,524 mm^2 to 70 mm and 2,589 mm^2, respectively. In particular, when the water glass concentration was 40%, the char length and char area were 117 mm and 5,151 mm^2, respectively, which did not satisfy the standard of flame retardant performance. However, those of the test specimen with 50 % glass water were greatly reduced to 70 mm and 2,589 mm^2, and it satisfied the standard. That is, the flame retardant performance was largely improved as the concentration of water glass increased from 40 % to 50 %, suggesting that more detailed studies on water glass concentration (e.g., 40, 42, 44, 46, 48 %) would be needed in the future.

In other words, increased water glass concentration led to the decreased char length and char area, which improved the flame retardant performance. However, stickiness and efflorescence occurred at 40 and 50% water glass concentrations, which lowered process-ability and aesthetic effect of wood. It was reported that the efflorescence may occur by the influence of free alkali in the specimen if alkali is added at a concentration above the appropriate range (Oh *et al.*, 2014). It was also reported that the stickiness occurs when water in water glass evaporates, which increases the viscosity and aggregates particles (Huusmann, 2001).

Table 3. Flame retardancy of plywood treated with difference additives

Sample	Remaining flame time (sec)	Smoldering time (sec)	Carbonized area (mm^2)	Carbonized length (mm)
	less than 10 sec	less than 30 sec	less than 5,000 mm^2	less than 200 mm
F	0	0	7,863	149
G	0	0	5,127	133
H	0	0	3,947	93
I	0	0	2,280	71
J	0	0	2,994	78
K	0	0	4,569	102
L	0	0	4,766	115
M	0	0	7,570	146
N	0	0	8,318	158

Considering these results from the previous studies, we determined that the water glass concentration of 30% is appropriate in this study and additionally evaluated the flame retardant performance using various additives to improve the performance.

3.2. Flame retardant performance of plywood treated with difference additives

Based on the standard of flame retardant performance of NFA Notification No. 2019-2, we used 45° Meckel burner method to measure afterglow time, after-flame time, char length, and char area based on additives, and the results are shown in Table 3 and Fig. 2~4.

As a result of measuring afterglow time and after-flame time of the plywood containing 30% of water glass based on the type and concentration of in-

Sample	Specimen before test	Specimen after test
F		
G		
H		

Fig. 2. Result of flame retardancy test for *Larix kaempferi* plywood treated with 30 % water glass and difference concentration of Potassium hydroxide: F: 5%, G: 10%, H: 15%.

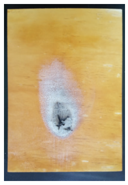
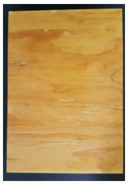
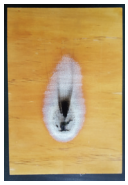
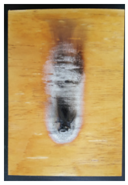
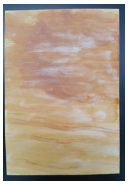
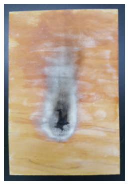
Sample	Specimen before test	Specimen after test
I		
J		
K		
L		

Fig. 3. Result of flame retardancy test for plywood treated 30 % water glass and difference concentration of Aluminium hydroxide: I: 1 %, J: 2 %, K: 5 %, L: 10 %.

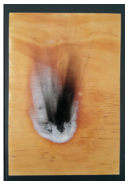
Sample	Specimen before test	Specimen after test
M		
N		

Fig. 4. Result of flame retardancy test for plywood treated with 30 % water glass and difference concentration of Magnesium sulfate: M: 0.5 %, N: 1%.

organic additives, it was found that all of them satisfied the standard and had excellent performance. In addition, it was determined that there was no significant difference in afterglow time and after-flame time based on the type and concentration of additives. Park *et al.* (2006) reported that such phenomenon is caused by combustible gases in the gaseous phase diluted by the inorganic additives, and these gases act to prevent approach of oxygen near the surface. At the same time, it was also argued that endothermic reactions occur on the solid surface, reducing the cooling of the material and the generation of pyrolysis products.

For the char length of the plywood based on the type of inorganic additives, it was measured in the range of 71~158 mm for the specimen treated with additives, which satisfied the flame retardant performance of 200 mm. The char area of the test specimen treated with magnesium sulfate was in the range of 7,570~8,318 mm^2, which did not satisfy the standard of 5,000 mm^2. However, in the case of the test specimens treated with 15% of KOH, 1, 2, 5, and 10% of $Al(OH)_3$, the maximum char area was measured as 4,766 mm^2, and it exceeded the standard. The previous studies showed that magnesium sulfate was hydrated to become magnesium sulfate heptahydrate ($MgSO_4 \cdot 5H_2O$) and it was used to improve the flame retardant performance (Mostashari *et al.*, 2007). Thus, the reason for these tendencies in this study can be explained by anhydrous $MgSO_4$ without having a hydrated structure which did not improve the flame retardant performance.

For the flame retardant performance based on the concentration of the additives, 5,127~7,863 mm^2 was measured for the test specimens treated with 5% and 10% KOH, and it did not satisfy the flame retardant performance of 5,000 mm^2 On the other hand, the test specimen treated with 15% KOH was measured as 3,947 mm^2, which satisfied the standard. Therefore, it can be inferred that KOH contributes to improving the flame retardant performance. Furthermore, such result showed a similar tendency to the previous study (Mostashari *et al.*, 2007) where the char length and char area decreased as the concentration of KOH increased.

As the concentration of KOH increased from 1% to 2%, the char length and char area decreased. However, they rather increased as the concentration increased from 5% to 10%. KOH affects the combustion reaction through physical processes, causing a series of endothermic reactions to lower the temperature of the combustion material so that the combustion reaction cannot be continued. However, Liang and Zhang (2010) reported that the high concentration of KOH diluted the flame retardants, generating too much of hydrates to lower the flame retardant performance. Similarly, the same phenomenon seems to have applied in this study.

In case of $MgSO_4$, as the concentration increased, the char length and char area rather increased. This result showed a similar tendency to the previous study (Mostashari *et al.*, 2008) where the char length increased as the concentration increased from 0.4 M to 0.5 M when the cellulosic fabric was treated with $MgSO_4$.

In summary, as a result of evaluating the flame retardant performance, it was determined that the optimum additive and concentration for a plywood treated with inorganic additives and 30% glass water concentration was 1% of KOH.

4. CONCLUSION

In this study, we evaluated the flame retardant performance based on the concentration of water glass and the type and ratio of additives by measuring afterglow time, after-flame time, char length, and char area of plywood prepared in accordance with the standard of NFA Notification.

1) As a result of measuring the flame retardant performance based on the water glass concentration, the char length and char area decreased as the concentration increased, which improved the flame retardant performance. At a 50 % concentration of water glass, the NFA's standard was satisfied, but the processability and aesthetic effect were lowered. In this regard, it is determined that 30% of water glass concentration is most suitable concentration for the flame retardant performance.
2) As a result of measuring the flame retardant performance based on the type and concentration of the additives treated on the plywood, we determined that 1% of KOH is most appropriate when inorganic additives are used in 30% of water glass concentration to make fire retardant plywood.

Through this study, we confirmed the flame retardant performance of water glass and additives on the plywood. Various concentrations of water glass and the additives have been shown to be effective in improving the flame retardant performance. However, as there is a difference based on the type and concentration of the additives, further researches on more various types of additives are needed. Consequently, we determined the most suitable concentration of water glass as 30 % and the type and concentration of the additive as 1% of $Al(OH)_3$.

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APPENDIX

(Korean Version)

물유리의 농도와 첨가제 종류에 따른 방염제의 성능

초록 : 소방청의 방염성능기준에 제시된 45°멕켈 버어너법을 이용하여 물유리 농도와 첨가제 종류에 따른 합판의 탄화길이 및 면적 등의 방염성능을 측정하였다. 합판에 농도 20-50%의 물유리를 처리한 결과, 방염성능은 물유리의 농도와 비례하는 경향을 나타냈다. 그러나 30%를 넘는 고농도의 물유리로 처리된 합판의 표면에서 백화현상과 끈적임이 발생하여 농도 30%를 최적 조건으로 결정하였다. 농도 30%의 물유리에 서로 다른 비율의 첨가제를 추가하여 실험을 수행한 결과, 수산화칼륨 15% 조건과 수산화알루미늄 1-10%의 조건에서 방염성능 기준을 만족하였다. 반면에 황산마그네슘은 방염성능에 크게 영향을 미치지 않았다. 물유리와 첨가제에 따른 방염성능의 결과는 방염제를 활용한 불연재에 대한 기초자료로 활용될 것으로 기대된다.

1. 서 론

목재는 심미적인 무늬를 지니며, 다양한 형태로의 가공이 용이한 장점을 갖는 재료이다. 이러한 특성 때문에 건축용 내·외장재, 가구재 등으로 목재 사용이 증가하고 있는 추세이다(Park *et al.*, 2005). 그러나 목재는 화재에 취약하다는 특징이 있어 화재로 인한 인적 및 물적 피해를 줄이기 위하여 방염제와 난연제의 개발이 필요한 상황이다(Park *et al.*, 2019; Kim *et al.*, 2002).

거의 모든 산업용 제품생산에 사용되는 방염제는 그 종류가 매우 다양하다(Shin and Baek, 2013). 할로겐계 방염제는 할로겐 원소를 포함하는 물질이며 방염효과는 F(불소) < Cl(염소) < Br(브롬) < I(요오드)의 순이다(Cha *et al.*, 2011). 불소계 방염제는 실질적으로 사용되지 않으며 요오드는 탄소와의 결합력이 약해 낮은 에너지에 의해서도 결합이 끊어져 열분해 온도 이하에서 이미 방염효과를 상실한다는 결함이 있다. 이러한 이유로 할로겐계 방염제 중에서는 염소계와 브롬계가 주로 이용되고 있다. 브롬화 방염제는 높은 방염효과와 낮은 가격으로 인해 전 세계적으로 많이 사용되고 있다(Cho *et al.*, 2002; Lee *et al.*, 2007; Shin *et al.*, 2009). 이처럼 브롬계 난연제를 선두로 하여 할로겐계 난연제의 사용량은 증가하고 있으나 독일에서 할로겐 난연재료 및 고분자의 연소 시 다이옥신이 발생된다는 주장이 대두되면서, 황경적 문제로 유해성 HCl, HBr 가스를 배출하는 할로겐 난연제의 사용이 유럽선진국을 중심으로 규제되기 시작했다(Jang and Choi, 2009). 인계 방염제는 응축상에서 일어나는 반응에 주로 영향을 미치는데 특히 산소를 함유하는 플라스틱이나 셀룰로스와 셀룰로스 치환체와 같은 높은 산소 함유량을 갖는 물질에서 효과적인 방염제이다(Cha *et al.*, 2011). 무기물질은 플라스틱의 일반적인 분해온도인 150~400℃ 사이에서 통상 불활성을 나타내기 때문에 효과적이지 못한 경우가 많아 방염제로 사용할 수 있는 화합물은 극히 제한되어 있다(Choi *et al.*, 2018). 그러나 할로겐계 방염제와 혼련하면 방염효과를 나타내며 수산화알루미늄($Al(OH)_3$)과 붕소(boron)를 함유한 무기 방염제는 물리적 방법에 의해 연소반응에 영향을 주기 때문에 가장 광범위하게 사용되는 무기 방염제이다(Cha *et al.*, 2011). 따라서 본 연구에서는 친환경 방염제 개발을 위한 기초 연구로써 무기계 물질을 첨가제로 이용하여 방염성능을 구명하였다.

규산나트륨(Sodium silicate)은 가장 유용한 무기물질 중 하나로 물유리라고도 알려진 가용성 규산염 계열에 속하는 물질이다(Medina and Schledjewski, 2009). 일반적으로 규산나트륨은 21~34 %의 SiO_2와 6~18 %의 NaO_2로 구성되어 있는 점성 액체이다. 규산나트륨은 오랜 기간 동안 내화성을 부여하기 위해 종이, 목재, 시멘트 등 다양한 재료에 사용되어왔다(Medina and Schledjewski, 2009; Lee and Thole, 2018). 특히, 난연제 분야에서 물유리는 내구성과 난연성을 향상시킬 수 있는 유용한 물질로 알려져 있으며(Lee and Thole 2018), 불연성 코팅제 혹은 도료에 사용되어 왔다(Pereyra and Giudice, 2009; Son *et al.*, 2013). 그동안 규산나트륨의 결합력과 난연성을 향상시키기 위하여 다양한 선행연구들이 진행되어왔다. 황산, 아세트산(Stark and Wicht, 1998), 그리고 붕산(Obut and Girgin, 2006)을 첨가한 산성 규산나트륨은 실록산(siloxane) 결합의 안정성을 향상시키는 것으로 나타났다. 규산나트륨과 붕소 화합물은 생물학적 저항성과 내화성 증가에 효과가 있는 것으로 보고된 바 있다(Furuno and Imamura, 1998; Yamaguchi, 2005).

따라서 본 연구에서는 목재 방염처리제로 물유리를 주 성분으로 이용한 방염성능 향상 연구의 기초자료로 방염제 내의 물유리의 농도, 첨가제의 종류와 비율에 따른 방염성능을 45° 맥켈버너법으로 방염성능을 분석하였다.

2. 재료 및 방법

2.1. 공시재료

물유리의 농도와 첨가제에 따른 방염성능 시험을 위하여 소방청의 방염성능기준을 만족하는 합판을 사용하였다. 시험편은 방염대상물의 방염성능기준(소방청고시 제2019-2호)의 45° 멕켈버너법에 제시된 것과 같이 가로 190 mm × 세로 290 mm × 두께 5 mm로 제조하였다. 물유리의 농도에 따른 방염성능의 측정에 20, 30, 40, 50 % 농도의 물유리를 사용했으며, 첨가제에 따른 방염성능의 측정에는 수산화칼륨(Potassium hydroxide), 수산화알루미늄(Aluminium hydroxide), 황산마그네슘(Magnesium sulfate)을 첨가제로 사용하였다. 시험편은 비교를 위한 무처리 대조군을 포함하여 물유리의 농도 및 첨가제별 3 반복을 위한 수량으로 제조하였다. 제조된 시험편은 방염성능기준에 의거하여 항량이 될 때까지 온도 23°C, 습도 50 % 조건의 항온항습기에서 항량에 도달할 때까지 24시간 조습처리한 후 실리카 겔을 넣은 데시케이터 안에서 2시간 동안 넣어둔 후 실험에 사용하였다. 실험에 사용된 시험편의 처리별 농도 및 첨가제의 함량을 Table 1에 정리하였다.

2.2. 물유리와 첨가제 처리조건

물유리와 첨가제 3종(수산화칼륨, 수산화알루미늄, 황산마그네슘)을 이용하여 도포처리를 수행하였다. 방염제의 도포량 차이에 따른 방염성능을 분석하기 위한 도포량, 도포방법, 도포횟수는 상용 방염제에 대한 선행연구의 결과(Seo *et al.*, 2017)를 바탕으로 결정하였다. 도포량은 물유리의 경우 500 g/m^{2}로 결정하였다. 도포처리 방법은 시험편의 표면이 충분히 젖을 때까지 붓을 이용해 방염제를 바른 다음 온도 23 ℃, 습도 50 % 조건에서 24시간 건조 후 다시 약제를 바르는 방법으로 3회 반복하였다. 첨가제에 따른 방염성능을 분석하기 위해 물유리 농도는 고정하고 첨가제의 농도는 수산화칼륨 5, 10, 15 %, 수산화알루미늄 1, 2, 5, 10 %, 황산마그네슘 0.5, 1 %로 선정하였다.

2.3. 45° 멕켈 버어너법

방염성능 평가는 「화재예방, 소방시설 설치유지 및 안전관리에 관한 법률 시행령」 제20조 제2항 “방염대상물의 방염성능기준(소방청고시 제2019-2호)”에 제시된 45° 맥켈버너법을 적용하였다. 연소를 위한 연료는 KS M 2150(액화석유가스)에 제시된 부탄가스를 이용하였다. 시험편은 45° 연소측정 장치 내의 받침대에 고정시킨 후 65 mm의 길이인 가열장치의 불꽃이 시험편의 중앙부 하단에 접하도록 하였다. 가열처리는 각 시험편에 대하여 2분간 진행하였으며 가열 중에 착염되는 시험편은 착염이 발생한 2초 후에 가열장치를 제거하였다. 각 시험편에 대하여 잔염시간(s), 잔신시간(s), 탄화길이(mm), 탄화면적(mm^2)의 방염성능을 측정하였다.

3. 결과 및 고찰

3.1. 물유리 농도에 따른 합판의 방염성능

합판에 처리된 물유리의 농도 차이에 따른 잔염시간, 잔신시간, 탄화길이, 탄화면적을 45° 맥켈버너법을 이용하여 측정한 결과를 Table 2와 Fig. 1에 제시하였다.

잔염시간과 잔신시간은 방염제의 유무와 상관없이 모두 0초로 측정되었다. 잔염시간과 잔신시간은 방염처리와 무관하게 방염성능기준을 모두 만족하였다. 그러나 화재 발생 시, 연소의 지속보다 유독가스의 발생이 더 큰 문제(White, 2000)가 될 수 있으므로 이에 대한 추가적인 연구가 필요할 것으로 사료된다(Kim and Lee, 2016).

탄화길이는 물유리가 처리되지 않은 시험편에서 201 mm로 측정되어 방염성능기준인 200 mm를 만족하지 못했으며, 물유리 처리된 시험편에서는 70~189 mm의 범위로 측정되어 방염성능기준을 만족하였다. 탄화면적은 물유리가 처리되지 않은 시험편과 물유리 농도 20~ 40 %로 처리된 시험편에서 8,590~16,524 mm^{2}의 범위로 방염성능기준인 5,000 mm^{2}를 만족하지 못한 반면에, 물유리 농도 50 %로 처리된 시험편에서는 2,589 mm^{2}로 측정되어 방염성능기준을 만족하였다. 이는 물유리의 농도가 증가할수록 방염성능이 향상되는 것으로 판단되며, 물유리 농도 증가함에 따라 파티클보드의 탄화속도가 감소한 선행연구(Lee and Thole, 2018)와 유사한 경향을 나타냈다. 한편 Seekamp (1954)는 이러한 경향은 물유리의 무기 중합체에 의한 것이라고 판단했으므로 본 연구에서도 물유리의 무기중합이 작용했을 것으로 추정된다.

물유리의 농도 차이에 따른 탄화길이와 탄화면적은 물유리 농도 20 %에서 50 %로 증가함에 따라 각각 201 mm와 16,524 mm^{2}에서 70 mm와 2,589 mm^{2}로 감소하는 경향을 보였다. 특히, 물유리 농도 40 %에서 탄화길이와 탄화면적은 117 mm와

5,151 mm^2으로 방염성능기준을 만족하지 않았지만, 물유리 농도가 50 %로 증가함에 따라 70 mm와 2,589 mm^2로 큰 폭으로 감소하여 방염성능기준을 만족하였다. 물유리 농도의 증가에 따른 방염성능은 물유리 농도가 40 %에서 50 %로 증가함에 따라 큰 폭으로 향상되어 추후 연구에서 보다 세부적인 물유리 농도 40, 42, 44, 46, 48 %에 대한 연구가 필요한 것으로 판단된다.

이와 같이, 물유리의 농도가 증가함에 따라 탄화길이와 탄화면적이 감소하여 방염성능이 증가하는 경향을 나타냈으나 물유리 농도 40 %와 50 %에서 끈적임과 백화현상이 일어나 가공성과 미적 효과가 좋지 않은 것으로 판단된다. 백화현상은 적정범위 이상 농도의 알칼리를 첨가할 경우 시편 내의 자유 알칼리의 영향으로 백화현상이 발생할 수 있다고 보고한 바 있다(Oh *et al.*, 2014). 또한 끈적임 현상은 물유리의 경우 물이 증발되면서 점도가 증가하고 입자가 서로 응집하면서 발생하는 현상임을 보고한 바 있다(Huusmann, 2001). 이러한 선행 연구결과를 감안하여 본 연구에서 합판에 대한 적정 물유리 농도는 30 %가 적절한 농도 범위라 판단되며, 방염성능을 향상시키기 위하여 다양한 첨가제를 이용한 방염성능을 추가로 평가하였다.

3.2. 첨가제 종류 및 농도에 따른 합판의 방염성능

방염성능기준 소방청고시 제 2019-2호에 의거하여 45° 맥켈버너법을 이용하여 합판에 대한 첨가제에 따른 잔염시간, 잔신시간, 탄화길이, 탄화면적을 측정하였으며 결과는 Table 3와 Fig. 2~4에 제시하였다.

물유리 30 %에 첨가된 무기계 첨가제 종류와 농도에 따른 합판의 잔염과 잔신시간 측정결과, 모두 방염성능기준을 만족하는 것으로 나타나 그 성능이 우수한 것으로 나타났다. 또한 첨가제 종류와 농도에 따라 잔염과 잔신시간에 대한 방염성능은 큰 차이가 없는 것으로 판단된다. Park *et al.* (2006)은 이러한 현상은 무기계 첨가제가 기체상에서 가연성 기체를 희석시키기 때문이며, 이 기체가 표면 가까이에서 산소의 접근을 막아주는 역할을 한다고 했다. 동시에 고체상 표면에서는 흡열반응이 일어나며, 이로 인해 재료의 냉각 및 열분해 생성물의 생성을 감소시키는 것으로 판단하였다.

무기계 첨가제 종류에 따른 합판의 탄화길이는 첨가제 처리된 시험편에서 71~158 mm의 범위로 측정되어 방염성능기준인 200 mm 미만을 만족하였다. 탄화면적은 황산마그네슘 처리된 시험편에서 7,570~8,318 mm^2의 범위로 방염성능기준인 5,000 mm^2를 만족하지 못한 반면에, 수산화칼륨 15 %, 수산화알루미늄 1, 2, 5, 10 % 첨가제가 추가된 시험편에서는 최대 4,766 mm^2로 측정되어 방염성능기준을 웃도는 결과를 나타내었다. 이러한 경향은 선행 연구결과, 방염시험에서 황산마그네슘을 수화시켜 Magnesium sulfate heptahydrate를 방염제 첨가제로서 이용하여 방염성능의 향상을 나타낸바 있어(Mostashari *et al.*, 2007), 본 연구에서 사용된 황산마그네슘은 수화구조를 가지고 있지 않아 방염성능의 향상 효과를 나타내지 않은 것으로 사료된다.

첨가제 농도에 따른 방염성능은 수산화칼륨 5 %와 10 % 농도로 처리된 시험편에서 5,127~7,863 mm^2의 범위로 방염성능기준인 5,000 mm^2을 만족하지 못한 반면에, 수산화칼륨 15 % 농도로 처리된 시험편에서는 3,947 mm^2로 측정되어 방염성능기준을 만족하였다. 이는 수산화칼륨이 방염성능 향상에 기여하는 것으로 판단되며, 수산화칼륨의 농도가 증가함에 따라 탄화길이와 탄화속도는 감소한 것으로 보고된 선행연구(Mostashari *et al.*, 2007)와 유사한 경향을 나타냈다.

수산화알루미늄 첨가제 농도가 1 %와 2 %로 증가할수록 탄화길이와 탄화면적이 감소하는 경향을 보였으나 첨가제 농도 5 %와 10 %에서는 오히려 증가하는 경향을 나타내었다. 수산화알루미늄은 물리적 방법에 의해 연소반응에 영향을 주어 일련의 흡열과정을 발생시켜 가연물질의 온도를 낮추어 연소반응이 지속할 수 없도록 한다. 그러나 Liang and Zhang (2009)의 보고에 의하면 고농도의 수산화알루미늄에서는 많은 수화물 생성으로 방염제가 오히려 희석되기 때문에 방염성능이 낮아지는 것으로 판단했으므로 본 연구에서도 동일한 현상이 작용한 것으로 사료된다.

황산마그네슘 첨가제는 농도가 증가할수록 탄화길이와 탄화면적이 오히려 증가하는 경향을 나타내었다. 이는 셀룰로오직 섬유에 황산마그네슘을 처리했을 때, 농도가 0.4 M에서 0.5 M로 증가할수록 탄화길이가 증가한다는 선행연구(Mostashari *et al.*, 2008)와 유사한 경향을 나타냈다.

따라서 방염성능 시험 결과, 물유리 농도 30 %에 무기계 첨가제를 넣어 합판을 방염처리할 경우 적절한 첨가제와 농도는 탄화길이와 탄화면적이 가장 작은 값으로 확인된 수산화알루미늄 1 %가 적정한 것으로 판단되었다.

4. 결 론

본 연구에서는 합판의 물유리의 농도와 첨가제의 종류와 비율에 따른 방염성능을 분석하기 위하여 소방청의 방염성능기준에

따라 합판의 잔염시간, 잔신시간, 탄화길이, 탄화면적을 측정하여 다음과 같은 결론을 얻었다.

1) 합판에 대한 물유리 농도 차이에 따른 방염성능 시험에서 물유리의 농도가 증가함에 따라 탄화길이와 탄화면적이 감소하는 경향을 나타내어 방염성능은 개선되었다. 물유리 농도 50 %에서 방염성능기준을 만족하는 결과를 보였으나 이 농도에서는 가공성과 미적인 효과가 떨어지므로 이를 감안하여 적정 물유리 농도는 30 %가 적합한 것으로 판단된다.
2) 합판에 대하여 첨가제의 종류와 농도 차이에 따른 방염성능 시험에서 물유리 농도 30 %에 무기계 첨가제를 넣어 합판을 방염처리 할 경우 첨가제로 수산화알루미늄이 적정하며, 그 농도는 1 %가 적정할 것으로 사료된다.

본 연구를 통해서 합판에 대한 물유리와 첨가제의 방염성능에 대해서 확인하였다. 다양한 물유리 농도와 첨가제는 방염성능 향상에 효과가 있는 것으로 나타냈으나, 첨가제 종류 및 농도에 따라 차이를 나타내어 보다 다양한 수종과 적합한 첨가제에 대한 추가적인 연구가 필요한 것으로 판단된다. 결과적으로 합판에 대한 적정 물유리 농도는 30 %로 선정하였고, 적합한 첨가제의 종류와 농도는 Aluminium hydroxide 1 %인 것으로 확인하였다.