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Article

Chung's equation-IX 및 Chung's equation-XII에 의한 목재 5종의 화재위험성과 화재위험성등급 예측

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Prediction of Fire Risk and Fire Risk Grade of Five Wood Species by Chung's Equation-IX and Chung's Equation-XII

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초 록

5종의 목재에 대한 화재위험성의 예측 및 화재위험성 등급을 평가하기 위해 Chung's equation-IX과 Chung's equation-XII를 이용하였다. 시험편은 미국물푸레나무, 사탕단풍나무, 버드나무, 들메나무, 산벚나무를 선정하였다. 연소시험은 ISO 5660-1의 콘칼로리미터 시험법을 이용하였으며, 화재위험성지수-IX (FRI-IX)과 화재위험성지수-XII (FRI-XII)에 대한 화재위험성과 화재위험성등급(FRR)을 비교하였다. 그 결과 화재성능지수-XI (FPI-XI)와 화재성장지수-XI (FGI-XI)은 0.44~1.05와 0.89~3.11로 얻어졌다. 그리고 화재위험성지수-XII (FRI-XII)는 산벚나무(0.85): 등급 A ≈ PMMA(1): 등급 A ≈ 미국물푸레나무(1.22): 등급 A ≈ 사탕단풍나무(1.53): 등급 A < 버드나무(4.00): 등급 C < 들메나무(7.07): 등급 D 의 순으로 증가하였다. 또한 화재위험성지수-IX (FRI-IX)은 PMMA(1): 등급 A ≈ 사탕단풍나무(2.28): 등급 A ≈ 산벚나무(3.24): 등급 A < 미국물푸레나무(5.73): 등급 B < 들메나무(10.29): 등급 C ≪ 버드나무(48.30): 등급 G의 순으로 나타났다. 공통적으로 화재위험성은 버드나무와 들메나무가 가장 높게 나타났다. 결론적으로 FRI-IX와 FRI-XII의 기준을 근거로 하여 보여준 바와 같이 지수의 표현은 다르나, 가연성 재료의 화재위험성평가에 의한 예측은 유사한 경향성을 제시하였다.

Abstract

Chung's equation-IX and Chung's equation-XII were utilized to predict the fire risk and evaluate fire risk ratings for five types of wood: white ash, hard maple, willow, fraxinus mandschurica, and sagent cherrys. The combustion tests were conducted using a cone calorimeter test method by ISO 5660-1 standards. The fire risk and fire risk rating (FRR) were compared with fire risk index-IX (FRI-IX) and fire risk index-XII (FRI-XII). The results yielded a fire performance index-XI (FPI-XI) ranging from 0.44 to 1.05 and a fire growth index-XI (FGI-XI) ranging from 0.89 to 3.11. Also, the fire risk index-XII (FRI-XII), indicated fire risk rating, exhibited an increasing order of sagent cherry (0.85): Grade A ≈ PMMA (1): Grade A ≈ white ash (1.22): Grade A ≈ hard maple (1.53): Grade A < willow (4.00): Grade C < faxinus mandschurica (7.07): Grade D. Additionally, the fire risk index-IX (FRI-IX) was PMMA (1): Grade A ≈ hard maple (2.28): Grade A ≈ sagent cherry (3.24): Grade A < white ash (5.73): Grade B < fraxinus mandschurica (10.29): Grade C ≪ willow (48.30): Grade G. In general, the willow and fraxinus mandschurica showed the highest fire risk. In conclusion, although the expression of the index is different as shown based on the criteria of FRI-IX and FRI-XII, predictions based on fire risk assessment of combustible materials showed a similar tendency.

Keywords: *Prediction of fire risk, Chung's equation-IX, Chung's equation-XII, Fire risk rating (FRR)*

1. Introduction

Fire causes enormous damage to life and property[1]. Fire risks include heat, smoke, and smoke toxicity generated from the combustion[2-5]. In order to devise countermeasures against this, combustion characteristic data obtained through fire testing of combustible materi-

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als have been utilized. Combustion characteristic tests are based on the cone calorimeter test method, one of the test methods[6]. The basis of this test is that approximately 13.1 × 10^3 kJ of energy is generated when 1 kg of oxygen is consumed when an organic polymer material is combusted[7].

Additionally, the smoke measurements test were based on the Beer-Bouguer-Lambert experiment, in which the intensity of light passing through a certain space decreases exponentially with distance[8]. When a combustible object burns, it produces combustible gases, and some of the soot is released as smoke in the flame combustion area through the incomplete combustion process[8]. In addition, all combustible materials have different heat release rates depending on their chemical composition[9,10].

Combustion characteristics include ignition time, the yield of smoke produced, smoke production rate, combustion gas, non-exposed area, and heat release rate[11-13]. However, these characteristic values are limited as a single value changes with instantaneous time, and many shortcomings in explaining the fire risk and prediction of the target object through precise and quantitative evaluation of heat and smoke generation.

To improve these shortcomings, previous studies have reported Chung's equations 1, 2, 3[14] and Chung's equation-V, Chung's equation-VI as models to predict and evaluate smoke hazards[15]. In addition, Chung's equation-II, Chung's equation-III, and Chung's equation-IV were established and published to extend the fire risk assessment that considers both heat and smoke[16]. In conclusion, the high value of Chung's equation-IV is explained as the increased fire risk[16]. This is for predicting and evaluating fire risk and fire safety.

In addition, carbon monoxide and carbon dioxide generated while a fire are very lethal, so there is a great need to evaluate them. To this end, previous studies reported the fire risk index-IX (FRI-IX) according to Chung’s equations-VII, Chung’s equations-VIII, and Chung’s equation-IX. Then, the fire risk rating (FRR) was assigned based on the calculated fire risk index-IX (FRI-IX)[17]. This method was the fire risk assessment method for evaluating the fire safety grade. However, since the extended fire progression stage is also important according to the combustion progress of the combustible materials, another method was proposed considering this.

That is, combustion resistance time (CRT) was used instead of time to ignition (TTI), which is one of the important factors of combustion, and accumulated smoke generation time (ASGT) was used instead of time to first peak smoke production rate ($TSPR_{1st\_peak}$). To this end, the fire performance index-X (FPI-X) and fire growth index-X (FGI-X) according to Chung‘s equations-X, and the fire performance index-XI (FPI-XI) and fire growth index-XI (FGI-XI) according to Chung’s equations-XI were established. Based on this, the fire risk index-XII (FRI-XII) was finally reported according to Chung‘s equation-XII[18].

Therefore, in this study, the fire risk rating (FRR) was assigned to comprehensively predict and evaluate the fire risk index-XII (FRI-XII). And it was compared with the fire risk rating (FRR) according to the fire risk index-IX (FRI-IX) previously reported in a previous study[20]. The test specimens were selected from five types of wood commonly used in general construction and interior materials: white ash, hard maple, willow, fraxinus mandschurica, and sagent cherry.

2. Materials and methods

2.1. Preparation of test materials

The test wood was purchased from MH Technologies and farmers, selected five species of hard maple, willow, fraxinus mandschurica, and sagent cherry, and used as test material without any special processing.

The wood test specimens have in the wood, it has a higher carbonization rate than other materials, although this varies depending on the species. The thickness of the test specimens was prepared as 10 mm, and polymethyl metacrlate (PMMA) was purchased from Fire Testing Technology Ltd. and tested.

2.2. Moisture content measurement

The wood specimens were dried in a drying oven at a temperature of 105 °C for 4 h until there was no change in the weight of the specimens. The water content (WC) was calculated using Equation (1)[19].

$$WC(\%) = \frac{W_m - W_d}{W_d} \times 100 \quad (1)$$

W_m is the weight of the wood specimen for which the moisture content is to be calculated (g), and W_d is the absolute dry weight (g) after drying the specimens. Table 1 shows data on the moisture content and bulk density of wood from previous studies[20].

2.3. Combustion characteristics test of building materials

The combustion test standard was ISO 5660-1, and a Dual cone cal-

Table 1. Moisture Content and Bulk Density of Each Specimen and PMMA

Materials	Scientific name	Classification	Moisture content (%)	Bulk density (kg/m^3)
White ash (WA)	*Fraxinus americana*	Hard wood	8.6	632.93
Hard maple (HM)	*Acer nigrum*	Hard wood	9.1	643.70
Willow (WL)	*Salix babylonica*	Hard wood	8.8	352.33
Fraxinus mandschurica (FM)	*Fraxinus chinensis*	Hard wood	9.0	552.63
Sagent cherry (SC)	*Prunus sargentii*	Hard wood	8.5	612.38
PMMA	-	-	-	1180.0

$$FPI-VII=\frac{TTI\,(s)}{SPR_{peak}(m^2/s)\cdot PHRR(kW/m^2)\cdot COP_{mean}\,(g/s)\,/\,CO_2P_{mean}\,(g/s)} \tag{2}$$

$$FPI-VIII=\frac{\dfrac{TTI\,(s)}{SPR_{peak}(m^2/s)\cdot PHRR(kW/m^2)\cdot COP_{mean}\,(g/s)\,/\,CO_2P_{mean}\,(g/s)}}{[\dfrac{TTI\,(s)}{SPR_{peak}(m^2/s)\cdot PHRR(kW/m^2)\cdot COP\,(g/s)\,/\,CO_2P_{mean}\,(g/s)}]_{PMMA}} \tag{3}$$

$$FGI-VII=\frac{SPR_{peak}\,(m^2/s)\cdot PHRR(kW/m^2)\cdot COP_{mean}\,(g/s)\,/\,CO_2P_{mean}\,(g/s)}{Time\ to\ SPR_{peak}\,(s)} \tag{4}$$

$$FGI-VIII=\frac{\dfrac{SPR_{peak}(m^2/s)\cdot PHRR(kW/m^2)\cdot COP_{mean}\,(g/s)\,/\,CO_2P_{mean}\,(g/s)}{Time\ to\ SPR_{peak\,(S)}}}{[\dfrac{SPR_{peak}(m^2/s)\cdot PHRR(kW/m^2)\cdot COP_{mean}\,(g/s)\,/\,CO_2P_{mean}\,(g/s)}{Time\ to\ SPR_{peak}\,(s)}]_{PMMA}} \tag{5}$$

orimeter from Fire Testing Technology Ltd. in the UK was used. The combustion test was conducted at an external radiant heat flux of 50 kW/m^2, is replicating the actual fire condition[7]. The test specimens were prepared with a material thickness of 10 mm (H) and a size of 100 mm (W) × 100 mm ($^{+0}_{-2}$) (L).

2.4. Prediction of fire risk index and evaluation of fire risk grade by Chung's equation-IX and Cgung's equation-XII

The equations of Chung's equation-IX[17] and Chung's equation-XII[18] applied to predict and evaluate the fire risk of combustible materials are presented as follows.

2.4.1. Definition of fire performance index-VII (FPI-VII) and fire performance index-VIII (FPI-VIII)

FPI-VII is as shown in equation (2). FPI-VII is expressed as whose numerator is TTI (s) and whose denominator is three important factors, SPR_{peak} (m^2/s), PHRR (kW/m^2), and COP_{mean} (g/s) / CO_2P_{mean} (g/s), multiplied and divided.

In addition, FPI-VIII was applied by referring to the fire risk assessment for all materials and the selected reference material (PMMA). Formula (3), which is FPI-VIII for calculating the dimensionless index, is defined as FPI-VII divided by $FPI\text{-}VII_{[PMMA]}$.

It can be predicted that the fire safety increases as the FPI-VIII increases.

2.4.2. Definition of fire growth index-VII (FGI-X) and fire growth index-VIII (FGI-VIII)

FGI-VII is expressed in equation (4). FGI-VII is the product of the ratio of three important factors: SPR_{peak} (m^2/s), PHRR (kW/m^2), and COP_{mean} (g/s) / CO_2P_{mean} (g/s), divided by Time to SPR_{peak}.

Also, the equation FGI-VIII was defined by referring to the selected reference material (PMMA). FGI-VIII is expressed as FGI-VII divided by $FGI\text{-}VII_{[PMMA]}$. It is as follows: Equation (5), which is an expression of a dimensionless index for calculating FGI-VIII.

The values of this equation are dimensionless indices, and the first peak smoke production rate (SPR_{1st_peak}) and the first peak heat release rate (HRR_{1st_peak}) were selected due to their importance in the early stage of fire. It can be predicted that the fire risk increases as the FGI-VIII increases.

2.4.3. Definition of fire risk index-IX (FRI-IX) and fire risk rating (FRR)

Fire risk index-IX (FRI-IX) is expressed as FGI-VIII as the numerator divided by FPI-VIII[17]. That is, as the FRI-IX value increases, the fire risk increases, and conversely, the fire safety decreases.

This equation can be used to predict risk and assign fire risk ratings by calculating the fire risk index. FRI-IX is given in equation (6).

$$FRI-IX=\frac{FGI-VIII}{FPI-VIII} \tag{6}$$

In addition, in order to predict and handle fire risk, the fire risk grade criteria according to the fire risk index-IX (FRI-IX) are presented in Table 2. That is, for values exceeding 0 to 30 of the calculated fire risk index-IX (FRI-IX), the combustion characteristics of combustible materials were classified into 7 grades at 5-unit intervals.

Table 2. Criteria for Fire Risk Rating of Calculated Fire Risk Index-IX

FRI-IX	Fire risk rating	Fire safety
5 or less	A	Very high
More than 5 up to 10	B	High
More than 10 up to 15	C	Medium 1
More than 15 up to 20	D	Medium 2
More than 20 up to 25	E	Low 1
More than 25 up to 30	F	Low 2
Over 30	G	Very low

$$FPI-X = \frac{CRT(s)}{SPR_{peak}(m^2/s) \cdot PHRR(kW/m^2) \cdot COP_{mean}(g/s)/CO_2P_{mean}(g/s)} \tag{7}$$

$$FPI-XI = \frac{\dfrac{CRT(s)}{SPR_{peak}(m^2/s) \cdot PHRR(kW/m^2) \cdot COP_{mean}(g/s)/CO_2P_{mean}(g/s)}}{\left[\dfrac{CRT(s)}{SPR_{peak}(m^2/s) \cdot PHRR(kW/m^2) \cdot COP(g/s)/CO_2P_{mean}(g/s)}\right]_{PMMA}} \tag{8}$$

$$FGI-X = \frac{SPR_{peak}(m^2/s) \cdot PHRR(kW/m^2) \cdot COP_{mean}(g/s)/CO_2P_{mean}(g/s)}{ASGT(s)} \tag{9}$$

$$FGI-XI = \frac{\dfrac{SPR_{peak}(m^2/s) \cdot PHRR(kW/m^2) \cdot COP_{mean}(g/s)/CO_2P_{mean}(g/s)}{ASGT(s)}}{\left[\dfrac{SPR_{peak}(m^2/s) \cdot PHRR(kW/m^2) \cdot COP_{mean}(g/s)/CO_2P_{mean}(g/s)}{ASGT(s)}\right]_{PMMA}} \tag{10}$$

2.4.4. Definition of fire performance index-X (FPI-X) and fire performance index-XI (FPI-XI)

FPI-X is as in equation (7). FPI-X is expressed as the combustion resistance time (CRT) (s) which replaced TTI (s) of FPI-VII, multiplied by the ratio of three important factors: SPR_{peak} (m^2/s), PHRR (kW/m^2), and COP_{mean} (g/s) / CO_2P_{mean} (g/s). CRT means the accumulated combustion time between the point of the first maximum heat release rate (HRR_{1st_peak}) and the point of the second maximum heat release rate (HRR_{2nd_peak}) during combustion of the combustion materials. Thermoplastic (liquid) materials have different combustion processes and forms after combustion from carbonized or solid materials, and only the first maximum heat release rate (HRR_{1st_peak}) is obtained during combustion. Therefore, in order to minimize their differences, the combustion time between HRR_{1st_peak} and TTI was selected and applied as the closest factor. In addition, equation FPI-XI was used on the basis of the reference material PMMA. FPI-XI is presented in equation (8).

The formula FPI-XI is defined as FPI-X with CRT (s) replacing TTI (s) of FPI-VIII, divided by $FPI-X_{[PMMA]}$ as the denominator. The larger FPI-XI means higher fire safety.

2.4.5. Definition of fire growth index-X (FGI-X) and fire growth index-XI (FGI-XI)

FGI-X is as in equation (9). The equation FGI-X is expressed as the value obtained by multiplying the three important factors of SPR_{peak} (m^2/s), PHRR (kW/m^2), and COP_{mean} (g/s) / CO_2P_{mean} (g/s), and dividing it by ASGT (s). ASGT (s) refers to the accumulated smoke generation time (ASGT) that replaced the Time to SPR_{peak} (s) of FGI-VII. ASGT (s) means the time interval between the positions of $TSRR_{1st\_peak}$ and $TSRR_{2nd\_peak}$ for the combustion materials. In particular, since the combustion pattern of non-carbonized materials is different from that of solid or carbonized materials, the interval between the TTI and $TSPR_{1st\_peak}$ positions, which are the closest combustion characteristics, was applied as ASGT. In addition, equation FGI-XI was defined based on PMMA. FGI-XI is as shown in equation (10).

FGI-XI is expressed as the value of FGI-X divided by $FGI-X_{[PMMA]}$, with ASGT (s) replacing Time to SPR_{peak} (s) of FGI-VIII. Therefore, it is explained that as the dimensionless index of FGI-XI increases, the fire risk increases, and conversely, the fire safety decreases.

2.4.6. Definition of fire risk index-XII (FRI-XII) and fire risk rating (FRR)

FRI-XII is the formula for another method corresponding to the equation FRI-IX[18] established by a previous study.

FRI-XII is presented in equation (11).

$$FRI-XII = \frac{FGI-XI}{FPI-XI} \tag{11}$$

The FRI-XII formula is defined as the value obtained by dividing FGI-XI by FPI-XI. That is, as the FRI-XII value increases, the fire risk increases, and conversely, as the FRI-XII value decreases, the fire safety increases. Accordingly, the fire risk were comprehensively predicted and evaluated, and the fire risk grade was assigned.

In addition, in order to finally predict and evaluate the fire risk, the FRR could be assigned based on the value of FRI-XII according to the criteria in Table 3. This classified the fire safety of the combustion target into 7 grades by dividing the values of FRI-XII from 0 to 12 or higher in intervals of 2 units.

Table 3. Criteria for Fire Risk Rating of Calculated Fire Risk Index-XII[21]

FRI-XII	Fire risk rating	Fire safety
less than 2	A	Very high
2 to less than 4	B	High
4 to less than 6	C	Medium 1
6 to less than 8	D	Medium 2
8 to less than 10	E	Low 1
10 to less than 12	F	Low 2
12 or more	G	Very low

3. Results and discussion

In this study, the fire risk of combustible materials was predicted and evaluated, and a fire risk grade was assigned. PMMA was used as a reference material, referring to data from a previous study[22], and important factors related to combustion properties are presented in Table 2. Using these results, the fire performance index-X (FPI-X) and fire growth index-X (FGI-X) were derived, and the fire risk rating (FRR) for the comprehensive fire risk index-XII (FRI-XII) was assigned based on the fire performance index-XI (FPI-XI) and fire growth index-XI (FGI-XI).

FRI-XII is a dimensionless index that predicts comprehensive fire risk. The time to ignition (TTI), heat release rate (HRR), smoke production rate (SPR), and average CO / CO_2 production rate ratio for each test specimen in Table 4 were based on previously reported data[20].

3.1. Thermal characteristics of the test specimen

The ignition time for a fire target is a very important property in determining the combustibility of building materials, and the later the ignition time, the more flammability is suppressed. When combustible materials are burned, the type, moisture content, heat penetration, thermal characteristics, and density of the material affect the gas toxicity, smoke generation, and energy release rate.

Table 4 refers to the combustion characteristics of test specimens obtained from previous studies[20], except the CRT and ASGT. The ignition times were 8 s for willow, 15 s for fraxinus mandschurica, 17 s for white ash, 19 s for hard maple, and 19 s for sagent cherry. Willow showed the fastest ignition time. Hard maple and sagent cherry showed the longest ignition times. This is understood to be because their volume densities are relatively high at 643.70 kg/m^3 and 612.38 kg/m^3, respectively, compared to other species. The ignition time of wood is proportional to the constant depending on the presence or absence of heat loss on the wood surface, volume density, thermal conductivity, specific heat of fuel, and the square of the ignition temperature, and inversely proportional to the square of the heat flux applied to the test piece[23]. Therefore, it is predicted that the ignition time will be delayed as the volume density increases.

The peak heat release rate is the most important fire characteristic and is an expression of fire intensity[24-26]. As the heat release rate increases, more target materials are ignited and burned, thereby expanding the fire scale. On the other hand, if the heat release rate is low, nearby target materials may not be ignited and may be limited to the ignition area. Combustible materials with low heat release rates in the event of a fire can be expected to have the effect of slowing down the spread of fire[27]. The peak heat release rate (HRR_{peak}) for a test specimen is expressed as the size of the maximum amount of heat released per surface area of the test specimen[28,29]. This is the point at which the test specimen is burned the most, so flaming combustion with a high heat release rate expands the fire scale.

Figure 1 shows the heat release rate curve by the test. It was found by research that the wood specimens produced carbonized materials had two maximum heat release rate values. The first peak of the heat release rate curve, HRR_{1st_peak}, occurs when volatile pyrolysis gases are generated after a heating period by an external flame igniter. The generated heat causes continuous pyrolysis of the wood specimen, releasing more volatile substances. In addition, the decrease in HRR_{1st_peak} is due to the formation of an insulating char layer that makes heat transfer difficult and delays the pyrolysis process. In addition, the second peak of the heat release rate curve, HRR_{2nd_peak}, appears because more

Table 4. Combustion Characteristics of Test Specimens at an External Radiant Heat Flux of 50 kW/m^2

Materials	[a]TTI (s)	[b]CRT (s)	[c]HRR_{1st_peak} (kW/m^2) at Time (s)	[d]HRR_{2nd_peak} (kW/m^2) at Time (s)	[e]SPR_{1st_peak} (m^2/s)
White ash (WA)	17	260	265.80 / 40	392.60 / 300	0.0248
Hard maple (HM)	19	260	233.69 / 40	423.43 / 300	0.0235
Willow (WL)	8	180	215.06 / 25	320.14 / 205	0.0226
Fraxinus mandschurica (FM)	15	215	241.03 / 35	444.60 / 250	0.0257
Sagent cherry (SC)	19	240	214.40 / 40	344.64 / 280	0.0216
PMMA	17	368	1110.56 / 385	-	0.0516

Materials	[f]$TSPR_{1st\_peak}$ (s)	[g]ASGT (s)	[h]SPR_{2nd_peak} (m^2/s) at Time (s)	[i]COP_{mean} (g/s)	[j]CO_2P_{mean} (g/s)
White ash (WA)	50	265	0.0702 / 315	0.0021	0.0511
Hard maple (HM)	105	195	0.0738 / 300	0.0025	0.0523
Willow (WL)	20	190	0.0588 / 210	0.0021	0.0300
Fraxinus mandschurica (FM)	90	165	0.0887 / 255	0.0033	0.0446
Sagent cherry (SC)	50	260	0.0648 / 310	0.0023	0.0493
PMMA	385	368	-	0.0007	0.1243

[a]Time to ignition; [b]combution resistance time; [c]1st_peak heat release rate; [d]2nd_peak heat release rate; [e]1st_peak smoke production rate; [f]time to 1st_peak smoke production rate; [g]accumulated smoke generation time; [h]2nd_peak smoke production rate; [i]mean carbon monoxide production rate; [j]mean carbon dioxide production rate

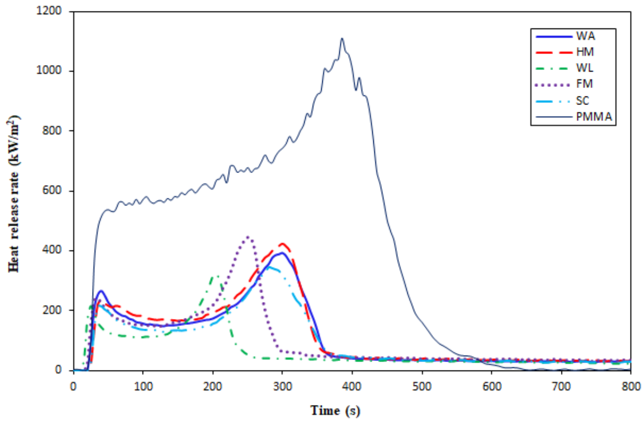

Figure 1. Heat release rate of the test specimen under an external radiant heat flux of 50 kW/m^2[20].

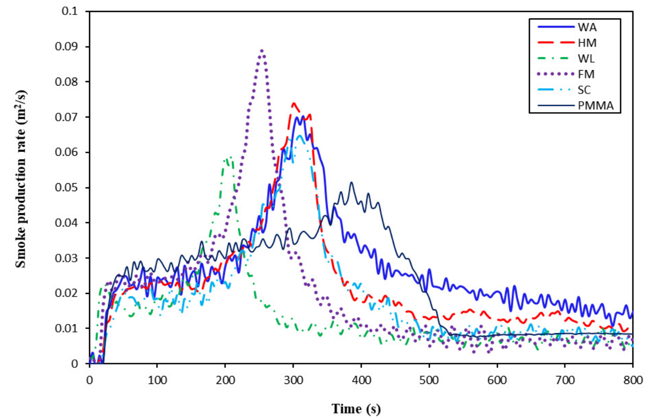

Figure 2. Smoke production rate of the specimen at an external heat flux of 50 kW/m^2[20].

volatile substances can be easily released from the specimen due to combustion and carbonization cracking of the specimen[30].

This is formed because a lot of heat is released simultaneously as heat is accumulated due to the back effect of the insulation layer on the back of the specimen[31]. Afterwards, as the volatile substances decrease, the flaming combustion ends and the heat release rate returns to a stable baseline. HRR_{2nd_peak} is recognized as a measure of fire growth under extreme combustion conditions.

Table 3 and Figure 1 show the combustion characteristics and heat release rate curves of wood. The HRR_{1st_peak} characteristics of wood increased in the order of sagent cherry 214.40 kW/m^2, willow 215.06 kW/m^2, hard maple 233.69 kW/m^2, fraxinus mandschurica 241.03 kW/m^2, and white ash 265.80 kW/m^2. Among them, white ash showed the highest value, 1.2 times higher than that of sagent cherry. HRR_{2nd_peak} increased to 320.14 kW/m^2 for willow, 344.64 kW/m^2 for sagent cherry, 392.60 kW/m^2 for white ash, 423.43 kW/m^2 for hard maple, and 444.60 kW/m^2 for fraxinus mandschurica. HRR_{2nd_peak} was highest in the fraxinus mandschurica, which was 1.4 times higher than that of the willow.

In the HRR_{1st_peak} area, white ash was the highest and sagent cherry was the lowest. In addition, the time to reach the maximum heat release rate (HRR_{1st_peak}) at the initial stage of the fire was delayed by 25 s for willow, 35 s for fraxinus mandschurica, and 40 s for white ash, hard maple, and sagent cherry, respectively. Therefore, willow is considered to have the greatest thermal hazard from fire compared to other species. This is because the amount of combustible gas generated decreases as the mass of the materials is depleted. In addition, the reason why the HRR_{1st_peak} value of willow is low is that, as shown in Table 3, although the moisture content is similar to that of other species, the volume density is lower, which increases the combustion speed and makes it vulnerable to fire.

3.2. Characteristics of smoke generation rate

The causes of death in the fire are known as incomplete combustion of carbon, thermal decomposition of cellulose, carbon monoxide generation through nitrogen oxides, and hydrogen-based chemical generation. Damage from smoke and toxic gases in fires is much more fatal to human life than damage from heat. Smoke in a fire hinders people's escape and evacuation, increases the probability of suffocation, and makes it difficult to visibility secure of people. Smoke generation is affected by the combustible material and the surrounding environment.

As shown in Table 3 and Figure 2, SPR_{1st_peak} shows that it reaches the maximum value rapidly in a short period of time. During this period, smoke is composed of volatile wood extracts, aerosol, and water vapor generated from gas and decomposed hemicellulose. SPR_{1st_peak} was difficult to distinguish between each species and it was similar with 0.0216 m^2/s to 0.0248 m^2/s. However, in the case of willow, since its own bulk density is low, the time it takes to reach SPR_{1st_peak} is the fastest at 20 s, so it can be predicted that the smoke hazard is high in the early stage. Due to the low own bulk density, the time to reach the SPR was the fastest at 20 s, so it can be predicted that the smoke risk is high initially.

As mentioned above, SPR_{2nd_peak} was 0.0588 m^2/s to 0.0887 m^2/s for all tests. The values were not large and their characteristics and tendencies were similar. In particular, willow was expected to show the greatest toxicity because it took the fastest time to reach SPR_{2nd_peak} at 210 s. In other words, although it is difficult to distinguish the difference in moisture content, it shows that the time to reach the maximum smoke generation speed is fast because the volume density is reduced and the generated charcoal is not hard.

The char produced on the test piece by the combustion process reduces the thermal penetration during fire, and increases the thermal resistance between the wood surface exposed to heat and the pyrolysis of wood front. This prevents the contact between the volatile substances released from the combustion materials and oxygen. Therefore, the maximum smoke production rate is reduced or the time until the maximum smoke production rate is reached is delayed.

3.3. Characteristics of combustion gases

Generally, the combustion phenomenon and toxic gases of fire are qualitatively and quantitatively greatly affected by the composition of materials, moisture, temperature, and oxygen concentration. The repre-

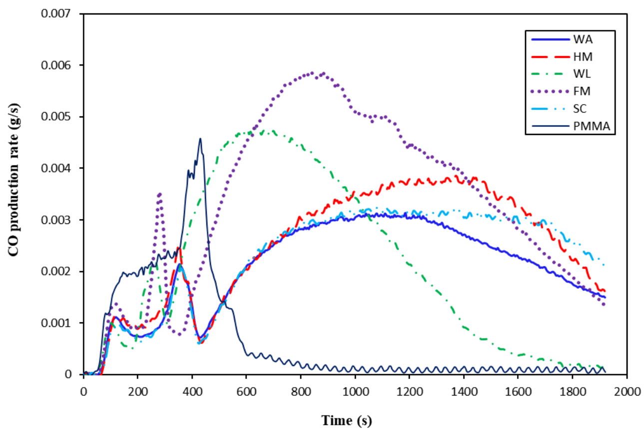

Figure 3. CO production rate (g/s) of the specimen under an external radiant heat flux of 50 kW/m²[20].

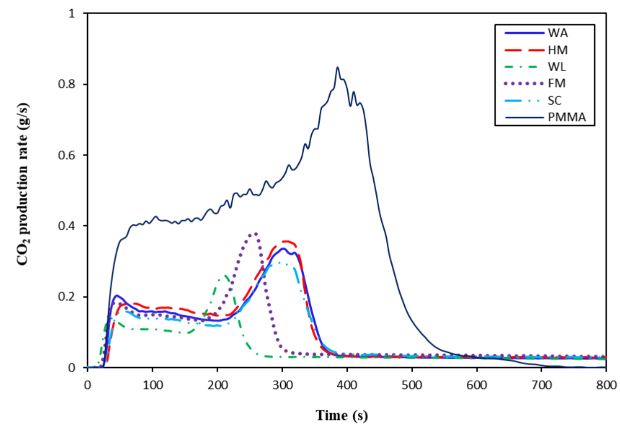

Figure 4. CO_2 production rate (g/s) of the specimen under an external radiant heat flux of 50 kW/m²[20].

sentative toxic gas generated during the combustion process of combustible materials is known as be carbon monoxide (CO). It is the most important incomplete combustion product of volatile substances generated between wood and flame. It is understood that the production of CO gas increases together as the heat release rate of volatile substances increases.

The COP_{mean} of the five test specimens shown in Table 3 and Figure 3 was 0.0021 to 0.0033 g/s. This was 3 to 4.7 times higher than that of the reference material PMMA (0.0007 g/s). Indicated that wood is a material that burns more incompletely than PMMA. Among them, the COP_{mean} of the fraxinus mandschurica was measured to be relatively high at 0.0033 g/s. This is understood to be due to the increase in CO generation due to thermal oxidation of charcoal generated after the fire is extinguished, compared to other specimens, in which the COP_{mean} of wood is increased.

As shown in Table 3 and Figure 4, CO_2P_{mean} was 0.0300 to 0.0523 g/s for all specimens. This was 2.4 to 4.1 times lower than the CO_2P_{mean} (0.1243 g/s) of the reference material PMMA. All specimens generated CO_2 in the heat release rate area during combustion rather than after combustion, which means that complete combustion occurred in the flame combustion area.

As shown in Fugure 3 and 4, the CO and CO_2 generation rates showed various forms such as the first, second, and third maximum values for each specimen as combustion progressed over time. Therefore, it is difficult to interpret their characteristics by focusing on a specific maximum value. Thus, the average value for the entire combustion time was taken.

The COP_{mean} / CO_2P_{mean} ratio of the wood specimens for the average CO and CO_2 generation rates in Table 3 was 0.0411 to 0.0740, which was 7.3 to 13.2 times higher than that of PMMA. This suggests that wood has a relatively higher CO toxicity than PMMA due to incomplete combustion.

3.4. Comprehensive fire risk and fire risk grade assessment

The peak value of the heat release rate (HRR) and the time to ignition indicate the fire hazard characteristics of combustible materials[16], and the smoke hazard is also explained in the same context[15]. Therefore, in a previous study, the fire performance index-II (FPI-II) was established by combining the three important combustion factors: time to ignition, maximum smoke production rate, and maximum heat release rate, and the fire hazard of combustible materials was predicted[16]. However, since it is very reasonable to include the generation of lethal CO and CO_2 gases generated during a fire in the developed model formula and to evaluate it, the FPI-VII was established and applied by linking four important factors that considered the average produced rate CO and CO_2 ratios[17].

In a previous study, TTI used as a combustion characteristic was reported by establishing the equation FPI-X as in equation (2) using CRT which is a substitute for TTI in another way[18]. CRT has defined the combustion resistance time as the time interval between the positions of the first heat release rate HRR_{1st_peak} and the second heat release rate HRR_{2nd_peak} while the combustibles are burning. In general, combustible materials show different differences in combustion rates depending on their composition and combustion conditions. In addition, non-carbonized (liquid) materials have a different combustion form compared to carbonized or thermosetting materials, and only HRR_{1st_peak} is obtained when burning. Therefore, for non-carbonized materials, the interval time between the positions of TTI and the HRR_{1st_peak}, which is the closest element defined in a previous study, was used as the combustion resistance time (CRT)[18].

Table 5 presents the fire performance index-X (FPI-X) of the test specimens. FPI-X is composed of a combination of CRT, heat, smoke, and the average production rate ratio of carbon monoxide and carbon dioxide. The fire safety by FPI-X increased in the order of fraxinus mandschurica (469.03 s^2/kW) < willow (529.06 s^2/kW) < white ash (959.68 s^2/kW) < hard maple (990.46 s^2/kW) < PMMA (1036.65 s^2/kW) < sagent cherry (1109.73 s^2/kW). Therefore, it is understood that faxinus mandsurica and willow have a high fire risk. This is understood to be due to the relatively low bulk density and fast time to ignition of faxinus mandsurica and willow.

In addition, the formula FPI-XI has been established and reported in order to make the fire risk of all combustible materials into a di-

Table 5. Fire Perfomance Index-XI (FPI-XI) of Specimens at 50 kW/m^2 External Radiant Heat Flux

Materials	CRT (s)	HRR_{1st_peak} (kW/m^2)	SPR_{1st_peak} (m^2/s)	COP_{mean} / CO_2P_{mean}	FPI-X (s^2/kW)	FPI-XI
White ash (WA)	260	265.80 / 40	0.0248	0.0411	959.68	0.91
Hard maple (HM)	260	233.69 / 40	0.0235	0.0478	990.46	0.94
Willow (WL)	180	215.06 / 25	0.0226	0.0700	529.06	0.50
Fraxinus mandschurica (FM)	215	241.03 / 35	0.0257	0.0740	469.03	0.44
Sagent cherry (SC)	240	214.40 / 40	0.0216	0.0467	1109.73	1.05
PMMA	368	1110.56 / 385	0.0516	0.0056	1056.65	1

Table 6. Fire Growth Index-XI (FGI-XI) of Wood Specimens at 50 kW/m^2 External Radiant Heat Flux

Materials	HRR_{1st_peak} (kW/m^2)	SPR_{1st_peak} (m^2/s)	ASGT (s)	COP_{mean} / CO_2P_{mean}	FGI-X (kW/s^2)	FGI-XI
White ash (WA)	265.80 / 40	0.0248	265	0.0411	0.0010	1.11
Hard maple (HM)	233.69 / 40	0.0235	195	0.0478	0.0013	1.44
Willow (WL)	215.06 / 25	0.0226	190	0.0700	0.0018	2.00
Fraxinus mandschurica (FM)	241.03 / 35	0.0257	165	0.0740	0.0028	3.11
Sagent cherry (SC)	214.40 / 40	0.0216	260	0.0467	0.0008	0.89
PMMA	1110.56 / 385	0.0516	385	0.0056	0.0009	1

mensionless index[18]. FPI-XI is expressed as FPI-X as a numerator divided by $FPI\text{-}X_{[PMMA]}$. Since this formula is an important factor in the early stage of fire, the first smoke production rate SPR_{1st_peak} and the first heat release rate HRR_{1st_peak} values were selected. Here, the maximum safety value assuming an actual fire was considered. It is understood that as the fire spread increases, the fire risk increases and the fire safety decreases, and the smoke safety also decreases. This means that the lower the FPI-XI value, the lower the fire safety.

In addition, in a previous study, the fire growth index-II (FGI-II) was reported in relation to three types of SPR_{peak} (m^2/s), PHRR (kW/m^2), and time to reach maximum smoke generation velocity [Time to SPR_{peak}, $TSPR_{1st\_peak}$ (s)] to predict and evaluate the fire hazard of combustible materials[16]. However, since the necessity of evaluating the generation of lethal CO and CO_2 is very high, equation FGI-VII was reported in relation to four important factors considering the average generation velocity ratios of CO and CO_2[17]. This equation was distinguished from the previous study and selected four types of SPR_{peak} (m^2/s), PHRR (kW/m^2), $TSPR_{peak}$ (s), and COP_{mean} / CO_2P_{mean} to predict the fire hazard in order to increase quantitativeness and precision.

However, in a previous study, instead of the first total smoke production rate, $TSPR_{1st\_peak}$ of the combustible material, the ASGT substituted above was newly established as the FGI-X formula as in equation (4)[18]. ASGT is defined as the time interval between the position where the combustible material reaches the first total smoke production rate, $TSPR_{1st\_peak}$ and the second total smoke generation rate, $TSPR_{2nd\_peak}$ is reached. In particular, since the combustion form of non-carbonized materials is different from that of carbonized or solid (thermosetting) materials, the interval between the TTI and the $TSPR_{1st\_peak}$ position was named and applied as ASGT as the closest element.

The fire risk by the FGI-X value in Table 6 increased in the order of sagent cherry (0.0008 kW/s^2) < PMMA (0.0009 kW/s^2) < white ash (0.0010 kW/s^2) < hard maple (0.0013 kW/s^2) < willow (0.0018 kW/s^2) < fraxinus mandschurica (0.0028 kW/s^2). Among them, fraxinus mandsurica had the highest value. According to the data shown, it is understood that SPR_{1st_peak}, PHRR, and COP_{mean} / CO_2P_{mean} are relatively high among the test specimens except PMMA. Therefore, it is understood that the materials with the highest fire risk are fraxinus mandsurica and willow, which are due to their low bulk density and fast time to ignition as mentioned above.

FGI-XI, shown in Table 6, increased in the order of sagent cherry (0.89) < PMMA (1) < white ash (1.11) < hard maple (1.44) < willow (2.00) < fraxinus mandschurica (3.11). The FGI-X and FGI-XI were observed to have the same tendency. As a result, the higher the value of FGI-XI, the higher the fire risk and lower the fire safety of combustible materials. FGI-XI is a value calculated using data obtained from combustion tests, and is a dimensionless index that comprehensively evaluates the fire safety of combustible materials.

Table 7 shows the FPI-VIII and FGI-VIII investigated in previous studies for reference. That is, the value of FPI-VIII increased in the order of willow (0.44) < faxinus mandschurica (0.62) < PMMA (1) < white ash (1.18) < hard maple (1.37) < sagent cherry (1.66). In addition, FGI-VIII increased in the order of PMMA (1) < hard maple (3.13) < sagent cherry (5.38) < fraxinus mandschurica (6.38) < white ash (6.75) << willow (21.25). Therefore, The correlation between FPI-VIII and FGI-VIII is the same.

By equation (11), the fire risk index-XII (FRI-XII) is expressed as FGI-XI divided by FPI-XI, which indicates that the fire safety decreases as the fire spreads. In other words, a larger value of FRI-XII indicates a higher fire risk, and conversely, a smaller value indicates a lower fire risk. By predicting and evaluating the fire risk, the fire risk grade can be assigned and a comprehensive judgment can be made.

Table 7. Fire Performance Index-VIII (FPI-VIII) and Fire Growth Index-VIII (FGI-VIII) of the Test Specimens at 50 kW/m^2 External Radiant Heat Flux[20]

Materials	FPI-VII (s^2/kW)	FPI-VIII	FGI-VII (kW/s^2)	FGI-VIII
White ash (WA)	62.75	1.18	0.0054	6.75
Hard maple (HM)	72.38	1.37	0.0025	3.13
Willow (WL)	23.51	0.44	0.0170	21.25
Fraxinus mandschurica (FM)	32.72	0.62	0.0051	6.38
Sagent cherry (SC)	87.84	1.66	0.0043	5.38
PMMA	52.97	1	0.0008	1

Table 8. Comparison of Each Fire Risk Ranking (FRR) by Fire Risk Index-IX (FRI-IX) and Fire Risk Index-XII (FRI-XII) of The Test Specimens at The External Radiant Heat Flux of 50 kW/m^2

Materials	FPI-VIII	FGI-VIII	FRI-IX	FRR by FRI-IX	FPI-XI	FGI-XI	FRI-XII	FRR by FRI-XII
White ash (WA)	1.18	6.75	5.72	B	0.91	1.11	1.22	A
Hard maple (HM)	1.37	3.13	2.28	A	0.94	1.44	1.53	A
Willow (WL)	0.44	21.25	48.30	G	0.50	2.00	4.00	C
Fraxinus mandschurica (FM)	0.62	6.38	10.29	C	0.44	3.11	7.07	D
Sagent cherry (SC)	1.66	5.38	3.24	A	1.05	0.89	0.85	A
PMMA	1	1	1	A	1	1	1	A

In addition, the final evaluation index that can be used to predict and evaluate fire risk was obtained by FRI-XII as shown in Table 8.

As shown in Table 8, FRI-XII according to the criteria in Table 3 increased in the following order: sagent cherry tree (0.85): Grade A ≈ PMMA (1): Grade A ≈ white ash (1.22): Grade A ≈ hard maple (1.53): Grade A < Willow (4.00): Grade C < fraxinus mandschurica (7.07): Grade D.

Also, regarding the FRR criteria proposed in a previous study on FRI-IX in Table 2[17], FRI-IX shown in Table 8 was in the following order: PMMA (1): Grade A ≈ hard maple (2.28): Grade A ≈ sagent cherry (3.24): Grade A < white ash (5.72): Grade B < fraxinus mandschurica (10.29): Grade C << Willow (48.30): Grade G. That is, as shown based on the respective criteria for the results of FRI-IX and FRI-XII, the expression of the index was different, but the fire risk rating (FRR) was similar.

Therefore, as examined above, the fire hazard of willow and ash trees was commonly presented as the highest. In conclusion, as shown based on the criteria of FRI-IX and FRI-XII, although the expression of the index is different, the prediction by fire hazard assessment of combustible materials presented a similar tendency.

4. Conclusions

Chung's equation-IX and Chung's equation-XII were applied to predict and evaluate the fire risk of combustible materials and to assign fire risk grades to five types of wood. The combustion characteristics test was conducted using the cone calorimeter test method according to the ISO 5660-1 standard. Finally, to perform fire risk prediction and evaluation, the fire risk rating (FRR) were compared by the fire risk index-IX (FRI-IX) and fire risk index-XII (FRI-XII).

1) The fire safety by FPI-X increased in the order of fraxinus mandshurica (469.03 s^2/kW) < willow (529.06 s^2/kW) < white ash (959.68 s^2/kW) < hard maple (990.46 s^2/kW) < PMMA (1036.65 s^2/kW) < sagent cherry (1109.73 s^2/kW).

2) The fire risk by FGI-X value increased in the order of sagent cherry (0.0008 kW/s^2) < PMMA (0.0009 kW/s^2) < white ash (0.0010 kW/s^2) < hard maple (0.0013 kW/s^2) < willow (0.0018 kW/s^2) < fraxinus mandschurica (0.0028 kW/s^2). This result showed a tendency for the values of FGI-X and FGI-XI to be consistent.

3) The Fire risk Index-XII (FRI-XII) increased in the following order: sagent cherry (0.85): Grade A ≈ PMMA (1): Grade A ≈ white ash (1.22): Grade A ≈ hard maple (1.53): Grade A < willow (4.00): Grade C < fraxinus mandschurica (7.07): Grade D.

4) The ire risk index-IX (FRI-IX) was in the following order: PMMA (1): Grade A ≈ hard Maple (2.28): Grade A ≈ sagent cherry (3.24): Grade A < white Ash (5.73): Grade B < fraxinus mandschurica (10.29): Grade C ≪ Willow (48.30): Grade G.

5) In general, the willow and fraxinus mandschurica showed the highest fire risk. In conclusion, as shown based on the criteria of FRI-IX and FRI-XII, although the expression of the index is different, the prediction by fire risk assessment of combustible materials showed a similar tendency.

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