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Physical and Mechanical Properties and Fire-endurance Characteristics of Recycled Particleboards

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ABSTRACT

In this study, fire-retardant chemicals were melt with mixed composition ratios of dibasic ammonium phosphate and each half of boric acid and borax in hot water, in which hammer-milled chips were immersed to increase swelling of waste particleboards. Also, fire-retardant treated particles from sawn lumber chip and recycled particleboard chip were composed in ratio of 70:30 in core layer to improve boards' properties.

Retention ratio of fire-retardant chemicals for the particles for face layer was high due to high specific surface area, and that of sawn lumber chips was somewhat higher than that of recycled particleboard chips.

The mixture of particles from sawn lumber chips and recycled PB of 70:30 in weight ratio exceeded bending strength of 100 kgf/cm^2. It seemed that the relatively greater portions of dibasic ammonium phosphate affected adversely to dimensional stability, however fire-retardants treatment resulted in distinct effect lowering formaldehyde emission such as E_0 type (0.5mg/ℓ or less) in KS F 3104.

In fire-retardancy, the recycled boards with a mixed ratio of dibasic ammonium phosphate to boric acid·borax (50:50 mixture) of 70% to 30% in weight satisfied fire-retardancy 3rd grade in KS F 2271, and also this composition from cone calorimeter test met same standard grade figuring total heat release of 4.6MJ/m^2.

Keywords: Fire-retardant chemicals, dibasic ammonium phosphate, boric acid, borax, fire-retardant treated particles, sawn lumber chip, recycled particleboard chip, cone calorimeter, fire-retardancy 3rd grade.

INTRODUCTION

Fire retardancy is one of the most commonly required subject for using wood and wood-based materials as interior and structural elements in public and dwelling buildings. It is well known that glued laminated timber (glulam) of large dimension and efficiently fire-retardant treated board show good fire performances.

White and Dietenger (2001) reported that thermal degradation of wood can be broken up into four temperature regimes. Between 100℃ and 200℃, wood becomes dehydrated and generates water vapor and other noncombustible gases and liquids including CO_2, formic acid, acetic acid and

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H_2O. Between 200℃ to 300℃, some wood components begin to undergo significant pyrolysis, and in addition to the previous gases and liquids, significant amounts of CO and high-boiling-point tar are given off. The hemicelluloses and lignin components are pyrolyzed in the ranges 200~300℃ and 225~450℃. The third temperature regime is from 300℃ to 450℃ because of the vigorous production of flammable volatiles. This begins with significant depolymerization of cellulose in the range 300~350℃, and carbon linkage between lignin structural units is cleaved from 370℃ to 400℃. At 450℃ above, the remaining wood residue is char, which undergoes further degradation by being oxidized to CO_2, CO and H_2O. This is referred to as afterglow.

In domestic researches on wood and wood-based materials, Kim, Chung and Lee (1984) immersion-treated 5 types of chemicals of ammonium sulfate, mono- and di-basic ammonium phosphates and mixed reagent of boric acid and borax, minalith on meranti plywood, and after plywoods were redried, their bending strengths were investigated.

Lee and Schaffer (1981) pressure-treated mixture of borax and boric acid, zinc chlorine chromate, minalith, pyresote and one type of commercial fire-retardant on Douglas-fir and poplar plywood, and drying characteristics were evaluated with drying methods by heat air and hot press platen.

Also, Kwon and Lee (1985) fabricated 5 types of fire-retardants-treated particleboard and complyboard, and evaluated chemical absorption, MOR, MOE, internal bond strength, screw holding strength, thickness swelling, ignition time, flame remaining time, flame length, charred area, mass loss rate, chemical types, and consistency affecting back side-temperature and as well its relationship.

On the other hand, LeVan and Winandy (1990) referred that fire-retardant chemical lowers a tempeature initiating thermal degradation, and increases amount of char, and plays role on a mechanism decreasing amount of flammable volatile gases. The elevated temperature decomposes fire-retardant chemical into acidic chemical type and this endowes fire-resistance. As a key point, the acidic fire-retardant chemicals lower flammability of wood and hold wood strength properties. However, LeVan and Winandy (1990) reported also that combination of acidic fire-retardant chemical and high temperature increases an acid hydrolysis rate in wood and causes a decrease of wood strength.

Hirata (1989) referred a mechanism of fire-resistance, in which the wood combustion was classified into flammable and non-flammable combustion and heated wood is decomposed, occuring combustible gas, and then this gas mixes with such oxidant as air and brings about flammable combustion. It was also mentioned that as fire-retardancy mechanism, there are an action decreasing the initiating temperature of thermal decomposition of fire-retardant chemicals, an action promoting the formation of non-combustible gas and an gas-phase action. This gas-phase action dilutes combustible gas produced by thermal decomposition with non-combustible gas of CO_2, NH_3, H_2O etc generated by thermal decomposition of wood so that mixed gaseous consistency may not reach critical combustible point. In addition to this, it was reported NH_3 becomes generated from ammonium salt, and dehydration from wood in acidic and basic chemicals becomes promoted and produces moisture.

Domestic particleboard industry depends on wood wastes as raw materials of board. The particleboard being low grade-wood wastes among wood wastes includes the compressed and hardened state of chips. So it would be possible that this particleboard recoveries original state of wood substance and thereafter is used as adequate raw materials, aiding to improve such board properties as strength etc. It was suggested that the glue-line of wood wastes would be hydrolyzed and swelled by immersing chips in heated water as a method of pretreatment, and in this swelling time, fire-retardant chemicals are able to be permeated easily by fire-retardant treatment.

From the result of preparatory experiment, though swelling ratio of chip is different according to temperature and elapsed time, it was thought that the fire-retardant treatment in relatively low water temperature of 60℃, which pre-treatment of immersion is easy, could be exhibited effectively. Correspondingly, a manufacturing possibility of recycled boards having interior materials-required properties and fire-retardancy was evaluated.

MATERIALS AND METHODS

Experimental materials

In this study, wood waste materials were particleboard chips and sawn lumber chips, which were mesh-screened and used as 8 mm or more size. Fire-retardant chemicals were $(NH_4)_2HPO_4$, and mixture composed with 50% of H_3BO_3 to 50% of $Na_2B_4O_7 \cdot 10H_2O$ in weight.

In order to manufacture 3 layer board, particles for face layer were screened and used to 20-80 mesh, and particles for core layer were 3-20mesh. Then, recycled boards were manufactured with urea-formaldehyde resin adhesive, wax emulsion as water repellent, and 20% NH_4Cl solution as hardening reagent.

Experiment methods

This study was conducted to manufacture the fire-endurable board to bring about the swelling effect by immersion in heated water and the fire-retardants treatment implementation. First, fire-retardant chemicals were treated and the recycled boards were made with only the recycled particleboard (PB) chip, and then the board properties and fire-endurance were estimated. Secondly, the improvement of board properties and the fire-endurance were aimed with composition in core layer for the purpose of reinforcement, applying the mixing ratio of 70:30 of sawn lumber and recycled PB chip, respectively.

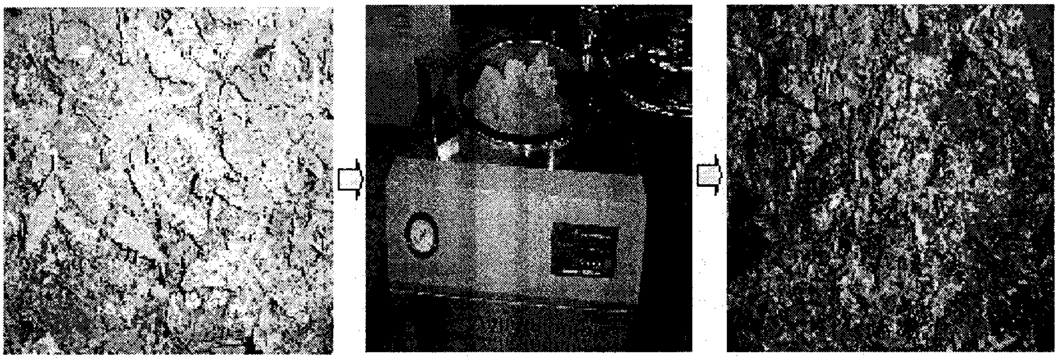


Fig.1. Fire-resistance treatment on the recycled particleboard particles using autoclave.

In order to investigate a manufacturing condition of fire-resistant 3 layer boards, on the basis of the previous study, $(NH_4)_2HPO_4$ figuring the superior and general usability and a combination of each half of H_3BO_3 (boric acid) and $Na_2B_4O_7 \cdot 10H_2O$ (borax) as low human toxicity and chemicals having fire- retardancy and insect-proof property were mixed at the ratios of 50:50, 60:40, 70:30 in weight, and prepared in fire-retardants melt water solution of 30% consistency.

First of all, particles for face layer and chips of PB and sawn lumber for composition in core layer were heated in 60℃ chemicals-water solution for 1 hour in an autoclave. Then, they were air-dried 1 day or more and moisture was driven out, and the less moist chips were hammer-milled and prepared into particles. Thereafter, the treated particles were oven-dried to 3% or less moisture content and used for manufacturing recycled boards.

Fire-retardant treated boards were manufactured with condition of dimension of 1.5 cm × 30 cm × 35 cm, press temperature of 200℃, pressing pressure of 30 kgf/cm^2, pressing time of 5 min, and then physical and mechanical properties and fire-resistibility of boards were evaluated.

RESULTS AND DISCUSSION

Fire-retardants treatment of waste particleboard chips and properties of boards composing the recycled particles in core layer

In terms of preparatory study, $(NH_4)_2HPO_4$ and the mixture of 50:50 in weight of H_3BO_3 (boric acid) and $Na_2B_4O_7{\cdot}10H_2O$ (borax) were melted in 40℃ heated water solution, and waste PB chips were immersed, and then the swelling and chemicals treatment effects were investigated.

As shown in Fig. 2, the distribution of particles size 2-4 mm obtained after 2 types of chemical treatment, water immersion or non-teated chips were hammer-milled and oven-dried showed tendency of water immersion (57.7%) > mixture of boric acid and borax (54.0%) > dibasic ammonium phosphate (51.8%) > non-treatment (47.3%). In the homogeneous 1 layer boards, water immersion compared with non-treatment brought about board properties improvement, however the bending strength and stiffness of chemicals-treated boards were decreased. Accordingly, the further experiments to improve the board properties with swelling of the recycled PB chips and chemicals treatment effects were required.

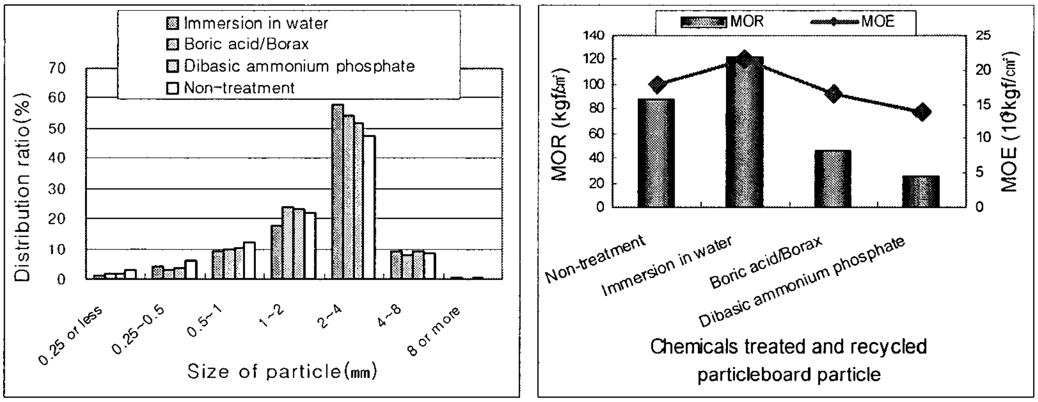


Fig.2. Distribution of particle size according to treatment of immersion in hot water with fire-retardant chemicals of recycled particleboard chips (left) and bending properties of boards composed with fire-retardants treated particleboard particles (right).

From the following experiment, the fire-retardants treated results at consistency of 30%, immersing recycled PB chips in 60℃ water for 1 hour, were resulted in Table 1. Because particles for face layer contained much fine particles and increased surface area, they increased retention ratio of chemicals. Also, chemicals retention ratio of recycled PB chips reached about 20%, and this value was similar to that value when they were immersed in room-temperature water for 1 day and were chemicals-treated.

Fire-retardants treated water solution immersing face particles and recycled PB chips showed alkalinity of pH 7.49-7.99. It was suggested this alkalinity would have influence on the hardening of board, therefore, these alkaline solutions were neutralized with glacial acetic acid. When the solution's pH were controlled to 6.45-6.63, the bending strengths of boards weren't higher and revealed a lower value at internal bond strength, but the free formaldehyde emission conspicuously decreased by fire-retardant treatment such as in Table 2.

On the other hand, the mat-forming height of 35-40 mm by fire-retardants treatment lessened by 22%, compared with that of non-treatment, therefore, compression ratio was lowered. It was thought that this low compression ratio would affect adversely the mechanical properties of boards.

In the fire-retardancy of board composed with only particles from recycled PB chips in core layer, when the mixed ratio of dibasic ammonium phosphate to boric acid·borax (50:50 mixture) was 70% to 30% in weight, these treated boards satisfied fire-retardancy 3rd grade (surface test in KS F 2271), as shown in Table 3. Also, dibasic ammonium phosphate was higher than mixture of boric acid and borax in fire-resistance, but larger portions of boric acid and borax gave greater strength properties, as shown in Table 2 and Table 3.

Table 1. Chemicals retention, solution pH and particle size distribution by fire-retardant treatment on recycled particleboard chips and face particles of particleboard

Furnish types by fire-retardant treatment	Composition of fire-retardant and neutralization of solution		Reten-tion ratio of chemicals (%)	pH		Dimensional distribution of fire-retardant treated particle furnish (%)		
				Before immersion	After immersion	3-20 mesh	20-80 mesh	80 mesh or more
Particles for board face use	50 : 50	Non-treatment	85.0	7.49	7.53	32.6	62.7	4.7
		Neutralization	-	6.49	6.45	40.4	56.4	3.2
	70 : 30	Non-treatment	84.1	7.81	7.89	34.7	60.8	4.5
		Neutralization	-	6.45	6.36	38.9	56.6	4.5
Recycled particleboard particles (core layer use)	50 : 50	Non-treatment	16.0	7.49	7.53	72.9	22.6	4.5
		Neutralization	21.6	6.49	6.45	77.6	18.5	3.9
Recycled particleboard chips	50 : 50	Non-treatment	19.0	7.77	7.73	76.7	20.3	3.0
		Neutralization	20.2	6.61	6.60	77.5	19.5	3.0
	70 : 30	Non-treatment	21.3	7.99	8.06	84.7	13.2	2.1
		Neutralization	21.6	6.63	6.64	81.1	16.6	2.3

Table 2. Physical and mechanical properties of recycled boards manufactured by fire- retardants treatment on recycled particleboard chips

Types of furnish	Composition of fire-retardant and neutralization of solution		Density (g/cm³)	MOR (kgf/cm²)	Internal bond strength (kgf/cm²)	Thickness swelling (%)	Water absorption (%)	Formaldehyde emission (mg/ℓ)
Recycled particleboard chips (fire-retardant treatment)*1	50 : 50	Non-treatment	0.73	91	7.1	12.9	42.0	0.26
		Neutralization	0.71	88	4.0	17.4	45.9	0.25
	70 : 30	Non-treatment	0.72	75	4.1	20.8	50.6	0.28
		Neutralization	0.70	47	0.6	25.2	49.6	0.26
Recycled particleboard chips (Non-treatment)*2	-		0.72	121	7.5	15.7	46.3	2.82

Note) 3 layer boards were fabricated with combination of face particles for particleboard use and recycled particles hammer-milled after fire-retardants treatment (*1 notification) or non-treatment(*2 notification) of recycled particleboard chips for core layer

Table 3. Fire retardancy of recycled boards manufactured with waste particleboard chips and particleboard particles which fire-retardants were treated for core layer

Mixing ratio of chemicals	Neutralization	Flame remaining time (sec)	Temperature·time area (℃× min.)		Smoking coefficient (CA)	Mass loss ratio (%)
			Within 3min	After 3min		
50 : 50 (Particleboard particles for core layer use)	Non-treatment	48	0	48.3	0.9	6.1
	Neutralization	50, 60 above	0	102.1	1.2	7.7
50 : 50 (Particleboard chips for core layer use)	Non-treatment	46	0	45.9	1.0	6.7
	Neutralization	46	0	82.0	1.4	6.9
70 : 30 (Particleboard chips for core layer use)	Non-treatment	24	0	47.8	1.0	6.7
	Neutralization	35	0	87.3	0.8	7.2
Non-treatment	-	60 above	above	442.2	17.8	15.3
Judging Standards		30 below	Not exceeded	350 below	120 below	-

Note) Other standards (Fire-retardancy 3rd grade, Surface test):
① Melting·destruction through overall thickness(Entire melting·destruction of heartwood)- Being absent, ② Crack width of back side(mm)- Thickness×1/10 below, ③ Harmful transformation etc. for prevention of fire propagation- Being absent.

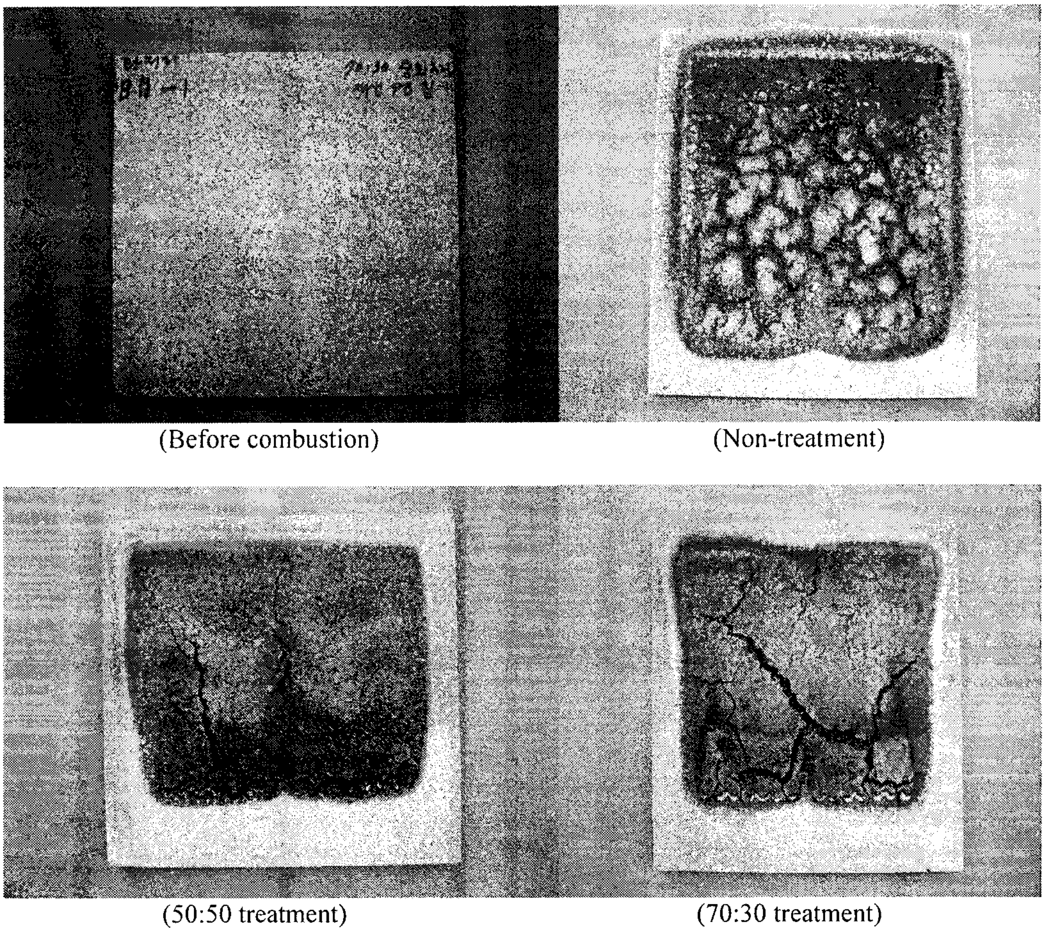


Fig.3. Recycled particleboards before and after combustion test by surface flammability tester.

Fire-retardants treatment of waste particleboard chips and sawn board chips and properties of boards by their mixed particle compositions in core layer

Retention ratio of chemicals, pH and distribution ratio of particle size according to fire-retardant treatment of recycled PB chips and sawn lumber chips were as in Table 4.

Retention ratios of chemicals for face layer particles, recycled PB chips and sawn lumber chips were 82.7-85.6%, 19.8-22.8%, and 21.6-35.5%, respectively. Therefore, retention ratios of sawn lumber chips were somewhat larger than those of recycled PB chips. pHs of chemicals-water solution which recycled chips were immersed were 7.31-7.56. Also, distribution ratios of particle size (3-20mesh) for core layer from sawn lumber chips were greater, compared with recycled PB chips.

Table 4. Retention ratios, pH and distribution of particle size by fire-retardants treatment of recycled chips (PB, sawn lumber) and particles

Types of furnish by fire-retardant treatment	Mixing ratio (%) (dibasic ammonium phosphate : boric acid·borax)	Retention ratio of chemicals (%)	pH (After immersion)	Dimensional distribution of fire-retardant treated particle furnish (%)		
				3-20 mesh	20-80 mesh	80 mesh or more
Particle for face particle	50 : 50	83.6	7.32	-	-	-
	60 : 40	85.6	7.31	-	-	-
	70 : 30	82.7	7.41	-	-	-
Recycled particleboard chip	50 : 50	22.8	7.32*	77.3(0.3)	19.5	2.9
	60 : 40	19.8	7.31*	82.0(0.6)	15.9	1.5
	70 : 30	21.2	7.41*	75.5(0.4)	21.6	2.5
Sawn lumber chip	50 : 50	21.6	7.41	91.8(0.5)	7.0	0.7
	60 : 40	30.7	7.56	91.4(0.6)	7.8	0.1
	70 : 30	35.5	7.46	91.6(0.5)	7.3	0.5

Note) 1. Numbers in parentheses denote the 3mesh or less particles.
2. Distribution of particle size was not measured for face layer particle.
3. The mark * means that recycled PB chips were done in same autoclave as face particles were immersed and treated.

On the other hand, for the purpose of improving a phenomenon of decreased bending strength when the particles from the recycled PB chips only were composed at core layer of board, the both particles from fire-retardants treated sawn lumber chips and recycled PB chips were mixed and composed in ratio of 70:30 in weight at core layer. As a result, physical and mechanical properties and fire-retardancy of fire-retardant treated boards were presented as in Table 5 and Fig. 5.

Bending strengths were 111kgf/cm^2, 108 kgf/cm^2, and 125 kgf/cm^2 at 50:50, 60:40, and 70:30 in the fire-retardants' mixed compositions of dibasic ammonium phosphate to boric acid·borax, respectively. Accordingly, when comparing with composition of the particles from the recycled PB chips only, the bending strengths with mixture of particles from sawn lumber chips increased. Though the bending strength by fire-retardant treatment of boards decreased by 20-31%, compared with non-treated boards, the boards of three fire-retardants treated composition exceeded 80 kgf/cm^2 of MOR (8.0 type of board) in KS F3104. In fire-retardants treated composition of 70:30, bending strength was somewhat higher than other compositions, however dimensional stability showed decreasing tendency as mixing ratio of dibasic ammonium phosphate rises. Particularly, the lessening effect of formaldehyde emission was shown with fire-retardants treatment and figured E_0 type (0.5mg/ℓ or less) in KS F 3104, but a height of formed particle mat by fire-retardants treatment decreased by 22%, compared with non-treated mat. As a result, it was assumed that fire-retardants treated boards showed the lowered mechanical properties due to decreased compression ratio.

In the fire-retardancy measured using cone calorimeter, total heat release (THR) was in the order of non-treated PB > fire-retardant's mixed composition of 50:50 > fire-retardant's mixed composition of 60:40 > fire-retardant's mixed composition of 70:30. THR of composition of 70:30 satisfied standard of fire-retardant 3rd class figuring 4.6 MJ/m^2. In heat release rate, that of non-treated PB evoluted typically same first and secondary peaks as a common wood, and also all fire-retardant compositions met a standard.

When a wood burns, first peak occurs as surface layer burns, and in second step a charred layer is formed and an exothermic status of is held back. Finally, it was known that secondary peak is formed according as back side layer burns. In this study, the fire-retardant's mixed composition of 70:30 had a low heat behavior values and changed little according to elapsed time from initial step of combustion test, and this composition was proved to have a superior fire-retardancy. Mass loss rate figured also fluctuating curve similar to a curve of heat release rate.

On the other hand, the gas toxicity according to mixing conditions of three chemicals from a combustion by surface flammability tester showed that fire-retardants treated board is less harmful than non-treated particleboards. From this result, it was supposed that the smoke density produced by combustion in a limited space will affect more harmfully to people's life at fire.

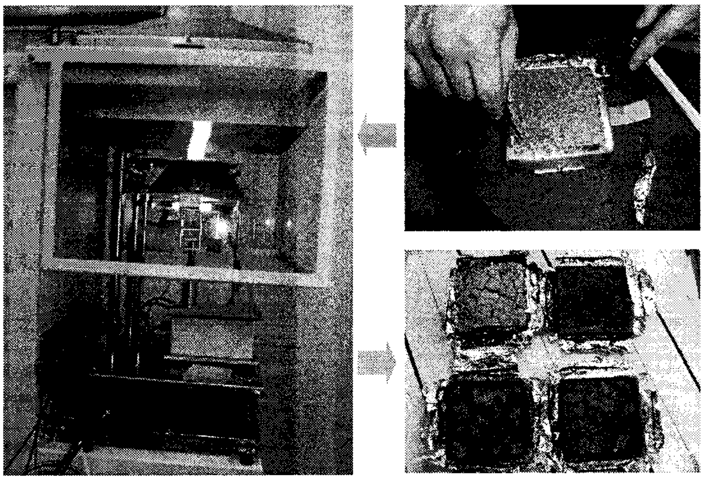
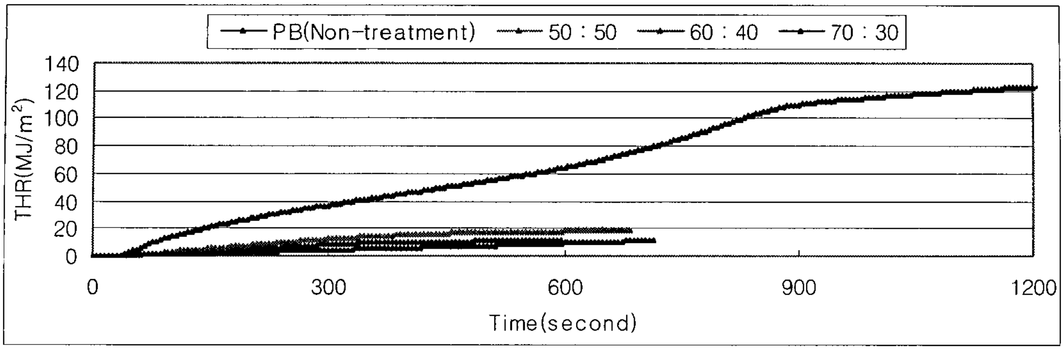


Fig.4. Fire test of boards composed with non-treated particles or fire-retardant treated particles by cone calorimeter.

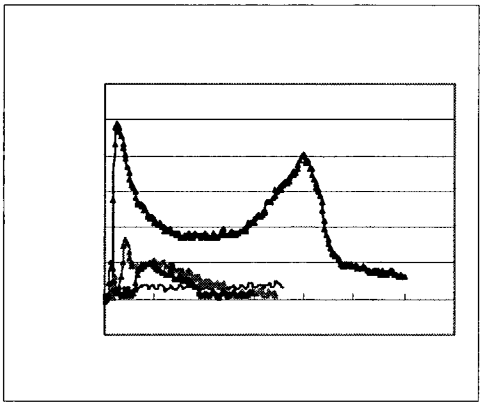
Table 5. Properties of recycled boards mixing the particles hammer-milled after sawn board chip and recycled particleboard (PB) chip were fire-retardants were treated

Types of furnish	Mixing ratio (%) (dibasic ammonium phosphate : boric acid·borax)	Bending strength (kgf/cm^2)	Internal bond strength (kgf/cm^2)	Thickness swelling (%)	Water absorption (%)
Particleboard(Control)	-	157	9.6	7.7	34.3
Board which face particles were combined with core particles*	50 : 50	111	8.4	8.3	35.2
	60 : 40	108	8.2	10.3	38.1
	70 : 30	125	7.6	16.5	44.4

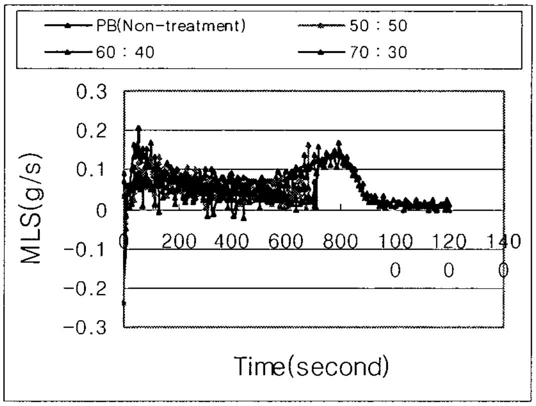
Note) Core particles (*) were composed with a mixture of sawn lumber chip and recycled PB chip in weight ratio of 70 to 30.



Total heat release: THR



Heat release rate: HRR



Mass loss rate: MLR

Fig.5. Combustion test results according to fire-retardants treatment by cone calorimeter.

Table 6. Fire-retardancy performance standards by Japanese construction standard law (ISO 5660-1 Cone calorimeter method)

Fire-retardancy grade	Test condition: Heating condition	Test condition: Heating time	Judging standards
Fire-retardancy 1st grade (Nonflammability)	50 kW/m^2	20 min	◦ Total heat release is less than 8MJ/m^2 ◦ Peak heat release rate is not more than 10 sec and does not exceed 200kW/m^2 ◦ Penetration, crack and hole etc. harmful for prevention of fire propagation do not occur
Fire-retardancy 2nd grade (Nonflammability) (Semi-nonflammability)		10 min	
Fire-retardancy 3rd grade (Fire-retardancy)		5 min	

Table 7. Gas toxicity of recycled boards by mixed ratios of fire-retardant chemicals

Mixing condition of chemicals-water solution	Stopping time of mouse behavior	Test method
PB (Non-treatment)	5min 54sec	◦ Main and auxiliary heat sources : electric heater, propane gas ◦ Heating time : 6 min ◦ Amount of air supply : 3ℓ/min at first time, 25ℓ/min at second time ◦ Amount of air exit in midterm : 10ℓ/min ◦ Standard panel : asbestos-perlite board, thickness 10mm ◦ Mouse : blood of ICR class, female, age of 5 week, weight of 18-22g
50:50	12min 12sec	
60:40	13min 26sec	
70:30	12min 45sec	

Note) Judging standard: 9min or more [On the basis of the test method for fire retardancy of interior materials of a building and structure (KS F 2271-2003)].

CONCLUSIONS

This study was carried out to manufacture fire-endurable boards using recycled waste woods efficiently and to evaluate their performance. In order to increase swelling of waste particleboards, the method immersing particles in hot water were applied, in which fire-retardant chemicals with mixed composition of dibasic ammonium phosphate, boric acid and borax were melt. Also, particles from sawn lumber were mixed with particles from recycled particleboard chip in core layer to improve boards' properties.

The obtained results were as follows:

1. The retention ratio of fire-retardant chemicals were in the order of the particles for face layer (82.7-85.6%), sawn lumber chips (21.6-35.5%), recycled particleboard chips (19.8-22.8%). Also, the neutralization with glacial acetic acid to alkalinity of fire-retardants chemicals solution immersing particles and chips showed pH 6.45-6.63, and didn't affect improvement of board properties.

2. In the mixed ratio of dibasic ammonium phosphate to boric acid·borax (50:50 mixture) of 70% to 30% in weight, the recycled boards satisfied fire-retardancy 3rd grade standard (KS F 2271). Accordingly, it was proved dibasic ammonium phosphate is more effective than mixture of boric acid and borax for fire-resistibility.

3. The composition of the particles from the recycled PB chips only in board core layer had a low bending strength, however the mixture of particles from sawn lumber chips of 70% and particles from recycled PB of 30% in weight ratio at core layer of boards increased bending strength. In fire-retardants treated composition, dimensional stability showed decreasing tendency as mixing ratio of dibasic ammonium phosphate rises. There was a particular effect lowering formaldehyde emission as E_0 type (0.5 mg/ℓ or less) in KS F 3104 with fire-retardants treatment.

4. From the fire performance test by cone calorimeter, total heat release of a composition of dibasic ammonium phosphate and mixture of boric acid and borax of 70 to 30 in weight satisfied fire-retardancy 3rd grade standard figuring total heat release of 4.6MJ/m^2. In combustion test, the

gas toxicity of all compositions of fire-retardants treated boards was less than non-treated particleboard.

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