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# Toxicity index and the time taken to incapacitate mice under combustion gases of burning wooden materials

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**Abstract** The purpose of this study was to investigate the toxicity of combustion gases from burning wooden materials. The toxicant index and mice exposure experiment were used to evaluate the toxicity index. The time taken to incapacitate mice under the impact of burning 19 solid wood species and 7 kinds of plywood were investigated. The results showed that the toxicity index of burning solid wood ranged from 1.5 to 2.5, and its main toxicant was $CO_2$. The toxicant index of burning plywood was higher, ranging from 3.0 to 6.0, and its main toxicity was $NO_x$. A good correlation was observed between the time taken to incapacitate mice (*X*s) and the weight loss rate of burning solid wood. When the concentration of CO was higher than 1% in the exposure chamber, the mice stopped their activity within 2 min. The time taken to incapacitate mice (*X*s) and the minimum concentration of $O_2$ in the exposure chamber could be represented by a positive linear regression formula. The concentrations of $O_2$ and $CO_2$ exhibited a positive effect and the concentration of CO had a negative effect on the *X*s values of mice.

**Key words** Toxicity index · Toxicity of combustion gases · Mice exposure experiment

## Introduction

Although the toxicity index of wood that was not treated with a fire retardant (China fir, red lauan) exhibited relatively low values in the mice exposure experiment, there was less active time for the mice exposed to untreated wood than for those exposed to the fire retardant-treated wood (FR-treated wood) during the burning stage. These findings were then related to the various combustion models and the method used to quantitate toxicity.

Because the main components of wood are C, H, and O, its main products are CO, $CO_2$, and $H_2O$ during the active oxidation process. Under the conditions of complete oxidation, which result in the formation of $CO_2$, $H_2O$,[1] and various other products, the toxicity level is elevated.[2] Morikawa and Yanai[3] have indicated that a curvilinear relation exists between $CO_2$/CO and toxicity, which means that the higher the $CO_2$/CO value, the lower is the toxicity index. Therefore the $CO_2$/CO values comprise an important index when simulating a combustion experiment. When the index is more than 20, it indicates a complete airiness type. If its value is less than 10, it indicates a ventilation limit fire type.[4] The NES 713 standard[5] was used for the former, and the CNS 8738 standard[6] was used for the latter.

In this study, 19 solid wood species and 7 kinds of plywood were used to produce a toxicity index. Mice exposure experiments were done to determine their consistency as a reference for the quantitative analysis of toxicity.

## Materials and methods

### Solid wood and plywood

Nineteen solid wood species with thickness of 0.17–1.55 cm and seven kinds of plywood with thickness of 0.30–1.80 cm, as shown in Tables 1 and 2, were used in this study. The specimens were cut into dimensions of 22 × 22 cm for the mice exposure experiment and 2 × 2 cm for the toxicity index test.

### Test animals

Female mice of the ICR series (*Mus musculus*), 5 weeks old and weighing 12–22 g, were used.

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**Table 1.** Basic data of sample woods

| Symbol of specimen | Common name | Scientific name | Density ($g/cm^3$) | Thickness (cm) | Moisture content (%) |
|---|---|---|---|---|---|
| D-1 | Douglas fir | *Pseudotsuga menzieii* | 0.48 | 1.25 | 13.6 |
| D-2 | Douglas fir | *Pseudotsuga menzieii* | 0.53 | 1.55 | 12.4 |
| D-3 | Douglas fir | *Pseudotsuga menzieii* | 0.47 | 1.49 | 12.7 |
| L | Port orford cedar | *Chamaecyparis lawsoniana* | 0.29 | 1.29 | 18.2 |
| H-1 | Western hemlock | *Tsuga* spp. | 0.32 | 1.31 | 14.3 |
| H-2 | Western hemlock | *Tsuga* spp. | 0.53 | 1.23 | 14.7 |
| J | Japanese cedar | *Cryptomeria japonica* | 0.43 | 0.98 | 15.3 |
| C | China fir | *Cunninghamia lanceolata* | 0.33 | 1.00 | 14.1 |
| A | Agathis | *Agathis philippinensis* | 0.43 | 1.44 | 12.1 |
| RO | Red oak | *Quercus* spp. | 0.60 | 1.23 | 10.5 |
| N | Nara | *Pterocarpus macrocarpus* | 0.80 | 1.27 | 14.0 |
| T | Teak | *Tectona grandis* | 0.57 | 1.29 | 20.8 |
| B | Beech | *Fagus grandifulia* | 0.66 | 1.35 | 23.3 |
| CR | Cherry | *Prunus* spp. | 0.53 | 1.17 | 26.6 |
| HM | Hard maple | *Acer* spp. | 0.64 | 0.97 | 13.0 |
| K-1 | Kapur | *Dryobalanosps aromatica* | 0.77 | 1.03 | 15.2 |
| K-2 | Kapur | *Dryobalanosps aromatica* | 0.79 | 1.20 | 15.0 |
| RM | Red lauan | *Shorea* spp. | 0.49 | 1.13 | 15.2 |
| LM | Light red meranti | *Shorea* spp. | 0.48 | 1.25 | 13.8 |

**Table 2.** Basic data of sample plywoods

| Symbol | Wood species of veneer | Adhesive | Density in air-dried ($g/cm^3$) | Moisture content (%) | Thickness (cm) |
|---|---|---|---|---|---|
| P-1 | Lauan | Urea resin | 0.46 | 14.5 | 0.30 |
| P-2 | Lauan | Urea resin | 0.44 | 12.9 | 0.40 |
| P-3 | Lauan | Urea resin | 0.62 | 13.4 | 0.66 |
| P-4 | Lauan | Urea resin | 0.52 | 10.5 | 0.90 |
| P-5 | Lauan | Urea resin | 0.49 | 11.4 | 1.20 |
| P-6 | Lauan | Urea resin | 0.40 | 12.6 | 1.45 |
| P-7 | Lauan | Urea resin | 0.46 | 11.8 | 1.80 |

## Mice exposure experiment

### *Reference standard*

This mice exposure experiment was conducted according to CNS 8738.[6] With this standard method the specimen was heated for 6 min and the time taken to incapacitate mice was determined. This was simulated by combustion conditions from initial fire to flashover. This has been recognized as an important method for mice exposure experiments worldwide.[7]

### *Calculation and evaluation*

Average time taken to incapacitate mice ($X$s). The average time taken to incapacitate mice was obtained from the formula

$$X\text{s} = X - \sigma$$

where $X$ is the average time taken to incapacitate eight mice (if the mice did not become incapacitated it was considered to be 15 min); $\sigma$ is the standard deviation of the time taken to incapacitate eight mice. One piece of standard material (red lauan) was subjected to the heating experiment according to the aforementioned method to obtain the average times taken to incapacitate the mice. Two pieces of the specimens were subjected to the heating experiment to obtain the average time taken to incapacitate mice. When its value was greater than that of standard material, it was considered to have met the standard.

Weight loss during burning. The weight loss during burning ($WL$) (in grams) was

$$WL = W\text{b} - W\text{a}$$

where $W$b is the weight before burning, and $W$a is the weight after burning.

The weight loss rate during burning ($WLp$) (in percent) was

$$WLp = W\text{b} - W\text{a}/W\text{a}$$

## Toxicity index experiment

### *Reference standard*

The English navy engineering standard NES713[5] was used to determine the reference standard. In this standard 14 gases were detected, as shown in Table 3.

**Table 3.** Lethal concentration for 30 min of gases ($Cf$) listed in NES-713

| Gases | $Cf$ (ppm) |
|---|---|
| CO | $4 \times 10^3$ |
| $CO_2$ | $1 \times 10^5$ |
| $H_2S$ | 750 |
| HCHO | 500 |
| HCl | 500 |
| $SO_2$ | 400 |
| $NO_x$ | 250 |
| $C_6H_5OH$ | 250 |
| HCN | 150 |
| HBr | 150 |
| $NH_3$ | 750 |
| $CH_2CHCN$ | 400 |
| HF | 100 |
| $COCl_2$ | 25 |

*Cf*, lethal concentration

### *Definition of toxicity index*

In a specific environment, the sum of the toxicity factors of selective gases that occurred from material burned completely in air was determined. The toxicity factor was determined from the ratio of the gases' concentration obtained from 100 g of material burned in 1 $m^3$ of air ($Cg$)/the lethal concentration of gases for 30 min ($Cf$). When the toxicity index was 1, it meant that the lethal time was 30 min. Higher toxicity indexes indicated stronger toxicity.

### *Calculation*

To calculate the concentration ($Cg$) of the various gases produced from each 100 g of material, the wood was burned in 1 $m^3$ of air, and the average value of each gas detected was calculated. The formula used for calculation was

$$Cg = \left(C * 100 * V\right)/M \qquad (\text{ppm})$$

where $C$ is the concentration of gases (ppm) produced from specimens; $V$ is the volume of the test chamber (0.7 $m^3$); and $M$ is the weight of the specimen (g).

$$\text{TI} = Cg1/Cf1 + Cg2/Cf2 + \ldots + Cgn/Cfn$$

where 1, 2 . . . $n$ represents the same kinds of gases; TI represents the toxicity index; and $Cf$ represents the lethal concentration (ppm) for 30 min in humans.

$$\text{Residual charcoal rate}\ (\%) = Wa/Wb$$

### Gas analysis apparatus

The gas automatic analysis apparatus for gases of rbr-ecom JM (RBR-ECOM Co., Germany) was used to detect and record the change with time in a mouse exposure chamber. This apparatus used electrochemical fuel cells through the coaxial probe to obtain samples and carry out the gas analysis immediately. Its detection ranges are as follows.

**Table 4.** Results of blank tests

| Burning time (min) | CO (ppm) | $CO_2$ (%) | $NO_x$ (ppm) | $CH_2CHCN$ (ppm) | HCHO (ppm) |
|---|---|---|---|---|---|
| 0 | 0 | 0.03 | 0 | 0 | 0 |
| 1 | 2 | 0.25 | 1 | 0.1 | 1 |
| 2 | 4 | 0.50 | 2 | 0.2 | 2 |
| 3 | 6 | 0.75 | 3 | 0.3 | 3 |

| | |
|---|---|
| $O_2$ | 0–21% |
| CO | 0–65 000 ppm |
| $CO_2$ | 0%–10% |
| NO | 0–2000 ppm |
| $NO_2$ | 0–200 ppm |
| $SO_2$ | 0–2000 ppm |

## Results and discussions

### Toxicity index experiment

The results of blank tests are shown in Table 4. The experimental results were calculated from the actual values minus the blank values. The results are shown in Figs. 1 and 2. It was found that the main products of wood and plywood were CO, $CO_2$, and $NO_x$ during the burning stage. Of course, a slight amount of CAN (acrylonitrile) was detected in this experiment. In the blank tests their amounts were less than 0.5 ppm and outside the range of color comparison for tube calibration. Therefore, they were omitted in this study. When the toxicity indexes were compared for wood and plywood, it was found that the index for wood was 1–2, which was lower than that of plywood. This meant that when humans are exposed to this environment their lifetime would be about 15–30 min. However, the toxicity index of plywood was 3–6, which meant that the lifetime was only 5–10 min. Based on this result, it is obvious that the toxicity of plywood in a completely burned environment is markedly more than that of wood. Morikawa and Yanai[3] also indicated that the toxicity index inside a room decorated with 100% natural materials was 13, but it was 26 for the room decorated with 27% synthetic polymer material.

In the case of the sample woods (Fig. 1), the main component of the toxicity index was $CO_2$. $NO_x$ was next, and CO was present in only a small amount. In the case of plywood (Fig. 2), it was found that the CO content was also slight. The $NO_x$ content increased significantly. It was higher than that of $CO_2$. This might be induced by burning of adhesives.

Figures 1 and 2 show that the maximum CO content was 2157 ppm for Japanese cedar and 2900 ppm for plywood (P-2 group). The highest amount of $NO_x$ was 242 (ppm) for China fir and 1092 (ppm) for plywood (P-1 group). The amount of $CO_2$ ranged from 60 000 ppm (for karin) to 160 000 ppm (for Douglas fir) and from 50 000 to 140 000 ppm for plywood.

In general, it was recognized that $CO_2$ was not a lethal component. It stimulates the brain and induces increased

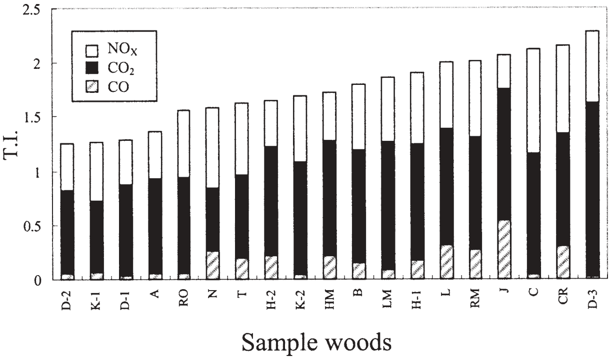


**Fig. 1.** Toxicity index (*T.I.*) and components of untreated sample wood

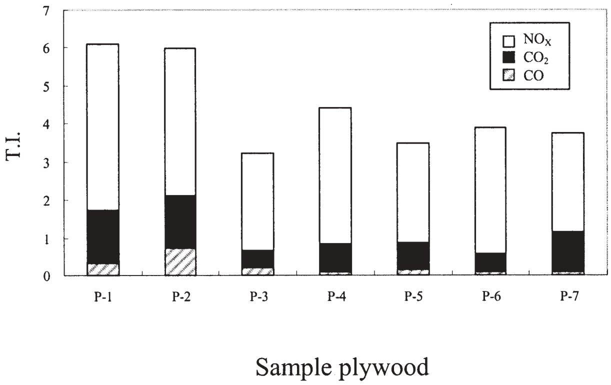


**Fig. 2.** Toxicity index and components of UF sample plywood

breathing frequency.[8,9] Crane[10] indicated that when mice were exposed to an environment with CO the concentration ranged from 5500 to 14 000 ppm. He was not concerned with whether the $CO_2$ concentration increased. The time to incapacitation of time to death did not significantly change. Therefore, its effect as a part of toxicity index must be clarified. The residual charcoal rate showed the greatest value for kapur-1 (26%) and the lowest values for Japanese cedar (0%) and hard maple (0%). This meant that (1) it was concerned with the heat that evolved after glowing. It also had a sampling time of 5–10 min. Thus the specimen had a 0% residual charcoal rate. It might be dissolved after glowing during this time period. Finally, it became gray-white ash and was different from that seen with a more self-extinguishing residual black carbon block. (2) It indicated that the carbon content in the specimen was dissolved by heat. Specimens with more residual charcoal showed a relatively lower content of carbon dissolved by heat. This meant that there was relatively less formation of CO and $CO_2$. This can be represented by the relation

$$Cg(\mathrm{CO}) + Cg(\mathrm{CO_2})$$

The values decreased with the increasing residual charcoal rate.

When the relation between the residual charcoal rate and wood density were investigated, it was found that karin and kapur wood, with their high densities, had higher residual charcoal rates, although there was no significant difference. Hung et al.[11] indicated that the residual charcoal rate ranged from 25% to 33% for six wood species carbonized under 1000°C with the no-oxygen condition and a lower residual charcoal rate for a higher carbonizing temperature. They also showed that wood density was not a main factor in the residual charcoal rate because in this toxicity index experiment the temperature was increased to 1150°C under the oxygen condition and had the effect of after-glowing. Thus its residual charcoal rate was not only lower but also unaffected by the wood density.

A theoretical discussion was conducted on the *Cg* values. In this toxicity index experiment, 2 g of mass was burned completely in a closed chamber with a volume of 0.7 $m^3$. It simulated the concentration of combustion gases of 100 g material burned completely in a volume of 1 $m^3$. First, 2 g of material was easy to burn completely, whereas 100 g of material might not burn completely. Fox example, an approximately square solid wood sample would not burn easily. Furthermore, the oxygen content in a volume of 0.7 $m^3$ was enough to burn 2 g of material completely; therefore higher values for $CO_2$/CO could be obtained in this experiment, whereas 1 $m^3$ volume of air would have about (1000/22.4) $\times$ 20% $\fallingdotseq$ 8.8 mol of oxygen content. For example, in the case of 100 g solid wood, the calculation was as follows: $C_{1.5}H_{2.1}O_{1.0}$ and the oxygen was about 3 mol. If it burned completely to produce $CO_2$ and $H_2O$, it must have 4.5 mol of oxygen content ($C_{1.5}H_{2.1}O_{1.0} + 1.5O_2 \rightarrow 1.5\ CO_2 + H_2O$); that is, it would consume 50% of the oxygen content. This air condition with 10% oxygen content could support complete burning or not; thus, the $CO_2$/CO values would fluctuate widely. For burning under the no-oxygen condition, the $CO_2$/CO values would be less than 10. Furthermore, this 10% oxygen content would affect the life of the animals. Based on the above viewpoint, the toxicity index without consideration of the oxygen content might be insufficient.

## Mouse exposure experiment

The mouse exposure experiment simulated a situation from the initial fire to before the flashover stage of fire. This stage also was an important time to evacuate. Therefore the time to incapacitation was measured (*ti*) and time to death was not measured (*td*). The $IC_{50}$ (median incapacitative concentration) values were different from the $LC_{50}$ (median lethal concentration). Einhorn and Grunnet[12] indicated that the $IC_{50}$ and $LC_{50}$ values for Douglas fir under the flame combustion condition were 13 $\pm$ 3 and 24 $\pm$ 4 g, respectively, and higher than that of the nonflame combustion condition.

Hartzell[8,9] carried out the mouse exposure experiment with burning polyester. They indicated that the values of *X*s and *td* were 23.2 $\pm$ 4.5 and 44.6 $\pm$ 11.9 min, respectively, for an oxygen concentration of 40 mg/l; however, *X*s and *td* were 11.1 $\pm$ 0.7 and 15.2 $\pm$ 0.9 min, respectively, for an oxygen concentration of 85 mg/l. It was found that *X*s and *td*

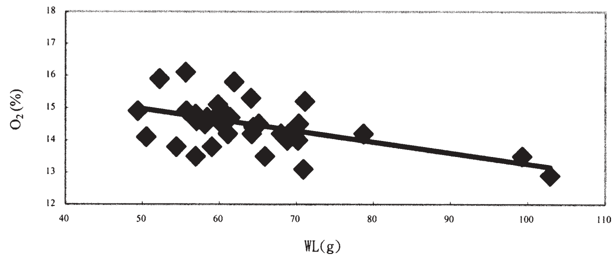


**Fig. 3.** Relation between weight loss ($WL$) and minimum $O_2$ concentration in exposure chamber

were lower for exposure in a high oxygen concentration environment than for exposure in a low oxygen concentration environment. Because the weight loss during the burning time of materials could not be measured in this experiment, the $IC_{50}$ value could not be determined. Therefore, the time taken to incapacitate mice ($X$s) was used to evaluate the toxicity of the combustion gases of the material used.

## Burning products

In the burning products experiment, the oxygen concentration in the exposure chamber decreased to 12.9%–16.1% for burning solid wood and to 13.8%–15.4% for burning plywood. The consumption of oxygen was influenced by combustion of the materials used (i.e., the more burning loss, the more oxygen consumed). The relation between the oxygen concentration and the weight loss of solid wood in the exposure chamber is represented in Fig. 3. A negative linear regression was obtained as follows:

$$O_2\,(\%) = -0.034\,(WL) + 16.684$$
$$R^2 = 0.256, \quad F = 11.9 > F_{0.01}$$

where $O_2$ (%) is the oxygen concentration, and $WL$ is the weight loss of solid woods (g). Although its $R^2$ (determination of coefficient) value was relatively low, it showed a significant difference (0.01 level) by the $F$-test.

The yield of CO and $CO_2$ in the exposure chamber was mainly induced by the heat decomposition of specimens. If the carbon origin was the specimens, the (CO + $CO_2$) concentration (percent) was related to the weight loss of burning materials, as shown in Fig. 4. It was found that the (CO + $CO_2$) concentration increased with increasing weight loss of the burning solid wood. A positive linear regression could be obtained as

$$\left(CO + CO_2\right)\% = 0.043\left(WL\right) + 2.385,$$
$$R^2 = 0.433, \quad F = 27.5 > F_{0.01}$$

where (CO + $CO_2$)% is the the concentration of (CO + $CO_2$). Although its $R^2$ value was also relatively low, it had a significant difference (0.01 level) by the $F$-test.

In this experiment, if the carbon content of solid wood was considered to be 50%, the carbon content of residual charcoal was considered to be 100%. The carbon content

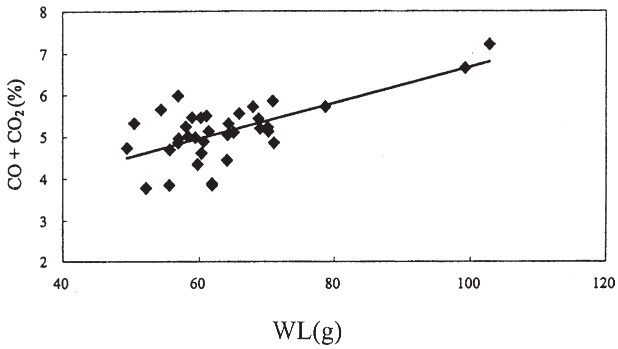


**Fig. 4.** Relation between weight loss and CO + $CO_2$ yield

for the unit weight loss during burning of each specimen was calculated. Based on these results the carbon content for weight loss due to burning can be adjusted for each specimen. It also was found that a positive linear regression existed between (CO + $CO_2$)% and the carbon content during weight loss ($WLC$) as follows:

$$\left(CO + CO_2\right)\% = 0.079\left(WLC\right) + 3.012,$$
$$R^2 = 0.566, \quad F = 46.9 > F_{0.01}$$

The $R^2$ value rose to 0.566, which means that the residual charcoal rate would affect the yield of (CO + $CO_2$)%.

## Time taken to incapacitate mice

The time taken to incapacitate mice ($X$s) ranged from 6.1 to 9.3 min for burning solid wood and from 5.4 to 6.7 min for burning plywood in this experiment. If the $X$s value for burning standard material (red lauan; *Shorea* spp. with a density of 0.43–0.53) specified in CNS 8738[6] was used as the standard requirement, the $X$s values for burning plywood, including all thicknesses of plywood in this experiment, could not meet the standard requirement. However, in the case of burning solid wood, seven wood species passed and 10 species failed the standard requirement. When the various densities of solid wood were considered, the lowest-density solid wood that passed the standard requirement was 0.47 (Douglas fir; D-3), but the solid woods with densities up to 0.7 (karin N and kapur: K-1, K-2) all passed the standard requirement. When the various thicknesses of solid wood were considered, it was found that the thickest solid wood (Douglas fir D-2, 1.55 cm) and thinnest solid wood (kapur K-1; 1 cm) met the standard requirements. This meant that the effect of density on $X$s was greater than the thickness of solid wood; that is, the higher density of the solid wood decreased its thickness (e.g., kapur K-1), and it passed the standard requirements. In contrast, the lower density of solid wood increased its thickness (e.g., teak T), which did not pass the standard requirements.

When the time taken to incapacitate mice ($X$s) was plotted against the density of solid wood ($\rho$), a positive linear regression was obtained.

$$Xs = 3.284\rho + 5.606, \quad R^2 = 0.388, \quad F = 22.8 > F_{0.01}$$

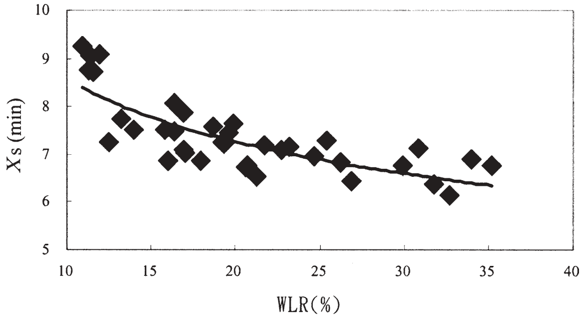


**Fig. 5.** Relation between weight loss rate of sample wood ($WLR\%$) and time taken to incapacitate mice ($X$s)

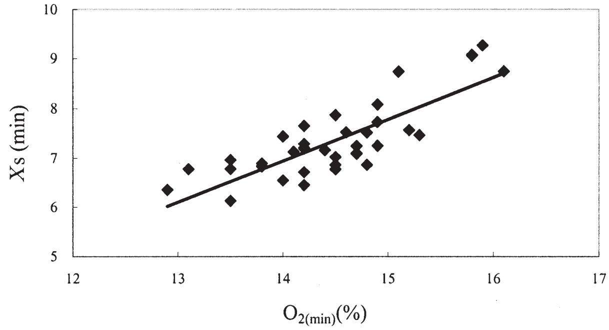


**Fig. 6.** Relation between minimum $O_2$ concentration and $X$s in exposure chamber

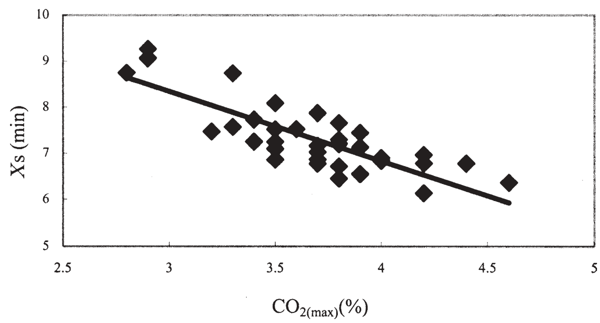


**Fig. 7.** Relation between maximum $CO_2$ concentration and $X$s in exposure chamber

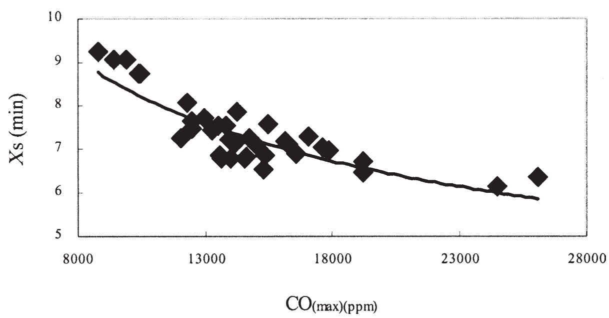


**Fig. 8.** Relation between maximum CO concentration ($CO_{(max)}$) and $X$s in exposure chamber

Although the $R^2$ value was relatively low, it showed significant difference (0.01 level) by the $F$-test.

When the combustion characteristics was considered, it was found that the value of $X$s decreased with the increase in weight loss ($WL$), and an exponential regression was obtained.

$$X\text{s} = 9.614e^{-0.004\text{wl}}, \quad R^2 = 0.225, \quad F = 8.9 > F_{0.01}$$

The $R^2$ value was also relatively lower. If the weight loss rate ($WLR$ %) was used instead of the weight loss itself, its relation could be represented as shown in Fig. 5, and an exponential regression was obtained.

$$X\text{s} = 14.832WLR^{-0.238}, \quad R^2 = 0.636, \quad F = 40.5 > F_{0.01}$$

It was obvious that the $R^2$ value rose to 0.636.

The factor directly affecting the time to incapacitate mice ($X$s) was the environment in the exposure chamber. When the minimum concentration of $O_2$ was considered, $X$s values increased with increasing the minimum concentration of oxygen, as shown in Fig. 6. A positive linear regression was obtained.

$$X\text{s} = 0.838O_{2(\min)} - 4.785, \quad R^2 = 0.658, \quad F = 69.4 > F_{0.01}$$

where, $O_{2(\min)}$ is the minimum concentration (%) of oxygen. This meant that the mice would survive for a longer time in an environment that exhibited a higher minimum concentration of oxygen.

Figure 7 shows the relation between $X$s and the maximum concentration of $CO_2$. A negative linear regression could be obtained.

$$X\text{s} = -1.510CO_{2(\max)} + 12.871, \quad R^2 = 0.655,$$
$$F = 68.2 > F_{0.01}$$

where $CO_2$(max) is the maximum concentration (%) of $CO_2$.

This meant that the reduced $X$s values were not due to the higher concentration of $CO_2$ inducing more toxicity in the environment, although it might be due to the increased concentration of $CO_2$ inducing an increase in the frequency and depths of breaths.[8,9] This practice then absorbs more toxicant and as a result decreases its $X$s values.

In the case of CO, it was found that the $X$s value decreased with increasing maximum concentration of CO, as shown in Fig. 8. An exponential regression formula was obtained.

$$X\text{s} = 251.484(\text{CO})_{(\max)}^{-0.370}, \quad R^2 = 0.722, \quad F = 52.7 > F_{0.01}$$

where $(CO)_{(\max)}$ is the maximum concentration (%) of CO.

From Fig. 8 it was found that when the maximum concentration of CO was up to 10000 ppm the mice found it difficult to survive more than 2 min (<8 min of $X$s); but when the maximum concentration of CO was increased to 15000 ppm, the mice found it difficult to live more than 1 min (<7 min of $X$s). Hirata et al.[13] noted the toxicity of wood combustion gases induced from CO. The relation could be represented by the regression

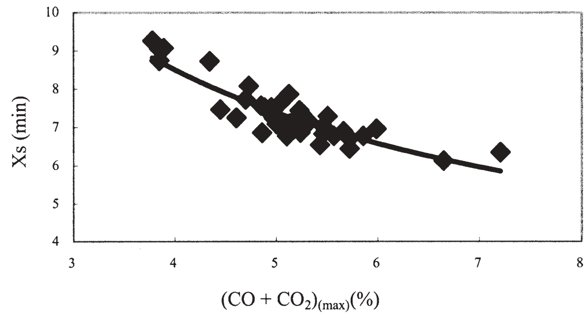


**Fig. 9.** Relation between maximum ($CO + CO_2$) concentration and $X$s in exposure chamber

$$X = 0.649(CO - 0.3)^{-1} + 5.6$$

When this is compared with Fig. 8, it shows a similar trend, but the time taken to incapacitate mice ($X$s) used by Hirata was not minus its standard deviation ($\sigma$). Czerezak and Stetkiewicz[14] recognized that CO was the main toxic substance released from burning building materials, and it was similar to this study.

From the discussion above, it is obvious that the concentrations of CO, $CO_2$, and $O_2$ significantly affect the activity of mice at the same time. when these factors are considered, a closer relation may be obtained. Figure 9 shows the relation between the maximum concentration of ($CO + CO_2$) and the $X$s values in an exposure chamber. It can be represented by an exponential regression formula.

$$Xs = 20.439\left[(CO + CO_2)_{(max)}\right]^{-0.632},$$
$$R^2 = 0.787, \quad F = 94.3 > F_{0.01}$$

where $(CO + CO_2)_{(max)}$ represents the maximum concentration (%) of ($CO + CO_2$). Actually, its $R^2$ value increases again. Based on this result it was found that when the concentration of ($CO + CO_2$) was greater than 5.5% the mice stopped their activity within 1 min, whereas when the concentration was reduced to 4.5% the activity duration increased to 2 minutes.

Finally, the effects of the concentration of $O_2$, CO, and $CO_2$ on $X$s values were examined using a stepwise regression method. A multiple regression formula was obtained.

$$Xs = 1.51* \; O_2 + 1.79* \; CO_2 - 9.0E$$
$$- 0.5* \; CO - 19.81, \quad R^2 = 0.738, \quad F = 31.9$$

Using this multiple regression formula it was found that these three factors ($O_2$, CO, $CO_2$) were considered at the same time. The concentrations of $O_2$ and $CO_2$ exhibited a positive effect on the $X$s value, whereas the concentration of CO had a negative effect on the $X$s value.

## Conclusions

The following conclusions were reached.

1. The toxicity index of burning solid wood ranged from 1.5 to 2.5, and the major toxicant was $CO_2$. The toxicity index of burning plywood was increased up to a range of 3–6, and its major toxicant was $NO_x$.
2. There were different residual charcoal rates for burning different solid woods, with a higher residual charcoal rate associated with lower production of $CO + CO_2$.
3. A significant correlation was obtained between the time taken to incapacitate mice and the weight loss rate of burning solid wood.
4. When the CO concentration was higher than 1% in the exposure chamber, the mice stopped their activity within 2 min. When the concentration was increased to 1.5%, the activity of mice would stop within 1 min.
5. The effects of the $O_2$, Co, and $CO_2$ concentrations on the $X$s values could be represented by a multiple regression formula.

$$Xs = 1.51* \; O_2 + 1.79* \; CO_2 \text{-} 9.0E \text{-} 0.5* \; CO \text{-} 19.81$$

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