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Estimating the fire behavior of wood flooring using a cone calorimeter

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Abstract This article analyzes the flammability characteristics in order to investigate the adequacy of a newly proposed sampling method for wood and PVC materials that are commonly used for residential flooring. Experiments on commercial products were performed using a cone calorimeter according to ISO 5660-1 specifications. Samples for the test procedure were prepared in two methods: either using a cone calorimeter sample preparation method (case 1), or the proposed sample preparation method, which a simplified form for the actual constructed shape (case 2). The thermal characteristics of the common wood products differed depending on the sampling method, where the peak heat release rate (PHRR) had either two peaks for case 1 or a single peak for case 2, and the total heat rate (THR) and smoke production rate (SPR) also differed according to the case. Especially, the wood flooring differed significantly between the two cases in terms of the number of PHRR peaks and the trend of the SPR curves. Due to these differences, we presented another HRR evaluation method depending on the raw material and the size of HRR to reduce the fire hazards in flooring.

Keywords Wood flooring · PVC flooring · Cone calorimeter · Heat release rate (HRR)

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Introduction

In modern society, the demand for environmentally friendly products used in building materials has begun to rise with increasing income levels. Moreover, due to recent national policy and increased interest in health care, conventional chemical products are being replaced by environmentally friendly products, such as wood, so that the use of environmentally friendly raw materials for building material has increased the demand for high efficiency products [1]. Consequently, a variety of products, such as floor finishes using timber, has been produced in increasing quantities. Fire hazards in buildings have also been increasing with the increasing frequency of wood use, so the wood products are required to evaluate for fire behavior. Additionally fire behavior analysis is needed for synthetic products with thermal characteristics that are different from wood [2–8].

Indoor decorative materials are mostly flammable products that are a serious risk for fire. In a fire, decorative materials increase the risk of high-temperature heat and the emissions of smoke and toxic gas. Fires are inevitably used to generate a lot of energy and this energy is released as heat. People can be seriously injured or killed by this heat [9–11]. Previous studies have investigated the fire behavior and evaluated the safety of a variety of building materials by using cone calorimeter testing. However, as most of the fire behavior assessment for interior upholstery merely focused on the characteristics of the raw materials, products in contact with or bonded to walls have not been accurately assessed [12, 13].

This study evaluated the fire behavior of wood flooring and PVC flooring according to ISO 5660-1 using both a cone calorimeter and a new sampling method to complement the conventional sampling method [14–16]. For each material, the two methods were compared with respect to fire behavior. The aim of this study was to compare test methods for deriving accurate fire behavior results for a variety of wood and PVC, indoor flooring materials. These flooring materials were evaluated with respect to fire behavior by using a cone calorimeter, and the sampling method proposed may be used to supplement the existing test method.

Experimental

Materials

Three kinds of wood flooring and three kinds of PVC flooring that are commonly used in building construction were tested to investigate their combustion performance and safety as floor finishing materials. The sample details are shown in Table 1.

Cone calorimeter

The cone calorimeter is recognized worldwide as one of the most acceptable fire testing apparatuses as shown in Fig. 1. Cone calorimeter tests were performed according to the procedures indicated in the ISO 5660-1 standard using a Fire Testing Technology cone calorimeter (Fire Testing Technology Ltd., UK). The dimensions of the samples were 100 mm × 100 mm and the thicknesses are shown in Table 1. The samples were conditioned to equilibrium at 55% relative humidity (RH) and 23 °C prior to testing. The prepared sample and sample holder were placed on a mass measurement device. All the experiments were conducted by placing the samples in the same holder in a horizontal position under a cone heater. The fire scenario was comprised of four steps: ignition, growth, fully developed, and decay. The tests were conducted with 50 kW/m^2 of heat flux which corresponded to the fully developed step. When ignition or temporary flame occurred, the time was recorded and the spark power and the igniter were removed. If the flame went out after removing the spark power, the igniter was re-inserted within 5 s and then the spark was maintained until test completion. The sample and sample holder were removed after the collection of all data during the test. The insulation substance was situated above the mass measurement device. Each pretreated sample (both cases 1 and 2) was tested three times. The results were calculated based on the average of three experimental data [17].

Preparation of test sample

Before the test, samples sized 100 mm × 100 mm were maintained at 23 ± 2 °C and 50 ± 5% RH. Pretreated samples were wrapped with aluminum foil that was 0.03–0.05 mm thick, with the shiny side of the foil facing the sample. Each material sample was produced in one of two methods. In the first method (case 1), the sample was wrapped without any treatment and the non-exposed surface was covered with foil, which typically forms to the cone calorimeter. In the second method (case 2), the sample was produced with cement mortar and the shape of the sample was formed according to construction methods in which the adhesive is coated or the vinyl is added. In other words, the sampling method is to simplify the form of actual buildings.

The appearances of the samples of the two cases are shown in Fig. 2. Cement mortar was used with a cement:sand ratio of 1:2 and a water/cement ratio of 45% by weight. Mortar samples sized 100 mm × 100 mm × 10 mm were each made with 90 g of cement. The height of each sample in the holder was increased with the addition of cement mortar. Because the sample thickness varied according to the case, the height from the sample surface to the heat surface was adjusted to prevent any variation in the distance between the sample and the cone heater before loading the sample into the sample holder. The height of the sample was adjusted to constant height by controlling the amount of glass wool that was placed at the bottom of

Table 1 Specification of the six samples

Type	Title	Adhesion method	Thickness/mm	Mass/g	Volume/cm^3	Density/g cm^{-3}
Wood flooring	Solid wood flooring	Adhesive epoxy resin adhesive for floor install	10.1	53.9	9.74	5.53
	Plywood flooring	Adhesive epoxy resin adhesive for floor install	8	55.5	78.42	7.08
	Laminate flooring	Covered with vinyl/PE-foam	8	75.7	80	9.46
PVC flooring	Pattern 1	–	2	15.3	20	7.65
	Pattern 2	–	2.3	28.1	23	12.22
	Pattern 3	–	2.3	14.7	23	6.39

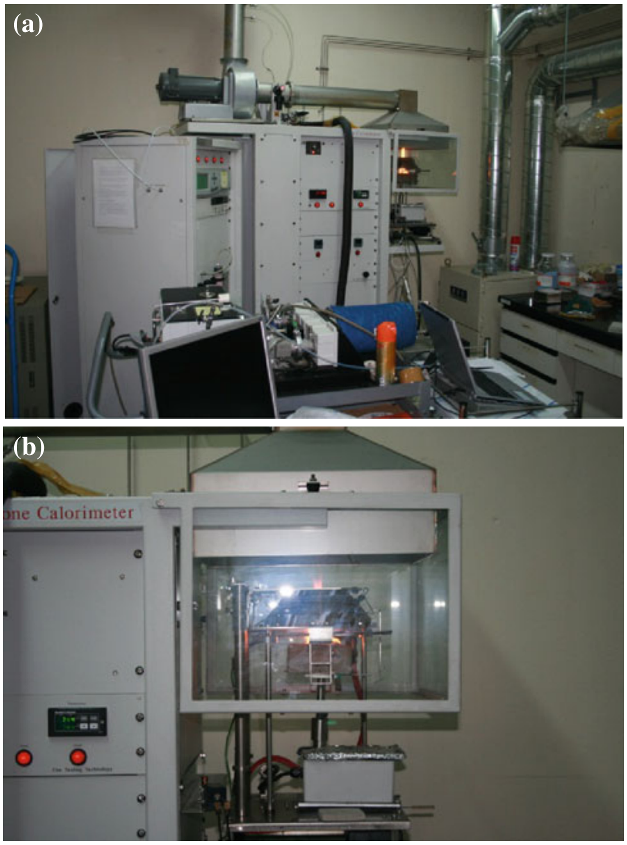


Fig. 1 Experimental set-up of the cone calorimeter. **a** Cone calorimeter, **b** cone heater

the holder. The schematic design for case 2 is shown in Fig. 3.

Flammability testing

All samples were measured in the horizontal position. The square samples were irradiated with a heat flux of 50 kW/m^2. During the test, the following parameters were determined: time to ignition (TTI), heat release rate (HRR), peak HRR (PHRR), smoke production rate (SPR), and carbon monoxide yield. The TTI index is the time to flame initiation on the sample surface due to heat radiation. HRR can be calculated using the following equations:

$$\dot{q}''(t) = \frac{\dot{q}(t)}{A_s} \tag{1}$$

$$\dot{q}(t) = \left(\frac{\Delta h_c}{r_0}\right)(1.10)C\sqrt{\frac{\Delta P}{T_e}}\frac{\left(X^o_{O_2} - X_{O_2}(t)\right)}{1.105 - 1.5X_{O_2}(t)} \tag{2}$$

where $\dot{q}''$ is the rate of heat release per unit area (kW/m^2), $\dot{q}$ the HRR (kW), A_s the initially exposed area (m^2), Δh_c the net heat of combustion (kJ/kg), 1.10 the ratio of oxygen to air molecular weights, and r_0 the stoichiometric oxygen/fuel mass ratio (–). PHRR is considered to be the parameter that best expresses the maximum intensity of a HRR curve

Results and discussion

For the two cases, both wood flooring and PVC flooring is shown in Fig. 4. The overall burning time of each wood samples and each PVC samples are about 700 to over 900 s and 200 to over 250 s, and TTI is 11–95 s. Because the TTI per overall burning time is under 10%, both cases 1 and 2 were not significantly different with respect to TTI in each sample. Wood flooring had a TTI of about 30–95 s, and laminate flooring had the longest time of 95 s. The TTI of laminate flooring was the longest of the wood panels, indicating that the laminate flooring was bonded to the face of the HDF as a core material with melamine–urea–formaldehyde, resin-treated, deco paper, which acted as a flame retardant in the laminate flooring. The TTI of PVC flooring ranged from 10 s to 25 s and the overall TTI of PVC flooring was shorter than that of wood flooring. In other words, PVC materials were more flammable than wood materials due to ignition. Contrary to general perception, wood materials were not seriously vulnerable to fire. The TTI values of dense materials were longer than those of low-density materials, indicating that even though there were differences with respect to surface treatments, the main factor was the density [18]. In addition, the tendency according to the case was not consistent. TTI was less than 1% compared to the total fire time. Other factors need to be checked due to the small difference with respect to TTI.

Figure 5 shows the HRR curves of the wood flooring and the PVC flooring. In the wood flooring, the burning behavior of the solid wood flooring in the non-construction condition exhibited two peaks similar to those of common wood burning behavior at the case 1. The maximum peaks were 161 and 225 kW/m^2 at 80 and 370 s, respectively. In contrast, case 2 had one peak at 7 5 s–155 kW/m^2 compared to the case 1, and the HRR curve had a tendency to decrease gradually after second peak. The PHRR of solid wood flooring was the lowest among all the wood floorings in both cases.

Plywood also showed two peaks in case 1. The PHRR values were 205 and 329 kW/m^2 at 80 and 208 s, respectively. In contrast, case 2 had only one peak at 95 s–175 kW/m^2, and this had a tendency to decrease gradually. In case 1, the maximum peak of the plywood sample was higher than any other wood flooring.

The laminate flooring also had two peaks in case 1 at 198 and 287 kW/m^2 at 140 and 445 s, respectively. In contrast, case 2 had one peak at 135 s–187 kW/m^2, and this had a tendency to decrease gradually. In both cases, the laminate flooring had the slowest time to PHRR. For the

Fig. 2 Sampling appearance by materials and method. **a** Solid wood flooring—general sample (*left*) and construction sample (*right*). **b** Plywood flooring—general sample (*left*) and construction sample (*right*). **c** Laminate flooring—general sample (*left*) and construction sample (*right*). **d** PVC tile pattern 1—general sample (*left*) and construction sample (*right*). **e** PVC tile pattern 2—general sample (*left*) and construction sample (*right*). **f** PVC tile pattern 3—general sample (*left*) and construction sample (*right*)

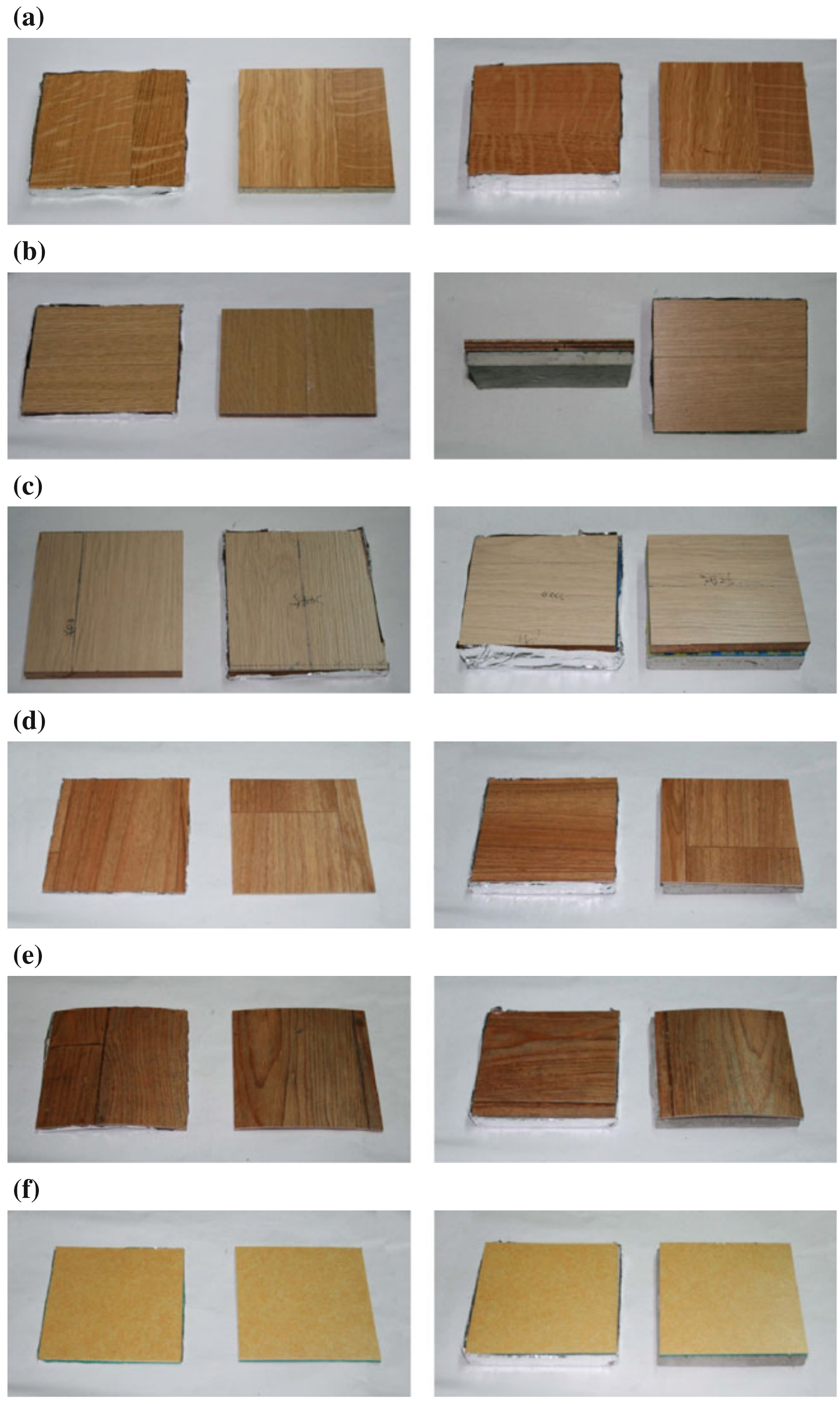
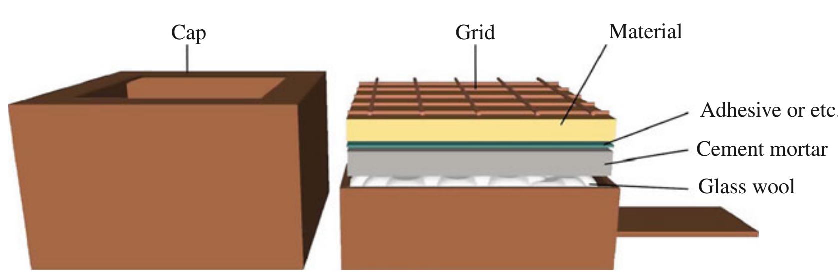


Fig. 3 Configuration of the sample holder



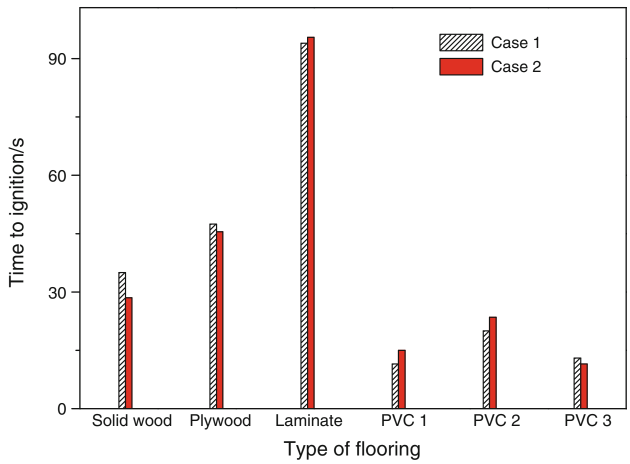


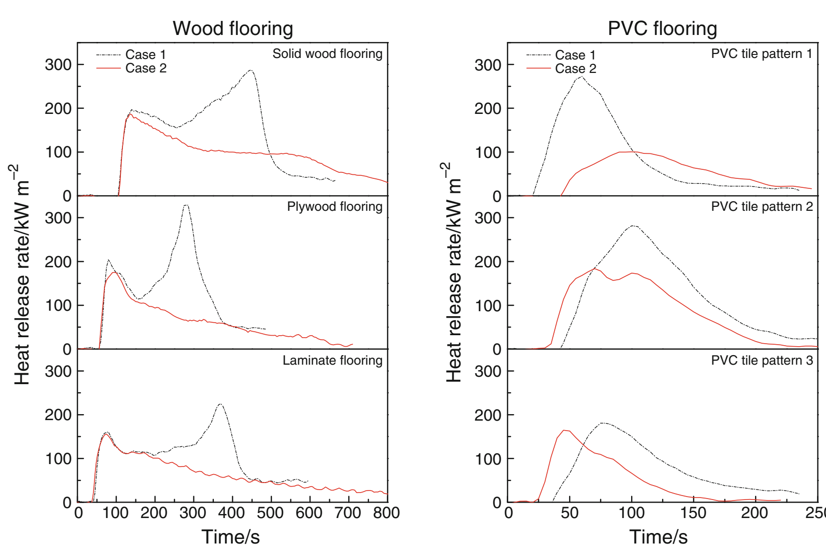
Fig. 4 Time to ignition (TTI) of the six samples

PVC flooring, PVC pattern 1 in both cases was equal to a single peak. The PHRR was 273 kW/m^2–60 s in case 1, which was the fastest time to reach the peak among the PVC floorings. In case 2, the PHRR was 100 kW/m^2–100 s, which was the lowest value among the PVC floorings. The differences of PHRR value between the two cases were larger than the others, and the PHRR for case 1 was faster than that of case 2, unlike the two other PVC floorings. PVC pattern 2 in both cases was a single peak. The PHRR was 282 kW/m^2–95 s in case 1, which was the largest value among the PVC floorings, and 184 kW/m^2–65 s in case 2. PVC pattern 3 was also a single peak in both cases. PHRR was 181 kW/m^2–75 s in case 1, which was the lowest value among the PVC floorings. In case 2, the maximum peak was 165 kW/m^2–45 s. The HRR of the two cases exhibited almost identical behavior.

In one previous study on the thermal behavior of wood, the HRR values of wood materials had two peaks, with the second being larger than the first [19]. Wood, both in its natural state and as wood panel, showed two peak times. However, in the case of wood paneling, due to the surface coating or influence of adhesive in the manufacturing process, the difference between the first and second peaks was a little or the first peak was larger but not significantly. Compared with previous studies associated with wood burning behavior, the data from the tests by the cone calorimeter in this paper can be judged to be reliable because shape and trend of HRR curve were similar to previous studies. Therefore, the differences between the two cases were substantial with respect to fire behavior. The difference of fire behavior according to sample preparation method is the difference between the lab-scale test and the actual fire condition. In case of an actual fire, such differences can help to achieve a more accurate understanding of fire behavior.

Figure 6 show the total heat rate (THR) of the wood and PVC products. Both materials showed higher values for case 1. In case 1 of wood flooring, THR rose sharply after ignition and then rose rapidly again at the time of the second HRR peak. THR tended to follow a smooth curve after ignition. Both solid wood flooring and plywood flooring had two points of contact at about 100 and 270 s and at about 75 and 175 s, respectively, due to the faster TTI of case 1 for these two wood floorings. In the PVC floorings, THR was higher in case 1 than in case 2. For patterns 2 and 3, PVC products were shown at the point of contact on THR curves and that was different from the trend of TTI in the wood products. Because of differences in material properties and experimental errors, the measurement times of PVC flooring were shorter than those of wood flooring. These experimental errors were caused by an inexperienced operator. In conclusion, in spite of the experimental errors in the THR measurements for the wood

Fig. 5 Heat release rate (HRR) of the wood flooring and the PVC flooring



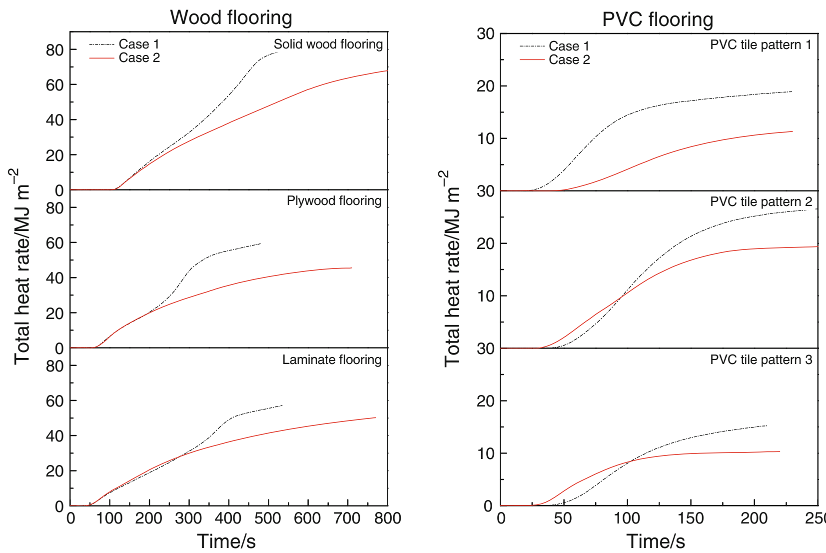


Fig. 6 Total heat rate (THR) of the wood flooring and the PVC flooring

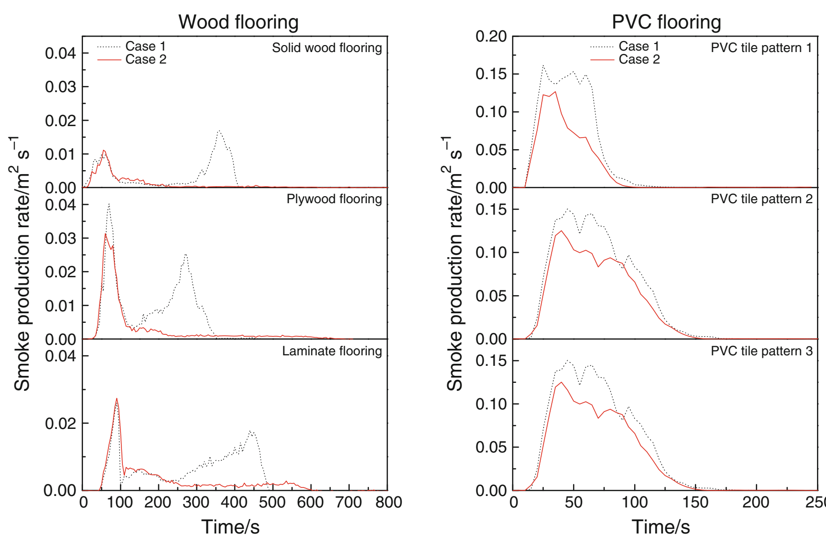


Fig. 7 Smoke production rate (SPR) of the wood flooring and the PVC flooring

and PVC products and the presence of the contact phenomenon, all the measured data were higher for case 1 than for case 2. This demonstrated the influence of the sample preparation method on the experimental results.

Figure 7 show the SPR for the wood and PVC products. Preferentially, the SPR of the wood products exhibited a similar pattern to that of the HRR curves. Therefore, smoke was generated as fire occurred. In addition, case 1 had two peaks that were attributed to HRR. Plywood flooring and solid wood flooring had higher values of SPR, because of the influence of the protective outermost surface coatings and adhesives [20]. In the PVC samples, the trend of SPR was similar to that of the HRR curves and also had higher values for case 1 than for case 2. In SPR, case 1 had higher values than case 2 for both wood and PVC samples, which exhibited the same trends as those for HRR and THR. In addition, wood flooring had either two peaks or a single peak, similar to HRR, which was a clear difference between the two cases.

Conclusions

The three kinds of wood flooring and the three kinds of PVC flooring were evaluated for flammability rating by using a cone calorimeter. Because of the difference in fire behavior between the lab-scale test and actual scale condition, two new sampling methods were proposed. HRR, THR, and SPR, but not TTI, had significant differences between the two cases. Especially, combustion behavior was significantly different between wood flooring and PVC flooring depending on the sampling method. In the wood flooring, as the PHRR was became lower and the combustion behavior changed along with the change to number of peaks. The two cases of PVC flooring were similar with respect to burning behavior compared to the wood flooring, but the PHRR differed widely according to the sampling method. In the conventional sample preparation method, the flammability test of the wood flooring and PVC flooring did not give accurate results with respect to the fire situation and the combustion behavior due to the material testing differences between the lab-scale condition and that in real buildings. So in conventional sample preparation method is not high reliability when the fire. Therefore, reliable data can be obtained for the burning behavior of building materials in buildings constructed through the sampling method by adding the cement mortar for samples, and this is better than the common sampling method.

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