# HRR, SMOKE AND TOXICITY OF CEILING AND WALL LININGS AND FINISHES

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## ABSTRACT

Results on HRR, smoke and toxicity of 19 ceiling and wall lining materials using a cone calorimeter are discussed. Among the specimens tested are gypsum boards with various surface finishes, plaster boards, calcium silicate boards and other wood materials.

The samples were tested at an irradiance of 50 kW/m$^2$ and for 900 seconds including the time before ignition. The RHR, PHR, MLR, EHC, CO and $CO_2$ yields, RSR values and other fire parameters of the tested samples are discussed.

Test results generated were found useful for assessing and comparing fire performances of samples. The large amount of quantitative data covering the various fire parameters provide a more accurate picture of the overall fire performance of a material/structure.

## 1. INTRODUCTION

Advancement in material science in recent years has led to the introduction of many new building materials. Conventional fire tests are often found too tedious and inadequate to provide data required for detail analysis e.g. fire modelling. There had since been a change in approach to the development of modern fire tests: away from simple ranking tests and geared towards results that can be used as input into mathematical fire models or fire hazard assessment of materials. Findings overseas had also indicated that the rate of heat release (RHR) is the prime hazard parameter [1-9].

This paper discusses the fire performance of 19 ceiling and wall linings and finishes based on a cone calorimeter according to ISO 5660.

## 2. EXPERIMENTAL STUDY

19 types of ceiling and wall linings and surface finishes commonly used in Singapore were studied. The thickness and density of these materials are listed in Table 1. The materials were classified under three categories namely board, insulation and wood materials. B1 to B11 are board materials. Among them, B1 to B3 are different types of gypsum board and B1 to B6 are gypsum boards each affixed with different surface finishes. B8 to B11 are other types of board materials. I1 and I2 are insulation products. W1 to W12 are different types of wood materials. The samples were tested at an irradiance of 50 kW/m$^2$ for 900 seconds including the time before ignition.

## 3. RESULTS AND DISCUSSIONS

Results obtained from the Cone Calorimeter for each test sample are summarised in Table 2A and 2B.

### 3.1 Rate of Heat Release (RHR)

Fig. 1 summarises the RHR curves of the tested samples. Wood samples in general are shown to consistently exhibit large RHR and PHR values. They reach their peak values quickly and attain an even higher peak at a later time. Fabric wallcovering (B6) also exhibits high PHR and reaches its peak quickly. This short time to peak value of wood and fabric wallcovering (B6) is not favourable as PHR represents maximum intensity of fire. The large amount of heat released can cause self-ignition as well as ignition of surrounding materials. The means of escape might then be delayed and/or difficult. Other samples, except for cemboard (B10), have comparatively low RHR. Despite having high RHR and PHR values, B10 is less hazardous as it takes longer time to reach the peak value.

Maple (W2) and Ramin (W1) ranked the highest in terms of PHR and THR values. Fibrous plaster (B8), calcium silicate (B11), and mineral fiber board (B9) achieved very low PHR and average RHR. Composite materials such as fiberglass with vinyl laminate (I2) and the various gypsum boards fixed with finishes have high PHR but low average RHR. The time to PHR values of these samples occurred at a very early stage and the RHR values achieved thereafter were generally low, except for

I1. This shows that the peak values are likely to be contributed by the thin surface finishes which was observed to burn out very quickly. The low average values are thus contributed by the gypsum board.

Fire rated and moisture resistant gypsum board (B2 & B3) have lower PHR values but higher RHR values than normal gypsum board (B1). This indicates that B2 and B3 may help to reduce maximum intensity of fire but not the total amount of heat released.

To compare fire performances of the various applied surface finishes, results for B1 to B6 samples are examined. Fabric wallcovering (B6) performed the poorest attaining the highest PHR value at 285 $kW/m^2$. The smoke production and yields of gases for B6 are also higher than most other samples. Vinyl wallcovering (B5) reaches its peak value in the shortest time. This however does not make it the most hazardous as its peak value is much lower than that of B6.

The RHR curves of all wood samples exhibit a similar pattern with two PHR values. However, Oak (W4), Teak (W5) and Mahogany (W6) reach their second PHR beyond the 900 seconds.

**Table 1: Key data for products tested**

| Code No. | Product Type | Initial Mass (g) | Thickness (mm) | Density ($kg/m^3$) |
|---|---|---|---|---|
| **BOARD MATERIALS** | | | | |
| B1 | Painted gypsum board | 67.40 | 9.7 | 694.85 |
| B2 | Painted 1 hr fire rated gypsum board | 96.70 | 14.0 | 690.71 |
| B3 | Painted moisture resistant gypsum board | 115.40 | 16.5 | 699.39 |
| B4 | Wallpaper on gypsum board | 97.80 | 13.0 | 752.31 |
| B5 | Vinyl wallcovering on gypsum board | 106.40 | 13.0 | 818.46 |
| B6 | Fabric wallcovering on gypsum board | 99.80 | 14.0 | 712.86 |
| B8 | Fibrous Plaster | 50.60 | 7.4 | 683.78 |
| B9 | Mineral Fibre | 32.70 | 15.0 | 218.00 |
| B10 | Cemboard | 98.70 | 8.0 | 1233.75 |
| B11 | Calcium Silicate Board | 61.70 | 6.0 | 1028.33 |
| **INSULATION MATERIALS** | | | | |
| I1 | Rigid Polyurethane Foam | 42.40 | 47.0 | 90.21 |
| I2 | Fiberglass with vinyl laminate | 8.80 | 33.0 | 26.67 |
| **WOOD MATERIALS** | | | | |
| W1 | Ramin | 102.60 | 15.0 | 684.00 |
| W2 | Maple | 108.30 | 15.0 | 722.00 |
| W3 | Cherry | 90.50 | 15.0 | 603.33 |
| W4 | Oak | 124.70 | 15.0 | 831.33 |
| W5 | Teak | 100.60 | 15.0 | 670.67 |
| W6 | Mahogany | 125.50 | 20.0 | 627.50 |
| W10 | Plywood (15 mm) | 98.60 | 15.0 | 657.33 |
| W12 | Plywood (9 mm at 25kW) | 58.20 | 9.0 | 646.67 |
| W8 | Plywood (9 mm at 50kW) | 56.90 | 9.0 | 632.22 |
| W11 | Plywood (9 mm at 75kW) | 56.30 | 9.0 | 625.56 |

**Table 2A: Results for all samples**

| Code No. | Product Type | PHR $kW/m^2$ | THR $MJ/m^2$ | Aver RHR $kW/m^2$ | Peak EHC MJ/kg | Aver EHC MJ/kg | Aver MLR g/s | Aver CO Yield kg/kg | Aver $CO_2$ Yield kg/kg |
|---|---|---|---|---|---|---|---|---|---|
| B1 | Painted gypsum board | 110 | 9.6 | 7 | 18.3 | 3.4 | 0.0173 | 0.0404 | 0.40 |
| B2 | Painted 1 hr fire rated gypsum board | 73 | 12.1 | 9 | 14.9 | 4.1 | 0.0195 | 0.0285 | 0.25 |
| B3 | Painted moisture resistant gypsum board | 41 | 9.0 | 8 | 13.4 | 4.2 | 0.0177 | 0.0138 | 0.24 |
| B4 | Wallpaper on gypsum board | 61 | 5.4 | 4 | 6.6 | 1.8 | 0.0185 | 0.0315 | 0.07 |
| B5 | Vinyl wallcovering on gypsum board | 65 | 20.5 | 15 | 17.5 | 6.3 | 0.0217 | 0.0253 | 0.22 |
| B6 | Fabric wallcovering on gypsum board | 285 | 4.6 | 4 | 21.3 | 1.7 | 0.0220 | 0.0316 | 0.30 |
| B8 | Fibrous Plaster | 2 | 0.2 | 0 | 0.7 | 0.0 | 0.0106 | -0.0056 | 0.20 |
| B9 | Mineral Fibre | 14 | 12.9 | 10 | 21.1 | 11.3 | 0.0078 | 0.1549 | 1.07 |
| B10 | Cemboard | 100 | 25.7 | 34 | 24.4 | 13.4 | 0.0223 | 0.0311 | 1.13 |
| B11 | Calcium Silicate Board | 13 | 5.1 | 5 | 18.4 | 5.3 | 0.0090 | 0.0515 | 0.21 |
| I1 | Rigid Polyurethane Foam | 30 | 19.9 | 19 | 16.8 | 10.0 | 0.0170 | 0.2873 | 0.71 |
| I2 | Fiberglass with vinyl laminate | 34 | 1.3 | 1 | 14.6 | 12.3 | 0.0009 | 0.2149 | 0.04 |
| W1 | Ramin Wood | 324 | 158.7 | 179 | 83.2 | 17.7 | 0.0891 | 0.0000 | 0.46 |
| W2 | Maple Wood | 335 | 162.7 | 158 | 81.9 | 13.8 | 0.1004 | -0.0017 | 0.30 |
| W3 | Cherry Wood | 223 | 140.9 | 153 | 68.0 | 17.8 | 0.0757 | 0.0019 | 0.79 |
| W4 | Oak | 258 | 134.4 | 118 | 20.7 | 10.1 | 0.1026 | 0.0000 | 0.00 |
| W5 | Teak | 185 | 120.1 | 88 | 18.7 | 11.8 | 0.0658 | 0.0002 | 0.01 |
| W6 | Mahogany | 106 | 84.0 | 49 | 15.2 | 7.2 | 0.0593 | 0.0000 | -0.02 |
| W10 | Plywood (15 mm) | 252 | 102.7 | 109 | 25.8 | 11.9 | 0.0803 | 0.0066 | 0.99 |
| W12 | Plywood (9 mm at 25kW) | 218 | 52.5 | 111 | 24.3 | 13.5 | 0.0721 | 0.0172 | 1.12 |
| W8 | Plywood (9 mm at 50kW) | 223 | 75.7 | 79 | 33.4 | 13.3 | 0.0523 | 0.0308 | 1.11 |
| W11 | Plywood (9 mm at 75kW) | 365 | 81.1 | 90 | 35.6 | 14.5 | 0.0547 | 0.0344 | 1.19 |

**Table 2B: Results for all samples**

| Code No. | Product Type | $t_{ig}$ s | PSR 1/s | Aver RSR 1/s | TSR | Peak SEA $m^2/kg$ | Aver SEA $m^2/kg$ |
|---|---|---|---|---|---|---|---|
| B1 | Painted gypsum board | 44 | 0.1708 | 0.0079 | 21.0 | 110.7 | -15.7 |
| B2 | Painted 1 hr fire rated gypsum board | 58 | 0.7831 | 0.0207 | 53.4 | 154.9 | 60.0 |
| B3 | Painted moisture resistant gypsum board | 45 | 0.1473 | 0.0105 | 37.5 | 223.9 | -11.2 |
| B4 | Wallpaper on gypsum board | 67 | 1.0652 | 0.0117 | 125.0 | 355.3 | -11.9 |
| B5 | Vinyl wallcovering on gypsum board | 15 | 6.1818 | 0.0270 | 119.5 | 1090.9 | -22.1 |
| B6 | Fabric wallcovering on gypsum board | 54 | 26.6802 | 0.1891 | 194.2 | 605.7 | 63.2 |
| B8 | Fibrous Plaster | No Ign | 0.0778 | 0.0042 | 3.8 | 24.1 | -48.6 |
| B9 | Mineral Fibre | No Ign | 1.0113 | 0.0484 | 43.8 | 261.4 | 32.2 |
| B10 | Cemboard | 386 | 0.0229 | 0.0002 | 6.4 | -8.8 | -62.5 |
| B11 | Calcium Silicate Board | No Ign | 0.1559 | 0.0201 | 18.3 | 94.3 | 0.0 |
| I1 | Rigid Polyurethane Foam | No Ign | 0.0617 | 0.0010 | 1.1 | -1.0 | -69.9 |
| I2 | Fiberglass with vinyl laminate | 7 | 2.7826 | 0.0542 | 63.1 | 506.5 | 443.7 |
| W1 | Ramin Wood | 27 | 2.9349 | 0.5323 | 481.6 | 187.4 | 46.3 |
| W2 | Maple Wood | 33 | 2.9740 | 0.4548 | 410.8 | 133.3 | 34.0 |
| W3 | Cherry Wood | 25 | 0.9547 | 0.1279 | 126.9 | 129.4 | 6.1 |
| W4 | Oak | 45 | 1.7899 | 0.2221 | 204.7 | 68.8 | 11.1 |
| W5 | Teak | 36 | 4.7026 | 0.8687 | 777.1 | 262.3 | 115.8 |
| W6 | Mahogany | 38 | 1.5316 | 0.0561 | 67.7 | 164.3 | -3.2 |
| W10 | Plywood (15 mm) | 24 | 4.2916 | 0.4158 | 376.8 | 751.3 | 36.4 |
| W12 | Plywood (9 mm at 25kW) | 476 | 1.8565 | 0.3651 | 547.3 | 139.9 | 33.9 |
| W8 | Plywood (9 mm at 50kW) | 47 | 2.1623 | 0.2135 | 218.1 | 122.8 | 27.3 |
| W11 | Plywood (9 mm at 75kW) | 12 | 4.7774 | 0.3991 | 364.2 | 190.8 | 42.2 |

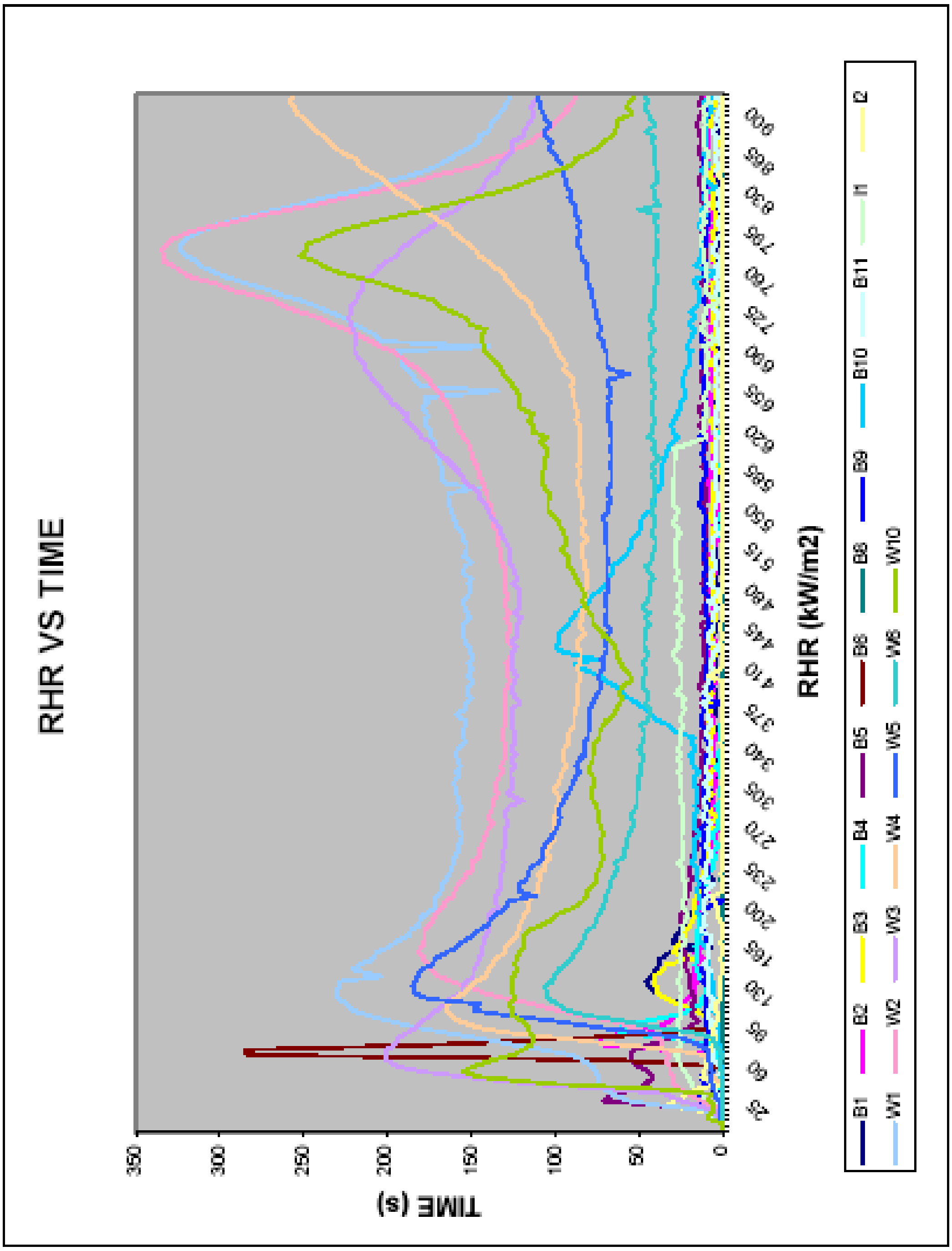


**Fig. 1: RHR curves of all samples**

### 3.2 Time to Ignition ($T_{ig}$)

The time taken for a material to ignite influences the potential and rate of fire spread. The faster a material ignites the quicker flame spread will take place. If the intention is to minimise flame spread rate it is important to consider the time to ignition as the inverse of time to ignition is proportional to the flame spread rate [1]. From Table 2B, samples with vinyl finishes (I2 and B5) ignite the fastest, within the time of 15 s followed by wood materials at within a time of 38s. Fibrous plaster (B8), mineral fiber (B9), calcium silicate (B11) and polyurethane (I1) show better resistance to fire spread. Cemboard (B10) ignites at only 386s.

### 3.3 Mass Loss Rate and Toxicity

MLR or burning rate is significant as it indirectly affects the amount of heat produced and thus the spread of fire. MLR also indicates overall toxicity of the material. A direct relationship is hence expected between MLR and yields of smoke, CO and CO2. Table 2A shows that fiberglass (I2), calcium silicate (B11), mineral fiber (B9) and fibrous plaster (B8) have the least average MLR values. Polyurethane (I1) have the highest peak CO yield and have consistently high CO yield throughout the test. This is followed by fiberglass (I2) and mineral fiber (B9). It is imperative to consider yield of CO as studies into fire deaths indicate that majority of fire victims may have died from CO poisoning. On the other hand, fibrous plaster (B8) and other wood materials produced the least amount of CO. Combined CO curves and the respective CO values are shown in Fig. 2.

When comparing normal gypsum board (B1) with fire rated gypsum board (B2), B2 has a higher CO value than B1. B2 also has a higher PSR and peak SEA values than B1. This demonstrates that although a fire rated gypsum board gives a low PHR value, the smoke and toxicity hazard levels of the material are higher than that of a normal gypsum board.

### 3.4 Smoke Parameters

Where smoke obscuration is of concern it is important to choose linings with relatively low smoke factors. Fig. 3 summarizes the RSR curves of the tested samples. Polyurethane (I1), fibrous plaster (B8) and cemboard (B10) are best in terms of smoke performance as shown in their low RSR and SEA values. In Table 2B, it can be seen that most of the wood materials emit a high TSR with teak (W5) obtaining the highest value and Mahogany (W6) the least. The most smoke hazardous material is fabric wallcovering (B6) as it emits a significantly high PSR of 27 1/s compared to I1 at 0.06 1/s. It also has high TSR and average SEA values. Vinyl wallcovering (B5) has the highest SEA at 1091 $m^2$/kg and a high PSR after B6. Fiberglass with vinyl laminate (I2) also has a high PSR value. The high value is likely to be contributed by the vinyl laminate since the peak value occurred at the early stage of testing. Hence vinyl produces high amount of smoke.

## 4. CFD SIMULATIONS

Much research has been carried out using computational fluid dynamics (CFD) on fire and smoke movements in forced ventilated enclosures [10-15].

To test the significance of the nature of material in terms of ignition time, nature of smoke particles and toxic gases on fire hazard, a hypothetical case involving a 30m atrium was simulated using PHOENICS. Factors considered in the simulations include the location and rate of exhaust, configuration such as the inclusion of smoke screens at different levels, fire size, fire source and location. Data generated earlier including the time to ignition, smoke obscuration and toxicity were used in the assessment. It was observed from the simulations that fire hazard could be significantly underestimated if these factors were not considered especially in cases where materials are of low $t_{ig}$, high RSR and high yield of toxic gases. The details of this study will be reported elsewhere.

## 5. CONCLUSIONS

From the results obtained during testing, several inferences can be drawn:

- Wood and fabric wallcovering emit the most amount of heat and smoke when compared to all other samples. Vinyl wallcovering and wood materials ignite most rapidly. Among the wood materials, Mahogany (W6) is the best in terms of fire and smoke performance. It has the lowest PHR, average MLR, CO and $CO_2$ yield and average RSR value. However, this is based on results for the time threshold of 900 seconds. This duration for testing may be too short for complete combustion of wood materials. Given a longer duration, it is possible that Mahogany (W6) and Teak (W5) may reach a higher PHR value. Therefore, test duration should vary according to the type of material tested. Wood materials, as well as materials that ignite more slowly such as cemboard, should be tested for a longer period of time.

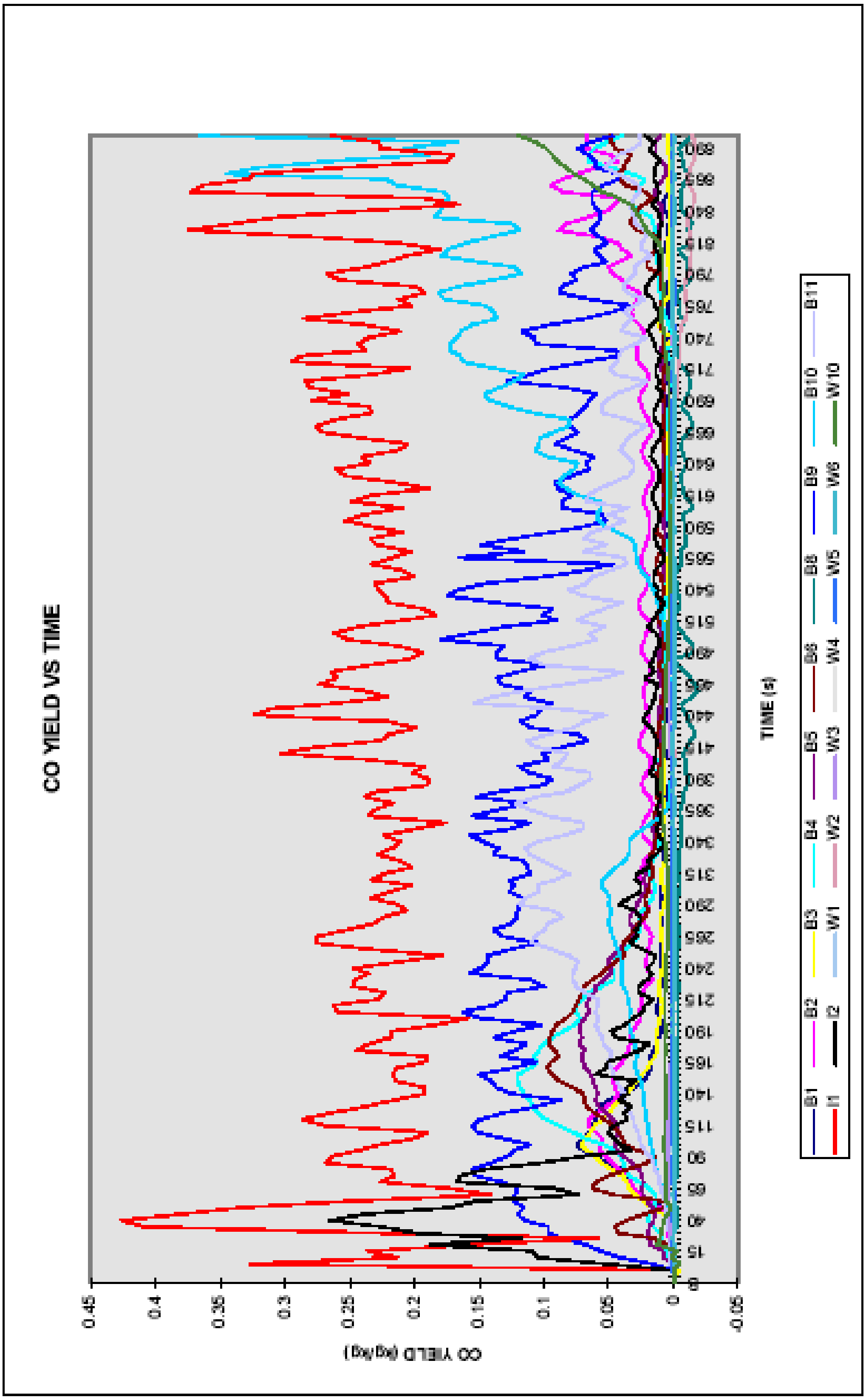


Fig. 2: CO Yield curves of all samples

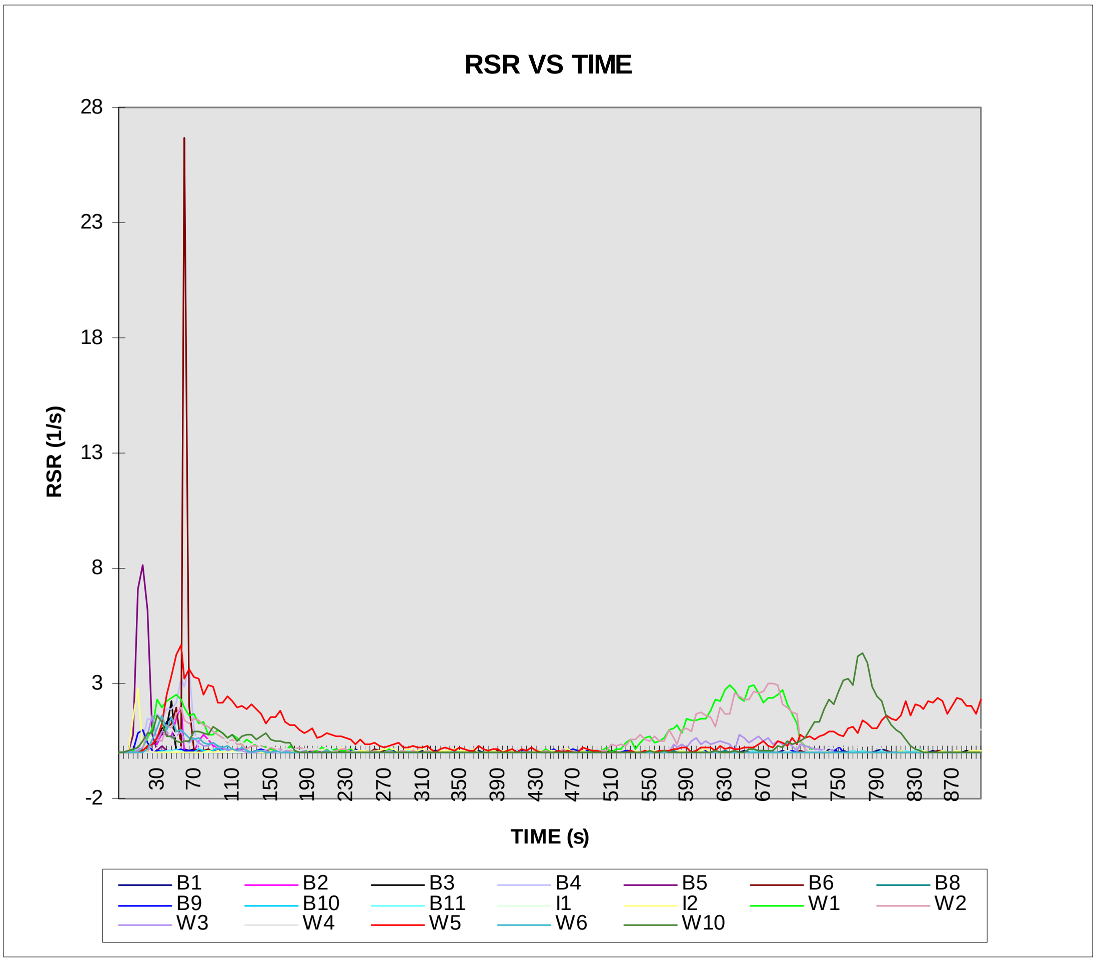


**Fig. 3: RSR curves of all samples**

- Teak (W5) and Ramin (W1) are generally more hazardous than the other wood samples. W1 has the second highest RHR, a short ignition time and reasonably high MLR, RSR and SEA values. W5 has the highest RSR and SEA values.

- Among all surface finishes, fabric wallcovering has a comparatively high PHR, CO yield and amount of smoke released. Fabric wallcovering is thus considered the most hazardous sample.

- Fibrous plaster ranked the best in almost all parameters and is overall the least hazardous material. Polyurethane performed well in terms of the smoke parameters.

- PHR of gypsum board can be lowered by the addition of fire retarding agents. However, the amount of smoke released increased as a result of this.

- Degree of combustibility of the samples can be measured using average RHR values. It was found the threshold for classifying materials as non-combustible lies between 34 $kW/m^2$ and 49 $kW/m^2$.

Test results generated from the Cone Calorimeter are found useful for assessing and comparing fire performances of samples. The instrument provides a large amount of quantitative data and measures the fire hazard of samples in terms of many aspects such as smoke and toxicity. It thus allows the tester to evaluate the overall fire performance of a sample from just one test. This is not possible in the present fire test methods as only one fire property of samples is measured.

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