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Bottom fire behaviour of thermally thick natural rubber latex foam

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Abstract: In this paper, the bottom fire behaviour of 25 cm × 25 cm × 5 cm natural rubber (NR) latex foam with uniformly distributed 6 mm diameter holes was investigated experimentally in a small-scale experimental platform under bottom ventilation. The bottom fire behaviour was analysed. The results show that the burning process of the thermally thick NR latex foam under bottom ventilation conditions can be divided into three stages: initial growing, full development, and decay. A deflagration covered the entire rear surface was observed at 308 s. The burning balls moving at a speed of 0.15 m/s were observed after the bottom ignition and they moved from the center to the sides along with the expansion. The mass loss rate of the sample was accelerated dramatically from 0.2 g/s to 0.5 g/s when the bottom surface was ignited at 308 s.

Keywords: natural rubber latex foam; fire behaviour; bottom flame spread; bottom ventilation

1 Introduction

With the wide use of natural rubber (NR) latex foam in both apartments and office buildings (1), more and more concerns have been triggered about its fire hazards (2-4). NR latex foam has various characteristics such as flexibility, light in weight, high elasticity, and sterility. According to our previous research (5), the main chemical components of latex foam were styrene-butadiene block copolymer and its structural formula is depicted in Figure 1 (6). However, due to its chemical property, NR latex foam is fusible and combustible. Once ignited, the fire spread very quickly accompanied by a large amount of heat and noxious smoke (7,8), which may pose a significant threat to people's lives and properties.

Many studies have focused on the fire behavior of foam materials. Y Zhou et al. (9) explored the characteristics of two typical heat insulating materials, rigid polyurethane and polystyrene foam. The heat transfer mechanism of polyurethane foam slabs was studied by numerical simulation by Prasad K et al. (10). The results indicated that its decomposition included phase change, shape change, charring, bubbling, etc. Rossi, Camino (11), Ergut and Levendis et al. (12) studied the combustion products of polystyrene (PS) and its smoke features. Oleszkiewicz (13) measured the maximum distance and maximum heat flux to clarify fire-spreading characters of different materials by studying of various thermal insulation materials. The fire risks of foam materials like flexible polyurethane foam (14,15), cubical-shaped polyurethane foam block (16) and others cause many concerns. According to our previous studies of thermally thin NR latex foam under bottom ventilation, once its bottom surface was ignited, the combustion of the top surface was accelerated (2,3). In addition, the soot aggregating from its burning influences negatively on the environment and human diseases (4). However, as for the thermally thick NR latex foam, the flammable range of the material, fire heights, and morphology of the soot aggregates are larger than thermally thin materials under bottom ventilation. The burning of the top surface may be accelerated to a greater extent. Therefore, the scope of fire and the fire hazard may be much more threatening to the security of people and properties.

Most of the recent studies have been focused on horizontal flame spread behavior over foam materials under different conditions, such as the effects of ventilation conditions (17), test altitude (9), heating time (18) and sample width (14,19,20) on horizontal fire

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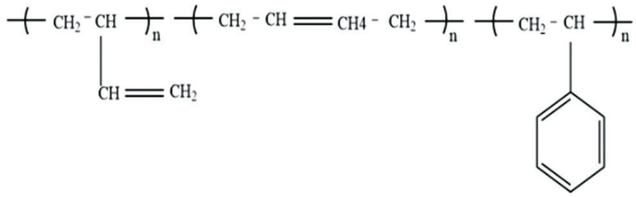

Figure 1: Structure of styrene-butadiene block copolymer.

behavior of foam materials. The research of X Ma et al. (21) indicated that the process of flame spread of flexible polyurethane board was accelerated under the external radiation condition. However, a few studies paid attention to bottom fire behavior of thermally thick NR latex foam under bottom ventilation. The 5 cm-thickness NR latex foam mattress is a representative kind of material in real scenarios. Therefore, in this paper, the bottom flame spread behaviour of NR latex foam (25 cm × 25 cm × 5 cm) under bottom ventilation was studied experimentally. The aim was to investigate the bottom flame spread behaviour and mechanisms.

2 Materials and methods

The experimental setup of this study is composed of two parts: (a) the sample holder and smoke exhausting system, and (b) measurement system, as shown in Figure 2. The sample holder included experiment stand and asbestos board. The experiment stand was surrounded by stainless steel boundary (60 cm × 60 cm), which was under the asbestos board (60 cm × 60 cm × 5 cm). A 0.8 m × 0.8 m × 0.005 m chassis made by stainless steel plate was fixed on the floor and independent on the sample holder to prevent ashes from splashing but not affect the sample. A stainless grid made of 0.52 mm diameter stainless steel and 2.3 mm distance interval was used underneath the sample, which was regarded as bottom ventilation. A 2.0 m × 3.0 m hood was used to collect and discharge the smoke produced in the experiment. To discharge all the smoke, a fire fan was connected to the hood via a 0.4 m-diameter smoke discharge pipe.

The measurement system consisted of six 1 mm K-type thermocouples connected to Agilent 34970A data-acquisition system to measure temperature profiles at the surface. Camera-a was set 0.3 m above the sample holder and tilted on 45° down to record the flame spread on the sample surface. Camera-b was fixed at the same height with the sample but 0.5 m away to record the flame height. Camera-c was set on the floor 0.5 m away from the sample holder with a 45° elevation to record the flame on the sample bottom. A weighbridge was connected with the computer to measure the mass loss of the sample during the experiment. A high-resolution field emission SEM (JSM-5610LV, JEOL Co. Ltd, Japan) was used to observe the structures of NR latex foam for the fuel and ash. The voltage used in SEM was 5 kV.

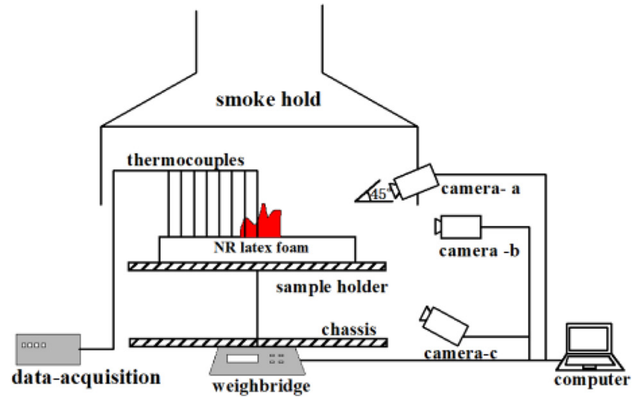

Figure 2: Schematic diagram of the experimental equipment.

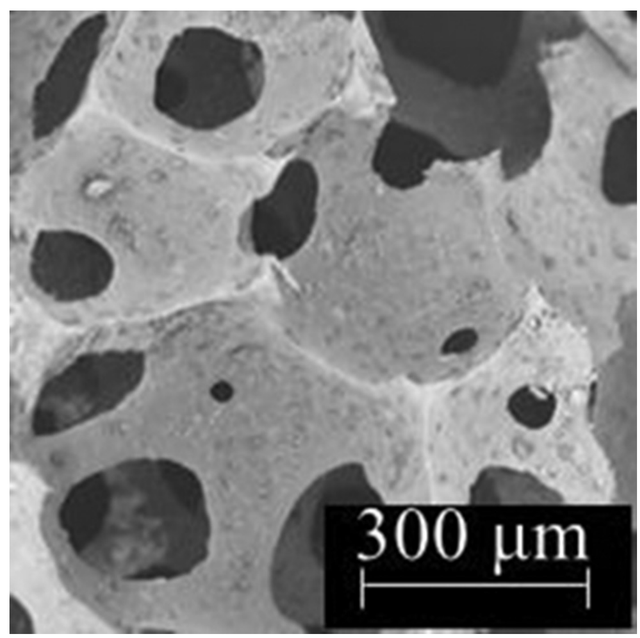

Figure 3: SEM image of initial NR latex foam.

In this experiment, 25 cm (length) × 25 cm (width) × 5 cm (height) NR latex foam sample supplied by Xilinmen Furniture Co., Ltd was used. The sample body was punctured in a plane by 6 mm diameter evenly distributed holes in rows and columns. The distance between two columns or rows was 3 cm, and two adjoining rows of holes were staggered. Before the experiment, the sample was dried in a vacuum dryer for 24 h. We use SEM to obtain the structure of the sample as showed in Figure 3 for following comparison with the combustion residues. As can be seen in Figure 3, the inner structure of NR latex foam is three-dimensional with uniformly distributed pores and fine open cells.To quantitatively describe flame spread both at the upper and rear faces, sample top and rear were divided by 100 equal grids, with a grid size of 2.5 cm. The experiment began while we ignited the ignition point of the sample. The ignition point was at the center point of the surface from where the flame spread to sample edges symmetrically. During the experiment, windows and doors were closed to avoid the effects of external airflow. After the combustion, we collected the burning residues of the sample to analyze the structure. Images sequence captured from camera-a and camera-c were used to respectively determine the top and bottom surface flame spread process. Ten images were extracted for each second from the video with an interval of 5 s. The mass loss rate was calculated by the data acquired from the weighbridge. The measurement interval of data during the experiment is 0.25 second.

3 Results and discussion

For thermally thick NR latex foam, the burning process under bottom ventilation conditions can be divided into three stages: initial growing, full development, and decaying. The bottom was ignited from the edge after the sample was almost burned through (3). Moreover, according to our previous research (3), the thermal penetration depth σ_T at ignition is about 3.8 cm. Therefore, a 5 cm thick sample in this study can be considered thermally thick.

The flame spread over NR latex foam sample was recorded by camera-a, and some representative pictures are shown in Figure 4. One may see that the combustion process also includes three stages like the thermally thick materials. However, the duration time of each stage is different as seen in Table 1.

Table 1 indicates that the completely burning process lasted for 410 s. The period of the bottom combustion was from 308 s to 410 s, which is the paramount observation analyzed in this paper. Overall, the bottom flame spread extremely fast and violently from the moment when the bottom surface was ignited. This was the result that bottom ventilation provided adequate oxygen to the bottom surface and the two stages before bottom combustion accumulated a large amount of heat and energy. When the flame died out at 410 s, a black char layer was observed covering the stainless grid. This was because char pieces produced in the burning process could not fall through the 2.3 mm stainless aperture. This layer prevented oxygen from flowing to the bottom surface, and prolonged the burning time. Some representative pictures are shown in Figure 5. A starting point for the timing was the moment when the bottom side of the material was ignited.

Before the flame spread to the bottom surface, a lot of smoke diffused outward through the holes and distributed close to the rear surface, as shown in Figure 6. With the horizontal combustion on the surface going on, more and more NR foam material was thermally decomposed. This resulted in the production of a large amount of smoke. When smoke came to the hole, it was pushed to spread up in it. This vertical flow and its original horizontal motion caused the diagonal down flows. Therefore, the smoke went through the holes and diffused outward.

Table 1: Time periods of each burning stage.

	Time period (s)	Duration (s)	Average flame height (mm)
Stage I	0-107	107	190
Stage II	107-308	201	580
Stage III	308-410	102	450

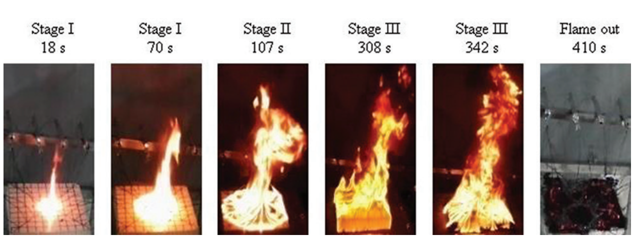

Figure 4: Typical flame spread images of NR latex foam.

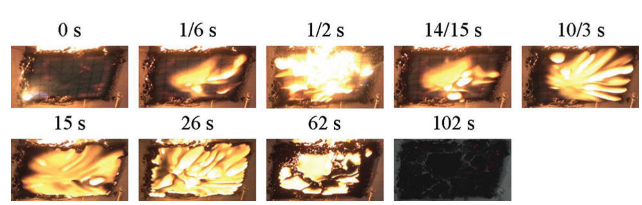

Figure 5: Typical bottom flame spread images.

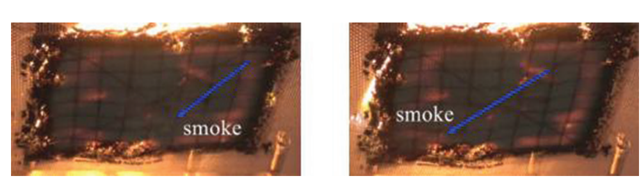

Figure 6: Smoke diffused outward.

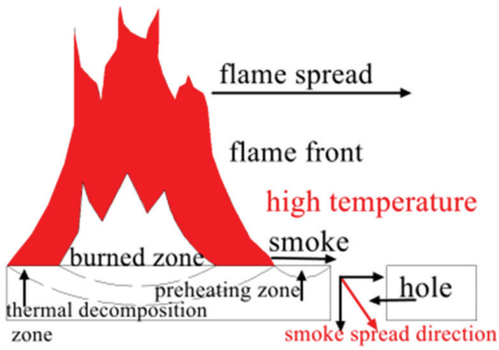

Figure 7: Schematic diagram of smoke spread.

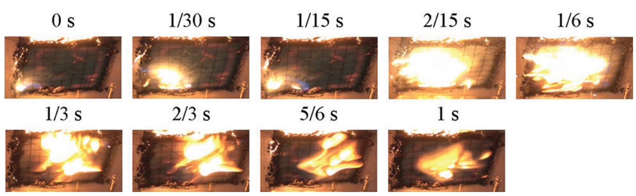

Figure 8: The process of the bottom surface ignition.

Figure 7 shows how smoke went through the holes and spread to the bottom surface. Combined with Figure 6, it shows that the thermal decomposition products of NR latex foam moved to the rear surface through the holes in the material. This possibly takes place because the temperature of the upper surface was higher than the rear one at combustion before the bottom ignited. As it is known, the synthetic block copolymer consists of methyl, hydroxyl, carbonyl and other functional groups and can be decomposed into small molecule materials (22-25). Those groups usually transfer to combustible gases, such as CH_4, C_2H_6 and so on (26). In our experiment, the combustible gases of NR latex foam cannot rise due to the thermal barrier effect (27-29). Therefore, they only can leave the material through the hole to the rear face. Those gases of NR latex foam mixed with air formed a combustible mixture. It was ignited until the flame spread to the edge of the rear surface. The ignition at the center indicated that the amount of combustible at the bottom center had reached the fire combustion limitation. Therefore, the combustion materials were the thermal decomposition products on the rear surface at the ignition moment. Then the rear NR latex foam was heated to accelerate decomposition. As a result, the rear of the material was ignited.

The flame spread from the upper surface to the bottom very rapidly just like a deflagration. The process is shown in Figure 8. The flame almost covered the entire rear surface at the ignition moment, and then it concentrated in the center of the rear surface. After that, the flame spread quickly from the center to the edges, and the whole surface was ignited within 15 seconds. The moment of the bottom side ignition was the starting timing point. A stable combustion period lasted from 15 s to 44 s. After that, the flame started to die out and finished at 58 s.

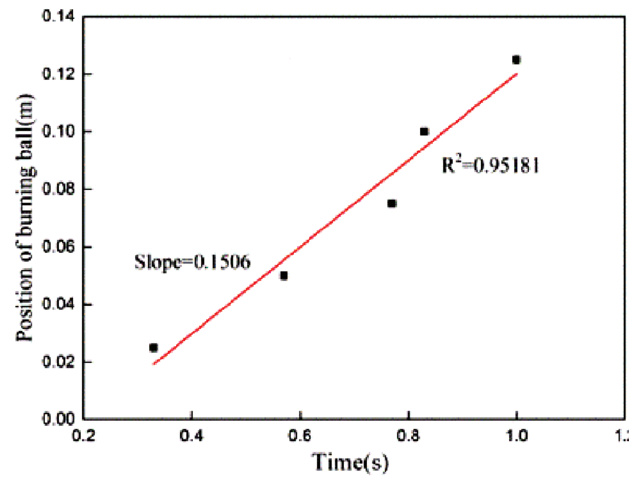

Figure 9: Burning balls movement speed.

After being ignited, the burning balls, which spread at a certain angle in the horizontal direction, were observed during the bottom combustion process. We deduce that the burning balls were the combustion of the thermally decomposed products spreading through the holes. We calculated the selected burning ball movement speed and it is shown in Figure 9. Its value is about 0.15 m/s. During the burning balls movement, the rear surface was heated permanently, and the material was thermally decomposed. Therefore, a motion of the burning balls accelerates the flame spread along the rear face. According to our previous research which focusing on the effects of bottom ventilation on the fire behavior of natural rubber latex foam (3), when the material was burned through, the flame spread speed and the flame height were accelerated to a greater extent.

The mass loss rate of the sample was measured and is shown in Figure 10. It is obvious that the rate kept going up slowly from the ignition but when the bottom surface was ignited at 308 s, the mass loss rate was accelerated dramatically from 0.2 g/s to 0.5 g/s.

We analyzed burning residues by SEM as shown in Figure 11. It shows that only ash left after combustion. This indicates the full combustion of the sample due to sufficient fresh air supply by bottom ventilation.

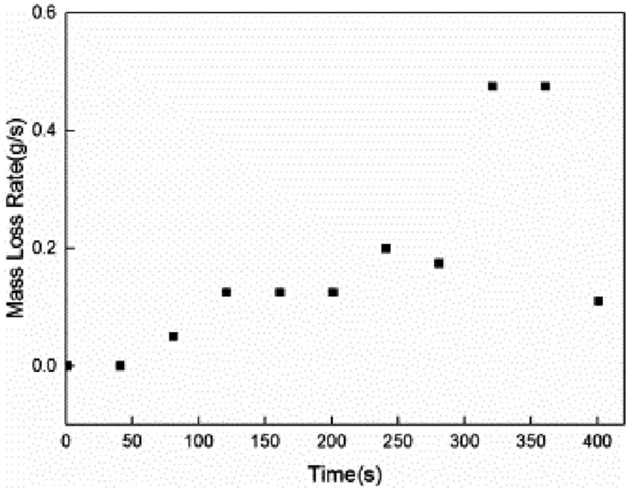

Figure 10: Mass loss rate.

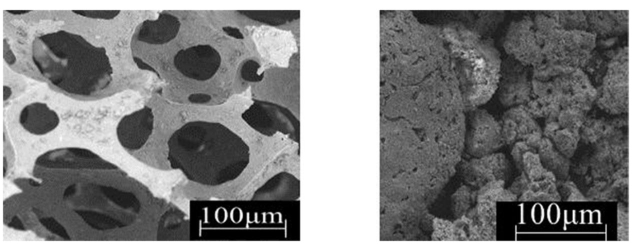

Figure 11: SEM images of NR latex foam before and after the burning.

4 Conclusions

In this work, the bottom flame behavior of NR latex foam was investigated experimentally at a bottom ventilation condition. The main conclusions are the following:

(1) The burning process of the thermally thick NR latex foam at the bottom ventilation condition can be divided into three stages: initial growing, full development, and decay. Bottom of the thermally thick NR latex foam ignited at 308 s.

(2) A deflagration of the thermally decomposed products was observed at the bottom ignition moment. The flame covered the entire rear surface and then concentrated in the center.

(3) The burning balls were observed after bottom ignited; they expanded and moved from the center to the sides. The movement speed was 0.15 m/s.

(4) The mass loss rate of the sample was accelerated dramatically from 0.2 g/s to 0.5 g/s when the bottom surface was ignited at 308 s.

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