Risk assessment for the spontaneous ignition of the rubble generated after the Great East Japan Earthquake

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ABSTRACT : *The Great East Japan Earthquake has resulted in the generation of large amounts of rubble. As a result, many 'outdoor rubble storage areas' have been established in the disaster areas. However, since the summer of 2011, a great number of fires have occurred in these areas of Tohoku district. One of the causes of these fires is believed to be the proliferation of microorganisms and fermentation of the organic material present in the rubble piles. The heat generated during fermentation ultimately results in spontaneous ignition. We conducted field surveys of two rubble storage areas in Yuriage and Kozukahara, Natori City, Miyagi prefecture where fires took place. Rubble samples containing material conducive to fermentation were collected from the fire-affected areas, and the risk of spontaneous ignition that is triggered by the heat generated during fermentation was examined. The results revealed that the heat generated during the fermentation of rotten tatami mats and wood chips most likely triggers and causes fires under adiabatic conditions.*

Keywords - *Great East Japan Earthquake, Rubble, Fermentation, Spontaneous ignition, Risk assessment*

I. INTRODUCTION

Japan is an earthquake-prone country, located above four tectonic plates: the North American plate, Eurasian plate, Pacific Ocean plate and Philippine Sea Plate. The Great East Japan Earthquake that occurred on 11 March 2011 was the biggest earthquake in recent Japanese history. The seismic vibrations and tsunami resulting from the Great East Japan Earthquake led to collapse of many houses and buildings, which became a large amount of rubble.

As a result, many 'outdoor rubble storage areas' were established in disaster areas to temporarily deposit rubble and to dispose it after sorting. Until 31 January 2012, there were 297 outdoor rubble storage areas comprising an area of approximately 973 ha (equivalent to 207 Tokyo Domes) in the Fukushima, Miyagi, and Iwate prefectures. However, fires have been continuously occurring in the Tohoku district outdoor rubble storage areas since summer 2011.

One of the causes of these fires is believed to be the large amount of items within the rubble piles where microorganisms can easily proliferate. Moreover, the heat generated by fermentation triggers a rise in the rubble temperature, ultimately resulting in spontaneous ignition.There are plans in place for the municipalities in Japan to cooperate in accepting rubble from disaster areas and provide support for rubble disposal. It is also necessary to pay attention to the outbreak of fires in the municipalities that have accepted rubble.

We conducted field surveys of two outdoor rubble storage areas in Yuriage and Kozukahara, Natori City, Miyagi prefecture, where fires have occurred, and collected rubble samples from the fire-affected areas, in which fermentation is possible.As the amount of heat generated by fermentation is small compared with that generated by a normal chemical reaction, the rubble samples were examined by combining high-sensitivity thermal analysis equipment to investigate the fire risk from heat generation due to fermentation and to obtain basic data for development of future safety measures.

II. DETAILS OF THE RUBBLE FIRES THAT OCCURRED IN MIYAGI PREFECTURE

Table1 shows the examples of fires that we observed first-hand. In addition to these examples, more than 20 fires have occurred in other areas in eastern Japan.

III. EXPERIMENTS

Samples

A list of the rubble samples used in this study is shown in Fig 1–4. The fact that grass and wood chips and waste deposited in large quantities pose fire risk following fermentation has previously been identified.[1]-[3]Tatami is a traditional flooring material in Japanese houses made by weaving straw and igusa (soft rush straw). The Kozukahara rubble fire originated from an area where tatamis were accumulated and broken into wood chips.

Measurements were also performed on samples to which distilled water was added (20% of the sample mass) to examine the effect of moisture.

In addition, samples were subjected to a 17 h sterilization treatment using ethylene oxide gas (EOG) to ascertain the effects of fermentation. EOG is widely used to sterilize medical devices and precision machinery and to kill all microorganisms.

Table 1 Details of the rubble fires that occurred in Miyagi prefecture

Number	Occurrence	Fire extinguished	Location	Damage situation
No.1	16 September 2011 7:39 a.m.	20 September 2011 4:40 a.m.	Yuriage outdoor rubble storage areas Natori City, Miyagi prefecture	Burned quantity : ~18000m^3 Burned area : ~1200 m^2
No.2	19 September 2011 3:06 a.m.	22 September 2011 12:26 a.m.	Yuriage outdoor rubble storage areas Natori City, Miyagi prefecture	Burned quantity : ~3000m^3 Burned area : ~300 m^2
No.3	22 September 2011 3:06 a.m.	22 September 2011 11:35 a.m.	Kozukahara outdoor rubble storage areas Natori City, Miyagi prefecture	Burned quantity : ~800m^3 Burned area : ~100 m^2

Fig 1. Yuriage rotten tatami

Fig 2. Yuriage wood chip

Fig 3. Kozukahara rotten tatami

Fig 4. Kozukahara tatami

Calorimetry

A Calvet calorimeter (Setaram C80, France) was used for additional thermal testing. The C80 is a twin-type highly sensitive heat-flux calorimeter. It can reduce the effects of the vaporization of water contained in the sample by using a high-pressure closed vessel (8 mL) and can take measurements from room temperature up to 100°C. The temperature of an approximately 1500 mg sample in the sealed vessel was increased at a rate of 0.1 K/min up to 300°C.

Highly sensitive isothermal calorimeter

To examine the micro heat generation from the fermentation and oxidization of fatty acid ether in detail, measurements were conducted using a highly sensitive isothermal calorimeter (Thermometric TAM-III Sweden). TAM can measure the amount of heat generated by microbial fermentation at nanoscale. A sample of approximately1000 mg was placed in a sealed container (4 mL) and was maintained at 50°C for two days.

Gas chromatography

To study the gas emission during storage, approximately 50 g were placed in a 1 L glass bottle that was sealed airtight and placed in a thermostatically controlled oven. The produced gas was collected (Fig 5) and measured by gas chromatography (Shimadzu, GC-14B) using a standard gas (CO: 0.0500%, C2H6: 0.995%, H2: 0.097%, CO2: 0.996%, CH4: 0.987%) for calibration and a thermal conductivity detector (TCD, 200 °C, sensitivity was 50 mA, carrier gas was Ar at 20 ml/min). The column temperature was ranged from 40 °C (6 min hold) to 80 °C (12 min hold) to 150 °C (10 min hold) and changed at a rate of 40 °C/min. Moreover, an air cylinder (O2: 21 %, N2: 79 %) was used as the standard gas for measurement of O2 and N2. For these measurements, we used a TCD (200 °C,
20 ml/min Ar carrier gas, 30 mA sensitivity) with the isothermal column temperature maintained at 30 °C.

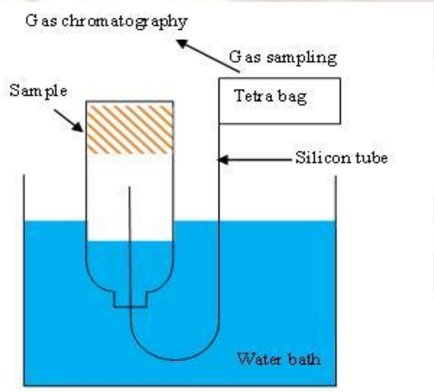

Fig 5. Schematic of gas chromatography measuring device.

IV. RESULTS AND DISCUSSION

Calorimetry

Fig 6–9 shown the C80 measurement results, where the data were collected with a scanning rate of 0.1 K/min. In addition, the heat-generation-onset temperature and the total heat generated between 25°C and 80°C is summarised in Table 2. When a shift was detected in the exothermic direction after the start of the measurements, the temperature at the beginning of the heat generation process was marked as the initial temperature. Immediately after the start of the measurements, fermentation was followed by heat generation.

This process was observed in the rotten tatami from Yuriage and Kozukahara, and also in the wood chips from Yuriage. Moreover, in all these samples, heat generation was observed in the fatty acid ester in the temperature range from 80°C to 100°C, and was caused by the oxidative decomposition at temperatures higher than 100°C. Furthermore, rotten tatami generates more heat and is considered to be a greater fire risk than wood chips.

The process of heat generation that leads to the combustion of these items begins with a small amount of heat generated from fermentation as a result of microbial activity. Next the oxidation of the fatty acid ester contained in these items begins with gradual rise in temperature, even if the microorganisms die, and the temperature continues to rise and ultimately results in combustion. Monitoring the internal temperature of large piles of rubble is one method to forecast fires occurrence in such piles.

On the basis of the C80 results, it is desirable to incorporate the following safety measures. First, if the internal temperature of a rubble pile is between 30°C and 50°C, fermentation begins and only a small amount of heat is generated, thus gradually breaking down the pile. A heat dissipation treatment at this stage lowers the possibility of an increase in temperature that may lead to combustion. Second, if the internal temperature of the rubble pile is between 50°C and 80°C, fermentation and oxidation of the fatty acid ester and materials produced by fermentation occurs. Thermal storage is already in progress at this stage and immediate treatment is required.

At this stage, the breaking down of the pile increases the oxygen supply to the area of thermal storage, thus rapidly increasing the temperature and the possibility of combustion. Accordingly, it is desirable to cover the pile with sand and cool the pile with water, if necessary.

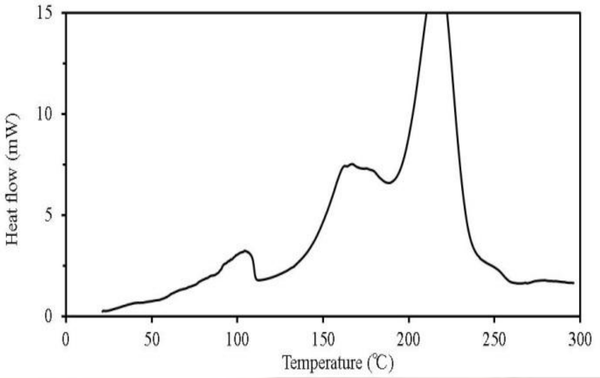

Fig 6. C80 results of Yuriage rotten tatami

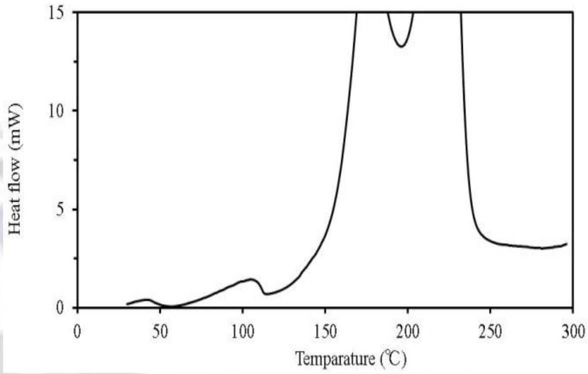

Fig 7. C80 results of Yuriage wood chip

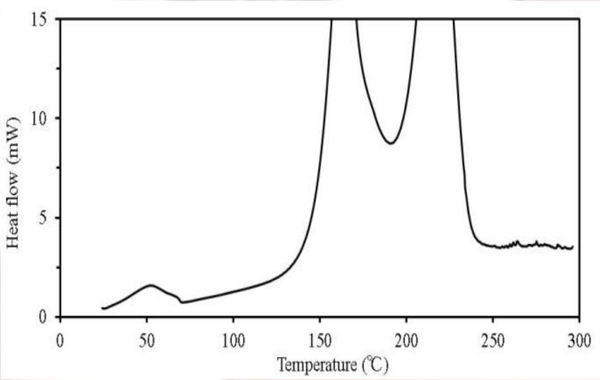

Fig 8. C80 results of Kozukahara rotten tatami

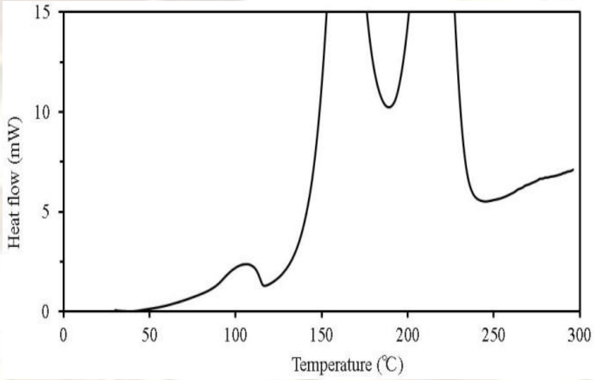

Fig 9. C80 results of Kozukahara tatami

Table 2. Heat generation onset temperature and total heat generated (room temperature to 80°C)

Sample	Heat generation onset temperature (℃)	Total heat generation (J/g) Room temperature to 80℃
Yuriage rotten tatami	29.0	10.0
Yuriage wood chips	29.4	1.5
Kozukahara rotten tatami	25.5	9.4
Kozukahara Tatami	-	≒0

Highly sensitive isothermal calorimeter

The TAM results are shown in Fig 10–13 (untreated samples) and Fig 14–17 (EOG-treated samples). The amount of heat generated is summarized in Table 3 (untreated samples) and Table 4 (EOG-treated samples). The heat generation data are summarized for 0–24 h, 24–48 h and for a combination of both periods. The TAM holding temperature was set to 50°C because microbial activity is active in this temperature range and gradually becomes inactive at higher temperatures.[4]-[5]

Looking at the thermal behaviour of the Kozukahara rotten tatami, heat generation tends to begin immediately after the start of the measurements and rapidly increases after a few hours of observation. This is thought to happen because the activity of the microorganisms increases over time. Furthermore, the oxygen in the sealed sample container is consumed as a result of the rapid fermentation and heat generation ceases. The results showed that heat generation ceased if oxygen was low; therefore, it is highly likely that the fermentation is aerobic. A greater amount of heat was generated in the moist samples, than in the as-is samples. A decrease in the exothermic peak within 12 h after the start of the measurements was observed in the EOG-treated samples. Furthermore, fermentation is thought to have a major impact on the temperature rise. The results from the samples with added moisture suggest that even if there has been an extinguished fire, fermentation may occur as a consequence of the water used to extinguish the fire and fire recurrence may follow thermal storage if there are items prone to fermentation near the water-treated area. Therefore, it is necessary to continue monitoring the area where fires originate, and it is desirable to prioritize the sorting and disposal of rubble, in which fermentation is possible near water-treated areas.

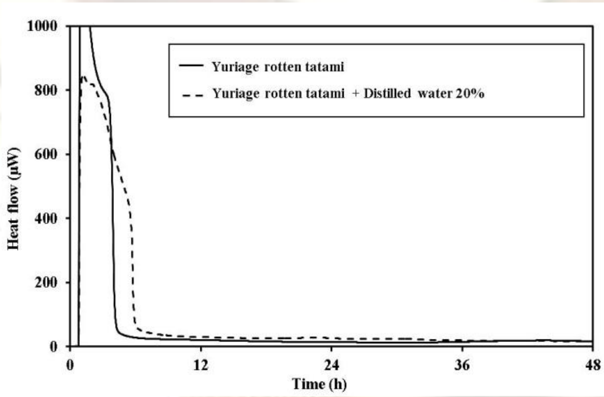

Fig 10. TAM results of Yuriage rotten tatami (untreated samples)

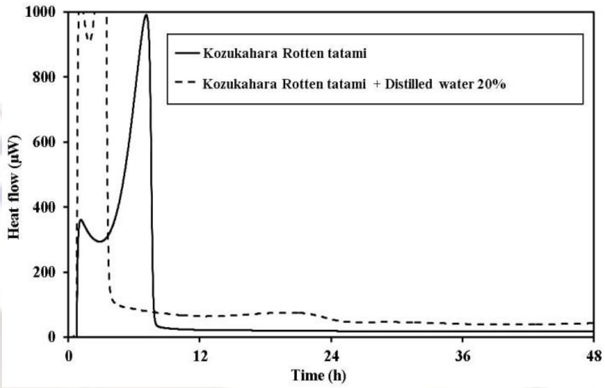

Fig 11. TAM results of Yuriage wood chip (untreated samples)

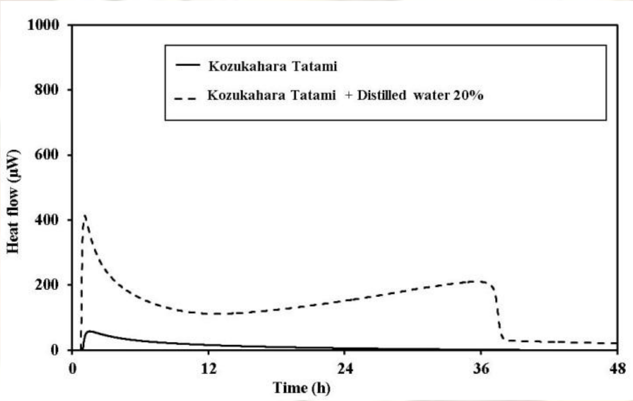

Fig 12. TAM results of Kozukahara rotten tatami (untreated samples)

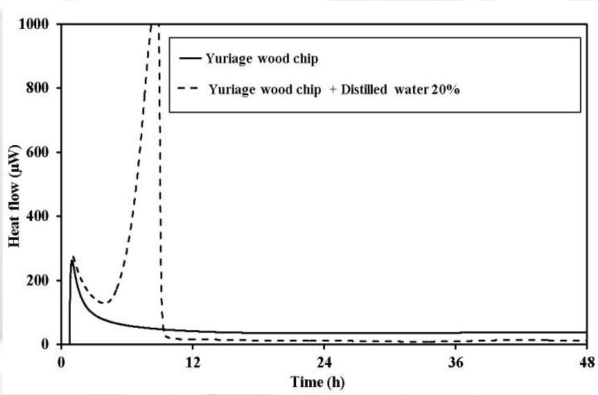

Fig 12. TAM results of Kozukahara rotten tatami (untreated samples)

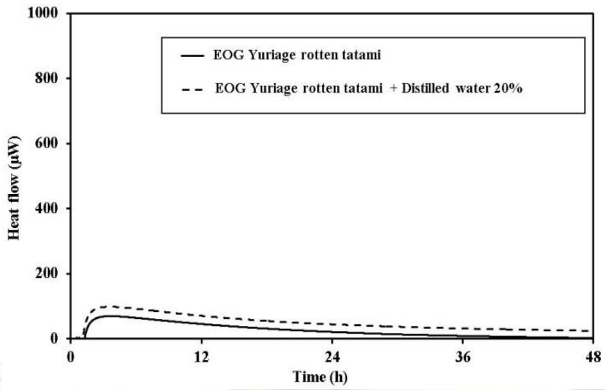

Fig 14. TAM results of Yuriage rotten tatami (EOG-treated samples)

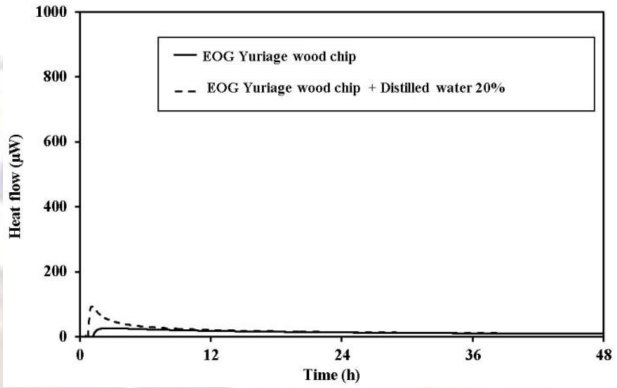

Fig 15. TAM results of Yuriage wood chip (EOG-treated samples)

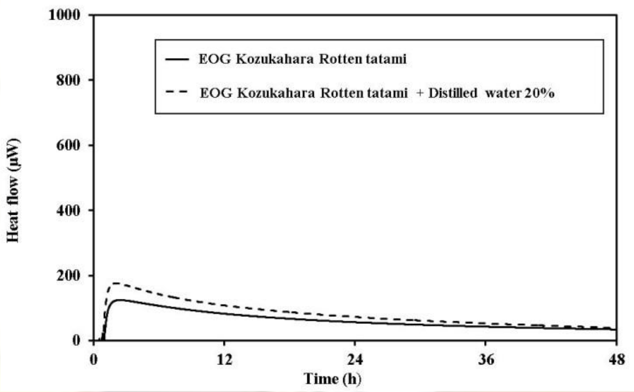

Fig 16. TAM results of Kozukahara rotten tatami (EOG-treated samples)

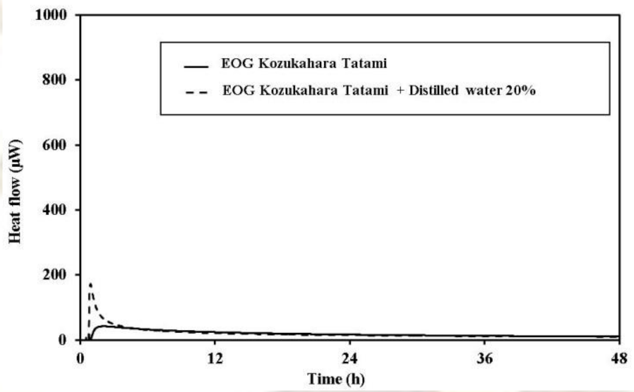

Fig 17. TAM results of Kozukahara tatami (EOG-treated samples)

Table 3. Heat generation at 50 ºC (untreated samples)

Sample	Heat generation (J/g) 0-24h	Heat generation (J/g) 24-48h	Heat generation (J/g) 0-48h
Yuriage rotten tatami	11.59	1.32	12.91
Yuriage rotten tatami +Distilled water 20%	13.88	1.76	15.64
Yuriage wood chip	4.76	3.15	7.91
Yuriage wood chip + Distilled water 20%	12.28	1.01	13.29
Kozukahara rotten tatami	13.76	1.56	15.32
Kozukahara rotten tatami + Distilled water 20%	16.31	3.71	20.02
Kozukahara tatami	2.13	1.08	3.21
Kozukahara tatami + Distilled water 20%	13.18	9.71	22.89

Table 4. Heat generation at 50 °C (EOG-treated samples)

Sample	Heat generation (J/g) 0-24h	Heat generation (J/g) 24-48h	Heat generation (J/g) 0-48h
EOG Yuriage rotten tatami	3.68	0.81	4.49
EOG Yuriage rotten tatami +Distilled water 20%	5.84	2.76	8.60
EOG Yuriage wood chip	1.59	0.95	2.54
EOG Yuriage wood chip + Distilled water 20%	2.28	1.04	3.32
EOG Kozukahara rotten tatami	7.14	3.74	10.88
EOG Kozukahara rotten tatami + Distilled water 20%	9.52	4.65	14.17
EOG Kozukahara tatami	1.69	0.28	1.97
EOG Kozukahara tatami + Distilled water 20%	2.42	1.03	3.45

Table 5. GC results for untreated samples (25°C)

Sample	GC analysis resaults (%)					
	O_2	N_2	H_2	CO	CH_4	CO_2
Yuriage rotten tatami	1.49	73.26	1.12	-	-	18.45
Yuriage rotten tatami +Distilled water 20%	1.55	69.62	0.029	-	-	22.78
Yuriage wood chips	5.34	77.79	-	-	-	12.11
Yuriage wood chips +Distilled water 20%	1.47	78.53	0.084	-	-	14.41
Kozukahara rotten tatami	1.75	77.43	0.082	-	0.063	17.32
Kozukahara rotten tatami +Distilled water 20%	0.98	72.81	0.10	-	0.079	20.19
Kozukahara Tatami	19.23	77.98	-	-	-	0.12
Kozukahara tatami +Distilled water 20%	13.59	77.55	0.021	-	-	5.52

Gas chromatography

The GC analysis results are shown in Table 5 (untreated samples) and Table 6 (EOG-treated samples). Based on the results of the untreated samples, we observe the generation of large amounts of carbon dioxide in the Yuriage rotten tatami, Yuriage wood chips and Kozukahara rotten tatami. In addition, the generation of hydrogen was observed in all untreated samples to which water was added.

We observed a significant reduction in the amount of generated carbon dioxide as well as the absence of hydrogen and methane generation in the measurements of the EOG-treated samples. Therefore, the reason for the generation of hydrogen and methane is likely because of anaerobic and aerobic fermentation. Considering these results in combination with the results of thermal analysis, the wood chips and rotten tatami are thought to have moderate amounts of moisture that facilitates fermentation.

The Kozukahara tatami contains less moisture and even if the tatami contains microorganisms, there is not enough moisture for microbial activity to occur. Therefore, fermentation is very unlikely to take place in Kozukahara tatami under normal conditions. However, if the moisture increases, it is believed that fermentation may occur even in non-rotten tatami; thus,

increasing the temperature and leading to spontaneous ignition.

There are cases where the waste in raw garbage processors has produced flammable gas and explosions after being burned in an airtight environment.[6] There have also been cases where waste stored in a warehouse has fermented, consuming the surrounding oxygen and producing large amounts of carbon dioxide that resulted in anoxic warehouse conditions causing hypoxia symptoms to on-site workers who subsequently died.[7]

Although flammable gas and carbon dioxide are produced in outdoor rubble storage areas, the concentration of these gases decreases as they disperse into the atmosphere, and the accompanying risks are not so high. However, it may be necessary to pay attention to fire, explosion and hypoxia when transporting and storing rubble in airtight containers. In addition, it is desirable to carry out temperature monitoring and gas detection.

Table 6. GC results for EOG-treated samples (25°C)

Sample	GC analysis resaults (%)					
	O_2	N_2	H_2	CO	CH_4	CO_2
EOG Yuriage rotten tatami	19.85	77.65	-	-	-	0.05
EOG Yuriage rotten tatami +Distilled water 20%	19.47	76.97	-	-	-	0.51
EOG Yuriage wood chips	20.30	77.63	-	-	-	0.05
EOG Yuriage wood chips +Distilled water 20%	20.29	76.68	-	-	-	0.36
EOG Kozukahara rotten tatami	19.02	77.86	-	-	-	0.08
EOG Kozukahara rotten tatami +Distilled water 20%	18.39	77.75	-	-	-	0.86
EOG Kozukahara Tatami	19.85	77.02	-	-	-	0.05
EOG Kozukahara tatami +Distilled water 20%	19.65	76.54	-	-	-	0.12

V. CONCLUSIONS

Based on the experimental results, the following conclusions were obtained.

1) Heat generation from rotten tatami and wood chips are considered to be the result of fermentation that was observed immediately after the start of measurements in the C80 measurement results. Heat generation may trigger thermal storage. The process leading to fire in rubble, in which fermentation is possible, begins with heat generation caused by microbial activity. It is thought that oxidation of fatty acid esters contained in the rubble begins to occur under adiabatic conditions resulting in further rise in temperature after which the thermal decomposition of the cellulose contained in the rubble begins, ultimately leading to combustion.

2) As seen from the results of the TAM measurements, all rubble samples with added moisture generated more heat as a consequence of the additional moisture. Therefore, it is believed that items with moderate moisture content are prone to fermentation and generate heat more easily.

Therefore, particular attention must be paid to fire during seasons with periods of repeated rainfall and warm weather. In addition, even if there has been a fire which has been and extinguished, fermentation may occur as a consequence of the added water used to treat the fire and fire recurrence may follow thermal storage if there are items prone to fermentation near the water-treated area. Therefore, it is necessary to continue monitoring the area where a fire had originated.

3) The generation of large amounts of carbon dioxide from wood chips and rotten tatami was observed in the GC data. In addition, the generation of hydrogen was observed in all samples to which water was added. Therefore, it is thought that anaerobic fermentation accompanied by the generation of flammable gas occurs in addition to aerobic fermentation that generates a high volume of heat. It is thought that it will become necessary to pay attention to fires and explosions when transporting and storing rubble in airtight containers in the future.

4) It is desirable for rubble piles to be broken down as often as possible and not leave them in a piled state for prolonged periods. A thermocouple should be inserted through the hole of the pipe to monitor the internal temperature and the generated gases at the time the pipe is driven into the pile for the purpose of heat dissipation. Rubble should be sorted as per types prone to fermentation, etc., and these types of rubble should be disposed of first. In addition, it is desirable for the slopes of rubble piles to be covered with sand and steel plates to stop the inflow of air and prevent fermentation.

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