Research on Combustion Properties and Pollutant Emission Characteristics of Blends of Maltol Byproduct/Pine Sawdust

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ABSTRACT: In this paper, the combustion and pollutant emission characteristics of maltol byproduct, pine sawdust, and their blends were experimentally studied by thermogravimetry, tube furnace experiment, and scanning electron microscopy. The results show that the combustion process of maltol byproduct, pine sawdust, and their blends can be divided into three stages, in which the volatile release of the maltol byproduct includes two stages. The ignition temperature of the blended fuel is lower than that of sawdust. The NO\textsubscript{x} produced by combustion of the blended fuel is lower than that produced by sawdust combustion alone, and the SO\textsubscript{2} emission is always at a low level. There is a certain synergy between maltol byproduct and pine sawdust mixed combustion. Comprehensively comparing the combustion characteristics and emission characteristics, the blended fuel made by adding less than 10% maltol byproduct into pine sawdust can improve the combustion characteristics and reduce emissions, and 10% is the best proportion of the blended fuel.

1. INTRODUCTION

Ethyl maltol is a commonly used food additive in daily life. It is also widely used in the food processing industry. However, its production process produces an asphaltic maltol byproduct, which can result in a few benzenes and alkanes; moreover, the harm to the human body is far less than that by asphalt. Therefore, it is not classified as hazardous waste and can be burnt directly. The byproduct has a large output, good rheology, water impermeability, and viscoelastic characteristics. Moreover, the fuel is a complex polymer material composed of carbon, hydrogen, and other elements and has a high calorific value; thus, it can be added to various fuels as a combustion aid.\textsuperscript{1} However, given that the maltol byproduct contains nitrogen, sulfur, and other elements, the combustion process produces pollutants, such as NO\textsubscript{x} and SO\textsubscript{2}, and causes serious environmental pollution. Therefore, the maltol byproduct has a broad development prospect to reduce energy consumption and emission using combustion reduction as a resource.\textsuperscript{2–4}

At present, studies on the combustion and pollutant emission characteristics of maltol byproduct fuels are few. Nevertheless, the similarity between these fuels and asphalt is high; thus, the combustion characteristics of asphalt can be used as a reference. Wu et al. used infrared spectroscopy to quantitatively analyze the release law of gaseous products caused by asphalt in the combustion reaction at high heating rates. The results showed that the content of active volatile components in asphalt materials is a key factor affecting the release of combustible gaseous products.\textsuperscript{5} Zhu et al. used a thermogravimetric Fourier transform infrared spectroscopy experiment to analyze the weight loss process of asphalt combustion at different heating rates and found that the maximum weight loss rate and infrared absorption peak intensity changed slightly with the heating rate.\textsuperscript{6} Xia et al. discussed the thermal behavior of asphalt components and volatile components, as well as the microstructure of combustion residues. The results showed that the thermogravimetry (TG), derivative TG (DTG), and Gram–Schmidt curves showed a two-stage feature, and the total ion chromatography result showed a one-stage feature.\textsuperscript{7} Xu et al. used a thermogravimetric analyzer and a Fourier transform infrared spectrometer to study the combustion mechanism of asphalt binders in a mixed gas environment containing 21% oxygen and 79% nitrogen. The results showed that the combustion process of the asphalt binder consisted of three main continuous stages; furthermore, the heating rate was low, and the combustion reaction became increasingly intense from the first stage to the third stage.\textsuperscript{8} Shi et al. discussed the combustion characteristics of each component and the dynamic evolution of volatiles released. They also analyzed the form of combustion residues and found that the dynamic evolution and composition of the released volatiles of each component vary. CO\textsubscript{2} and H\textsubscript{2}O are the most important
combustion products of the four components. Under the conditions of different temperatures, different mixture ratios of asphalt flue gas, natural gas, and different catalysts were found.9 Liu et al. used the combustion method to treat the flue gas produced in asphalt melting. They found that the best conditions for asphalt flue gas treatment were a flow ratio of natural gas to asphalt flue gas of 2.3:1 and a temperature of combustion furnace of approximately 510 °C.10 Xia et al. monitored the mass loss evolution of asphalt and tracked the direction of the main elements in the combustion process of asphalt using thermal gravimetry mass spectrometry and Fourier transform infrared spectroscopy. They found that the combustion residues are relatively complete, mainly containing C, O, and S elements.11 Wu et al. used the Popescu method to analyze the kinetics of the asphalt combustion process and found that the three stages of asphalt combustion can be explained by the spherical boundary reaction model, the second-order chemical reaction model, the nucleation model, and the subsequent growth model.12 Research on the maltol byproduct mixed asphalt using thermal gravimetry mass spectrometry and Fourier transform infrared spectroscopy. They found that the three stages of asphalt combustion can be explained by the spherical boundary reaction model, the second-order chemical reaction model, the nucleation model, and the subsequent growth model.13 Research on the maltol byproduct mixed asphalt using thermal gravimetry mass spectrometry and Fourier transform infrared spectroscopy. 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2. EXPERIMENTAL MATERIALS AND METHODS

2.1. Experimental Materials. Table 1 shows the material collection locations. The industrial and elemental analysis results of the maltol byproduct and pine sawdust are shown in Table 2. As shown in Table 2, the maltol byproduct and the volatile content of pine sawdust were significantly higher than the fixed carbon content; the ash content of pine sawdust was 0.40%, which is lower than that of the maltol byproduct, and the low calorific value of pine sawdust was significantly lower than that of the maltol byproduct.

During the sample preparation process, the maltol byproduct and pine sawdust were dried and ground into powder separately. Then they were placed in a drying oven at 70 °C for 48 h and stored for use. Because the material will be damped during storage before incense production, this storage step is to simulate the real production process. The maltol byproduct was mixed with pine sawdust at different mass percentages (0, 5, 10, 15, and 20%) and stirred for 3 h with a micromixer to ensure uniform mixing.

2.2. Experimental Methods. The sample was thermogravimetrically analyzed using a German Netzsch STA-409PC thermobalance and was heated from room temperature to 1000 °C at a heating rate of 20 °C/min.21–23 In each experiment, approximately 10 mg of the sample was taken, the combustion atmosphere was air, and the flow rate was 100 mL/min.

A GASMET DX4000 flue gas analyzer was used to detect the combustion pollutant emission, and the tube furnace was heated from room temperature to the target temperature of 1000 °C. Half a gram of the sample was weighed and placed into a quartz boat and pushed into the constant temperature zone of the tubular furnace. The air-flow rate was set to 1 L/min, and each test lasted for approximately 20 min.

Figure 1 shows the tube furnace experimental system, which is mainly composed of (1) the gas circuit part, (2) the combustion part, (3) the drying part, and (4) the flue gas monitoring part.

Fuel ash characterization was observed using a Gemini-SEM500 field emission scanning electron microscope, and the pollutant emission change rule was studied and verified.24

![Image](https://doi.org/10.1021/acsomega.1c04703)

**Figure 1.** Pipe furnace experimental system.

### Table 1. Material Collection Sites

| sample           | collecting sites   | collecting time |
|------------------|--------------------|-----------------|
| pine sawdust     | Jilin, Jilin province | 2019.8          |
| maltol byproduct | Shizuishan, Ningxia province | 2020.9         |

### Table 2. Proximate and Ultimate Analysis

| sample           | proximate analysis (%) | ultimate analysis (%) | Qnet,ar (MJ/kg) |
|------------------|------------------------|-----------------------|-----------------|
|                  | A_d        | V_d         | M_d         | FC_d       | C     | H     | O     | N     | S     | Qnet,ar |
| pine sawdust     | 0.40      | 79.60       | 6.00        | 17.00      | 51.00  | 6.00  | 39.41 | 0.08  | 0.00  | 19.05   |
| maltol byproduct | 0.91      | 64.97       | 5.09        | 29.03      | 61.51  | 4.19  | 32.07 | 1.00  | 0.32  | 25.38   |

*a_d—Air-dried basis; A—Ash; V—Volatile matter; M—Moisture; FC—Fixed carbon; Qnet,ar—Net calorific value of received basis.*
3. THERMOGRAVIMETRIC RESULT ANALYSIS AND DISCUSSION

3.1. Separate Combustion Process of the Maltol Byproduct. Figure 2 shows the TG and DTG curves when the maltol byproduct is burnt alone. The corresponding temperature ranges for the dehydration and drying stage, the first volatilization analysis and combustion stage, and the second volatilization analysis combined with the coke combustion stage during the combustion process of the maltol byproduct are as follows: 45−80, 180−340, and 420−630 °C. The ignition temperature is 247.6 °C and the burnout temperature is 583.5 °C. From the DTG curve of the maltol byproduct in Figure 2, the maltol byproduct has an evident water loss peak at around 45−100 °C, the water loss rate slowly decreased to approximately 100 °C, and the water analysis phase basically ended. The second weight-loss peak of the maltol byproduct was caused by a large amount of volatilization and combustion. The reaction temperature range was narrow, and the weight loss reached approximately 30%. The weight loss range and the rate of the third weight-loss peak were greater than those of the second weight-loss peak, with a weight loss of approximately 45%. The weight loss at this stage was mainly due to the precipitation and combustion of the secondary volatiles, accompanied by the combustion of coke. Therefore, the combustion of volatiles and coke at this stage formed the third weight-loss peak, and then the TG curve tended to be stable and the DTG curve gradually returned to zero, suggesting the end of the combustion process.

3.2. Separate Combustion Process of Pine Sawdust. Figure 3 shows the TG and DTG curves when pine sawdust was burnt alone. The corresponding temperature ranges of the dehydration and drying stage, the volatilization analysis and combustion stage, and the coke combustion stage during the combustion process of pine sawdust are as follows: 40−130, 200−420, and 430−520 °C. The ignition temperature is 338.4 °C and the burnout temperature is 489.3 °C. From the DTG curve of pine sawdust, a water loss peak in the sludge was observed at approximately 40−130 °C, and at approximately 130 °C, the water analysis phase basically ended. The second weight-loss peak was also mainly caused by the precipitation and combustion of volatiles; the corresponding temperature range was narrow, but the weight loss can reach more than 60%. The third weight-loss peak was mainly caused by the combustion of coke, the peak strength was weaker than that of the second weight-loss peak, and the corresponding temperature range increased, with a weight loss of approximately 15%. Then, the TG curve tended to be stable, and the DTG curve gradually returned to zero, indicating the end of the combustion process.

3.3. Comparative Analysis of the Mixed Fuel Combustion Process. Figure 4 shows the TG and DTG curves when the maltol byproduct was burnt with pine sawdust at different proportions. The amount of the maltol byproduct in panel (a) is 5%, that in panel (b) is 10%, that in panel (c) is 15%, and that in panel (d) is 20%. The figures show that the different mixing ratios of the maltol byproduct had no effect on the differentiation of the combustion stage. The combustion process was still divided into three stages: dehydration and drying, volatilization and combustion, and coke combustion.

Figure 5 shows the DTG curves of pine sawdust burnt alone and mixed fuel combustion in four different ratio configurations.

Analyzing Figure 5 reveals that the dehydration rate and the amount of dehydration decreased with the increase in the mixing proportion of the maltol byproduct, indicating that as the maltol byproduct addition increased, the degree of fuel moisture decreased, that is, it is harder to make the fuel damp and it becomes more hydrophobic. Analyzing the precipitated burnt section of volatiles reveals that as the proportion of the maltol byproduct increased, the precipitate quantity gradually decreased, and the precipitation rate of mixed fuels was lower than that of pine sawdust alone, indicating that the addition of the maltol byproduct inhibited the precipitation of volatiles to a certain extent, and increased with the increase of the proportion of maltol byproduct. The mixed fuel and pine sawdust in the coke combustion stage were almost the same, indicating that the coke in the mixed fuel was mainly pine sawdust coke.

Ignition temperature is an important factor for measuring fuel combustion. The analysis in Table 3 shows that with the increase in the proportion of maltol byproduct, the ignition temperature $T_i$ did not change much. However, the ignition temperature of the mixed fuel was lower than that of pine sawdust alone, indicating that the addition of the maltol byproduct improved the ignition characteristics. At the same time, the high volatile content of pine sawdust can reduce the burnout temperature of the maltol byproduct and improve its burnout characteristics.25−27
The combustion characteristic index $S$ can measure the comprehensive characteristics of fuel ignition and burnout. The larger the $S$, the better the fuel combustion characteristics. The fuel combustion characteristic index was calculated by the following formula

$$S = \frac{(dw/dt)_{\text{max}} \cdot (dw/dt)_{\text{mean}}}{T_i \cdot T_e}$$

(1)

where $T_i$ is the ignition temperature, °C; $T_e$ is the burnout temperature, °C; $(dw/dt)_{\text{max}}$ is the maximum burning rate, %·min$^{-1}$; and $(dw/dt)_{\text{mean}}$ is the average burning rate, %·min$^{-1}$.

Table 3 shows that with the increase in the amount of the maltol byproduct, the ignition temperature of the mixed fuel was significantly lower than that of the pine sawdust, which improved the ignition characteristics of pine sawdust, but the ignition temperature of the four mixed fuels did not change remarkably; the addition of pine sawdust also lowered the burnout temperature of the mixed fuel significantly than that of the maltol byproduct and improved the burnout characteristics of the maltol byproduct; however, the burnout temperature difference between the mixed fuels was not evident. Analyzing the combustion characteristic index reveals that the addition of pine sawdust increased the combustion characteristic index of the maltol byproduct to a certain extent, and as the proportion of the maltol byproduct increased, the index decreased significantly. A significant synergistic effect was found between the maltol byproduct and pine sawdust.

The above analysis reveals that the addition of the maltol byproduct reduced the water content of the fuel and the ignition temperature of the mixed fuel and improved the combustion process of pine sawdust. The addition of pine sawdust improved the combustion characteristic index and the

Figure 4. TG and DTG analysis of mixed fuels.

Figure 5. DTG comparison.
Table 3. Characteristic Combustion Parameters of Different Blended Fuels\textsuperscript{a}

| Combustion characteristic parameters | Pine sawdust | Maltol byproduct | 5\% maltol byproduct | 10\% maltol byproduct | 15\% maltol byproduct | 20\% maltol byproduct |
|--------------------------------------|--------------|------------------|----------------------|-----------------------|-----------------------|-----------------------|
| \( T_i /{^\circ}C \)                  | 338.4        | 247.6            | 334.1                | 332.2                 | 329.8                 | 328.5                 |
| \( T_f /{^\circ}C \)                  | 489.3        | 583.5            | 493.4                | 500.9                 | 508.3                 | 513.5                 |
| \( \tau /s \)                         | 47.0         | 56.4             | 47.4                 | 47.9                  | 48.8                  | 49.5                  |
| \((dw/dt)_{\text{max}} /{(\% \cdot \text{min}^{-1})}\) | 60.3         | 11.3             | 46.8                 | 38.7                  | 31.6                  | 26.3                  |
| \((dw/dt)_{\text{mean}} /{(\% \cdot \text{min}^{-1})}\) | 7.36         | 5.23             | 7.03                 | 6.76                  | 6.23                  | 5.98                  |
| \( S /{(\% \cdot \text{min}^{-1} \cdot {^\circ}C^{-2}) \times 10^{-8}} \) | 7.92         | 1.65             | 5.97                 | 4.73                  | 3.56                  | 2.84                  |

\textsuperscript{a}\( T_i \)--Ignition temperature, \(^\circ\)C; \( T_f \)--Burnout temperature, \(^\circ\)C; \((dw/dt)_{\text{max}}\)--Maximum burning rate, \(\% \cdot \text{min}^{-1}\); \((dw/dt)_{\text{mean}}\)--Average burning rate, \(\% \cdot \text{min}^{-1}\); \( \tau \)--Burnout time, s; \( S \)--Combustion characteristic index.

quantity of precipitated volatiles of the maltol byproduct fuel and reduced the burnout temperature. As the proportion of the maltol byproduct increased, the burnout time gradually increased. When the maltol byproduct ratio was 10\%, the combustion characteristic index was about half that of pine sawdust, and the burnout time was 0.9 s longer than that of pine sawdust. When blended at 15\%, the combustion characteristic index dropped to less than half of pine sawdust, and the burnout time was increased by 1.8 s compared with pine sawdust. The burnout time was prolonged significantly, but the combustion effect was not ideal, and the economy of making mosquito repellent incense should also be taken into account. The mixing ratio of the maltol byproduct is recommended to be less than 10\%.

4. POLLUTANT DISCHARGE ANALYSIS AND DISCUSSION

4.1. Effect of the Maltol Byproduct Ratio on CO Emissions. Figure 6 shows the change of CO emissions from the combustion of different fuel mixtures. The combustion of the maltol byproduct alone produced a higher amount of CO, whereas the CO emission was low when pine sawdust was burnt alone, and the combustion was more thorough. As the proportion of the maltol byproduct increased, CO emission increased significantly. The incorporation of the maltol byproduct inhibited the diffusion of oxygen, and the reaction produced a large amount of CO and reacted with oxygen, which reduced the reaction rate of the volatiles generated by the pyrolysis of sawdust cellulose with the surrounding oxygen. Therefore, the maximum combustion rate of the volatile section decreased considerably with the increase in the ratio, and the burnout effect of the fuel also became worse.

4.2. Effect of the Maltol Byproduct Ratio on NO\textsubscript{x} Emissions. Figure 7 shows that with the increase in the proportion of the maltol byproduct, the amount of NO\textsubscript{x} emitted by fuel combustion decreased, which is not significant; however, it is much lower than the emission of NO\textsubscript{x} when pine sawdust was burned. The reasons are mainly divided into two aspects: (1) the incorporation of the maltol byproduct reduced the binding rate of pine sawdust volatiles with the surrounding air and inhibited the production of NO\textsubscript{x} and (2) the large amount of CO generated during combustion had a reduction effect on NO\textsubscript{x} thus inhibiting the production of NO\textsubscript{x}. The co-combustion of the maltol byproduct and pine sawdust had a synergistic effect, which can significantly inhibit NO\textsubscript{x} emission and reduce pollution.

4.3. Effect of the Maltol Byproduct Ratio on SO\textsubscript{2} Emission. SO\textsubscript{2} emission mainly depends on the S content in the fuel. Table 1 shows that the S content in the maltol byproduct and biomass was extremely low; thus, the amount of SO\textsubscript{2} emission from combustion was also small. As shown in Figure 8, the SO\textsubscript{2} emission from mixed fuel combustion increased slightly with the increase in the proportion of the maltol byproduct, with little difference from the SO\textsubscript{2} emission when pine sawdust was burnt alone. Nevertheless, it was significantly better than the case of burning the maltol byproduct alone. Among the four mixed fuels, the effect of mixed fuels below 10\% was slightly better.
4.4. Gray Microanalysis. First, through SEM analysis, the emission reduction mechanism of blended fuels was understood from a micro perspective and the low emission characteristics of four kinds of blended fuels were explained. Figure 9a shows the pine sawdust ash surface map, and the dotted line marks the ash pores; b is the internal cross-sectional view after pine sawdust ash particles were broken, and the dashed line indicates the cross-sectional part. The surface of the ash particle was rough with some pores, and the cross section of the ash was rough and irregular.

Figure 10 shows that the structure of the maltol byproduct was relatively closed and compact, and no pores were detected. In Figure 10b, the cross section of the maltol byproduct ash particles was fibrous streaks.

Figure 11 shows the SEM image of the surface of the mixed fuel, where the mixing rate of the maltol byproduct in panel (a) is 5%, in panel (b) is 10%, in panel (c) is 15%, and in panel (d) is 20%. The figure also shows that the ash surface of the four mixed fuels was dense, with some fine ash particles attached, and no evident pores; these characteristics were similar to that of the maltol byproduct ash.

Figure 12a−d represents the ash cross-sectional view when the maltol byproduct was 5, 10, 15, and 20%, respectively, and the dashed line is the ash boundary. Dividing lines were evident in the ash cross section of the four mixed fuels. The ash outside the dividing line had a regular structure, which was the ash of the maltol byproduct; the structure inside the dividing line had no evident regularity, including mainly SiO₂, which was pine sawdust ash. The SEM cross-sectional image shows that the ash content of pine sawdust was covered by the maltol byproduct ash, and the particle surface was dense without pores, indicating a significant synergistic effect between the combustion of the maltol byproduct and pine sawdust mixed fuel. Maltol byproduct ash covered the surface of pine sawdust ash, reducing the emission of pollutant gases from pine sawdust. However, the addition of too much maltol byproduct inhibited the burning of pine sawdust and reduced its contact area with air, and the covering phenomenon prevented the burning of pine sawdust and coke.

In summary, the SEM analysis results show that the mixed fuel can not only reduce the emission of NOₓ but also reduce the emission of SO₂, which can save energy and protect the environment.

In addition, through X-ray diffraction (XRD) analysis, the ash composition was determined, and the reason for ash coverage was further analyzed. Figure 13 shows the XRD spectrum of the gray sample. The ash composition is complicated. The composition of ash formed after the burning of pine sawdust mainly includes SiO₂ and a small amount of CaO and metasilicate, with a higher melting point. The ash products after the combustion of the mixed fuel are mainly Ca₃SiO₅(OH)₂, CaMg(CO₃)₂, and KAlSiO₄ and these low-melting eutectic have high adhesion. Therefore, during the combustion process, the ash content of the maltol byproduct covers the outside of the pine sawdust, thereby reducing the emission of fuel pollutant gas.

The following reactions may occur during the combustion process of the mixed fuel

\[
4\text{CaO} + 3\text{SiO}_2 + \text{H}_2\text{O}(g) = \text{Ca}_2\text{Si}_3\text{O}_5\text{(OH)}_2
\]

\[
\text{CaO} + \text{MgO} + \text{CO}_2 = \text{CaMg(CO}_3)_2
\]

\[
2\text{KCl} + \text{Al}_2\text{O}_3 + 2\text{SiO}_2 + \text{H}_2\text{O}(g) = 2\text{HCl}(g) + 2\text{KAlSiO}_4
\]
5. CONCLUSIONS

In this study, the combustion and emission characteristics of maltol byproduct, pine sawdust, and its mixed fuel were investigated in detail through a thermogravimetric experiment, a tube furnace experiment, scanning electron microscopy, and XRD analysis, and the following conclusions were drawn:

1. As the proportion of the maltol byproduct added to pine sawdust increased, the ignition temperature of the mixed fuel did not change much, but it was significantly lower than that of pine sawdust. Upon increasing the proportion of the maltol byproduct, the fuel burnout temperature and hydrophobicity increased. Adding pine sawdust also increased the volatilization of the maltol byproduct.

2. When the maltol byproduct is added to pine sawdust for combustion, the maltol byproduct can suppress NO\textsubscript{x} emission in pine sawdust; moreover, SO\textsubscript{2} emission was at a low level and the fuel showed a good synergistic effect and improved the combustion process.

3. SEM found that the ash content of the maltol byproduct was wrapped on the ash surface of pine sawdust tightly, thus reducing the emissions of NO\textsubscript{x} and SO\textsubscript{2} of the mixed fuel.

4. In consideration of the combustion and emission characteristics, the maltol byproduct blending ratio is preferred to be less than 10\%. Mixed fuel is a good mixed fuel because it has a synergistic effect, and it can improve combustion conditions and reduce emissions to a great extent.
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Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS
The authors acknowledge the support from the Shaanxi Innovation Talents Promotion Project (NO. 2019KJXX-042) and the Special Technical Support Project of Administration for Market Regulation (Hbscqg,JS202008). Dr. Li is acknowledged for help in the inorganic chemistry part and figure modification in this manuscript.

REFERENCES
(1) Xia, W.; Xu, T.; Wang, H.; et al. Combustion kinetics of asphalt binder components and the release processes of gaseous products. Combust. Flame 2019, 26, 322–333.
(2) Hao, J.; Zhang, J.; Qiao, Y.; et al. Thermal cracking characteristics and kinetics of oil sand bitumen and its SARA fractions by TG-FTIR. Energy Fuels 2017, 31, 1295–1309.

Figure 12. SEM analysis of the mixed fuel ash section.

Figure 13. XRD patterns of the ash samples.
(3) Qiu, J.; Yang, T.; Wang, X.; et al. Review of the flame retardancy on highway tunnel asphalt pavement. Constr. Build. Mater. 2019, 195, 468−482.

(4) Liu, Z.; Quek, K.; Kent, H.; et al. Production of solid biochar fuel from waste biomass by hydrothermal carbonization. Fuel 2013, 103, 943−949.

(5) Wu, K.; Zhu, K.; Huang, Z.; et al. Research on the combustion mechanism of asphalt and the composition of harmful gas based on infrared spectral analysis. Spectrosc. Spectral Anal. 2018, 32, 2089−2094.

(6) Zhu, K.; Wang, Y.; Qin, X.; et al. Effect of heating rate on asphalt combustion and gaseous products release characteristics. J. Zhejiang Univ. 2020, 54, 1805−1811.

(7) Xia, W.; Xu, T.; Wang, S.; et al. Mass loss evolution of bituminous fractions at different heating rates and constituent conformation of emitted volatiles. Energy Sci. Eng. 2019, 76, 2782−2796.

(8) Xu, T.; Huang, X. Study on combustion mechanism of asphalt binder by using TG−FTIR technique. Fuel 2010, 89, 2185−2190.

(9) Shi, H.; Jiang, R.; et al. Combustion mechanism of four components separated from asphalt binder. Fuel 2017, 192, 18−26.

(10) Liu, J. The Technique of asphalt mist treatment by burning. CEOG 2014, 29, 209−213.

(11) Xia, W.; Xu, T.; Wang, H. Thermal behaviors and harmful volatile constituents released from asphalt components at high temperature. J. Hazard. Mater. 2019, 373, 741−752.

(12) Wu, K.; Zhu, K.; Han, J.; et al. Non-isothermal kinetics of styrene-butadiene-styrene asphalt combustion. Chin. Phys. B. 2013, 22, No. 068801.

(13) Mothé, M.; Leite, L.; Mothé, C. Thermal characterization of asphalt mixtures by TG/DTG, DTA and FTIR. J. Therm. Anal. Calorim. 2008, 93, 105−109.

(14) Hong, H.; Zhang, H.; Huang, L. Study progress of characterization of asphalt materials by nuclear magnetic resonance, thermal analysis and scanning electron microscopy. J. Highw. Transp. Res. Dev. 2019, 36, 15−28.

(15) Zhao, J.; Huang, X.; Li, X.; et al. Analysis on combustion mechanism of asphaltene using TG-MS technique. JSEU EE 2014, 26, 178−182.

(16) Yao, H.; Dai, Q.; You, Z. Molecular dynamics simulation of physicochemical properties of the asphalt model. Fuel 2016, 164, 83−93.

(17) Shishehboran, M.; Ziai, H.; Korayem, A.; et al. Environmental and mechanical impacts of waste incinerated acidic sludge ash as filler in hot mix asphalt. Case Stud. Constr. Mater. 2021, 14, No. e00504.

(18) Wang, M.; Wang, C.; Huang, S.; Yuan, H. Study on asphalt volatile organic compounds emission reduction: A state-of-the-art review. J. Cleaner Prod. 2021, 318, No. 128596.

(19) Wang, T.; Rong, H.; Chen, S.; Zhou, Y.; et al. TG-MS study on in-situ sulfur retention during the co-combustion of reclaimed asphalt binder and wood sawdust. J. Hazard. Mater. 2021, 403, No. 123911.

(20) Wang, Y.; Liu, Y.; Yang, W.; et al. Evaluation of combustion properties and pollutant emission characteristics of blends of sewage sludge and biomass. Sci. Total Environ. 2020, 720, No. 137365.

(21) Riaza, J.; Gil, M.; Álvarez, L.; et al. Oxy-fuel combustion of coal and biomass blends. Energy 2012, 41, 429−435.

(22) Liang, A.; Hui, S.; Xu, T.; et al. TG-DTG Analysis and Combustion Kinetic Characteristic Study on Several Kinds of Biomass. Renewable Energy Resour. 2008, 26, 56−61.

(23) Contreras, M.; García-Frutos, F.; Bahillo, A. Study of the thermal behaviour of coal/biomass blends during oxy-fuel combustion by thermogravimetric analysis. J. Therm. Anal. Calorim. 2016, 123, 1643−1655.

(24) Zhang, Q.; Li, Q.; Zhang, L.; et al. Experimental and kinetic investigation of the pyrolysis, combustion, and gasification of deoiled asphalt. J. Therm. Anal. Calorim. 2014, 115, 1929−1938.

(25) Zhang, Q.; Li, Q.; et al. Experimental study on co-pyrolysis and gasification of biomass with deoiled asphalt- ScienceDirect. Energy 2017, 134, 301−310.

(26) FirooziFar, S.; Foroutan, S.; Foroutan, S. The effect of asphaltene on thermal properties of bitumen. Chem. Eng. Res. Des. 2011, 89, 2044−2048.

(27) Wu, B.; Huang, Z.; Zhu, K. Investigation on the Combustion Process and Flame Retardant Performance of asphalt with Metal Hydroxides. Adv. Mater. 2014, 1065−1069, 749−754.