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Review

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*Review*

# Inertinite Reflectance in Relation to Combustion Temperature

**Di Gao [1,*], Di Chen [1], Chi Cui [1], XueBo Fu [1], JunJiao Yang [1], Shilong Zhang [1] and ZhenZhi Wang [1]**

[1]  School of Resources and Environment, Henan Polytechnic University, Jiaozuo, China; gaodi1119@163.com
[2]  Collaborative Innovation Center of Coal Work Safety and Clean High Efficiency Utilization, Jiaozuo, China; gaodi1119@163.com
*  Correspondence: gaodi1119@163.com; Tel.: 156-3911-0691

**Abstract:** Inertinite, a product of wildfire, holds important information on global temperature change. The relationship between its reflectance and temperature has been widely used to identify wildfire events in paleo-sedimentary environments, but the currently used equations relating inertinite reflectance and combustion temperature are subject to large errors. Therefore, to clarify the relationship between inertinite reflectance and combustion temperature further, we systematically analyzed the changes in inertinite reflectance under different combustion durations based on literature data. The results confirmed that inertinite reflectance is related to combustion duration. Disregarding combustion duration, the combustion equation is $T = 267.52 + 110.19 \times Ro \left( R^2 = 0.91 \right)$, where T is the combustion temperature, Ro% is the measured inertinite reflectance, and $R^2$ is the correlation coefficient. Under a combustion duration of 1 hour, the equation is $T = 273.57 + 113.89 \times Ro \left( R^2 = 0.91 \right)$, and under a combustion duration longer than 4 hours, the equation is $T = 232.91 + 110.6 \times Ro \left( R^2 = 0.94 \right)$. These three equations not only account for the temporal factor but are also more precise than the commonly used formula. This study provides a scientific basis for research on paleo-wildfire.

**Keywords:** inertinite; paleo-wildfire; reflectance; combustion equation; correlation

## 1. Introduction

Currently, Earth is experiencing climate change characterized by global warming. According to the Climate Change 2023 report released by the United Nations' Intergovernmental Panel on Climate Change (IPCC) on March 20, 2023, the global surface temperature in 2011–2020 was 1.1℃ higher than that in 1850–1900 [1], and various types of environmental problems induced by climate change seriously threaten the environment in which we live. Wildfires are an essential component of the Earth system [2]. Wildfire events play a critical role in the Earth's climate system, as evidenced by the release of greenhouse gases, such as $CO_2$, $CH_4$, $NO_2$, and $O_3$, during wildfire combustion, which exacerbates global warming and thus leads to global-scale climate change. The weather changes caused by wildfire activity can affect the characteristics of terrestrial vegetation and biogeochemical cycles [3], fundamentally alter local ecosystems [4–7], and promote the evolution of plants and animals [8–10]. In geological history, increases in wildfire frequency typically coincided with global warming [11]. Hence, studying the interactions between paleo-wildfire events and paleoclimate can help us reconstruct the climatic conditions that existed when paleo-wildfires occurred, which has great significance for addressing the sixth global warming currently being experienced by Earth.

The paleo-wildfire history is mainly reconstructed based on the combustion products in strata, including charcoal, black carbon, and combustion-derived polycyclic aromatic hydrocarbons (PAHs), as well as related parameters [12]. In recent years, progressively more scholars have demonstrated experimentally that inertinite (fusinite, semifusinite, and inertodetrinite) in coals originates from wildfire activity and are equivalent to charcoal [13–18]. Fires in natural environments may be caused by many factors, such as lightning strikes, meteorite impacts, volcanic eruptions, and spontaneous combustion of vegetation, among which lightning strikes are the most common factor [19]. Based on

the spatial distribution of the burning materials and the combustion intensity [20], wildfires can be classified into surface fires, ground fires, and crown fires [19,21]. Surface fires usually burn at a temperature below 400℃, ground fires burn at a temperature as high as about 600℃, and crown fires burn at a temperature of 800℃ or even higher [22] (Figure 1).

The temperature variation during combustion determines the isotopic composition, physical appearance, and chemical structure of charcoal [24,25]. The inertinite reflectance is an indicator with important information on the carbonization process as it can be used to calculate the maximum temperature to which biochar is exposed during pyrolysis. Additionally, inertinite (charcoal) reflectance has long been applied to estimate the burning temperature of paleo-wildfires. Many studies have suggested a good positive correlation between inertinite reflectance and combustion temperature [11,13,14,19,20], and the correlation equations are available. Jones et al. investigated the relationship between the reflectance of charcoal and the maximum pyrolysis temperature for three types of plants (Picea abies, Betula pendula, and Pinus) by controlling the heating duration, the part of the plant, and other influencing factors and obtained the equation $T = 198.8Ro + 237.6Ro^2 + 9.36Ro^3 \left(R^2 = 0.98\right)$ [26]. Jones further explored the relationship between temperature and reflectance and obtained the linear relationship $T = 184.10 + 117.76 \times Ro \left(R^2 = 0.91\right)$ [27]. Hudspith heated wood samples of trembling aspen, dwarf birch, paper birch, black spruce, and white spruce at 300℃ to 800℃ with temperature increments of 100℃ for a duration of one hour for each temperature. The charcoals obtained were then embedded in epoxy resin and polished. The data from the five types of wood were combined to generate the following polynomial curve: $T = -6.0 \times 10^{-8} Ro^3 + 1.0 \times 10^{-4} Ro^2 - 4.4 \times 10^{-2} Ro + 5.9 \left(Ro = 0.99\right)$ [28].

However, after fitting all of the data of inertinite reflectance and combustion temperature collected from available literature, we found that the combustion temperature of paleo-wildfires calculated using the resulting equation has a large error. In addition, because the combustion duration has a significant impact on inertinite reflectance, it is necessary to construct more accurate equations between inertinite reflectance and combustion temperature by fitting the data under different combustion durations so as to provide a basis for further research in related fields.
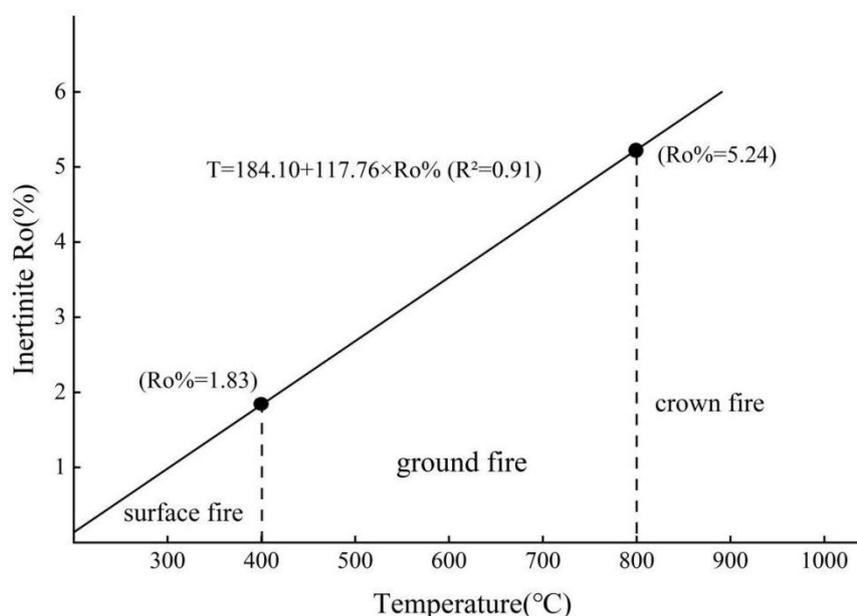


**Figure 1.** Diagram of the relationship between combustion temperature and fire type(according to Petersen and Lindström, 2012 [37], with modifications)。 In the figure, T is the combustion temperature and Ro is the reflectance of the inert group.

## 2. Materials and Methods

To clarify the relationship between inertinite reflectance and combustion temperature further, we collected 134 sets of data from the published literature in the SCI database and the CNKI Chinese Academic Journal Database (Table 1), which contain inertinite (charcoal) reflectance values obtained under different combustion durations, different fuel materials, and different combustion temperatures. Studies have shown that it is inappropriate to ignore the influence of combustion duration on the relationship between inertinite reflectance and combustion temperature. Therefore, in this study, we analyzed the relationship between inertinite reflectance and combustion temperature under different combustion durations based on the available data.

**Table 1.** Statistical table of data sources on the relationship between combustion temperature and inert reflectivity.

| Jones T P, et al. 1991[29] | | | | Mcparland L C, et al. 2009[30] | | | | Braadbaart F ,et al. 2008[31] | | | | Li Gang, et al. 2022[32] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature |
| 0.49 | 340℃ | 0.6 | 270℃ | 0.13 | 300℃ | 7.22 | 1100℃ | 0.40 | 310℃ | 1.20 | 440℃ | 0.17 | 250℃ | 0.52 | 350℃ |
| 1.39 | 440℃ | 0.95 | 300℃ | 0.80 | 400℃ | 0.46 | 300℃ | 0.65 | 340℃ | 1.88 | 500℃ | 0.51 | 300℃ | 1.02 | 400℃ |
| 3.7 | 560℃ | 1.13 | 340℃ | 1.58 | 500℃ | 1.46 | 400℃ | 0.87 | 370℃ | 3.17 | 600℃ | 0.90 | 350℃ | 1.26 | 450℃ |
| 4.5 | 640℃ | 1.33 | 370℃ | 2.34 | 600℃ | 2.60 | 500℃ | 1.30 | 400℃ | 4.80 | 700℃ | 1.07 | 400℃ | 1.60 | 500℃ |
| 5.4 | 840℃ | 1.83 | 400℃ | 3.81 | 700℃ | 3.55 | 600℃ | 1.83 | 440℃ | 5.89 | 900℃ | 1.15 | 450℃ | 1.73 | 550℃ |
| 5.6 | 920℃ | 2.2 | 500℃ | 5.05 | 800℃ | 4.36 | 700℃ | 2.50 | 500℃ | 1.70 | 440℃ | 1.43 | 500℃ | 2.01 | 600℃ |
| 6 | 1060℃ | 2.5 | 560℃ | 6.02 | 900℃ | 5.05 | 800℃ | 3.70 | 600℃ | 2.21 | 500℃ | 1.58 | 550℃ | 2.16 | 650℃ |
| 0.55 | 300℃ | 2.6 | 600℃ | 6.26 | 1000℃ | / | / | 4.09 | 650℃ | 1.43 | 440℃ | 0.20 | 250℃ | / | / |
| 1.11 | 340℃ | 0.13 | 220℃ | 6.72 | 1100℃ | / | / | 4.96 | 700℃ | 3.26 | 600℃ | 0.66 | 300℃ | / | / |

*(continuation of table from previous page)*

| Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.39 | 500℃ | 0.47 | 220℃ | 0.25 | 300℃ | / | / | 6.19 | 900℃ | 5.96 | 900℃ | 0.98 | 350℃ | / | / |
| 4.3 | 600℃ | 0.63 | 250℃ | 2.16 | 500℃ | / | / | 0.20 | 310℃ | 5.69 | 800℃ | 1.12 | 400℃ | / | / |
| 4.6 | 700℃ | 0.58 | 250℃ | 6.84 | 1100℃ | / | / | 0.49 | 370℃ | 6.24 | 900℃ | 0.11 | 250℃ | / | / |
| 5.2 | 820℃ | / | / | 5.05 | 800℃ | / | / | 0.65 | 400℃ | 6.29 | 1000℃ | 0.33 | 300℃ | / | / |

| Scott A C ,et al. 2007[33] | | Scott A C, et al. 2015[33] | | Mcparland L C, er al. 2007[34] | | Scott A C. 2010[35] | | Scott A C. 2010[35] | | Hudspith V A ,et al. 2014[36] | | Poole, F.B., 2008[31] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature | Ro% | Temperature |
| 0.10 | 280℃ | 3.90 | 600℃ | 0.25 | 250℃ | 0.23 | 300℃ | 0.4 | 275 | 0.65 | 400℃ | 0.46 | 310℃ |
| 0.27 | 300℃ | 1.0 | 300℃ | 1.81 | 400℃ | 0.50 | 350℃ | 0.43 | 300 | 1.65 | 500℃ | 1.64 | 440℃ |
| 0.55 | 325℃ | 0.47 | 350℃ | 2.43 | 450℃ | 1.03 | 400℃ | 1.57 | 400 | 2.45 | 600℃ | 3.58 | 600℃ |
| 1.00 | 350℃ | 0.86 | 400℃ | 3.68 | 525℃ | 1.14 | 450℃ | 3.33 | 500 | 4.47 | 700℃ | / | / |
| 1.24 | 400℃ | 1.47 | 450℃ | 0.42 | 300℃ | 1.62 | 500℃ | 4.97 | 600 | 4.73 | 800℃ | / | / |
| 1.47 | 450℃ | 1.99 | 500℃ | 1.51 | 400℃ | 2.19 | 600℃ | 6.86 | 900 | / | / | / | / |
| 2.29 | 500℃ | 2.34 | 550℃ | 3.17 | 500℃ | / | / | / | / | / | / | / | / |
| 2.81 | 550℃ | 2.59 | 600℃ | 4.73 | 600℃ | / | / | / | / | / | / | / | / |

**3. Discussion**

As shown in Figure 2, the combustion temperature varies between 200℃ and 1200℃, and the reflectance varies greatly within the combustion temperature range of 500℃ to 600℃, indicating that different sample materials exhibit significant differences in this combustion temperature interval. In contrast, the Ro values are concentratedly distributed below the combustion temperature of 500℃ or above the temperature of 700℃, suggesting that the difference in reflectance between different fuel materials is minor under low combustion temperatures.
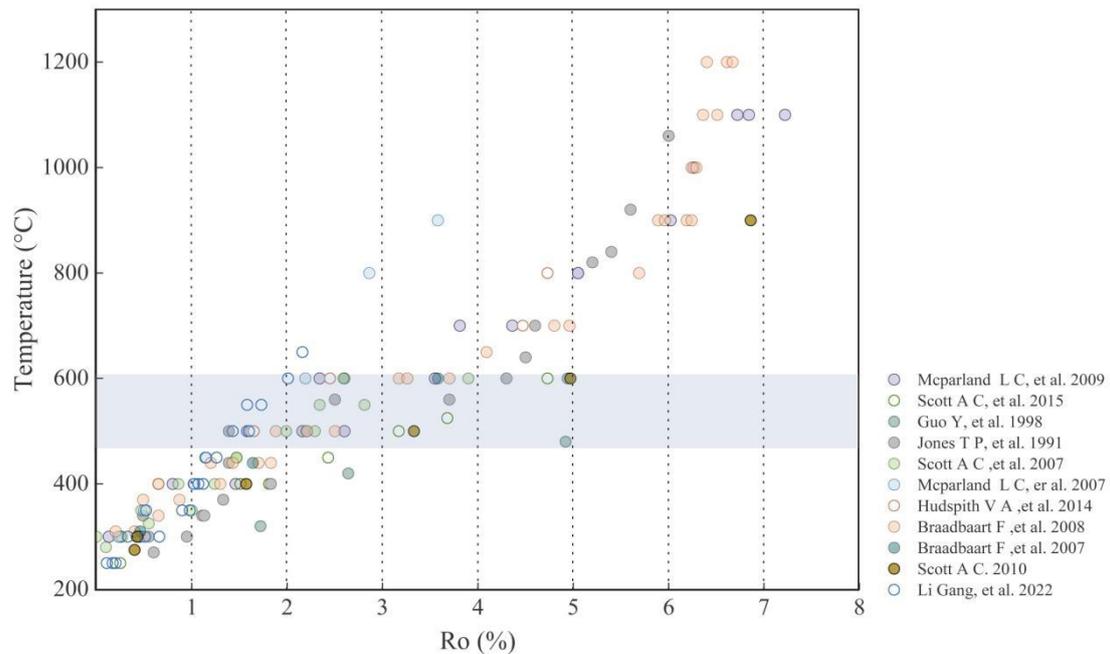


**Figure 2.** Scatter plot of combustion temperature versus inertinite reflectance and the data sources.

*3.1. Results Disregarding Combustion Duration*

As shown in Figure 3, the relationship between temperature and inertinite reflectance fitted based on the literature data is $T = 267.52 + 110.19 \times Ro \left( R^2 = 0.91 \right)$. To verify the accuracy of this equation, we compared its error with that of the empirical formula $T = 184.10 + 117.76 \times Ro \left( R^2 = 0.91 \right)$ by substituting the experimental data into the empirical formula and calculating the error between the resulting combustion temperature and the actual combustion temperature.
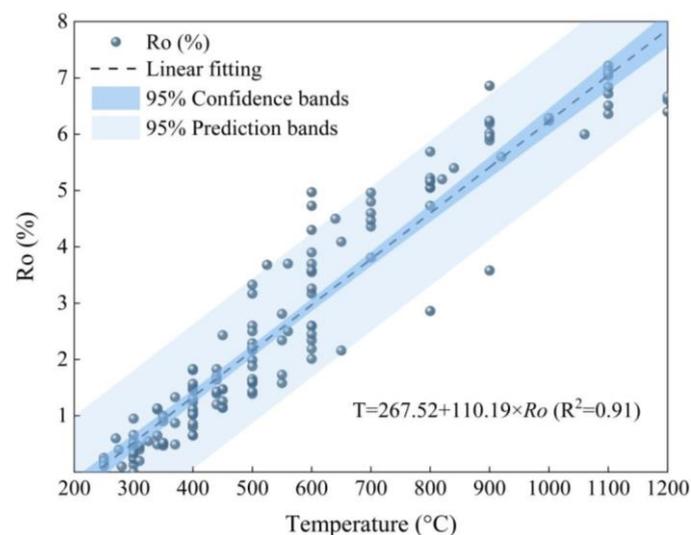
**Figure 3.** Relationship between combustion temperature and inertinite reflectance (disregarding combustion duration).

The comparison results are plotted in Figure 4. The results show that the fitted equation has higher accuracy. When the combustion temperature is between 250℃ and 550℃, the error of this equation is significantly smaller than that of the empirical formula, and this temperature level is the most commonly reached level by low-temperature surface fires. The error corresponding to the combustion temperature intervals of 550℃–700℃ and > 700℃ is relatively higher, which may be attributable to the following reasons. First, most of the experimental samples (60% of all samples) were heated for one hour. Second, the combustion durations of the samples were 1 hour, 1.5 hours, 5 hours, and 24 hours, respectively, having significant differences in duration. Finally, only a small proportion of the samples experienced a combustion temperature higher than 550℃, and most samples were treated below 600℃.
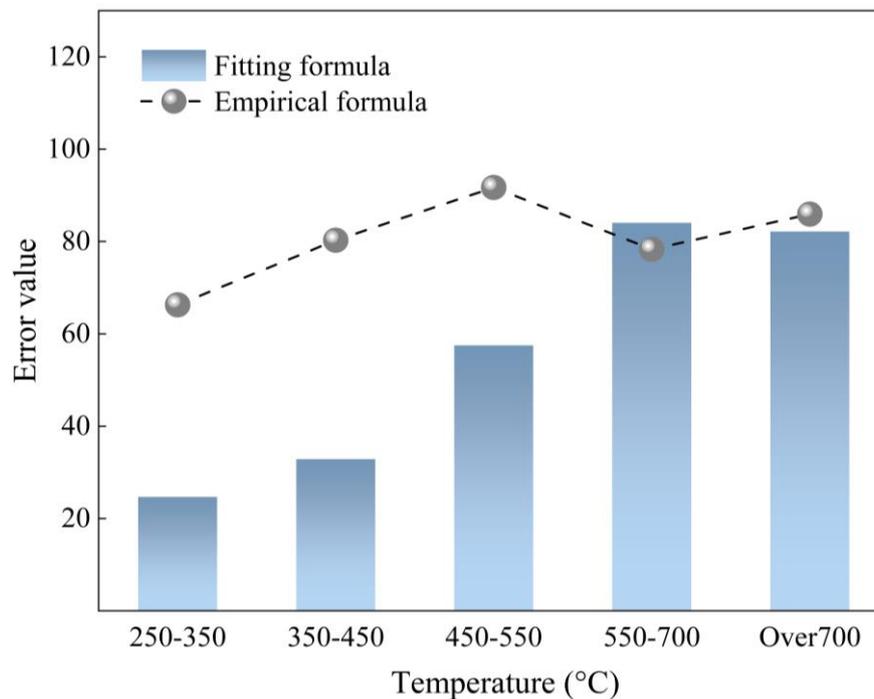


**Figure 4.** Comparison of the errors between the fitted combustion equation and empirical formula (disregarding combustion duration).

*3.2. Results under a Combustion Duration of 1 Hour*

The correlation analysis results of the data are shown in Figure 5. As shown, the inertinite reflectance increases significantly with increasing combustion temperature, and the relationship can be expressed as $T = 273.57 + 113.89 \times Ro\left(R^2 = 0.91\right)$. The error analysis revealed that the fitted combustion equation has lower error than the empirical formula during any Combustion temperature range and that the error level is the lowest when the combustion temperature is between 250℃ and 550℃.
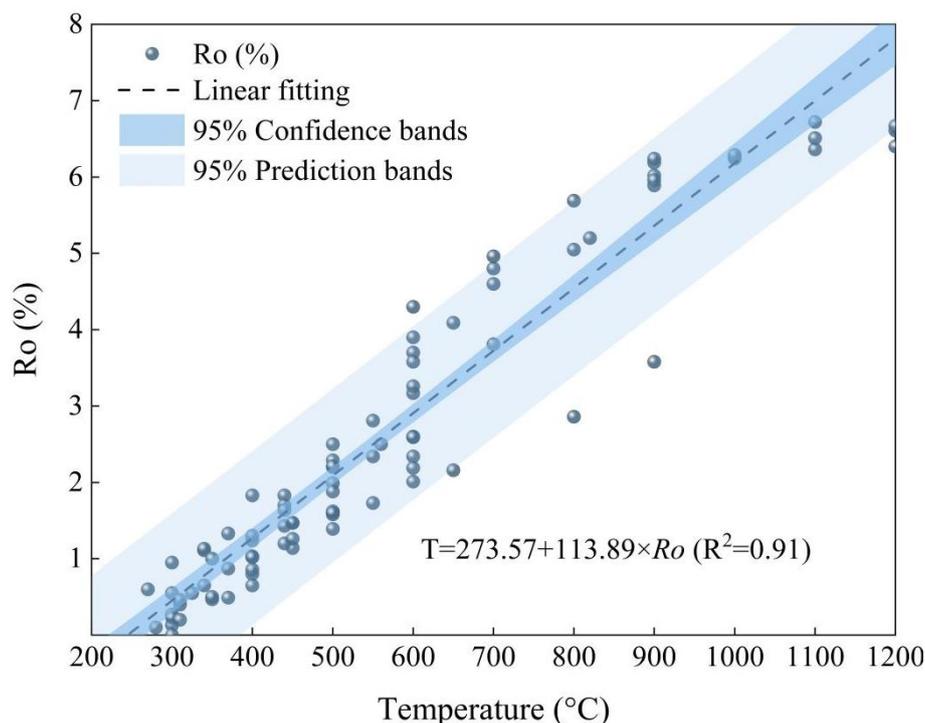
**Figure 5.** Relationship between combustion temperature and inertinite reflectance (combustion time is 1 hour).
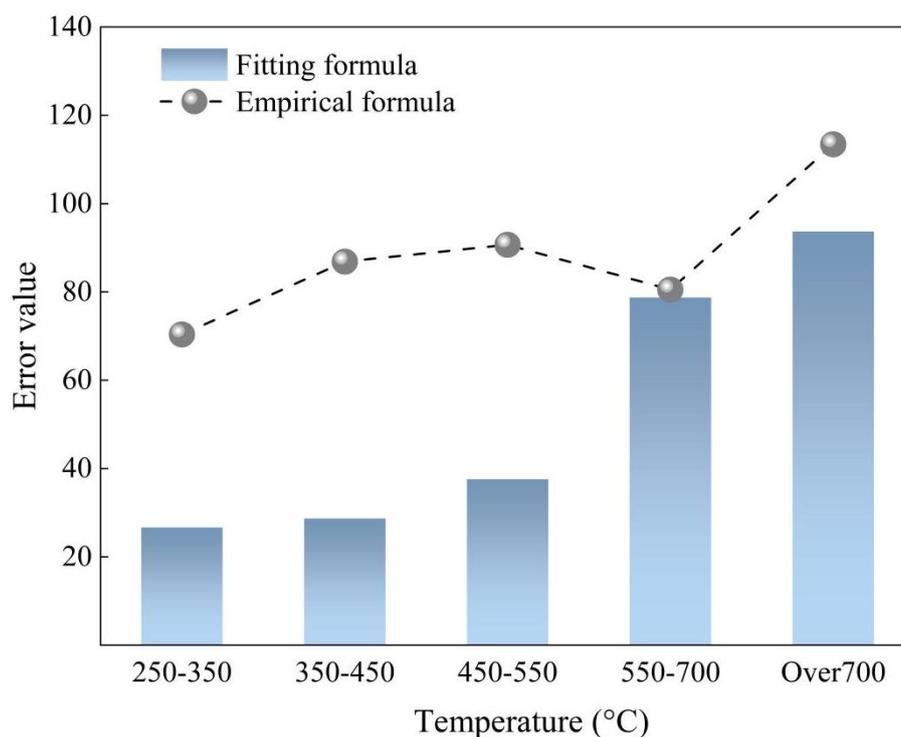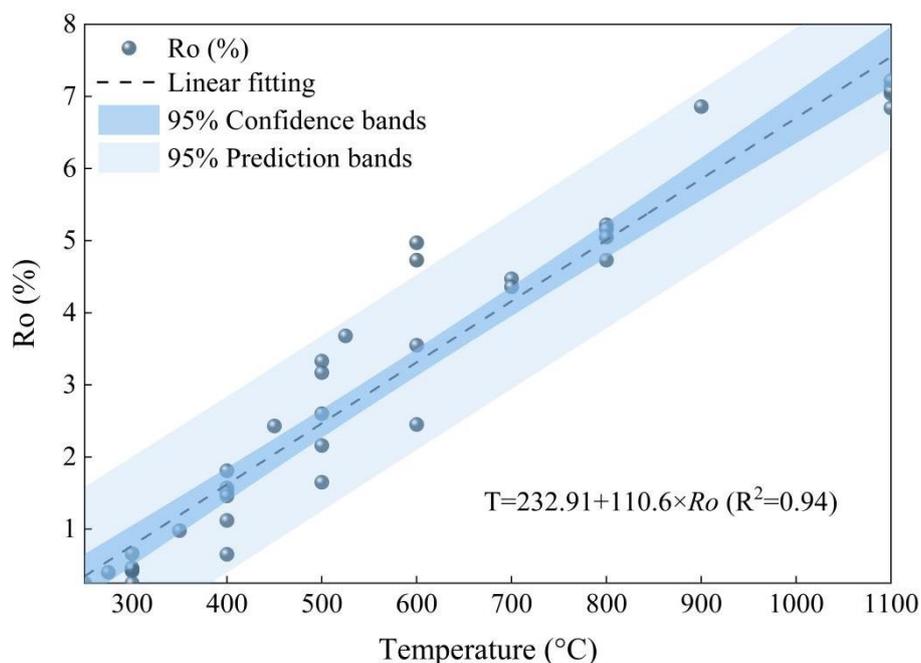


**Figure 6.** Comparison of the errors between the fitted combustion equation and empirical formula(combustion time is 1 hour).
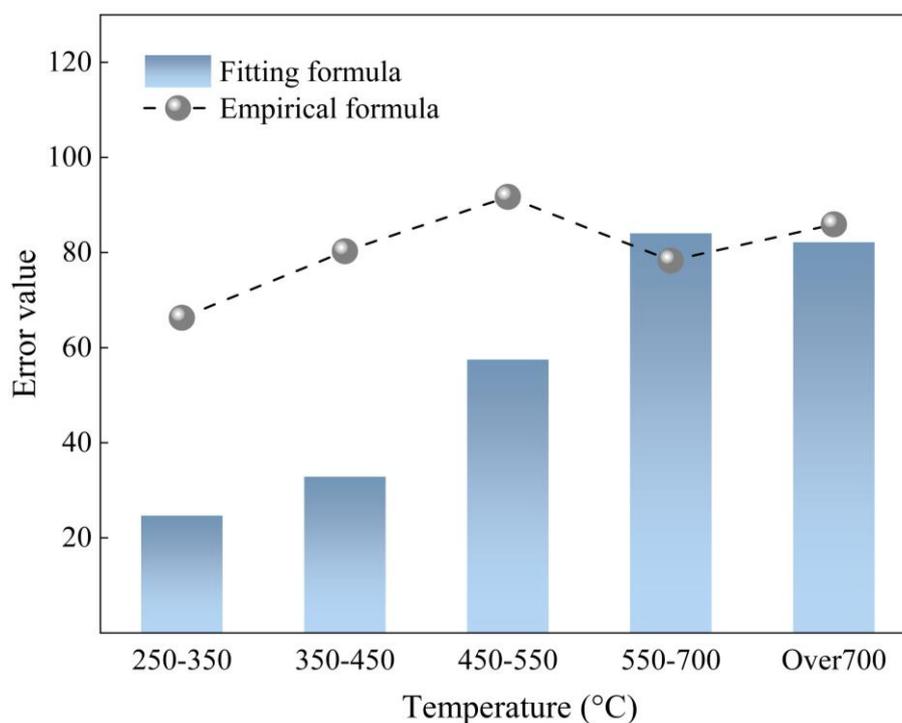
### 3.2. Results under a Combustion Duration Longer than 4 Hours

After analyzing the data with a combustion duration longer than 4 hours, we obtained a relationship between combustion temperature and inertinite reflectance of $T = 232.91 + 110.6 \times Ro \left( R^2 = 0.94 \right)$. The statistical results suggest that the average error of the fitted equation (47.44°C) is lower than that of the empirical equation (58.89°C) under a combustion duration

longer than 4 hours. The actual carbonization temperature of plant materials can be obtained under a combustion duration exceeding 4–5 hours [6], and the increasing trend of inertinite reflectance with increasing combustion temperature levels off when the combustion duration is more than 5 hours. Therefore, this equation can be used to determine the actual carbonization temperature of the inertinite. As the carbonization associated with volcanic activity is characterized by a long reaction time, the relationship between combustion temperature and reflectance fitted with the data obtained under a combustion duration longer than 4 hours can provide qualified support for research on the charcoal generated by volcanic activity.



**Figure 7.** Relationship between combustion temperature and inertinite reflectance (combustion duration longer than 4 hours).

**Figure 8.** Comparison of the errors between the fitted combustion equation and empirical formula(combustion duration longer than 4 hours).

## 4. Conclusions

(1) The relationship between inertinite reflectance and combustion temperature disregarding combustion duration is $T = 267.52 + 110.19 \times Ro \left( R^2 = 0.91 \right)$. Under a combustion duration of 1 hour, the equation is $T = 273.57 + 113.89 \times Ro \left( R^2 = 0.91 \right)$; and under a combustion duration longer than 4 hours, it is $T = 232.91 + 110.6 \times Ro \left( R^2 = 0.94 \right)$.

(2) The error analysis results show that the fitted equation expressing the relationship between inertinite reflectance and combustion temperature has a significantly lower error than the empirical formula under any combustion duration condition. The error of the fitted equation under a combustion duration of 1 hour is greater than that under a combustion duration longer than 4 hours, and the correlation coefficient ($R^2$) between inertinite reflectance and combustion duration is also smaller, indicating that the reflectance tends to stabilize as the combustion duration extends.

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