การหาระยะเวลาการได้รับความร้อนและฟลักซ์ความร้อนของไม้พาร์ติเคิลบอร์ดโดยใช้สมการถดถอยเชิงพหุคูณเพื่อประยุกต์ใช้ในการตรวจสถานที่เกิดเหตุเพลิงไหม้

Determination of Heating Time and Heat Flux of Particle Board by Multiple Regression Models to Apply for Fire Scene Investigation

ร.ต.อ.ธนวิน ทัตธนนันท์* ผศ.ดร.รัชภาคย์ จิตต์อารี และ ผศ.ดร.ทศพร บุญยฤทธิ์

คณะวิทยาศาสตร์ มหาวิทยาลัยมหิดล

Tanawin Tattananan* Ratchapak Chitaree and Tosporn Boonyarith

Faculty of Science, Mahidol University

บทคัดย่อ

การตรวจสถานที่เกิดเหตุเพลิงไหม้มีจุดมุ่งหมายอยู่ที่การหาสาเหตุและระยะเวลาของการเกิดเพลิงไหม้ งานวิจัยชิ้นนี้ได้ให้ความสำคัญไปที่ การเผาไหม้ของไม้พาร์ติเคิลบอร์ดโดยทดสอบด้วยเครื่อง cone calorimeter ในกระบวนการเผาไหม้ ขนาด, มวล, และความหนาแน่นของชิ้นไม้ทดสอบได้ถูกบันทึกไว้ ภายใต้เงื่อนไขการทดสอบที่ฟลักซ์ความร้อนเป็น 10, 15, 20, 25, 30, และ 40 kW/m^2 โดยระยะเวลาการเผาไหม้อยู่ระหว่าง 5 ถึง 60 นาที ขึ้นอยู่กับขนาดของฟลักซ์ความร้อนที่ใช้ เมื่อการทดสอบเสร็จสิ้นจึงทำการวัดความลึกของการเป็นถ่านและบันทึกผลไว้ ผลการทดลองถูกนำไปวิเคราะห์ทางสถิติและสมการการวิเคราะห์การถดถอยพหุคูณที่ได้จากผลการทดลอง คือ

1) ความลึกของการเป็นถ่าน(mm) = 15.245 + 0.314ระยะเวลาการเผาไหม้(min) + 0.271ฟลักซ์ความร้อน(kW/m^2) – 27.457ความหนาแน่น(g/cm^3) * R^2 = 0.580
2) ฟลักซ์ความร้อน(kW/m^2) = 4.049 – 0.715ระยะเวลาการเผาไหม้(min) + 1.223ความลึกของการเป็นถ่าน(mm) + 31.710ความหนาแน่น(g/cm^3) * R^2 = 0.631
3) ระยะเวลาการเผาไหม้(min) = -7.759 – 0.881ฟลักซ์ความร้อน(kW/m^2) + 1.749ความลึกของการเป็นถ่าน(mm) + 46.698ความหนาแน่น(g/cm^3) * R^2 = 0.751

คำสำคัญ: ฟลักซ์ความร้อน ระยะเวลาการเผาไหม้ พาร์ติเคิลบอร์ด สถานที่เกิดเหตุเพลิงไหม้

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* ผู้ประสานงานหลัก **(Corresponding Author)**

Email : tanawin.note@gmail.com

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Abstract

Fire investigation targets mainly include the determination of the cause of fire and the burning time. In this study, the burning of particle board is of particular interest. The wood was burnt in a standard device called a "cone calorimeter". Parameters recorded in this burning process were size, mass, and density. Test specimens were exposed to a constant heat flux of 10, 15, 20, 25, 30, and 40 kW/m^2. The period of exposed time was between 5 to 60 mins depending on the quantity of heat flux used. After the test finished, char depth was measured and the results were recorded. Then the results were statistically analysed and the multiple regression models of the results are found to be:

1) char depth(mm) = 15.245 + 0.314heating time(min) + 0.271heat flux(kW/m^2) – 27.457density(g/cm^3) * $R^2 = 0.580$
2) heat flux(kW/m^2) = 4.049 - 0.715heating time(min) + 1.223char depth(mm) + 31.710density(g/cm^3) * $R^2 = 0.631$
3) heating time(min) = -7.759 - 0.881heat flux(kW/m^2) + 1.749char depth(mm) + 46.698density(g/cm^3) * $R^2 = 0.751$

Key words: heat flux, heating time, particle board, fire scene

Introduction

Whenever a fire occurs, witness generally must report the incident to officers. Members of the local fire department are normally the first officers to arrive at the scene of the fire and suppress the fire until the fire is extinguished. Following that, the fire investigators come to the scene for investigating the cause of fire. The investigation conducted by the fire investigators must include essential information obtained from witness and physical evidences in the fire scene. The information from the fire investigation may include the origin of the fire, the cause of the fire. This goes along with a statement from Fire Debris Analysis by Stauffer, Dolan, and Newman (2008) saying that "The goals of fire scene investigation are to answer the following two specific questions: 'Where did the fire start?' and 'Why did the fire start?' ".

There are many effects in a fire scene that can assist in investigating the origin of the fire. (Almirall and Furton, 2004; Kirk and DeHaan, 2002) The effects are called fire patterns or fire indicators. In this study, charring is of interest because charred wood materials are commonly found at fire scenes. When wood materials were burnt or exposed to heat, the surface of wood becomes black. The amount and depth of charring is commonly used by investigators to evaluate fire spread, heat flux, and burning time. Many researchers have conducted experiments so as to know what information can be obtained from the wood charring. Friquin (2011) reviewed articles, books and theses from as far back as 1958 then concluded that materials and external factors influencing the increasing charring rate including the lignin content, char oxidation, area of surface, the longitudinal direction, heat flux, oxygen concentration, and opening factors. On the contrary, the decrease in density of wood, moisture content, the perpendicular direction, and char contraction factor increases the charring rate. From reviewed paper of Maciulaitis, Lipinskas, and Lukosius (2006), and Vytenis (2005), the wood charring studies in the fire investigation can be separated into 3 groups based on experimental methods : 1) the study using the standard time-temperature curve (ASTM E 119 or ISO 834) 2) the study using the cone calorimeter 3) the study in case of developed fire.

A cone calorimeter is a modern equipment used to study the fire behavior of small samples of various materials in condensed phase. It is widely used in the field of Fire Safety Engineering. However, a number of different scientists applied this instrument to test various species of wood in terms of charring because the cone calorimeter can accurately control the intensity of the heat flux. They used the cone calorimeter to heat wood specimens and adjust any factors of charring rate. Vytenis (2005) gathered the results of wood charring rates by using a cone calorimeter. He could conclude an equation from the data. The density was observed on charring test with cone calorimeter by Harada (1996). The effects of the concentration of oxygen in charring test were investigated by Mikkola (1990).

Fire research in Thailand mostly covers the fire protection, not the fire investigation. However, there were some works which studied about burning behavior of wood. An interesting research was a study of Boonmee and Quintiere (2002). He investigated the glowing and flaming autoignition of insulated redwood by a radiant cone heater. The other studies by Boonmee and Quintiere (2005) was the glowing ignition of wood: the onset of surface combustion. Charaspredalap and Boonmee (2010) investigated 8 types of wood products by a cone calorimeter.

The charring of particle board is a particular interest. This kind of wood is popularly used as the composition of the ready-to-assembled furniture nowadays. Because of being cheap and easy to buy, the particle board furniture has become common household items often found in many Thai residences. To examine the charring of the particle board, in this investigation, the wood is burnt in a standard equipment called "cone calorimeter". Parameters and preset conditions to be studied in this burning process are based on the burning patterns recorded from real fire scenes. The experimental results from this research were analyzed by the multiple regression method. The analysis is often used to create a predicting equation from the relationship between several dependent or predictor variables and a dependent or criterion variable. An example of the implementation of the method can be found from the work of Rattanapanadda (2009) which shows the use of the multiple regressions to create an equation for predicting an amount of protein content in the wheat flour.

The multiple regression models from this research are expected to provide valuable information for the investigation of fire scene where the burnt particle board furniture is found. Questions about burning heat flux and time on fire of the particle board could be answered systematically and the burning behavior of the wood in association with traditional knowledge and other evidences should reasonably clarify the origin and burning behavior of the fire in the crime scene. Furthermore, this research should be of great benefit to persons who are interested in burning characteristics of materials from industry, insurance and the law enforcement agency.

Objective

The aim of this study is to determine burning heat flux and time of burnt particle board in a fire scene by multiple regressions.

Materials and method

Materials

1) 10 cm x 10 cm particle board of 75 specimens in each kind. In total, three kinds of particle board were used in this research. The first kind was the particle board made from rubber wood. The second kind was the particle board made from bagasse. Both kinds were produced by the same manufacture named Panel Plus Co., Ltd. The last kind was unknown particle board. The total number of specimens was 225 pieces. (see in Figure 1)
2) Cone calorimeter laboratory at Fire Safety Research Unit, Chulalongkorn University
3) Aluminium foil
4) Digital vernier sliding caliper
5) Timer
6) Jigsaw
7) Digital camera
8) Computer

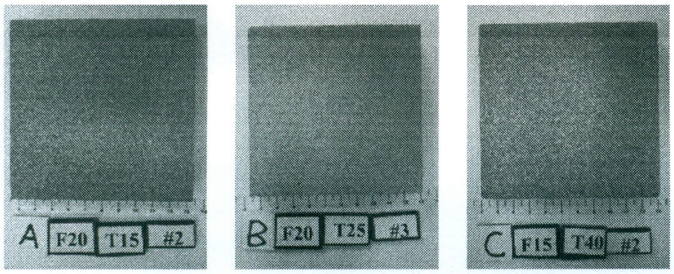

Figure 1 Top views of a rubber wood particle board specimen (left), a bagasse particle board specimen (center), and an unknown particle board specimen (right).

Methods

The tests were carried out by using the Cone Calorimeter equipment available at the Fire Safety Research Unit of Chulalongkorn University (see in Figure 2).

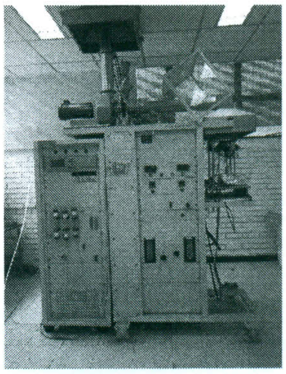

Figure 2 The Cone Calorimeter at the Fire Safety Research Unit at Chulalongkorn University.

All wood specimens were prepared with approximately the same size: 10 cm x 10 cm. Dimensions including width, length, and thickness of all specimens were precisely measured by a digital vernier sliding caliper. The mass of the specimen was measured by the load cell of the Cone Calorimeter. Then the density of each specimens were calculated. Specimens were wrapped in a thin aluminium foil (except the upper surface) for one dimensional heat conduction (see in Figure 3).

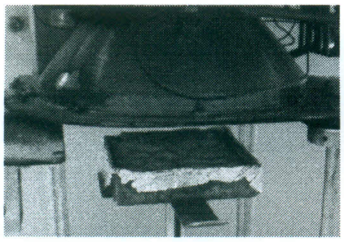

Figure 3 Specimens were wrapped in a thin aluminium foil (except the upper surface).

After the heat exposure was completed, the exposed specimen was sawed into two similar pieces to measure the char depth at the center point of the specimens (see in Figure 4). The char depth was the distance measured between the original upper surface and the lowest char layer (Just and Tera, 2010) (see in Figure 5). For the char depth measuring, each piece of specimens was measured 3 times and the obtained values were used for calculating the mean and standard deviation of the char depth.

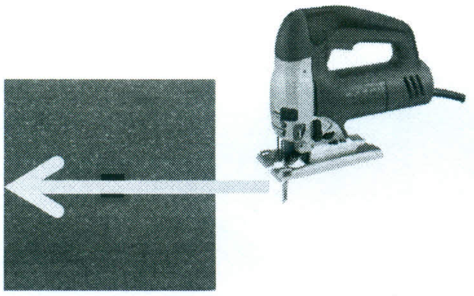

Figure 4 A specimen was sawed along the direction shown by the arrow into two similar pieces. A black square was the measuring position.

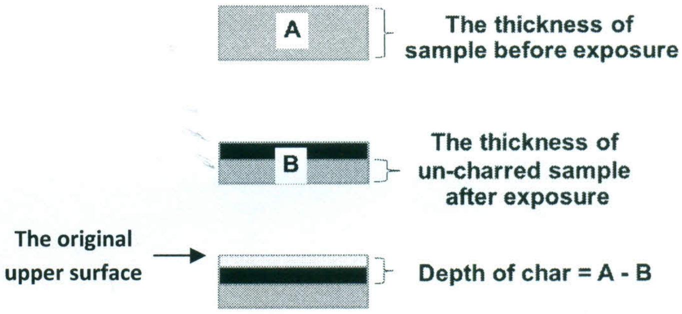

Figure 5 Depth of char determination

Test specimens were exposed in conditions in Figure 6. When the specimen exposure finished, a box was immediately taken to cover the specimen for extinguishment. Three specimens of each kind were tested within each condition. Data was used for descriptive statistics. Mean and standard deviation were calculated by using Microsoft Excel 2010. Multiple regressions were calculated by using IBM SPSS statistics 19.

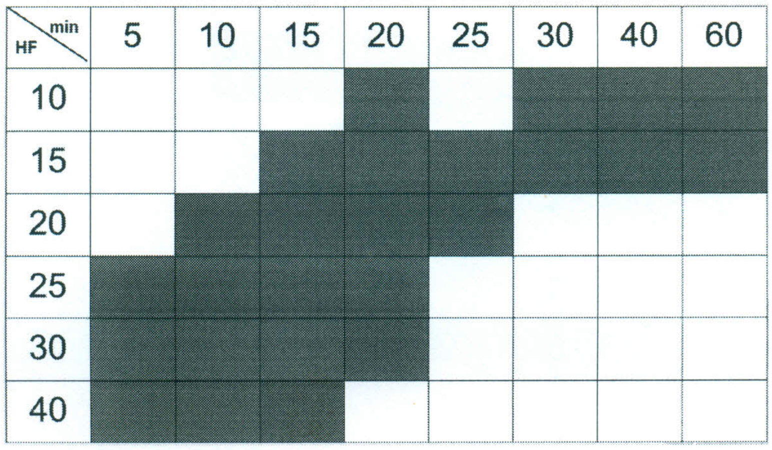

Figure 6 The heat flux (HF) and time (in minute) conditions for the investigation

* The values in the 1st column represent the heat flux level in unit of KW/m^2

** The values in the 1st row represent the heating time in unit of min

*** Dark blocks are the conditions used in this investigation

Results

1. The details of specimens

Table 1 The details of specimens before heat exposure

Types of Specimens	Width (mm)		Length (mm)		Thickness (mm)		Volume (cm^3)		Mass (g)		Density (g/cm^3)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Rubber wood	98.14	0.85	98.20	0.58	18.41	0.10	177.46	1.94	119.21	2.97	0.67	0.01
Bagasse	98.17	0.10	98.15	0.10	18.44	0.22	177.73	2.11	105.85	3.47	0.60	0.02
Unknown	100.93	0.23	100.94	0.15	18.48	0.07	188.29	0.96	125.43	3.36	0.67	0.02

2. Multiple regression of heating time

The target of this part is to predict the heating time. All of results consisting of heat flux, char depth, density, and sample type, "type" was categorized using the following assignments; "type" = 1 is rubber wood, 2 is bagasse, and 3 is unknown. Correlation and multiple regression analyses were conducted to examine the relationship between the heating time and various potential predictors by using IBM SPSS statistics 19.

Figure 7, correlations part showed that the Pearson correlation coefficients between each predictor was 0.000 to 0.670. They were not overabundant (less than 0.8). The total variability in y (heating time) explained by the regression model is shown in Figure 7 Model Summary part. The highest R^2 was 0.751 or 75.1% that determined by using the heat flux, the char depth, and the density as predictors. The R-squared value means that 75.1% of the variation in the heating time could be explained by the regression on these predictors and the standard error of the estimation equaled 6.397 min. However, Stepwise method of SPSS sort out the sample type from the model because the sample type was not significantly correlated with the model and useless to predict the model. Furthermore, as shown in Figure 7, ANOVA part indicated that the three models were appropriate to use, since they significantly accounted for more variance in the criterion variable than would be expected by chance (Sig. < 0.01).

The multiple regression model coefficients are presented in Figure 7 Coefficients part. The multiple regression model for predicting attitude towards the heating time was:

heating time(min) = -7.759 - 0.881heat flux(kW/m^2) + 1.749char depth(mm) + 46.698density(g/cm^3)

* $R^2 = 0.751$, Standard error of the estimate = 6.397, Sig. < 0.01

** Example : in case of a particle board which had 0.68 g/cm^3 of density was exposed by 30 kW/m^2 of heat flux then investigated the char depth at 7.4 mm. The predicted heating time is:

The predicted heating time(min) = -7.759 - 0.881(30.000) + 1.749(7.400) + 46.698(0.680) = 10.508

Thus, the predicted heating time is 10.508 ± 6.397 min

Correlations

		Time	HF	Char	Density	Kind
Pearson Correlation	Time	1.000	-.670	.553	-.002	.000
	HF	-.670	1.000	-.029	-.010	.000
	Char	.553	-.029	1.000	-.261	.019
	Density	-.002	-.010	-.261	1.000	-.070
	Type	.000	.000	.019	-.070	1.000

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.670[a]	.448	.446	9.48208
2	.856[b]	.733	.730	6.61302
3	.867[c]	.751	.748	6.39658

a. Predictors: (Constant), HF

b. Predictors: (Constant), HF, Char

c. Predictors: (Constant), HF, Char, Density

ANOVA[d]

Model		Sum of Squares	Df	Mean Square	F	Sig.
1	Regression	15340.966	1	15340.966	170.626	.000[a]
	Residual	18881.086	210	89.910		
	Total	34222.052	211			
2	Regression	25082.049	2	12541.025	286.770	.000[b]
	Residual	9140.002	209	43.732		
	Total	34222.052	211			
3	Regression	25711.482	3	8570.494	209.465	.000[c]
	Residual	8510.570	208	40.916		
	Total	34222.052	211			

a. Predictors: (Constant), HF

b. Predictors: (Constant), HF, Char

c. Predictors: (Constant), HF, Char, Density

d. Dependent Variable: Time

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients			95.0% Confidence Interval for B		Collinearity Statistics	
		B	Std. Error	Beta	T	Sig.	Lower Bound	Upper Bound	Tolerance	VIF
1	(Constant)	40.041	1.675		23.904	.000	36.739	43.343		
	HF	-.905	.069	-.670	-13.062	.000	-1.042	-.769	1.000	1.000
2	(Constant)	23.541	1.608		14.637	.000	20.370	26.712		
	HF	-.885	.048	-.654	-18.291	.000	-.980	-.789	.999	1.001
	Char	1.636	.110	.534	14.925	.000	1.420	1.852	.999	1.001
3	(Constant)	-7.759	8.130		-.954	.341	-23.787	8.270		
	HF	-.881	.047	-.652	-18.836	.000	-.974	-.789	.999	1.001
	Char	1.749	.110	.571	15.918	.000	1.532	1.965	.931	1.074
	Density	46.698	11.906	.141	3.922	.000	23.226	70.171	.931	1.074

a. Dependent Variable: Time

Figure 7 The multiple regression of heating time computed by using IBM SPSS statistics 19

3. Multiple regression of heat flux

Similar to the previous paragraph, the multiple regression model (The figure of heat flux SPSS results is not shown) for predicting attitude towards the heat flux was:

heat flux(kW/m^2) = 4.049 - 0.715heating time(min) + 1.223char depth(mm) + 31.710density(g/cm^3)

* $R^2 = 0.631$, Standard error of the estimate = 5.763, Sig. < 0.01

4. Multiple regression of char depth

The multiple regression model (The figure of char depth SPSS results is not shown) for predicting attitude towards the char depth was:

char depth(mm) = 15.245 + 0.314heating time(min) + 0.271heat flux(kW/m^2) – 27.457density(g/cm^3)

* $R^2 = 0.580$, Standard error of the estimate = 2.711, Sig. < 0.01

Discussions

The multiple regressions were used to create predicting equations or multiple regression models. A few predictors or independent variables which were conducted in the analysis should be used. If there are many predictors, the multiple regression model will be inappropriate to use in crime scene. However, R^2 of the multiple regression model should not be low. Then the number of predictors should be appropriate for analysis. Stepwise method which considers principles regarding variance and regression were used to exclude some insignificant predictors in the same way as illustrated in the research of Pothimamaka, Panomwan, and Linitda (2010). The value of R^2 is a prime indicator of the percentage of the variation in a predicted variable which can be explained by the regression on predictors. The comparison of R^2 of the multiple regression models in each predictor from the results is presented in Table 2.

Table 2 The comparison of R^2 of the multiple regression models in each predictor from the results

Predicted variable	Predictors					
	Char depth	Heating time	Heat flux	Density	Type (123)	R^2
Char depth	-	/	-	-	-	0.305
	-	/	/	-	-	0.516
	-	/	/	/	-	0.580
	-	/	/	/	not sig.	none
Heat flux	-	/	-	-	-	0.448
	/	/	-	-	-	0.616
	/	/	-	/	-	0.631
	/	/	-	/	not sig.	none
Heating time	-	-	/	-	-	0.448
	/	-	/	-	-	0.733
	/	-	/	/	-	0.751
	/	-	/	/	not sig.	none

* - denotes this variable was not conducted to be a predictor.

** / denotes this variable was conducted to be a predictor.

*** not sig. means this variable was conducted to be a predictor but not significantly correlated with the model and useless to predict the model.

**** none means no model in this condition.

***** Type (123) means "Sample type" was categorized using the following assignments; "Type" = 1 is rubber wood, 2 is bagasse, and 3 is unknown.

From Table 2, all results of every specific condition were conducted to calculate multiple regression models. That means these models can apply to predict a variable in all specific conditions of this study (5 – 60 min of heating time and 10 – 40 kW/m^2 of heat flux).

The R-squared value of the multiple regression model for predicting attitude towards the char depth or call "the char depth model" equaled 0.305 for the model in which the heating time was a predictor and became higher when added other predictors. The highest R^2 of the char depth model was 0.580 determined by using the heating time, the heat flux, and the density as predictors. The predictors that significantly correlated with the char depth model were the heating time, the heat flux, and the density in descending order.

The R-squared value of the heat flux model equaled 0.448 for the model in which the heating time was a predictor and also became higher when added other predictors. The highest R^2 of the heat flux model was 0.631 and the predictors that significantly correlated with the heat flux model were the heating time, the char depth, and the density in descending order.

The R-squared value of the heating time model equaled 0.448 for the model in which the heat flux was a predictor and also became higher when added other predictors. The highest R^2 of the heating time model was 0.751 and the predictors that significantly correlated with the heating time model were the heat flux, the char depth, and the density in descending order.

However, the sample type was not included in these models because this was not significantly correlated with the models and useless to predict the models.

2. Discussion of the studying results applied for a fire scene

In this study, the wood under investigation is a particle board. To apply the results for a fire scene, investigators should search some burnt particle boards. Then the results can be applied to indicate that the particle board with a deeper char depth may be burnt for a longer time or burnt with a higher heat flux. These trends harmonized with the review of Friquin (2011). In a more advanced step, the multiple regression models can be applied to calculate heating time or heat flux in the fire scene.

For example, if investigators find some burnt particle boards and would like to determine heating time of the area that the burnt particle boards were found. The investigator should estimate the quantity of heat flux which expose on the burnt particle boards. The information which include decorations, structures, windows, doors, fire flows, experiences, demonstrations, etc can support the estimation of the heat flux. Then the investigators determine the sample type, the density, and the char depth as the previous paragraph stated. All variables are conducted to predict the heating time by the heating time model. The predicted heating time can be used to support the fire investigation.

The errors of prediction are committed because the investigators cannot determine exactly the variables (the sample type, the density, the char depth, the heat flux, and the heating time). There are many causes that the investigators cannot determine the exact heat flux in a real scene. Examples may include that the heat flux was not constant, fire fighters had probably removed something, witnesses did not know the real situations in fire scene etc. The heating time said by the witnesses may be incorrect. Furthermore, there are some errors from the multiple regression models. The highest R-squared values found from this study were 0.580 from the char depth model, 0.631 from the heat flux model, and 0.751 from the heating time model. Although, these values were not close to 1 which is the best expected value, they are still acceptable. This is because the conditions 10 kW/m^2 of heat flux in this experiment was nearly the critical heat flux of particle board (Charaspredalap and Boonmee, 2010). The critical heat flux corresponds to the heat flux that an exposed object starts to ignite. Then the results obtained under this condition varied highly and this leads to rather low values of R^2. However, the models help the investigators to narrow the range of relevant variables and obtain scientifically backed up information for a fire scene.

Conclusions

The multiple regression models of the results are:

1) char depth(mm) = 15.245 + 0.314heating time(min) + 0.271heat flux(kW/m^2) – 27.457density(g/cm^3) * $R^2 = 0.580$

2) heat flux(kW/m^2) = 4.049 - 0.715heating time(min) + 1.223char depth(mm) + 31.710density(g/cm^3) * $R^2 = 0.631$

3) heating time(min) = -7.759 - 0.881heat flux(kW/m^2) + 1.749char depth(mm) + 46.698density(g/cm^3) * $R^2 = 0.751$

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