UNIVERSITI PUTRA MALAYSIA

ENHANCING RICE HUSK ASH-BASED ALUMINOSILICATE FIRE RETARDANT ADDITIVE AS A PASSIVE FIRE PROTECTION MATERIAL

MOHD NA'IM BIN ABDULLAH

FK 2021 55

ENHANCING RICE HUSK ASH-BASED ALUMINOSILICATE FIRE RETARDANT ADDITIVE AS A PASSIVE FIRE PROTECTION MATERIAL

By

MOHD NA'IM BIN ABDULLAH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

June 2021

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

ENHANCING RICE HUSK ASH-BASED ALUMINOSILICATE FIRE RETARDANT ADDITIVE AS A PASSIVE FIRE PROTECTION MATERIAL

By

MOHD NA'IM BIN ABDULLAH

June 2021

Chairman : Faizal bin Mustapha, PhD, PEng
Faculty : Engineering

Several major research studies have concluded that most fire retardants (FR) are associated with numerous environmental and human health concerns, which led them to be replaced by more eco-friendly alternatives. Since Malaysia has been producing abundant of rice husk (RH), the utilisation of rice husk ash (RHA) as an aluminosilicate source in fire-resistant coating could reduce the environmental pollution and can turn agricultural waste into industrial wealth. The main objective of this research is to develop an eco-friendly RHA-based aluminosilicate FR additive. Four experiments were conducted; namely fire resistant, tensile, adhesion, and water absorption tests to assess the microstructure behavior of the developed RHA-based aluminosilicate FR additive. Response surface methodology (RSM) was used to design the experiments incorporating two factors; namely ratio of FR additive to paint and their interrelationship and effect on FR coating properties were analysed using analysis of variance (ANOVA). The relationship of different pre-treatment on the production of silica content from RH were also studied to understand the relationship of each pre-treatment on the produced silica content from RHA. From the fire resistance test and scanning electron microscopy images, higher ratio of RHA-based aluminosilicate contributed a better fire protection efficiency due to the formation of thicker char layer thickness which affected the equilibrium temperature. For both tensile and adhesion strength, the addition of RHA-based aluminosilicate FR improved the ultimate tensile strength and adhesion strength due to dense gel phase which has a well-connected structure and less unreacted particles on the surface coating. However, major drawback on the addition of RHA-based aluminosilicate is the enhancement of water permeation which led to the deterioration of the coating samples. Thus, it can be summarized that silica efficiently improved the strength and compactness of the char layer, which resulted in a relatively higher fire retardant efficiency. In this research, RHA proved to be a good aluminosilicate source alternative for fire retardant additive due to its intumescent process, which can potentially improve building fire safety through passive fire protection.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENINGKATAN ADITIF TAHAN API SEKAM PADI BAKAR BERASASKAN ALUMINOSILIKAT SEBAGAI BAHAN PERLINDUNGAN KEBAKARAN PASIF

Oleh

MOHD NA'IM BIN ABDULLAH

Jun 2021

Pengerusi : Faizal bin Mustapha, PhD, PEng
Fakulti : Kejuruteraan

Beberapa penyelidikan utama telah menyimpulkan bahawa kebanyakan bahan tahan api (FR) dikaitkan dengan pelbagai masalah alam sekitar dan kemudaratan kepada kesihatan manusia, menyebabkan ia digantikan dengan sumber yang lebih mesra alam. Oleh kerana Malaysia menghasilkan sekam padi (RH) yang berlebihan, penggunaan abu sekam padi (RHA) sebagai sumber aluminosilikat dalam salutan tahan api dapat mengurangkan pencemaran alam sekitar dan dapat mengubah bahan buang pertanian kepada kekayaan industri. Objektif utama penyelidikan ini adalah untuk mengembangkan aditif FR aluminosilikat berasaskan RHA yang mesra alam. Empat eksperimen dijalankan; iaitu ujian tahan api, tegangan, lekatan, dan penyerapan air untuk menilai tingkah laku mikro struktur aditif aluminosilikat FR berasaskan RHA yang dibangunkan. Kaedah tindak balas permukaan (RSM) telah digunakan untuk merancang eksperimen yang merangkumi dua faktor; iaitu nisbah aditif FR kepada cat dan hubungannya serta kesan terhadap sifat salutan FR dianalisis menggunakan analisis varians (ANOVA). Hubungan pra-rawatan yang berbeza terhadap pengeluaran kandungan silika dari RH juga dikaji bagi memahami hubungan setiap pra-rawatan terhadap kandungan silika yang dihasilkan dari RHA. Dari ujian ketahanan api dan imbasan mikroskop elektron, nisbah aluminosilikat berasaskan RHA yang lebih tinggi menyumbang kepada kecekapan perlindungan kebakaran yang lebih baik kerana pembentukan ketebalan lapisan arang yang lebih tebal yang mempengaruhi suhu keseimbangan. Untuk kekuatan tegangan dan lekatan, penambahan aluminosilikat FR berasaskan RHA meningkatkan kekuatan tegangan dan kekuatan lekatan utama kerana fasa gel yang padat yang mempunyai struktur yang bersambung dengan baik dan zarah yang kurang bereaksi pada lapisan permukaan. Walau bagaimanapun, kelemahan utama penambahan aluminosilikat berasaskan RHA adalah peningkatan penyerapan air yang menyebabkan kemerosotan sampel salutan. Oleh itu, dapat disimpulkan bahawa silika secara efisien meningkatkan kekuatan dan kekompakan lapisan char, yang menghasilkan kecekapan tahan api yang lebih tinggi. Dalam

penyelidikan ini, RHA terbukti menjadi sumber alternatif aluminosilikat yang baik untuk bahan tambahan tahan api kerana proses intumensinya, ia juga berpotensi untuk meningkatkan keselamatan kebakaran bangunan melalui perlindungan kebakaran pasif.

ACKNOWLEDGEMENTS

Praised to Allah S.W.T. for His generous blessing, kindness, guidance and undying strength bestowed upon me to successfully complete my doctoral study. My special appreciation and acknowledgement dedicated to my supervisor, Professor Ir. Dr. Faizal Mustapha for his continuous support, invaluable guidance, patience and motivation throughout my period of completing the Ph.D. study.

I would like to extend my appreciation to my supervisory committee, Associate Professor Dr. Khamirul Amin Matori, and Associate Professor Dr. Mohd Halim Shah Ismail for their advices and assistance during this period of study. They provided me with great guidance, excellent teaching, their enlightening experience, and the necessary facilities to keep me on track and focused during my Ph.D. study.

I respectfully acknowledge the blessings and good wishes of all my dearest friends for their help, encouragement, and support. Special thanks to my dearest father, Abdullah Ibrahim; my beloved mother, Mariah Awang; my sisters, and brother for their endless love, great sacrifice, patience, and support during my study. Last but not least, my sincere gratitude to Universiti Putra Malaysia for funding my study under the Geran Putra IPS (GP-IPS/2017/9523700) and Ministry of Education Malaysia for granting me MyPhD Scholarship under the MyBrain15 Program.

THANK YOU

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Faizal bin Mustapha, PhD, PEng
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Halim Shah bin Ismail, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Khamirul Amin bin Matori, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 09 September 2021

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: _____ Date: _____

Name and Matric No.: _____

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: _____
Name of Chairman of Supervisory Committee: _____

Signature: _____
Name of Member of Supervisory Committee: _____

Signature: _____
Name of Member of Supervisory Committee: _____

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AA	Activated Alkaline
ANOVA	Analysis of Variant
APP	Ammonium Polyphosphate
ASTM	American Society for Testing and Materials
CCD	Central Composite Design
CFD	Computational Fluid Dynamic
DAQ	Data Acquisition
DF	Degree of Freedom
EDX	Energy Dispersive X-Ray Spectroscopy
FAO	Food and Agriculture Organization
FEM	Finite Element Method
FFD	Full Factorial Design
FR	Fire Retardant
GB	Geopolymer Binder
HCL	Hydrochloric Acid
ISO	International Organization for Standardization
LOI	Loss Of Ignition
LPG	Liquid Petroleum Gas
Na	Sodium
Na_2SiO_3	Sodium Silicate
NaOH	Sodium Hydroxide
OH	Hydroxide
OSHA	Occupational Health and Safety Association
POFA	Palm Oil Fuel Ash

PVA/MMT	Poly Montmorillonite
PVC	Pigment Volume Concentrate
RH	Rice Husk
RHA	Rice Husk Ash
RSM	Response Surface Method
SEM	Scanning Electron Microscopy
Si	Silica
TAE	Temperature at Equilibrium
TEOS	Tetraethylorthosilicate
TGA	Thermogravimetry Analysis
TT200	Time Taken to Reach 200°C
UTS	Ultimate Tensile Strength
Wt.	Weight (g)
VOC	Volatile Organic Compounds
XRD	X-Ray Diffraction

CHAPTER 1

INTRODUCTION

This chapter describes the research background, problem statement, objectives, scope of the research work and the importance of the study to the engineering community in general and to researchers in particular.

1.1 Research Background

Materials flammability is one of the most important elements that require strict measures and precautions necessary to maintain fire safety, especially for building and construction products. This is due to the growing loss of life because of the spread of fire. Thus, comprehensive research on this issue is the main focus of this study. In order to overcome this consequence, various measuring techniques of fire properties have been developed and improved such as lowering the heat release, controlling ignitability, or improving the extent of flame spread across the surface of flammable materials. Therefore, these factors allow a greater time for people to evacuate to safe areas before the fire takes hold and thus, saving more lives. To ensure the safe use of materials for the end-use environment, the selection of materials is critical for fire behaviour. For example, in order to prevent fire, protection is often needed for cellulosic materials, such as textiles, plastics and wood, whereas protection for steel structures is required to avoid catastrophic failure in the event of a fire.

In the case of fire incident at the World Trade Centre on September 11, it was reported that the collapse of the tower mainly due to the structure and rigidity of structural steel under heat and pressure, not because of flammability (Kiakojouri et al., 2020). Hence, this well-known accident has received attention on the use of fire protection materials in constructions and buildings. Without the fire protection material, people inside the building are at high danger during a building fire. The United States fire department reported that an estimated annual average of 4,100 structure fires in dormitories, fraternities, sororities, and barracks from 2011 to 2015. These fires caused annual averages of 35 civilian injuries and cost $14 million in direct property damage (Campbell, 2017). Therefore, the fire protection systems of active and passive are advised to be installed in the building for human safety. Fire protection material is one of the passive building fire protection systems which is crucial in delaying the spread of fire, and thus increase the time for human lives to escape the building (Kodur et al., 2019).

The ‘classic' process of acid source + char former + blowing agent + binder has been used in the vast majority of intumescent coatings in recent years (Mazela et al,. 2020). It contains a large amount of organic compounds, and the foam that develops during intumescence is mainly carbonaceous char. Silicon-based

coatings containing expandable graphite and organoclay particles are among the more recent approaches. These systems have the advantage of producing a more mechanically and thermally stable residue after foaming, making them ideal to be applied at a higher temperatures areas or areas with higher concentrations of abrasive particles or corroding gases (Krueger et al., 2016). Fire-protective coatings for extreme conditions will continue to evolve as a result of increased demands, leading to the production of new materials.

Geopolymers have emerged as one of the most exciting materials in recent years. Geopolymer Binder (GB) is known for its outstanding thermal properties, so it has been used in many industrial applications and has drawn global marketing investments in many categories, such as resin, paint, binder, grout, cement, concrete, ceramic, panels and fiber reinforced composites. (Lahoti et al., 2019). GB material has been verified to demonstrate outstanding fire resistance properties (Basri et al., 2016), high mechanical strength (Neupane et al. 2018), high durability (Mohseni, 2018) and numerous aluminosilicates sources have been used such as fly ash, mekaolin, Palm Oil Fuel Ash (POFA) and dolomite (Zain et al., 2017). Geopolymers possessed high thermal stability and fire resistance properties and would be an ideal alternative to conventional intumescent paint due to their unique properties. However, there is still not as yet well establish research about the foaming process or intumescent of geopolymers.

Furthermore, the progressive global switch from non-renewable (fossil-based) to renewable (plant-based) raw materials has stepped up the hunt for alternative industrial raw materials. The paint and coating industry has also not excluded in this growing demand for renewable materials because several plant-based materials have been introduced, particularly as fillers (Bayer, 2020). Since these products are readily available, silica flour, kaolin, and calcium carbonate are probably the most commonly used fillers in the paint industry (Civancik-Uslu et al., 2018). Rice Husk Ash (RHA) with its known high silica content has a vast potential in offering an alternative to commercial paint as a filler or an additive. In recent studies, RHA has been shown to be ideal used as a filler. It is inexpensive and reusable, and certain mechanical properties of paints can be improved most significantly (Azadi et al., 2011).

Due to potential from previous studies, RHA could be next generation of geopolymer technology and environmentally friendly sources for paint filler or additive. The effective use of RHA-based aluminosilicate as a fire retardant (FR) additive therefore need to be studied so that an efficient coating produced can have maximum advantage. In this study, a novel formulations of RHA-based aluminosilicate FR additive for alkyd paint was developed. This coating is expected to contribute high mechanical properties and auspicious fire resistance properties. Thus, an eco-friendly, efficient, and green product can be produced and has extensive potential application in industry.

1.2 Problem Statement

The rising number of fire incidents in Malaysia has never stopped. From statistics in 2017 alone, 49 cases were reported and half of them involved fire fatalities and losses. On top of that, RM5 billion in losses nationwide was recorded by The Malaysian Fire and Rescue Department because of the fire incidents. According to the Malaysian Fire and Rescue Department deputy director-general (Operations) Datuk Soiman Jahid the losses amount increase up to RM1 billion compared to RM4 billion of the previous year (Bakar, 2018).

Moreover, the deadly fire incident at a religious school in Kampung Datuk Keramat shocked the nation that year. 23 people were killed in the fire at the Darul Quran Ittifaqiyah Tahfiz School (Sahalani, 2019). The incident has been dubbed the worst fire tragedy in the country in 20 years. Several fire incidents have occurred in Malaysia over the last five years, with the most notable cases depicted in Figure 1.1. The most recent incident, which occurred in 2020 at Sultanah Aminah Hospital Johor, demonstrates that Malaysians' awareness on fire safety is still lacking. Despite numerous fire outbreaks, Sultanah Aminah Hospital (HSA) still does not have a fire certificate issued by the Malaysian Fire and Rescue Department (Su-Lyn, 2020).

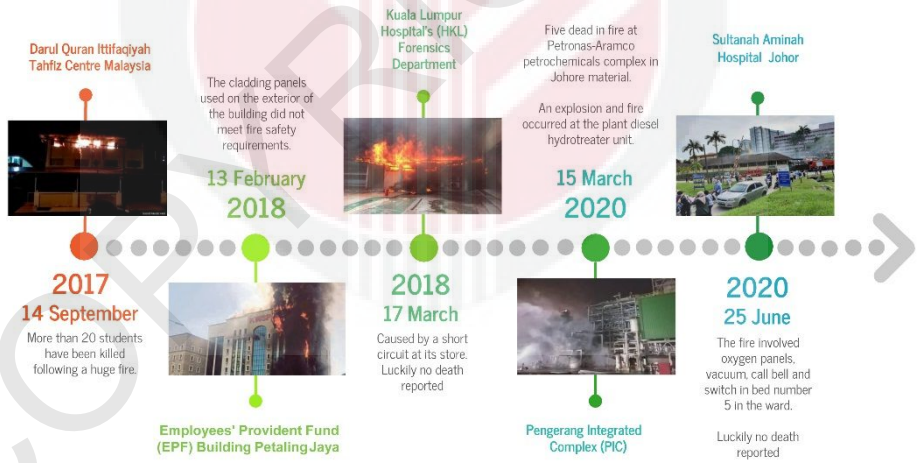

Figure 1.1: Notable cases of fire incident in Malaysia over the past five years.

Fire incidents occurred all over the world not only in Malaysia. One of the worst modern fire tragedies was Grenfell Tower in June 2017. A small refrigerator fire ravaged the 24-story Grenfell Tower apartment building in London. Seventy-one people were killed and was dubbed as Great Britain's deadliest fire incident in decades. An initial key finding of the inquiry's first report in 2019 was that the

external cladding that surrounded Grenfell Tower was largely responsible for the fire spreading so quickly (McKenna et al., 2019). Similar fire incidents also happened in Dubai Torch Tower that year, which involved highly-combustible external cladding panels. This incident demonstrated that the use of highly combustible exterior material leads to rapid fire spread and propagation along the building. More than 40 floors were burning on one side of the building and large quantities of flaming materials fell from the high-level fire which started a secondary fire at lower levels (Chet et al., 2019). Several fire incidents have occurred globally over the last five years, with the most notable cases depicted in Figure 1.2. Another infamous fire incidents was the Notre Dame Cathedral in which destroyed the symbol of the beauty and history of Paris. Approximately 400 firefighters battled the blaze for two days, saving the structure of the gothic cathedral after a fire gutted the roof and destroyed the spire. The blaze, which broke out in the early evening of April 15, 2019, stunned France and others from around the world (Glorennec et al., 2021).

.

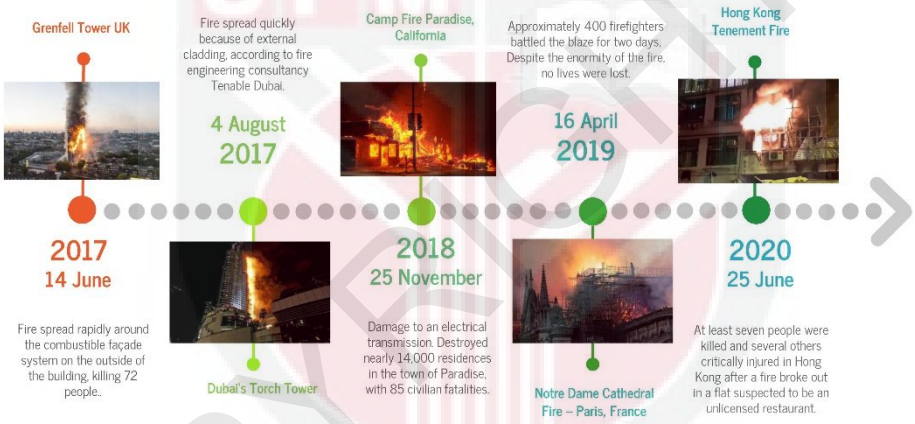

Figure 1.2: Notable cases of fire incident globally over the past five years.

From the data obtained from the Malaysian Fire and Rescue Department for 2017, 96.47% of 5,485 major incidents reported that structural or building fires were caused by accident. Meanwhile, the increase in total fire cases is reported in housing areas. Thus, the numbers highlighted the crucial fact of avoiding structural fires with high fire safety awareness within the community in residential buildings. This is because of the majority of structural fire incidents involved residential properties such as landed, high-rise, squatter and longhouse/traditional house with 60% cases, and followed by shop lots with 16% cases, stores with 12% cases, academic institution with 7% cases and public places with 5% cases as in Figure 1.3. Electrical, cooking gas, and unknown causes were reported as the top causes of residential fires (Chew, 2017).

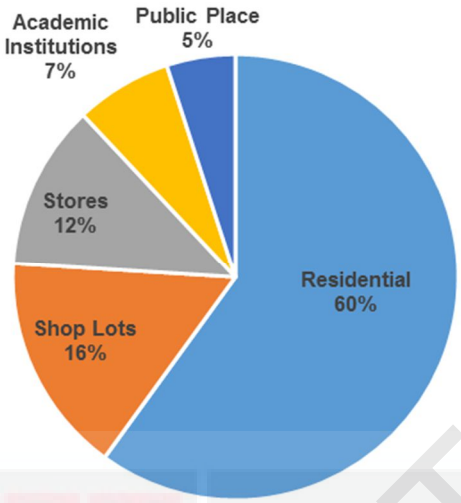

Figure 1.3: Fire incidents by premise types 2016. (Source: Chew, 2017)

In order to avoid a rise in the risk of fire, today's daily products including building materials, furniture, and clothing most made of FRs materials. However, some of these compounds present in the materials had adverse and harmful effects on the environment, hence leading to change to more eco-friendly alternatives in recent years. In the study by Chen et al. (2013), heat or ultraviolet light could decompose FR into potentially harmful compounds (Chen et al., 2013). In the past decades, several major research studies concluded that most FRs, especially halogenated FRs and Organophosphorus FRs are highlighted as major impacts towards environmental and health (Ali et al., 2018). Some of these products have been related to cancer and fertility issues. Moreover, during combustion, they induce an increase in smoke and corrosive gases.

Fire retardant systems that promote the formation of an insulating char layer on the surface of the burning sample are among the most promising environmentally friendly strategies for replacing halogenated fire retardants. In recent years, there has been an increasing interest on the development of a bio-based FRs. Researchers have discovered that Lignocellulosic Plant Fibers (LPF) have a natural defence behaviours against the aggression of fire. Rice husk (RH) which is categorized as a Lignocellulosic Plant Fibers, consist 35% cellulose, 25% hemicellulose, 20% lignin, 3% crude protein and 17% ash. In Malaysia, the Food and Agriculture Organization (FAO) reported that rice paddy production is estimated to increase 0.1 tons every year (Leong, 2015). The growing demand for rice paddy produced about 0.52 tons of RH annually (Macleon et al., 2002). While about 20% of the total grain weight obtained from the average husk weight. Therefore approximately 200 kilograms of husk produced from a ton of rough rice, which is considered as the biodegradable waste product in the rice mill industry and is commonly burned in the open area or dumped in landfills. Rice husk is known as a good source of renewable energy but if improperly incinerated could potentially lead to environmental pollution.

Furthermore, the utilisation of rice husk ash as an aluminosilicate source in fire-resistant coating could reduce the environmental pollution and can turn agricultural waste into industrial wealth. Therefore, an investigation on the addition of RHA-based aluminosilicate in alkyd paint as a FR additive is needed, with the attention of assessing the thermal and mechanical properties of the coating. In summary, below are the research questions formulated from the problem statement mentioned above, and these need to be answered by the end of this thesis;

i. In terms of thermal and mechanical properties, how synergistic is the use of RHA-based aluminosilicate addition in alkyd paint as a FR additive?
ii. What are the factors that will influence the ability of the RHA-based FR additive in thermal and mechanical test?
iii. What is the optimal formulation for RHA-based aluminosilicate FR additive in order to produce the best thermal and mechanical performance?
iv. Does the silica content in RHA-based aluminosilicate FR additive affects the insulating char layer on the surface of burning sample?

Despite the growing popularity of RHA in various applications, limited research has been devoted to identify the influence of several factors on the properties of RHA-based aluminosilicate. The effective use of RHA-based aluminosilicate as a fire retardant (FR) additive therefore need to be studied so that an efficient coating with good mechanical and auspicious fire properties can be produced. Rather than relying on the classic intumescent process for fire retardant material, an eco-friendly, efficient, and green product can be produced to replace the current existing halogen based fire retardant materials, which proved to be harmful to the environment and health. Ultimately, this research is targeted to enhance and fully utilized the usage of bio waste in FR coating applications.

1.3 Research Objectives

The overall objective of this research is to provide the necessary understanding for the development of an eco-friendly FR additive. Various parameters will be investigated to establish the effect on burning behaviour and the mechanical properties of the coating.

The specific objectives are:

i. To design experimental works using response surface methodology (RSM) on the thermal and mechanical properties of the addition of RHA-based FR additive in alkyd paint.
ii. To assess the microstructure behavior and material characterization of the RHA-based FR additive performance under thermal and mechanical test.
iii. To evaluate the optimum range for RHA-based FR additive, which produced the best thermal and mechanical performance.

iv. To compare the thermal performance of the RHA-based FR additive using commercial RHA and high purity RHA by investigating the relationship of different pre-treatment on the production of silica content from RH.

1.4 Scope and Limitation of Work

In achieving the objectives of this study, a series of experimental work were conducted. First, response surface methodology (RSM) were employed in experimental design and analysis. A different ratio of RHA-based aluminosilicate FR additive to alkyd paint were prepared. Then, the coating samples were then characterized into four main tests:

i. Thermal properties (Fire resistant test UL-1709)
ii. Thermal analysis by using thermogravimetry analysis (TGA)
iii. Morphological analysis by using scanning electron microscopy (SEM)
iv. Mechanical properties test (Tensile test, pull-off adhesion test, crosshatch adhesion test, water absorption test)

RH morphological analysis were studied. The parameters of the study are the different pre-treatment through chemical pre-treatment and combustion process on the production of high purity, RHA composition. The collected rice husk was pre-treated with distilled water and hydrochloric acid (HCl) separately. Then, RH are burned in furnace with a temperature of 600°C and 1000°C for duration of one hour and two hours. Subsequently, the RHA are characterize into three main analysis.

i. Analysis of high-energy radiation by using X-ray fluorescence (XRF) is involved for element characterization.
ii. Microscopy analysis by using scanning electron microscope (SEM).
iii. Phase identification analysis by using X-ray Powder Diffraction (XRD).

The major limitations in this study that could be addressed in future research is this study only focused on using RHA to act as a thermal insulation layer source in paint. Other agricultural waste with high silica content could be an alternative resource to replace RHA. Moreover, the development of RHA-based aluminosilicate FR was focused to be incorporated with oil based paint. Further development of formulations should consider the use of a different type of paint such as latex paint. Further research on incorporating the FR additive with latex paint would be useful in order to broaden the potential application of the FR additive

1.5 Thesis Outline

This thesis consists of six chapters. Chapter one discusses the background of the research and problem statement on the current fire retardant materials. The research objectives, scope, limitation of work and outline of the dissertation.

Chapter two presents the extensive review related to the knowledge of this study including of the composition of paints, composition of RHA, factors that influence RHA properties, effect of pre-treatment on RH which affects the mechanical properties of RHA-based paint. The properties of intumescent coating and intumescent phenomenon, as well as the preparation methods are also presented. Literature review on the properties of intumescent coating related to the current study are presented to gauge the development of intumescent coating research. Review on related studies that have been carried out and reported previously for geopolymer, properties of geopolymer were also presented in this chapter. Statistical design method including response surface methodology (RSM) were also reviewed.

Chapter three illustrates the experiment work, materials used, equipment required and sample preparation of the coating samples are described. The mechanical properties, thermal testing and morphological study involved are reported in detail.

Results and discussions are presented in chapter four that includes the thermal properties test, mechanical test, microstructure analysis and fire resistance test. The results are shown in graph and table and supported by statistical data through ANOVA technique. Afterwards, the mathematical model is developed and compared with experimental results. The thermal properties comparison for commercially available RHA and optimum RHA is presented in chapter five. Eight different samples of RHA were analysed to obtain optimal silica content. Samples were analysed through element characterization surface characterization and phase identification.

Finally in chapter six, the conclusions on the mechanical properties and thermal properties of RHA-based aluminosilicate FR on steel substrate are drawn. The effects silica content on the formation of char layer are also summarized. Finally, contribution, and recommendations for future research are also presented.

REFERENCES

Abdullah, M. M. A. B., Hussin, K., Bnhussain, M., Ismail, K. N., Yahya, Z., & Abdul Razak, R. (2012). Fly ash-based geopolymer lightweight concrete using foaming agent. International journal of molecular sciences, 13(6), 7186-7198.

Adam, F., Balakrishnan, S., & Wong, P. L. (2006). Rice husk ash silica as a support material for ruthenium based heterogenous catalyst. Journal of Physical Science, 17(2), 1-13.

Ahsan, M. B. (2017). Performance evaluation of rice husk ash (RHA) modified concrete. Arkansas State University.

Aksu, R., & Saygi, B. (2019). Investigation of Silica Aerogels Effect on Paint Characteristics. European Journal of Engineering and Natural Sciences, 3(2), 139-146.

Ali, M. S., Hanim, M. A., Tahir, S. M., Jaafar, C. N. A., Mazlan, N., & Amin Matori, K. (2017). The effect of commercial rice husk ash additives on the porosity, mechanical properties, and microstructure of alumina ceramics. Advances in Materials Science and Engineering, 2017.

Ali, N., Ismail, I. M. I., Kadi, M. W., & Albar, H. M. S. A. (2018). Currently used organophosphate flame retardants determined in the settled dust of masjids and hotels of Saudi Arabia, a new insight into human health implications of dust exposure. Environmental Science: Processes & Impacts, 20(5), 798-805.

Anderson, M. J., & Whitcomb, P. J. (2017). DOE simplified: practical tools for effective experimentation. CRC press.

Anderson JR, C. E., Dziuk JR, J., Mallow, W. A., & Buckmaster, J. (1985). Intumescent reaction mechanisms. Journal of Fire Sciences, 3(3), 161-194.

Anees, S. M., & Dasari, A. (2018). A review on the environmental durability of intumescent coatings for steels. Journal of Materials Science, 53(1), 124-145.

Awolusi, T. F., Oke, O. L., Akinkurolere, O. O., & Sojobi, A. O. (2019). Application of response surface methodology: Predicting and optimizing the properties of concrete containing steel fibre extracted from waste tires with limestone powder as filler. Case studies in Construction materials, 10.

Azadi, M., Bahrololoom, M. E., & Heidari, F. (2011). Enhancing the mechanical properties of an epoxy coating with rice husk ash, a green product. Journal of coatings technology and research, 8(1), 117-123.

Azani, Y. M., Adlina, S., Alias, Y. M., Vikneswaran, M., Aida, J., Halyna, L., & Aishah, A. S. N. (2020). Perception of Security Protection Using Grill for Building. International Journal of Social Science Research, 2(2), 154-161.

Azat, S., Sartova, Z., Bekseitova, K., & Askaruly, K. (2019). Extraction of high-purity silica from rice husk via hydrochloric acid leaching treatment. Turkish Journal of Chemistry, 43(5), 1258-1269.

Aziz, H., & Ahmad, F. (2016). Effects from nano-titanium oxide on the thermal resistance of an intumescent fire retardant coating for structural applications. Progress in Organic Coatings, 101, 431-439.

Aziz, I. H., Abdullah, M. M. A. B., Yong, H. C., Ming, L. Y., Panias, D., & Sakkas, K. (2017, June). Correlation of the processing parameters in the formation of granulated ground blast furnace slag geopolymer. In IOP Conference Series: Materials Science and Engineering (Vol. 209, No. 1, p. 012040). IOP Publishing.

Bakar, B. (2018, February 5), M'sians suffered RM5.2 billion in fire-related property losses last year. New Straits Times. https://www.nst.com.my/news/nation/2018/02/332315/msians-suffered-rm52-billion-fire-related-property-losses-last-year

Bakar, R. A., Yahya, R., & Gan, S. N. (2016). Production of high purity amorphous silica from rice husk. Procedia Chemistry, 19, 189-195.

Balard, H., & Papirer, E. (1993). Characterization and modification of fillers for paints and coatings. Progress in organic coatings, 22(1-4), 1-17.

Basri, M. S. B. M. (2016). Development of Rice Husk Ash-Based Geopolymer Binder for Fire Resistant Coating. (Doctoral dissertation, UPM)

Basri, M., Salahuddin, M., Mustapha, F., Mazlan, N., & Ishak, M. R. (2016). Fire Retardant performance of rice husk ash-based geopolymer coated mild steel-A factorial design and microstructure analysis. In Materials Science Forum (Vol. 841, pp. 48-54). Trans Tech Publications Ltd.

Basri, M. S., Mustapha, F., Mazlan, N., & Ishak, M. R. (2020). Optimization of Adhesion Strength and Microstructure Properties by Using Response Surface Methodology in Enhancing the Rice Husk Ash-Based Geopolymer Composite Coating. Polymers, 12(11), 2709.

Bayer, I. S. (2020). Superhydrophobic coatings from ecofriendly materials and processes: a review. Advanced Materials Interfaces, 7(13), 2000095.

Beg, S., Swain, S., Rahman, M., Hasnain, M. S., & Imam, S. S. (2019). Application of design of experiments (DoE) in pharmaceutical product and process optimization. In Pharmaceutical quality by design (pp. 43-64). Academic Press.

Beh, J. H., Yew, M. C., Yew, M. K., & Saw, L. H. (2019). Fire Protection Performance and Thermal Behavior of Thin Film Intumescent Coating. Coatings, 9(8), 483.

Bell, J. L., Driemeyer, P. E., & Kriven, W. M. (2009). Formation of ceramics from metakaolin-based geopolymers: part I—Cs-based geopolymer. Journal of the American Ceramic Society, 92(1), 1-8.

Bentley, J. (2001). Composition, manufacture and use of paint (pp. 123-142). Taylor and Francis, Inc.: New York.

Bezerra, M. A., Santelli, R. E., Oliveira, E. P., Villar, L. S., & Escaleira, L. A. (2008). Response surface methodology (RSM) as a tool for optimization in analytical chemistry. Talanta, 76(5), 965-977.

Billong, N., Kinuthia, J., Oti, J., & Melo, U. C. (2018). Performance of sodium silicate free geopolymers from metakaolin (MK) and Rice Husk Ash (RHA): Effect on tensile strength and microstructure. Construction and Building Materials, 189, 307-313.

Boateng, A. A., & Skeete, D. A. (1990). Incineration of rice hull for use as a cementitious material: The Guyana experience. Cement and Concrete Research, 20(5), 795-802.

Bourbigot, S., Le Bras, M., & Delobel, R. (1993). Carbonization mechanisms resulting from intumescence association with the ammonium polyphosphate-pentaerythritol fire retardant system. Carbon, 31(8), 1219-1230.

Brock, T., Groteklaes, M., & Mischke, P. (2000). European coatings handbook. Vincentz Network GmbH & Co KG.

Bromann, M. (2016). Fire protection for commercial facilities. CRC Press.

Campbell, R. B. (2017). Structure fires in dormitories, fraternities, sororities and barracks. National Fire Protection Association. Fire Analysis and Research Division.

Castrovinci, A., Camino, G., Drevelle, C., Duquesne, S., Magniez, C., & Vouters, M. (2005). Ammonium polyphosphate–aluminum trihydroxide antagonism in fire retarded butadiene–styrene block copolymer. European Polymer Journal, 41(9), 2023-2033.

Chakraverty, A., Mishra, P., & Banerjee, H. D. (1988). Investigation of combustion of raw and acid-leached rice husk for production of pure amorphous white silica. Journal of Materials Science, 23(1), 21-24.

Chandrasekhar, S. A. T. H. Y., Satyanarayana, K. G., Pramada, P. N., Raghavan, P., & Gupta, T. N. (2003). Review processing, properties and applications of reactive silica from rice husk—an overview. Journal of materials science, 38(15), 3159-3168.

Chen, D., Letcher, R. J., Gauthier, L. T., & Chu, S. (2013). Tetradecabromodiphenoxybenzene flame retardant undergoes photolytic debromination. Environmental science & technology, 47(3), 1373-1380.

Chen, T. B. Y., Yuen, A. C. Y., Yeoh, G. H., Yang, W., & Chan, Q. N. (2019). Fire risk assessment of combustible exterior cladding using a collective numerical database. Fire, 2(1), 11.

Chen, X., Kirsch, B. L., Senter, R., Tolbert, S. H., & Gupta, V. (2009). Tensile testing of thin films supported on compliant substrates. Mechanics of materials, 41(7), 839-848.

Cheng, T. W., & Chiu, J. P. (2003). Fire-resistant geopolymer produced by granulated blast furnace slag. Minerals engineering, 16(3), 205-210.

Cheumani Yona, A. M., Žigon, J., Dahle, S., & Petric, M. (2021). Study of the adhesion of silicate-based coating formulations on a wood substrate. Coatings, 11(1), 61.

Chew, R. (2017). Majority of Structural Fires Can Be Avoided. https://www.theedgemarkets.com/article/majority-structural-fires-can-be-avoided.

Chindaprasirt, P., Jaturapitakkul, C., Chalee, W., & Rattanasak, U. (2009). Comparative study on the characteristics of fly ash and bottom ash geopolymers. Waste management, 29(2), 539-543.

Cicková, Z., Vojtková, M., & Reiff, M. (2019). Determination of the Control Parameters of Evolutionary Techniques Utilizing Analysis of Variance. TEM Journal, 8(3), 951.

Cioffi, R., Maffucci, L., & Santoro, L. (2003). Optimization of geopolymer synthesis by calcination and polycondensation of a kaolinitic residue. Resources, Conservation and Recycling, 40(1), 27-38.

Civancik-Uslu, D., Ferrer, L., Puig, R., & Fullana-i-Palmer, P. (2018). Are functional fillers improving environmental behavior of plastics? A review on LCA studies. Science of the total environment, 626, 927-940.

Cullis, C. F., Hirschler, M. M., & Rogers, R. L. (1981). The oxidation of decane in the liquid and gaseous phases. Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences, 375(1763), 543-563.

Das, R., Ghosh, S., & Naskar, M. K. (2014). Synthesis of single crystal zeolite L rods with high aspect ratio using rice husk ash as silica source. Indian Journal Of Chemistry Section A-Inorganic Bio-Inorganic Physical Theoretical & Analytical Chemistry, 53(7), 816-819.

Davidovits, J. (1989). Geopolymers and geopolymeric materials. Journal of thermal analysis, 35(2), 429-441.

Davidovits, J. (1991). Geopolymers: inorganic polymeric new materials. Journal of Thermal Analysis and calorimetry, 37(8), 1633-1656.

Davidovits, J. (2002, October). Years of successes and failures in geopolymer applications. Market trends and potential breakthroughs. In Geopolymer 2002 conference (Vol. 28, p. 29). Saint-Quentin, France; Melbourne, Australia: Geopolymer Institute.

Dawkins, J., Gautam, L., Bandey, H., Armitage, R., & Ferguson, L. (2020). The effect of paint type on the development of latent fingermarks on walls. Forensic science international, 309, 110186.

Dehan, V., Bourgeat-Lami, E., d'Agosto, F., Duffy, B., Fortini, A., Hilton, S., ... & Thomas, B. (2017). High-performance water-based barrier coatings for the corrosion protection of structural steel. Steel Construction, 10(3), 254-259.

Della, V. P., Kühn, I., & Hotza, D. (2002). Rice husk ash as an alternate source for active silica production. Materials letters, 57(4), 818-821.

Dilim, I. O. C. (2016). Formulation of Matt Wood Varnish Using Rice Husk Ash as a Flatting Agent. Int. J. Chem. Sci.: 14(3), 1683-1697.

Emad, S. G. R., Zhou, X., Morsch, S., Lyon, S. B., Liu, Y., Graham, D., & Gibbon, S. R. (2019). How pigment volume concentration (PVC) and particle connectivity affect leaching of corrosion inhibitive species from coatings. Progress in Organic Coatings, 134, 360-372.

Farooq, M., Bhutta, A., & Banthia, N. (2019). Tensile performance of eco-friendly ductile geopolymer composites (EDGC) incorporating different micro-fibers. Cement and Concrete Composites, 103, 183-192.

Fernandes, I. J., Calheiro, D., Sánchez, F. A., Camacho, A. L. D., Rocha, T. L. A. D. C., Moraes, C. A. M., & Sousa, V. C. D. (2017). Characterization of silica produced from rice husk ash: comparison of purification and processing methods. Materials Research, 20, 512-518.

Ferreira, S. L. C., Bruns, R. E., da Silva, E. G. P., Dos Santos, W. N. L., Quintella, C. M., David, J. M., ... & Neto, B. B. (2007). Statistical designs and response surface techniques for the optimization of chromatographic systems. Journal of chromatography A, 1158(1-2), 2-14.

Fletcher, R. A., MacKenzie, K. J., Nicholson, C. L., & Shimada, S. (2005). The composition range of aluminosilicate geopolymers. Journal of the European Ceramic Society, 25(9), 1471-1477.

Garaniya, V., Lim, J. W., Baalisampang, T., & Abbassi, R. (2020). Numerical assessment of passive fire protection in an oil and gas storage facility. In Advances in Industrial Safety (pp. 1-21). Springer, Singapore.

Gilman, J. W., Kashiwagi, T., & Lichtenhan, J. D. (1997, May). Nanocomposites: a revolutionary new flame retardant approach. In International Sampe Symposium and Exhibition (Pp. 1078-1089). Sampe Society for the Advancement of Material.

Glorennec, P., Azema, A., Durand, S., Ayrault, S., & Le Bot, B. (2021). The Isotopic Signature of Lead Emanations during the Fire at Notre Dame Cathedral in Paris, France. International journal of environmental research and public health, 18(10), 5420.

Gonçalves, M. R. F., & Bergmann, C. P. (2007). Thermal insulators made with rice husk ashes: Production and correlation between properties and microstructure. Construction and Building Materials, 21(12), 2059-2065.

Grillet, A. M., Wyatt, N. B., & Gloe, L. M. (2012). Polymer gel rheology and adhesion. Rheology, 3, 59-80.

Gu, J. W., Zhang, G. C., Dong, S. L., Zhang, Q. Y., & Kong, J. (2007). Study on preparation and fire-retardant mechanism analysis of intumescent flame-retardant coatings. Surface and coatings technology, 201(18), 7835-7841.

Habeeb, G. A., & Fayyadh, M. M. (2009). Rice husk ash concrete: the effect of RHA average particle size on mechanical properties and drying shrinkage. Australian Journal of Basic and Applied Sciences, 3(3), 1616-1622.

Hamzah, H. N., Abdullah, M. M. A. B., Yong, H. C., Zainol, M. R. R. M. A., Nor, A. M., & Wazien, A. W. (2016). Correlation of the Na2SiO3 to NaOH Ratios and Solid to Liquid Ratios to the Kedah's Soil Strength. In MATEC Web of Conferences (Vol. 78, p. 01071). EDP Sciences.

Hanrahan, G., & Lu, K. (2006). Application of factorial and response surface methodology in modern experimental design and optimization. Critical Reviews in Analytical Chemistry, 36(3-4), 141-151.

Hao, J., & Chow, W. K. (2003). A brief review of intumescent fire retardant coatings. Architectural science review, 46(1), 89-95.

Hartzell, G. E. (2001). Engineering analysis of hazards to life safety in fires: the fire effluent toxicity component. Safety Science, 38(2), 147-155.

Heller, B. (1986). Statistics for experimenters, an introduction to design, data analysis, and model building: GEP Box, WG Hunter and JS Hunter, John Wiley and Sons, New York, NY. 1978.

Hussein, M. Z., Al Ali, S. H., Zainal, Z., & Hakim, M. N. (2011). Development of antiproliferative nanohybrid compound with controlled release property using ellagic acid as the active agent. International Journal of Nanomedicine, 6, 1373.

Igwebike-Ossi, C. D. (2011). Effects of Combustion Temperature and Time on the Physical and Chemical Properties of Rice Husk Ash and its Application as Extender in Paints (Doctoral dissertation, University Of Nigeria Nsukka).

Igwebike-Ossi, C. D. (2017). Elemental Analysis of Rice Husk Using Proton-Induced X-Ray Emission (Pixe) Spectrometry. International Journal of Applied Chemistry, 13(4), 801-811.

James, J., & Rao, M. S. (1986). Silica from rice husk through thermal decomposition. Thermochimica acta, 97, 329-336.

Jaya, R. P., Nor, M. A. A. M., Ahmad, Z. A., & Amin, Z. M. (2013). Properties of mortar containing rice husk ash at different temperature and exposed to aggressive environment. In Advanced Materials Research (Vol. 620, pp. 87-93). Trans Tech Publications Ltd.

Jimenez, M., Duquesne, S., & Bourbigot, S. (2006). Multiscale experimental approach for developing high-performance intumescent coatings. Industrial & engineering chemistry research, 45(13), 4500-4508.

Junaidi, M. U. M., Ahmad, N. N. R., Leo, C. P., & Yee, H. M. (2016). Near superhydrophobic coating synthesized from rice husk ash: anti-fouling evaluation. Progress in Organic Coatings, 99, 140-146.

Kaharudin, K. E., Salehuddin, F., Zain, A. S. M., & Aziz, M. N. I. A. (2017). Comparison of Taguchi method and central composite design for optimizing process parameters in vertical double gate MOSFET. ARPN Journal of Engineering and Applied Sciences, 12(19), 5578-5590.

Kajimoto, T., Hata, T., Ishihara, S., Kawai, S., & Getto, H. (1998). Improving fire retardancy of fast growing wood by coating with fire retardant and surface densification. Fire and materials, 22(5), 207-212.

Karakas, F., & Çelik, M. S. (2018). Stabilization mechanism of main paint pigments. Progress in Organic Coatings, 123, 292-298.

Karami, S., Motahari, S., Pishvaei, M., & Eskandari, N. (2018). Improvement of thermal properties of pigmented acrylic resin using silica aerogel. Journal of Applied Polymer Science, 135(1), 45640.

Khan, K. A., Raut, A., Chandrudu, C. R., & Sashidhar, C. (2019). Mechanical and water transport performance of sustainable geopolymer composite using binary blends of pozzolanic materials. Jurnal Teknologi, 81(5).

Khan, W., Shehzada, K., Bibi, T., Islam, S. U., & Khan, S. W. (2018). Performance evaluation of Khyber Pakhtunkhwa Rice Husk Ash (RHA) in improving mechanical behavior of cement. Construction and Building Materials, 176, 89-102.

Kiakojouri, F., De Biagi, V., Chiaia, B., & Sheidaii, M. R. (2020). Progressive collapse of framed building structures: Current knowledge and future prospects. Engineering Structures, 206, 110061.

Kodur, V., Kumar, P., & Rafi, M. M. (2019). Fire hazard in buildings: review, assessment and strategies for improving fire safety. PSU Research Review.

Koleske, J. V. (2006). Mechanical properties of solid coatings. Encyclopedia of Analytical Chemistry: Applications, Theory and Instrumentation.

Koleske, J. V., Springate, R., & Brezinski, D. (2011). Additives Handbook. Paints & Coatings Industry.

Kong, D. L., Sanjayan, J. G., & Sagoe-Crentsil, K. (2007). Comparative performance of geopolymers made with metakaolin and fly ash after exposure to elevated temperatures. Cement and concrete research, 37(12), 1583-1589.

Krishnarao, R. V., Subrahmanyam, J., & Kumar, T. J. (2001). Studies on the formation of black particles in rice husk silica ash. Journal of the European Ceramic Society, 21(1), 99-104.

Krueger, S., Gluth, G. J., Watolla, M. B., Morys, M., Haessler, D., & Schartel, B. (2016). New ways: reactive fire protection coatings for extreme conditions. Bautechnik, 93(8), 531-542.

Kurama, H., & Kurama, S. K. (2003). The effect of chemical treatment on the production of active silica from rice husk. In 18th international mining congress and exhibition of Turkey-IMCET (pp. 431-435).

Kurt, I., Acar, I., & Güçlü, G. (2014). Preparation and characterization of water reducible alkyd resin/colloidal silica nanocomposite coatings. Progress in Organic Coatings, 77(5), 949-956.

Kurtoglu, A. E., Alzeebaree, R., Aljumaili, O., Nis, A., Gulsan, M. E., Humur, G., & Cevik, A. (2018). Mechanical and durability properties of fly ash and slag based geopolymer concrete. Advances in concrete construction, 6(4), 345.

Kwang Yin, J. J., Yew, M. C., Yew, M. K., & Saw, L. H. (2019). Preparation of intumescent fire protective coating for fire rated timber door. Coatings, 9(11), 738.

Lahoti, M., Tan, K. H., & Yang, E. H. (2019). A critical review of geopolymer properties for structural fire-resistance applications. Construction and Building Materials, 221, 514-526.

Lee, J. H., Kwon, J. H., Lee, J. W., Lee, H. S., Chang, J. H., & Sang, B. I. (2017). Preparation of high purity silica originated from rice husks by chemically removing metallic impurities. Journal of Industrial and Engineering Chemistry, 50, 79-85.

Lee, J. S. (2019). Investigation of Water-based and Solvent-based Polymer Binders on the Fire Protection Performance and Mechanical Properties of Intumescent Coating (Doctoral dissertation, UTAR).

Leong, T. L. (2015). Effects of Rice Husk Ash (RHS) Produced from Different Temperatures on the Performances of Concrete (Doctoral dissertation, UTAR).

Li, J., Zhuang, X., Querol, X., Font, O., & Moreno, N. (2018). A review on the applications of coal combustion products in China. International geology review, 60(5-6), 671-716.

Li, N., Xia, Y., Mao, Z., Wang, L., Guan, Y., & Zheng, A. (2013). Synergistic effect of SiO2 on intumescent flame-retardant polypropylene. Polymers and Polymer Composites, 21(7), 439-448.

Lotfy, W. A., Ghanem, K. M., & El-Helow, E. R. (2007). Citric acid production by a novel Aspergillus niger isolate: II. Optimization of process parameters through statistical experimental designs. Bioresource technology, 98(18), 3470-3477.

Lucherini, A., & Maluk, C. (2019). Intumescent coatings used for the fire-safe design of steel structures: A review. Journal of Constructional Steel Research, 162, 105712.

Luna-Galiano, Y., Cornejo, A., Leiva, C., Vilches, L. F., & Fernández-Pereira, C. (2015). Properties of fly ash and metakaolín based geopolymer panels under fire resistance tests. Materiales de Construcción, 65(319), 059.

McKenna, S. T., Jones, N., Peck, G., Dickens, K., Pawelec, W., Oradei, S., & Hull, T. R. (2019). Fire behaviour of modern façade materials–Understanding the Grenfell Tower fire. Journal of hazardous materials, 368, 115-123.

MacKenzie, K. J., Bradley, S., Hanna, J. V., & Smith, M. E. (2013). Magnesium analogues of aluminosilicate inorganic polymers (geopolymers) from magnesium minerals. Journal of Materials Science, 48(4), 1787-1793.

Maclean, J. L., Dawe, D. C., Hettel, G. P., & Hardy, B. (Eds.). (2002). Rice almanac: Source book for the most important economic activity on earth. Int. Rice Res. Inst.

Mariappan, T. (2017). Fire Retardant Coatings. New Technologies in Protective Coatings, [Carlos Giudice and Guadalupe Canosa, IntechOpen], 101-122.

Mazela, B., Batista, A., & Grzeskowiak, W. (2020). Expandable Graphite as a Fire Retardant for Cellulosic Materials—A Review. Forests, 11(7), 755.

Meurant, G. (1993). Atmospheric oxidation and antioxidants. Elsevier Science.

Mohsen, Q., & Mostafa, N. Y. (2010). Investigating the possibility of utilising low kaolinitic clays in production of geopolymer bricks. Ceramics-Silikaty, 54(2), 160-168.

Møller, V. B., Dam-Johansen, K., Frankær, S. M., & Kiil, S. (2017). Acid-resistant organic coatings for the chemical industry: a review. Journal of Coatings Technology and Research, 14(2), 279-306.

Montgomery, D. C. (2017). Design and analysis of experiments. John Wiley & Sons.

Morgan, A. B., & Wilkie, C. A. (Eds.). (2007). Flame retardant polymer nanocomposites. John Wiley & Sons.

Morgans, W. M. (1990). Outlines of paint technology. Wiley.

Mouritz, A. P., & Gibson, A. G. (2007). Fire properties of polymer composite materials (Vol. 143). Springer Science & Business Media.

Naqi, A., & Jang, J. G. (2019). Recent progress in green cement technology utilizing low-carbon emission fuels and raw materials: A review. Sustainability, 11(2), 537.

Nematollahi, B., Qiu, J., Yang, E. H., & Sanjayan, J. (2017). Microscale investigation of fiber-matrix interface properties of strain-hardening geopolymer composite. Ceramics International, 43(17), 15616-15625.

Neupane, K., Chalmers, D., & Kidd, P. (2018). High-strength geopolymer concrete—properties, advantages and challenges. Advances in Materials, 7(2), 15-25.

Nguyen, H. T., Gallardo, S. M., Bacani, F., Hinode, H., Do, Q. M., & Promentilla, M. A. (2015). Evaluating thermal properties of geopolymer produced from red mud, rice husk ash and diatomaceous earth. ASEAN Engineering Journal, 4(1), 51-65.

Norvaišiene, R., Burlingis, A., & Stankevicius, V. (2010). Durability tests on painted facade rendering by accelerated ageing. Materials Science (Medžiagotyra), 16(1).

Nourbakhsh, A., Baghlani, F. F., & Ashori, A. (2011). Nano-SiO2 filled rice husk/polypropylene composites: physico-mechanical properties. Industrial Crops and Products, 33(1), 183-187.

Nwakaudu, M.S.; Oghome, P. (2012). Production of Paint from Locally Sourced Raw Materials. International Journal of Science and Engineering Investigations vol. 1, issue.

Oladipo, G. O., Eromosele, I. C., & Folarin, O. M. (2013). Formation and characterization of paint based on alkyd resin derivative of Ximenia americana (wild olive) seed oil. Environment and Natural Resources Research, 3(3), 52.

Olawoyin, R. (2018). Nanotechnology: The future of fire safety. Safety science, 110, 214-221.

Oliveira, R. B. R. S., Moreno Junior, A. L., & Vieira, L. C. M. (2017). Intumescent paint as fire protection coating. Revista IBRACON de Estruturas e Materiais, 10(1), 220-231.

Pimenta, J. T., Gonçalves, C., Hiliou, L., Coelho, J. F., & Magalhaes, F. D. (2016). Effect of binder on performance of intumescent coatings. Journal of coatings technology and research, 13(2), 227-238.

Ploeger, R., Scalarone, D., & Chiantore, O. (2009). Thermal analytical study of the oxidative stability of artists' alkyd paints. Polymer Degradation and Stability, 94(11), 2036-2041.

Politis, S., Colombo, P., Colombo, G., & M. Rekkas, D. (2017). Design of experiments (DoE) in pharmaceutical development. Drug development and industrial pharmacy, 43(6), 889-901.

Prasad, C. S., Maiti, K. N., & Venugopal, R. (2001). Effect of rice husk ash in whiteware compositions. Ceramics international, 27(6), 629-635.

Prasetyoko, D., Ramli, Z., Endud, S., Hamdan, H., & Sulikowski, B. (2006). Conversion of rice husk ash to zeolite beta. Waste management, 26(10), 1173-1179.

Puri, R. G., & Khanna, A. S. (2017). Intumescent coatings: A review on recent progress. Journal of Coatings Technology and Research, 14(1), 1-20.

Purser, D. (2001). Toxicity of fire retardants in relation to life safety and environmental hazards. Fire retardant materials, 69-127.

Puspitasari, W. C. (2010). The study of adhesion bonding between stell substitute and instrument coating (Doctoral dissertation, Universiti Teknologi PETRONAS).

Ramadhansyah, P. J., Mahyun, A. W., Salwa, M. Z., Bakar, A., Johari, M., & Wan Ibrahim, M. H. (2012). Thermal analysis and pozzolanic index of rice husk ash at different grinding time.

Rasaki, S. A., Bingxue, Z., Guarecuco, R., Thomas, T., & Minghui, Y. (2019). Geopolymer for use in heavy metals adsorption, and advanced oxidative processes: A critical review. Journal of Cleaner Production, 213, 42-58.

Real, C., Alcala, M. D., & Criado, J. M. (1996). Preparation of silica from rice husks. Journal of the American ceramic society, 79(8), 2012-2016.

Rhodes, J. (2012). Fire protection of surface coatings (Doctoral dissertation, University of central Lancashire).

Rickard, W. D., Temuujin, J., & van Riessen, A. (2012). Thermal analysis of geopolymer pastes synthesised from five fly ashes of variable composition. Journal of non-crystalline solids, 358(15), 1830-1839.

Rodriguez, E. D., Bernal, S. A., Provis, J. L., Gehman, J. D., Monzó, J. M., Payá, J., & Borrachero, M. V. (2013). Geopolymers based on spent catalyst residue from a fluid catalytic cracking (FCC) process. Fuel, 109, 493-502.

Romagnoli, M., & Andreola, F. (2007). Mixture of deflocculants: A systematic approach. Journal of the European Ceramic Society, 27(2-3), 1871-1874.

Rosace, G., Castellano, A., Trovato, V., Iacono, G., & Malucelli, G. (2018). Thermal and flame retardant behaviour of cotton fabrics treated with a novel nitrogen-containing carboxyl-functionalized organophosphorus system. Carbohydrate polymers, 196, 348-358.

Sahalani, I. M. B. (2019). Design and development of mobile applications for automatic window grill with fire alarm system.

Saxena, M., Asokan, P., & Tiwari, S. (2004). New Raw Materials for Bio Composites and Paints. Recent Trends in Building Materials, RTBM (2004), 17-27.

Schoff, C. K. (2017). Craters and Other Coatings Defects: Mechanisms and Analysis. In Protective Coatings (pp. 403-425). Springer, Cham.

Sekifuji, R., Le Van, C., & Tateda, M. (2017). Case study of fire flame resistance improvement of a plywood board coated with paint containing added rice husk amorphous silica. Journal of Scientific Research and Reports, 1-9.

Sharma, A., & Ahmad, J. (2017). Factors affecting compressive strength of geopolymer concrete-a review. Int. Res. J. Eng. Technol, 4(5), 2026-2031.

Shaw, S. (2010). Halogenated flame retardants: do the fire safety benefits justify the risks?. Reviews on environmental health, 25(4), 261-306.

Shebeko, Y. N., Bolodian, I. A., Filippov, V. N., Navzenya, V. Y., Kostyuhin, A. K., Tokarev, P. M., & Zamishevski, E. D. (2000). A study of the behaviour of a protected vessel containing LPG during pool fire engulfment. Journal of hazardous materials, 77(1-3), 43-56.

Shinohara, Y., & Kohyama, N. (2004). Quantitative analysis of tridymite and cristobalite crystallized in rice husk ash by heating. Industrial health, 42(2), 277-285.

Singh, B. J. (2014). RSM: A Key to Optimize Machining: Multi-Response Optimization of CNC Turning with Al-7020 Alloy. Anchor Academic Publishing (aap_verlag).

Sittinun, A., Chang, Y. H., & Ummartyotin, S. (2021). Development of geopolymer derived from slag waste based composite film on cotton fabric: A preliminary approach for flame retardant behavior. Materialia, 15, 101052.

Soleimani, M. A., Naghizadeh, R., Mirhabibi, A. R., & Golestanifard, F. (2012). Effect of calcination temperature of the kaolin and molar Na2O/SiO2 activator ratio on physical and microstructural properties of metakaolin based geopolymers. Iranian journal of materials science and engineering, 9(4), 43-51.

Solomon, D., Kiflie, Z., & Van Hulle, S. (2020). Using Box–Behnken experimental design to optimize the degradation of Basic Blue 41 dye by Fenton reaction. International Journal of Industrial Chemistry, 11(1), 43-53.

Srinivasan, K., & Sivakumar, A. (2013). Geopolymer binders: a need for future concrete construction. International Scholarly Research Notices, 2013.

Stroganov, V. F., & Amel'chenko, M. O. (2019). The Effect of the Mechanical Activation of Silicate Nature Fillers on the Properties of Styrene—Acrylic Polymer Coatings. Polymer Science, Series D, 12(3), 227-230.

Su-Lyn, B. (2020, July 1), After Six Fires, Sultanah Aminah Hospital Still Lacks Fire Cert. CodeBlue. https://codeblue.galencentre.org/2020/07/01/after-six-fires-sultanah-aminah-hospital-still-lacks-fire-cert/

Tadros, T. F. (Ed.). (2011). Colloids in paints (Vol. 6). John Wiley & Sons.

Tan, Y. R., Akashah, F. W., & Mahyuddin, N. (2016). The analysis of fire losses and characteristics of residential fires based on investigation data in Selangor, 2012-2014. In MATEC Web of Conferences (Vol. 66, p. 00109). EDP Sciences.

Tarley, C. R. T., Silveira, G., dos Santos, W. N. L., Matos, G. D., da Silva, E. G. P., Bezerra, M. A., ... & Ferreira, S. L. C. (2009). Chemometric tools in electroanalytical chemistry: methods for optimization based on factorial design and response surface methodology. Microchemical journal, 92(1), 58-67.

Temuujin, J., van Riessen, A., & MacKenzie, K. J. D. (2010). Preparation and characterisation of fly ash based geopolymer mortars. Construction and Building materials, 24(10), 1906-1910.

Temuujin, J., Rickard, W., Lee, M., & van Riessen, A. (2011). Preparation and thermal properties of fire resistant metakaolin-based geopolymer-type coatings. Journal of non-crystalline solids, 357(5), 1399-1404.

Umeda, J., Kondoh, K., & Michiura, Y. (2007). Process parameters optimization in preparing high-purity amorphous silica originated from rice husks. Materials Transactions, 48(12), 3095-3100.

Van Jaarsveld, J. G. (2000). The physical and chemical characterisation of fly ash based geopolymers (Doctoral dissertation).

Vashist, P., Basak, S., & Ali, W. (2019). Green Flame Retardants–Keeping Out Fires.

Villa, C., Pecina, E. T., Torres, R., & Gómez, L. (2010). Geopolymer synthesis using alkaline activation of natural zeolite. Construction and Building Materials, 24(11), 2084-2090.

Wang, H., Wu, H., Xing, Z., Wang, R., & Dai, S. (2021). The Effect of Various Si/Al, Na/Al Molar Ratios and Free Water on Micromorphology and Macro-Strength of Metakaolin-Based Geopolymer. Materials, 14(14), 3845.

Wang, S. D., Scrivener, K. L., & Pratt, P. L. (1994). Factors affecting the strength of alkali-activated slag. Cement and concrete research, 24(6), 1033-1043.

Wang, X., Song, L., Yang, H., Lu, H., & Hu, Y. (2011). Synergistic effect of graphene on antidripping and fire resistance of intumescent flame retardant poly (butylene succinate) composites. Industrial & Engineering Chemistry Research, 50(9), 5376-5383.

Wang, Y. T., Zhao, H. B., Degracia, K., Han, L. X., Sun, H., Sun, M., ... & Schiraldi, D. A. (2017). Green approach to improving the strength and flame retardancy of poly (vinyl alcohol)/clay aerogels: incorporating biobased gelatin. ACS applied materials & interfaces, 9(48), 42258-42265.

Wang, Y., & Zhao, J. (2018). Preliminary study on decanoic/palmitic eutectic mixture modified silica fume geopolymer-based coating for flame retardant plywood. Construction and Building Materials, 189, 1-7.

Wang, Z., Han, E., & Ke, W. (2007). Influence of expandable graphite on fire resistance and water resistance of flame-retardant coatings. Corrosion Science, 49(5), 2237-2253.

Weimer, R. B., Wright, D. M., & Hodgins, T. (2020). Paints and Polymers. Handbook of Trace Evidence Analysis, 157-218.

White, R. H., & Dietenberger, M. A. (1999). Fire safety. Wood handbook: wood as an engineering material. Madison, WI: USDA Forest Service, Forest Products Laboratory, 1999. General technical report FPL; GTR-113: Pages 17.1-17.16, 113.

Wool, R. P. (2005). Polymers and composite resins from plant oils. Bio-based polymers and composites, 1.

World Health Organization. (1997). Flame retardants: a general introduction; environmental health criteria 192. International Programme on Chemical Safety (WHO/IPCS), Geneva.

Wu, Q., Andersson, R. L., Holgate, T., Johansson, E., Gedde, U. W., Olsson, R. T., & Hedenqvist, M. S. (2014). Highly porous flame-retardant and sustainable biofoams based on wheat gluten and in situ polymerized silica. Journal of Materials Chemistry A, 2(48), 20996-21009.

Wu, Z. H., Qu, J. P., Zhao, Y. Q., Tang, H. L., & Wen, J. S. (2015). Flammable and mechanical effects of silica on intumescent flame retardant/ethylene–octene copolymer/polypropylene composites. Journal of Thermoplastic Composite Materials, 28(7), 981-994.

Xia, Z., Kiratitanavit, W., Yu, S., Kumar, J., Mosurkal, R., & Nagarajan, R. (2018). Fire Retardants from Renewable Resources. Advanced Green Composites, 275.

Xie, J., Zhang, H., Shao, Y., Bao, D., Zhang, H., & Zhu, J. (2020). Investigation of the Performance of Fumed Silica as Flow Additive in Polyester Powder Coatings. Coatings, 10(10), 977.

Xu, W., Wei, J., Chen, J., Zhang, B., Xu, P., Ren, J., & Yu, Q. (2018). Comparative study of water-leaching and acid-leaching pretreatment on the thermal stability and reactivity of biomass silica for viability as a pozzolanic additive in cement. Materials, 11(9), 1697.

Yan, L., Xu, Z., & Wang, X. (2017). Influence of nano-silica on the flame retardancy and smoke suppression properties of transparent intumescent fire-retardant coatings. Progress in Organic Coatings, 112, 319-329.

Yang, K. C., & Hsu, R. (2009). Structural behavior of centrally loaded steel columns at elevated temperature. Journal of Constructional Steel Research, 65(10-11), 2062-2068.

Yasir, M., Ahmad, F., Yusoff, P. S. M. M., Ullah, S., & Jimenez, M. (2020). Latest trends for structural steel protection by using intumescent fire protective coatings: a review. Surface Engineering, 36(4), 334-363.

Yeh, J. M., Huang, H. Y., Chen, C. L., Su, W. F., & Yu, Y. H. (2006). Siloxane-modified epoxy resin–clay nanocomposite coatings with advanced anticorrosive properties prepared by a solution dispersion approach. Surface and Coatings Technology, 200(8), 2753-2763.

Yew, M. C., Sulong, N. R., Yew, M. K., Amalina, M. A., & Johan, M. R. (2015). Influences of flame-retardant fillers on fire protection and mechanical properties of intumescent coatings. Progress in Organic Coatings, 78, 59-66.

Yunsheng, Z., Wei, S., & Zongjin, L. (2010). Composition design and microstructural characterization of calcined kaolin-based geopolymer cement. Applied Clay Science, 47(3-4), 271-275.

Zahid, M., Shafiq, N., Isa, M. H., & Gil, L. (2018). Statistical modeling and mix design optimization of fly ash based engineered geopolymer composite using response surface methodology. Journal of cleaner production, 194, 483-498.

Zain, H., Abdullah, M. M. A. B., Hussin, K., Ariffin, N., & Bayuaji, R. (2017). Review on various types of geopolymer materials with the environmental impact assessment. In MATEC Web of Conferences (Vol. 97, p. 01021). EDP Sciences.

Zarib, Noratiqah. (2019). Extraction Of Silica From Rice Husk Via Acid Leaching Treatment. 175-183. 10.15405/epsbs.2019.05.02.16.

Zhang, M., El-Korchi, T., Zhang, G., Liang, J., & Tao, M. (2014). Synthesis factors affecting mechanical properties, microstructure, and chemical composition of red mud–fly ash based geopolymers. Fuel, 134, 315-325.

Zhang, Y., Wang, B., Sheng, H., Yuan, B., Yu, B., Tang, G.,& Hu, Y. (2016). Enhanced fire-retardancy of poly (ethylene vinyl acetate) electrical cable coatings containing microencapsulated ammonium polyphosphate as intumescent flame retardant. RSC advances, 6(88), 85564-85573.

Zhang, Z., Chen, J., He, G., & Yang, G. (2019). Fatigue and Mechanical Behavior of Ti-6Al-4V Alloy with CrN and TiN Coating Deposited by Magnetic Filtered Cathodic Vacuum Arc Process. Coatings, 9(10), 689.

Zhu, Y., Bousfield, D., & Gramlich, W. M. (2019). The influence of pigment type and loading on water vapor barrier properties of paper coatings before and after folding. Progress in Organic Coatings, 132, 201-210.

Zolgharnein, J., Shahmoradi, A., & Ghasemi, J. B. (2013). Comparative study of Box–Behnken, central composite, and Doehlert matrix for multivariate optimization of Pb (II) adsorption onto Robinia tree leaves. Journal of Chemometrics, 27(1-2), 12-20.