PERFORMANCE CONCRETE CONTAINING COAL BOTTOM ASH ON THE STRENGTH PROPERTIES UNDER ELEVATED TEMPERATURE AND VARIOUS COOLING METHOD

R. Embong, M. Albiajawi, A.I. Syameer Harudin

Abstract

In recent years, excessive quantities of industrial by-products dumped from coal-thermal power plants have resulted in environmental contamination and landfills. Recycling industrial waste will help to minimise the consumption of cement in concrete. Hence, carbon dioxide emission from cement production can be reduced simultaneously. The current trend in the construction industry has also highlighted the use of silica-rich supplementary cementitious materials from industrial wastes in concrete production. Numerous studies have also validated the properties of these potential waste materials. Yet, there is less information on coal bottom ash (CBA) performance in concrete exposed to elevated temperature as partial cement replacement. Therefore, this study was done to investigate the strength performance of CBA subjected to elevated temperature with a different cooling method. Several tests were conducted to examine the performance of CBA concrete at elevated temperatures of 200º C, 400º C and 600º C; compressive strength, visual appearances and mass loss. The test of concrete specimens with a replacement proportion of 5%, 10%, 15% and 20% is measured and compared with those of the control concrete specimens. Replacement level of 5% with CBA had shown comparable strength value with the control specimen, even after the elevated temperature up to 600º C. In addition, the characteristics of CBA particles having high water absorption

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R. Embong, M. Albiajawi, A.I. Syameer Harudin

Faculty of Civil Engineering Technology, Universiti Malaysia Pahang, 26300, Gambang, Kuantan Malaysia

R. Embong (Corresponding Author)
e-mail: rahimahe@ump.edu.my

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properties have strongly influenced the overall strength performance in concrete. Therefore, it is strongly suggested to reduce the particle size of CBA before being utilised in concrete.

Keywords Cement replacement material, Coal Bottom Ash, Elevated Temperature, Cooling method

Introduction

Concrete is an essential building material used in construction projects from the precious nineteenth horn. Concrete is produced when cement and water combine to form a paste that solidifies with (fine and coarse) aggregates (AlBiajawi et al., 2021; Kanyal et al., 2021). With rapid development in construction industries, primary materials such as cement, river sand and coarse aggregate will rise significantly. However, the increased manufacturing of cement has offered various harmful effects on the environment (Nwofor et al., 2015). Specifically, cement manufacturing processes emit a large quantity of greenhouse gases into the atmosphere, such as carbon dioxide (CO_2). Thus, it could contribute to air pollution and global warming (Kamal et al., 2016). In fact, about 3,300 million tons of cement are produced worldwide and the carbon dioxide emissions from cement manufacturing are estimated to be about 1.35 billion tons per year (Acharya & Patro, 2015).

In addition, limestone is the raw material in cement manufacturing and a non-renewable resource that requires a long time to recreate. At the same time, coal waste disposal is also wreaking havoc on the ecosystem due to the risk of heavy metal leaching (Aydin, 2016). In Malaysia, CBA has been categorised under Scheduled Waste (SW104) by the Department of Environmental (DOE) (Ibrahim et al., 2020). Moreover, finding new alternative materials for sustainable development is vital to protect the interests of future generations (Argiz et al., 2018). Thus, it is necessary to develop a material that can replace cement in concrete to mitigate environmental issues (Uwasu et al., 2014). Therefore, a comprehensive study on the characteristics of composite cement needs to be conducted before it can be incorporated as a part of the building materials.

The present study uses CBA produced from a thermal power plant in Manjung, Perak, Malaysia, to partially replace cement in concrete. The main focus is to investigate the impact of elevated temperature on the CBA concrete specimens. Few factors affect the thermal capacity of concrete, moisture content due to environmental factors, the porosity of the substituent materials, type of aggregates and cement composition. However, the influence of elevated temperatures on the mechanical properties of concrete is essential for fire resistance studies. Furthermore, heat-resistant materials are increasingly being used for structural purposes. The need for such building materials is particularly significant in chemical and metallurgical industries.

This study is conducted to achieve the following objectives:

- To determine the compressive strength, crack and mass loss of CBA concrete after exposure to the elevated temperature.

- To determine the impact of cooling conditions on CBA concrete's performance after exposure to the elevated temperature.

- To determine the optimum percentage of cement replacement that can contribute to the enhancement of concrete properties.

Experimental Programme

The experimental works are divided into three stages: materials, detail of testing and sample preparation.

Materials

This experimental research uses ordinary Portland cement (OPC), coarse and river sand aggregates, coal bottom ash, and tap water in the concrete mixture. The maximum aggregates size used was

4.75 mm for river sand and 10 mm for coarse aggregate. The CBA was collected from Coal Power Plant located in Perak, Malaysia. The raw CBA was sieved passing a 300µm sieve plate. CBA samples were treated and soaked in 1.0 M of hydrochloric acid for a 1-hour duration. The treatment's purpose is to reduce the risk of metal leaching and unburned carbon in CBA particles (Embong et al., 2016; Ismail et al., 2020). The solution was left overnight to allow complete sedimentation of CBA at the bottom of the beaker. The treated CBA was washed with an excess of distilled water until it achieves PH-neutral. Lastly, the adsorbent was filtered, dried in an oven at 100°C overnight and kept in a container before use.

Mix Proportion

Mixture design is the process of selecting the appropriate ingredients for the concrete mix, and estimating their relative proportions to achieve the targeted strength and durability at the lowest cost. In this study, concrete mix design Grade M-25 (25MPa) used non-air entrained concrete at 3, 7, 28 and 56 days in accordance with the Design of Experimental (DOE) method according to BS EN 12620 standard guideline (BS EN, 2013). The total of concrete mixes was prepared about 12 samples for one proportion as partial replacement of cement by volume; control, 5 % (F05), 10 % (F10), 15 % (F15) and 20 % (F20). The water to cement ratio was maintained constant at 0.50 and several trial mixes were performed to verify that the workability was within the specified slump limits. The mix proportions and amount of materials used in the concrete mixture are listed in Table 1.

Table 1: Concrete mix design details

	Replacement %	Cement Kg/m^3	CBA Kg/m^3	Water Kg/m^3	Sand Aggregate. Kg/m^3	Coarse Aggregate Kg/m^3
Control	0	325	0	230	835	1020
(F05)	5%	308.75	16.25	230	835	1020
(F10)	10%	292.5	32.5	230	835	1020
(F15)	15%	276.25	48.75	230	835	1020
(F20)	20%	260	65	230	835	1020

Details of Testing

The concrete samples with 100 mm cube size were prepared for testing fire resistance test in accordance with standard BS EN 13501. The grain size examination was performed in accordance with BS 1377-2. Furthermore, the fine aggregate and bottom ash were analysed in line with BS. The characteristics of hardened concrete were determined for the produced samples; compressive strength tests were conducted following ASTM C109. There were two cooling processes incorporated in this study, which are air cooling and water cooling process. The specimens were dried at 100ºC ±5 ºC until they reached a consistent weight, removing capillary moisture and minimising the danger of spalling. Also, to avoid thermal shock in the specimens, a cooling rate of about 10°C/min was used (Abdulkareem et al., 2014; Ahn et al., 2016). The concrete samples were exposed to the elevated temperature of 200ºC, 400ºC and 600ºC for a soaking time of 1-hour duration. The furnace was heated at a constant rate of 10°C/min for 2 hours (Abdulkareem et al., 2014; Ahn et al., 2016). The performance of concrete when exposed to elevated temperatures was investigated according to the requirement of previous studies and standards EN 13501. The visual appearance of the CBA concrete specimen was recorded after the sample achieved the maximum temperature. In addition, the CBA sample specimens were weighed accordingly before and after elevated temperature exposure to record the mass loss. The experimental details in this study are tabulated in Table.

Table 2: Experimental test details

Test Name	Standard	Testing Age	Specimen Size	Number of Specimen	Unit
Treated CBA	Equipment Operating Procedure	24 hour	300µm powder	100 gram	kg
Compressive Strength	ASTM C109	3, 7, 28, 56 (days)	100 mm cube	3 per testing age	MPa

Test Name	Standard	Testing Age	Specimen Size	Number of Specimen	Unit
Fire Resistance	EN 13501 (Abdulkareem et al., 2014), (Ahn et al., 2016)	3, 7, 28, 56 (days)	100 mm cube	3 per testing age	-

Sample preparation

In this experiment, concrete was mixed using a plate mixing machine and cube samples with 100 x 100 x100 mm. The mixing procedure began with pouring the new mix into the pan and filling the molds in three levels, shaking each layer with a vibrating table to establish an upper limit and ensuring consistent compaction until a workable concrete was produced. Next, the molded sample was stored in the laboratory for 24 hours at a temperature of 25+/-5°C according to standard guidelines with MS 26: Part 1:2009. Finally, samples were exposed to various curing procedures. Each mix was used to produce 12 cubes compressed after 7, 28 and 56 days of drying. The curing time was prolonged beyond 28 days to investigate the impact of CBA's pozzolanic response, which usually happens after 28 days.

Result and Discussion

Compressive strength of concrete

Figure 1 shows the compressive strength of the CBA concrete specimens subjected to water curing at 3, 7, 28 and 56 days. At the early age of 3 and 7 days, the compressive strength decreases with the addition of CBA as partial replacement of cement in concrete. It can be seen at 3 days of CBA mixtures of control, F05, F10, F15 and F20 were 13.10 MPa, 9.78 MPa, 12.53 MPa and 11.36 MPa, respectively, lower than the control specimen at 14.93 MPa. Meanwhile, at 7 days of curing age, the strength value for F05, F10, F15 and F20 obtained were 19.27 MPa, 17.69 MPa, 12.55MPa, 16.01MPa and 14.74 MPa, respectively. This is due to the high water absorption characteristics of CBA particles. The higher water content in CBA particles is reported to be influenced by the lower strength value at other substitution levels before 28-days of curing age.

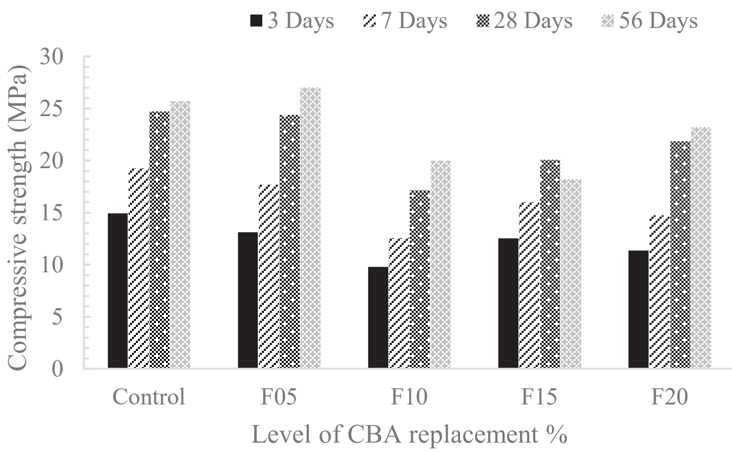


Figure 1: Compressive strength of pre-treated CBA concrete

However, it can be observed that the compressive strength of the concrete started to show comparable results after 28 days of curing, where 5% incorporation contributed 24.37 MPa than the control specimen 24.70 MPa. Meanwhile, other substitutions of F10, F15 and F20 were 17.14 MPa, 20.06 MPa and 21.86 MPa, and were noticeably lower than control specimens. This result proves a pozzolanic effect, where the strength began to increase after 28-days of curing (Gooi et al., 2020; Singh & Bhardwaj, 2020). After 28-days of curing, the silica particles in CBA starting to react with excess calcium-hydrate (C-H) in the cement grain and produce additional Calcium-silicate-hydrate (C-S-H), hence contributing to the strength increments.

At 56-days of curing, F05 replacement of CBA is able to increase its strength value up to 5% higher than the control specimen. Meanwhile, other proportions remain lower strength values of F10, F15 and F20 at 19.97 MPa, 18.23 MPa and 23.20 MPa, respectively. Thus, the present experimental work shows that 5% CBA is suitable for a partial cement replacement in the concrete mixture. However, it is recommended to include mechanical treatment to reduce the particle size and porosity of the CBA particles before being incorporated in cementitious-based components.

Visual observations of CBA concrete after elevated temperatures exposure

The visual observations of concrete were recorded containing 0%, 5%, 10%, 15% and 20% CBA after exposure to different high temperatures ranging from 200°C to 600°C, respectively. In summary, it was observed that the cubes did not sustain any serious damage or alterations to their surfaces other than a change in color after exposures to the air cooling at temperatures ranging from 200°C to 400°C, as shown in Figure 2. However, as the temperature reached 400°C, noticeable tiny cracks appeared and the colour changed slightly to whitish-yellow. At 600°C, the concrete samples became white-gray and the hairline fracture became visible. The colour of the concrete specimen is similarly light brown, and the cracks grew deeper and wider when the temperature rose to 600°C, as shown in Figure 3. Such results are similar to earlier research that used the same visual observations on concrete samples (Awal & Shehu, 2015; Khaliq & Mujeeb, 2019).

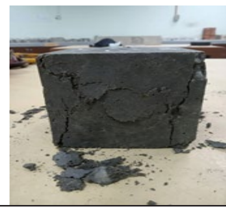
(a) (b)

Figure 2: Appearances of F5% of CBA samples exposed to the air cooling at (a) 200 ºC and (b) 400 ºC temperatures.

The colour changes of the sample in water cooling are the same when firing at 200ºC. When the temperature increased at 400ºC, the concrete turned to brownish-yellow and had some hairline crack on the surface of the concrete sample. When the concrete was exposed to 600ºC, the color changed to brownish-red and the crack deep was detected. Ahn et al., (2016) had reported this change of colour due to the siliceous aggregate in the concrete after high-temperature exposure. The main trend is a discolouration towards brownish-red mainly related to the oxidation of the present iron (Ahn et al., 2016). Undeniably, the iron content in CBA itself also contributed to the colour changes when the level of replacement increases to 600 º C. In addition, water cooling seems to induce deeper and wider cracks than natural cooling (air cooling) at a temperature of 600ºC, as shown in Table 3.

Figure 3: Appearances of F5% of CBA samples exposed to the air cooling at 600C temperature.

Table 3: Cracking and changing of colour exposed to the water cooling at elevated temperature.

Temp	CBA %5 at 28days	CBA %10 at 28days	CBA %15 at 28days
200 ^{0} C			
400 ^{0} C			
600 ^{0} C			

Influence of CBA concrete on mass loss at various temperature

The concrete specimen (100 x 100 x 100 mm) was weighed before and after being exposed to the elevated temperature at 28 days of curing. In addition, the electronic scale has an accuracy of 0.1 grams employed to weigh the cube samples. The difference in weight before and after heat exposure represents the mass loss. Based on Figure 4, at 200º C, the mass loss (%) during the increase in the temperatures in the compositions of control, F05, F10, F15 and F20 are 2.37, 7.06, 6.98, 7.14 and 6.54 respectively. At 400º C, the mass loss (%) in the composition of control, F05, F10, F15 and F20 are 7.37, 8.38, 7.85, 7.92 and 7.77 respectively. When the temperature of CBA concrete increases to 600º C, the mass loss (%) in the composition of control, F05, F10, F15 and F20 are 8.11, 7.78, 8.08, 9.05 and 8.46 respectively. The mass loss was related to the amount of water that also produces a wider evaporation plateau (Arenas et al., 2011).

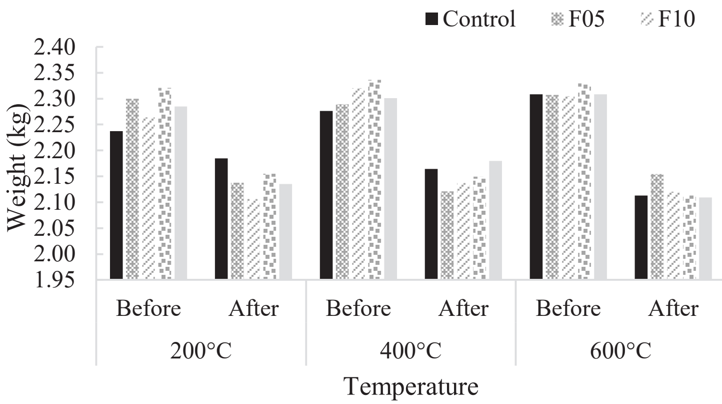


Figure 4: Mass loss of CBA concrete subjected to air cooling at 28 days of curing.

However, based on Figure 5, it can be seen that the method of cooling also influenced the mass loss after elevated temperature exposure. At 200º C, the mass loss (%) in the composition of control, F05, F10, F15 and F20 are 4.87, 5.83, 3.25, 3.43 and 3.15, and were recorded. When the temperature increased to 400º C, the mass loss (%) in the composition of control, F05, F10, F15 and F20 are 3.45, 4.43, 2.35, 1.69 and 2.37 respectively. Lastly, at 600º C, the mass loss (%) in the composition of control, F05, F10, F15 and F20 are 2.18, 2.03, 1.70, 1.21 and 1.44, respectively. The decreasing mass loss value from 200º C to 600º C was attributed to the heat absorbing the water during the water cooling process. The cube sample was sprayed with water immediately after taken out from the incinerator. Based on the mass loss differences obtained in this study, it can be concluded that the permeability and porosity affect the water absorption capacity in the concrete specimens. Moreover, studies also reported that replaced materials like CBA have a higher water absorption capacity than sand (Ankur & Singh, 2021; Kusbiantoro et al., 2019).

Consequently, the replacement ratio should be investigated further in concrete and considered, to minimise its water absorption capacity.

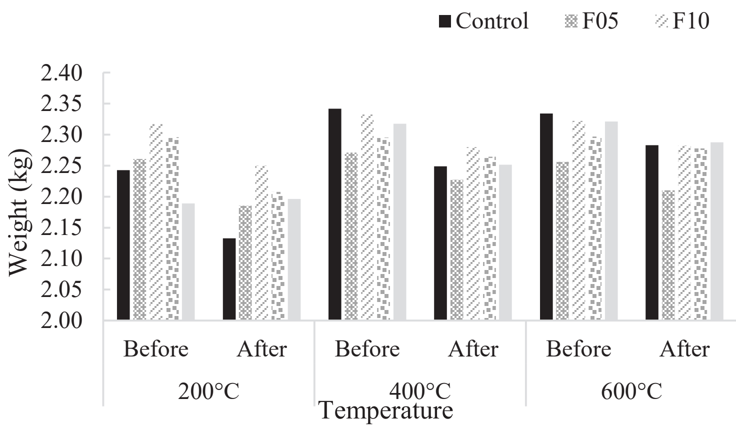


Figure 5: Mass loss of CBA concrete subjected to water cooling at 28 days of curing.

Compressive strength after exposure to elevated temperature

Figures 6 and 7 present the compressive strength of CBA concrete after exposure to the elevated temperature at a different cooling method on 28 days of curing. It can be observed that the CBA content influenced the compressive strength when subjected to a different temperature. The compressive strength is reduced by the increment of the level of cement replacement in concrete. The results are consistent with the other studies on the coal bottom ash regarding its insulating capacity (Özkan et al., 2007). Notably, the data obtained in this study at 5% and 10% replacement of CBA with OPC in concrete show a slight decrease compared to the control specimens up to 600º C.

Regarding the air cooling process, the compressive strength obtained after heating at 200º C for the control, 5%, 10%, 15% and 20% are 28.63 MPa, 25.6 MPa, 24.89 MPa, 22.19 MPa and 21.80 MPa respectively at 28 days of curing. However, when the temperature is heated up to 400º C, the strength value for control, 5%, 10%, 15% and 20% at 28 days of curing, are 20.36 MPa, 19.94 MPa, 18.63 MPa, 16.94 MPa and 14.47 MPa respectively. Meanwhile, after reaching 600ºC, CBA concrete's strength is decreased critically at control, 5%, 10%, 15% and 20% at 28 days of curing are 14.28 MPa, 12.3 MPa 12.22 MPa, 11.21 MPa and 10.52 MPa, respectively.

Based on Figure 6, strength performance at 5% and 10% replacement level of CBA in concrete had displayed the same pattern with the air cooling method. At 200ºC, the compressive strength of control, 5%, 10%, 15% and 20% at 28 days of curing are 20.84 MPa, 18.43 MPa, 18.91 MPa, 16.31 MPa and 15.11 MPa, respectively. However, at 400º C, 5% replacement indicates a slower strength value compared to the control specimens at 18.36 MPa and 22.63 MPa. Meanwhile, other proportions at 10%, 15% and 20% levels of CBA replacements are 16.12 MPa, 16.1 MPa and 15.65 MPa, respectively. A strong decrease of strength performance was observed for all proportions when the temperature was heated up to 600º C, where control, 5%, 10%, 15% and 20% obtained 8.03 MPa, 7.07 MPa, 7.10 MPa, 6.43 MPa and 6.04 MPa. Compressive strength was influenced by the evaporation plateau becoming wider with the increment of CBA content in concrete, since CBA is a porous material with a high capacity to retain water and work as a water reservoir. The block porosity was increased, thereby resulting in the moisture transport behaviour within the pore block during the heating process (Andrade et al., 2007; Lee et al., 2010).

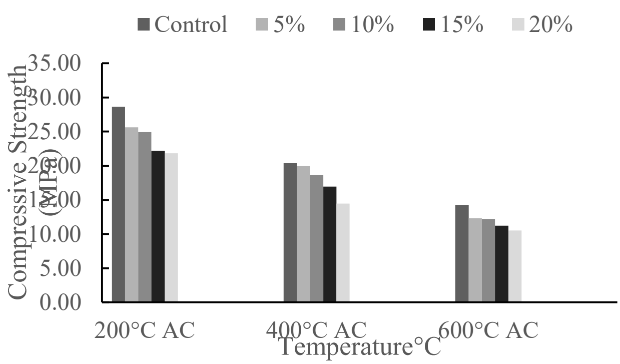


Figure 6: Compressive strength after elevated temperature exposure subjected to air cooling.

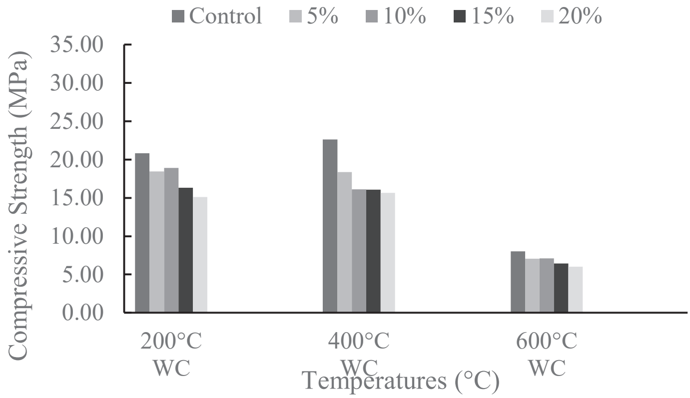


Figure 7: Compressive strength after elevated temperature exposure subjected to water cooling.

Conclusion

This experimental work examined the impact of elevated temperatures and cooling regimes on coal bottom ash as partial cement replacement in the concrete mixture. Based on the test results of this experimental work, several conclusions can be drawn:

1. Concrete produced from 5% coal bottom ash as partial cement replacement displays comparable strength results with the control specimens.
2. The cooling conditions had a severe impact on the strength results and mass loss. The evaporation plateau widens with high CBA replacement in concrete, since CBA particles are a porous material with a high capacity to retain water and work as a water reservoir.
3. It is recommended to include mechanical treatment to reduce the particle size and porosity of the CBA particles before being incorporated in cementitious-based components.

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Author(s) Biodata

Rahimah Embong is a senior lecturer in the Faculty of Civil Engineering Technology at Universiti Malaysia Pahang. Her research experience and interest focus on the futuristic advanced materials, including engineered cementitious composites and green construction. She completed her Ph.D. at Universiti Malaysia Pahang and Master's study at Universiti Teknologi PETRONAS. She was born on 25 October 1990.
Email: rahimahe@ump.edu.my

Mohammad I. Al Biajawi is a full-time Ph.D. student in the Faculty of Civil Engineering Technology at Universiti Malaysia Pahang (UMP). His research interests are in recycled wastes in Malaysia and the development of concrete technology. His present project focuses on the properties of self-compacting concrete using recycled wastes materials. He completed his master's degree study at the Universiti Sains Malaysia (USM). He was born on 14/1/1994.
Email: PAH20001@stdmail.ump.edu.my

Ahmad Izzat Syameer is a graduate degree student in the Faculty of Civil Engineering Technology at Universiti Malaysia Pahang (UMP). His final year project focused on the performance of concrete containing industrial waste products as cement replacement materials. He completed his Bachelor's degree study at University Malaysia Pahang (UMP). He was born on 19/9/1996. He can be contacted at izzatsyameer44@gmail.com