Enhanced Thermal Resistance of CFRP in Robotic Body Covering

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***Abstract*—Carbon Fiber Reinforced Polymer (CFRP) composites are widely used in major manufacturing industries, including the robotics industry. To provide robot technology protection against high temperatures, composites with good thermal resistance are needed. The thermal resistance is completed by adding a refractory material in the form of silica from Rice Husk Ash (RHA). This research was conducted to determine the effect of adding silica on the thermal resistance of CFRP composites using the vacuum bag method. The CFRP itself is made of composite samples using polyester resin, woven carbon fabric, and silica extract with composition variations: 0 g (without silica), 5 g, 15 g, 25 g, and 35 g. CFRP is tested using Thermogravimetric Analysis (TGA). Based on the research results, it can be concluded that the addition of 35 g of silica from rice husk ash can increase environmental temperature resistance up to 414.2 °C. The increased environmental temperature resistance of this composite material will be very suitable for use in robotics components that are in direct contact with heat temperature.**

***Keywords*—Carbon Fiber Reinforced Polymer (CFRP) composites, Silica, rice husk ash, thermal resistance**

I. Introduction

Carbon Fiber Reinforced Polymer (CFRP) is an example of a material with stronger characteristic than that of iron, yet lighter in weight and resistant to high temperatures [1–2]. Hence, CFRP is often used in applications that require high performance. Its high performance main criteria are a high strength-to-weight ratio (specific strength) and stiffness. The primary components of CFRP are carbon fibers with high strength, stiffness, and corrosion resistance. This qualification attracts the attention of major industrial sectors such as construction, automotive, aerospace, marine, biomedical, and robotics [3–7].

A robot is a structure consisting of various components and different electronic devices. The operational temperature of these electronic components has a direct impact on the robot's performance. Consequently, a thermal resilience system must be analyzed and designed to maintain the ideal temperature for each component in the robot [8]. Robotic devices can be used as fire-fighting drones. The materials required must be lightweight and resistant to high temperatures. Lightweight materials such as CFRP composites are currently used in designing lightweighted robot arms also fire-fighting drones. In the present, robotic components are susceptible to damage when exposed to prolonged heat. Therefore, specific attention is needed for heat resistance, especially in the battery covering. Polymer materials can be used to improve the heat resistance of robot components [9].

In general, current robot technology is not designed for extreme temperature environments. When operated outdoors, robots can function within a temperature range from −30 °C to 50 °C [8]. Robot components, especially the control system consisting of electronic or electrical circuits can controlling mechanical systems, and batteries serve as the main power source for the robotic systems. Zhang [10] found that heat transfer begins from the battery, generating heat during operation. Potential risks to the electrical system during robot operation include overheating, exposure to high radiation, and sunlight exposure. Complex computational electrical systems, such as robots, require more power for higher performance. Hence, thermal control plays a crucial role in the reliability of electronic components like robotics.

Materials possessing good thermal properties can provide extra protection and an extended reaction time when facing high temperatures until the occurrence of fire [11]. Zhang *et al*. [12] revealed that CFRP matrix presents potential hazards such as the risk of fire propagation, smoke risk, and combustion heat. To address these risks, the addition of other elements is needed to enhance heat resistance.

The addition of fire-retardant substances in composites can enhance the thermal resistance of the material. One of the fire-retardant substances is silica. Silica is denoted as the compound silicon dioxide (SiO_2). It has a high

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melting point of 1710 °C, making it suitable for use in environments that require resistance to extreme heat. The DTA characterization results showed that silica's thermal properties exhibited heat absorption events (endotherm), indicating the presence of polymerized polysaccharides [13].

Silica has low thermal conductivity, therefore, materials with added silica can reduce heat transfer. This can decrease the thermal enhancement potential of CFRP and maintain the thermal stability. Silica can be extracted from Rice Husk Ash (RHA). RHA silica has finer particles and more reactive than mineral silica. RHA is produced by burning rice husks at temperatures of 400 °C–500 °C, resulting in amorphous silica, while temperatures exceeding 1000 °C leads to crystalline silica [14].

In this research, the parameters used to show the thermal resistance of CFRP are based on the value of extrapolated onset temperature, mass change value, and thermal decomposition temperature value. In general, from the test results conducted by the author, it is found that the addition of 35 g RHA silica to the CFRP composition can increase its thermal resistance when compared to CFRP without RHA silica.

II. Literature Reviews

Several studies serve as background for conducting experiments on adding silica to CFRP composite materials, including research by Wirawan *et al.* [15], and Sutrisno *et al.* [16]. The findings from these studies indicated that silica extracted from RHA can inhibit fire propagation. Theoretically, silica has the properties of filling empty spaces in the composition of materials. In general, it can also be used to absorb ions by the principle of ion exchange, but the ability to absorb metals is limited [17].

Jung *et al.* [18] claims that rice husk has exclusive nanoporous silica layers that have developed through years of natural evolution of the plant. This makes producing highly reactive silica from rice husk a simple process with several advantages compared to conventional production methods. Additionally, one of the researches stated that silica from RHA, when used as a mixed material in the CFRP composite matrix, has a positive relationship with its thermal properties, although there is a decrease in thermal properties with the addition of silica at certain concentrations.

When the polymer matrix reaches high temperatures, it can soften due to reduced strength and stiffness. At high temperatures, the polymer matrix may ignite and produce toxic smoke. The limited research on heat-resistant technology to protect the internal parts of the robot and maintain its functionality becomes an innovation for researchers to conduct further experiments related to efforts to enhance the thermal resistance of CFRP composites added with silica for application in robotic components [19–21]. Based on research conducted by Jewani *et al.* [22], the idea of firefighter drone will help improve the response and reduce the time required to monitor an area and help a distressed civilian.

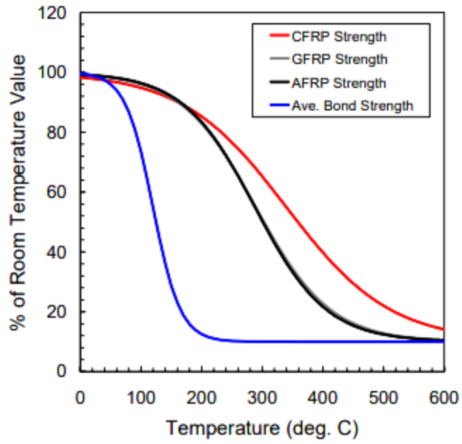


Fig. 1. Properties of FRP (Carbon, Glass, and Aramid) at elevated temperatures.

Fig. 1 illustrates the curve of tensile strength variation with temperature on FRP, where the CFRP composite type exhibits good strength compared to other polymer composite materials. Thermal property analysis is based on the gradual increase in specimen temperature. These properties can include weight, energy, conductivity, and so on [23].

Currently, robotics relies on new materials with rigid and flexible properties, microelectronics, and manufacturing technology. With the research and development of carbon fiber composite materials and technologies, CFRP robots will be the one of the future development directions. Compared with other composite alloys, Carbon Fiber Composites (CFRP) reduce weight and have higher mechanical properties. Some industrial robots have already used CFRP in some parts of the robot. However, they are still in the prototype stage and need development of the design [24–27].

The analysis of thermal properties is as important as mechanical properties because temperature has an important role in determining component quality apart from material and mold properties. Significant thermal resistance and thermal stability are affected by fiber incorporation [28, 29]. Thermogravimetric Analysis (TGA) is a method for thermal analysis of a sample, considering the mass decrease as the sample undergoes heat treatment in a controlled atmosphere. The resulting data is presented in a graph/TG curve (thermogravimetry) showing the mass decrease as a function of temperature increase [30].

III. Methods

The research method applied is the Experimental Method, specifically the Quasi-Experimental Design Method. The researcher utilizes the Non-equivalent Control Group Design, where the experimental and control groups are not randomly chosen. To obtain data on the thermal resistance of CFRP, the research steps were conducted in the preparation of the material and thermal testing methods.

In this experiment, CFRP composite samples with different percentages of RHA silica are compared but subjected to the same treatment. Subsequently, the obtained results undergo an analysis process. The procedure for manufacturing CFRP begins with the extraction of silica from RHA. The first step starts with drying the rice husk ash under the sun, then adding KOH and heating it using an oven. Then, filter the mixture and adding HCL to form silica extract as shown in Fig. 2.

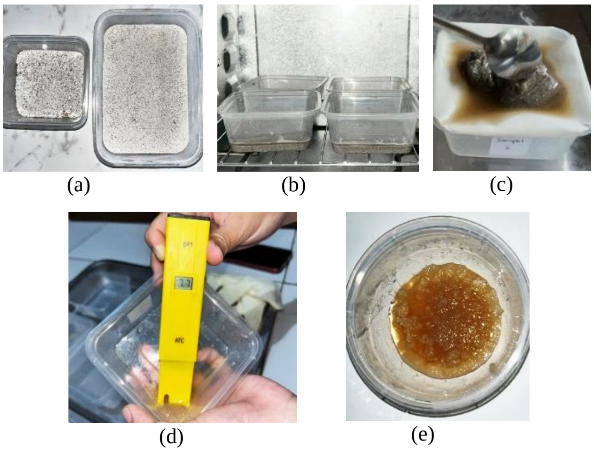


Fig. 2. Silica extraction process. (a) Drying the rice husk ash for 15 hours under the sun; (b) Dissolving rice husk ash with KOH and heated using an oven; (c) Filtering process to produce filtrate; (d) Addition of HCL to neutral pH; (e) Results of silica extract.

After silica extraction is carried out, the next stage is the manufacture of CFRP composite materials. The composition and material of CFRP can be seen in Table I below:

TABLE I. CFRP SPECIFICATIONS

Item	Detail
Matrix Type	Polyester Resin Isophthalic
Curing Agent Type	*methyl ethyl ketone peroxide*
Amplifier Type	Woven type Carbon Fiber
Silica Type	RHA silica
Number of Reinforcing Layers	5 layers
Matrix: reinforce composition	75:25

In Table I, it is shown that the CFRP made has a matrix composition of reinforcement of 75:25 where 25% reinforces is the total mass of carbon fiber consisting of 5 layers. while 75% is a matrix in the form of Isophthalic polyester resin along with RHA silica. Thus, the more silica composition in the matrix will reduce the mass percentage of the matrix relative to carbon fiber.

To determine the effect of adding silica to CFRP, the percentage of RHA added to the CFRP matrix consists of 5 variants with symbols as in Table II. Meanwhile, the process of making CFRP can be seen in the figure below.

Fig. 3 shows the CFRP manufacturing process. The matrix consists of polyester resin with catalyst and silica extract added. The addition of silica extract to the matrix is by hand mixing. Fig. 3(a) shows the first step starting with coating the carbon fiber on the surface of the mold that has been smeared with release agent and matrix. Furthermore, Fig. 3(b) shows the process of 5 times matrix and carbon fiber coating. After that, the vacuum process is carried out as in Fig. 3(c). that shows that the vacuum bag pump machine is turned off and remained still in the mold stand in the plastic for 2×24 hours, or it can be estimated until the CFRP composite material mold is hard enough to be perfect. The finished CFRP composite results are shown in Fig. 3(d).

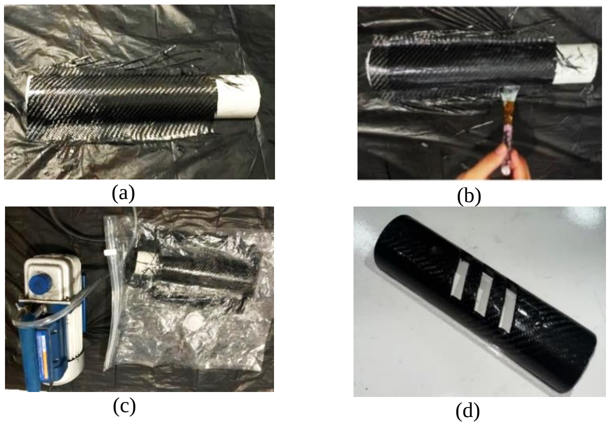


Fig. 3. CFRP manufacturing process. (a) Laying the carbon fiber on the surface that has been smeared with the matrix; (b) Layering of 5-times matrix and carbon fiber coatings; (c) Vacuum process; (d) CFRP composites.

The amount of silica selected is based on the research that does not use RHA silica in proportions exceeding 20 g–30g. Therefore, using silica amounts above these percentages is considered an innovative practice that has not been widely applied. CFRP samples will be tested, including the following below.

TABLE II. CFRP SAMPLES

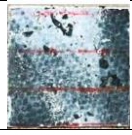
Sample Name	Detail	Figure of Sample
TS	CFRP without silica	
S5	CFRP with RHA silica 5 g	
S15	CFRP with RHA silica 15 g	
S25	CFRP with RHA silica 25 g	
S35	CFRP with RHA silica 35 g	

Table II shows CFRP samples with and without silica added. The figure shows that CFRP samples without silica are transparent, while the samples with 5 g, 15 g, 25 g, 35 g of silica show a more intense white color.

The following section explains the thermal resistance testing process. Thermal resistance testing using a TGA machine begins with preparing the sample to be tested, then measuring the mass weight of each sample in the crucible, The following, the testing process is ready to be carried out as shown in Fig. 4.

Fig. 4 shows the thermal stability testing process, which begins with preparing of the sample to be tested and weighing the mass. The sample was tested using a TGA machine.

(a) (b) (c)

Fig. 4. Thermal stability testing process (a) Sample to be tested (b) Weighing the mass of the sample before testing (c) Sample testing process with TGA machine.

IV. Results and Discussion

To ensure that the RHA silica used has high thermal resistance, the TGA test for RHA silica was performed on heating up to 300 °C, as shown in Fig. 5.

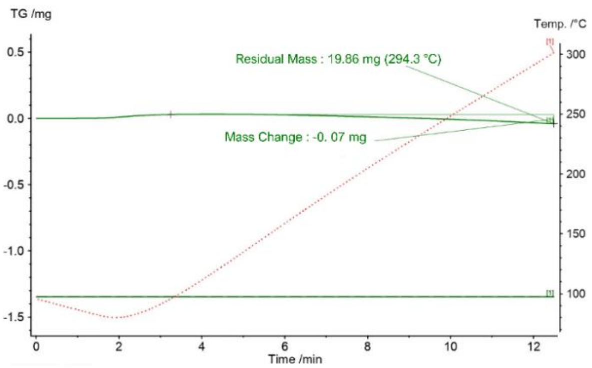


Fig. 5. Mass change data of RHA silica.

Fig. 5. shows a graph of the thermal resistance of RHA silica when heated to 300 °C. During the heating process to reach this temperature, silica only loses 0.07 mg of mass. This indicates that silica can maintain the strength at high temperatures. After determining the thermal resistance of RHA silica, the process of researching and analyzing CFRP using RHA silica continued as follows.

A. *Extrapolated Onset Temperature*

According to ISO 11358–1:2022 Plastics—Thermogravimetry (TG) of polymers—Part 1: General principles, extrapolated onset temperature is the point of intersection between the baseline and the tangent line of the TGA curve at the maximum gradient [24]. Based on ASTM E2550 [25], onset temperature is used to evaluate the thermal properties of the sample. Extrapolated onset temperature indicates the temperature at which CFRP composite material begins to experience mass loss. The Thermogravimetric (TG) curve is displayed, showing the extrapolated onset temperature data from the test results of three specimens from each sample, which are then averaged to create a new curve (average curve).

Fig. 6 shows an evident that the sample with the addition of 35 g silica (S35) produces the highest extrapolated onset temperature value at 386.8 °C. On the other hand, the sample of CFRP without silica addition exhibits the lowest temperature value at 363.5 °C. The isothermal distribution process occurs when temperatures begin to increase that is to exceed around 360 °C. When this happens, the composite begins to undergo mass changes where the resin degrades at that temperature. Silica can be used as a thermal insulator to inhibit heat transfer to maintain CFRP strength at high temperatures. The overall tested samples indicate that as the concentration of silica added to the sample increases, and so does the value of the extrapolated onset temperature.

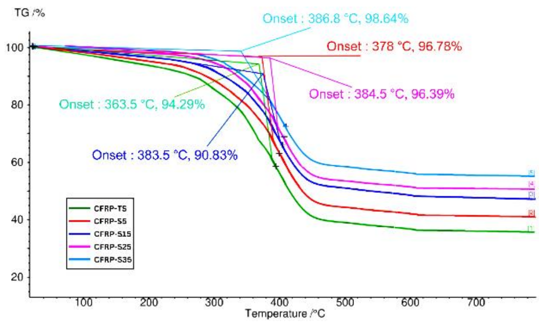


Fig. 6. Extrapolated onset temperature curve.

B. *Mass Changes (Δm)*

In this parameter, TG curves are generated from the results of testing three specimens of each sample in the form of percentage (%) mass, which are then averaged. In this case, the TG curve indicates data on the mass changes occurring in CFRP composite material.

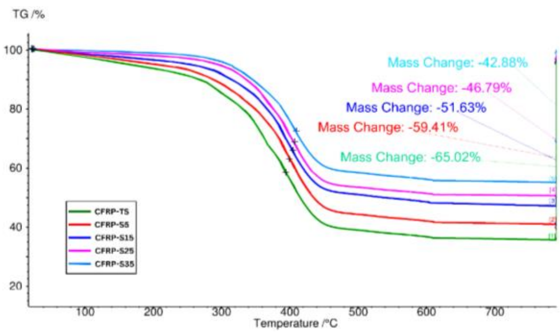


Fig. 7. Mass changes curve.

The elastic modulus and shear properties decrease rapidly and the viscosity increases when it reaches a certain higher temperature. This state is maintained within a certain temperature range. According to existing research, the large loss of modulus at this stage leads to significant strength loss and mass change of CFRP. Fig. 7 shows a smaller percentage of mass loss, specifically 42.88%, exhibited by the sample with the addition of 35 g silica. It can be concluded that, considering the percentage of mass loss, the addition of silica to the tested CFRP sample can reduce its decomposition at high temperatures. Therefore, the addition of silica enhances its thermal properties.

Fig. 8. Residual sample after the testing process.

From Fig. 8, the remaining mass of all specimens consists of carbon fibers that have decomposed (with no matrix remaining). This phenomenon aligns with the theory that decomposition under nitrogen leads to the formation of carbon residues covering the carbon fibers due to resin carbonization. Resin can decompose in a nitrogen atmosphere, leaving behind residues in the form of carbon fibers.

C. *Decomposition Temperature*

The decomposition process occurs due to exposure to heat. The decomposition temperature is the temperature at which a material undergoes chemical decomposition. To properly detect all stages of decomposition, the process at a low heating rate is observed.

Thermal decomposition temperature (Td) indicates the temperature at which the composite material has reached its final mass reduction. The Td value is considered the temperature point at which the mass reduction of the CFRP composite reaches its peak (indicated by the peak or highest point of the DTG curve).

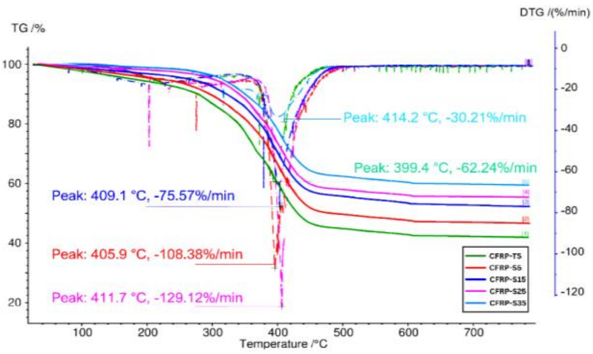


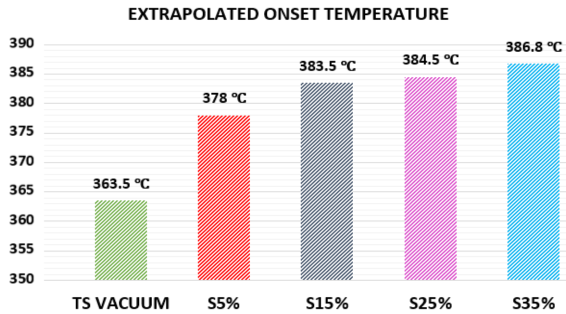
Fig. 9. Decomposition temperature curve.

The curve of derivative thermogravimetry (DTG) is displayed, providing the Td value. Below is the first derivative curve (DTG) showing Td data from the test results of the third specimen of each sample, which is then averaged. From Fig. 9, It can be seen that the highest Td value is obtained by the sample with the addition of 35 g of silica (S35) at 414 °C. Meanwhile, the lowest temperature value is found in the TS sample (without silica) at 399.4 °C.

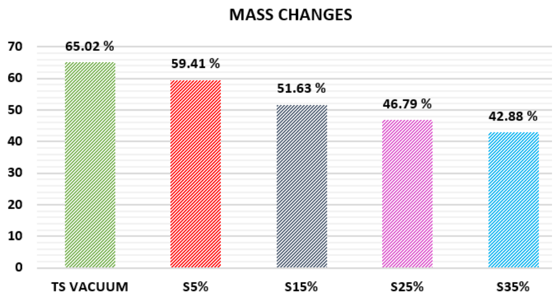
The thermal and oxygen decomposition occurred when the temperature exceeded the thermal decomposition temperature, releasing a significant number of toxic gases. Burning and carbonization may occur if the temperature is further increased, which will cause a further decrease in the strength of CFRP. CFRP can be treated as a fiber bundle once the resin is completely decomposed. From all the tested samples, it is evident that the higher the concentration of added silica to the sample is, the greater its thermal resistance will be, as indicated by the Td value.

Then, from several experiments above, we can see a significant difference between CFRP without silica and CFRP which has the largest silica element (as seen in Fig. 10(a)) which has a difference of up to 23 °C.

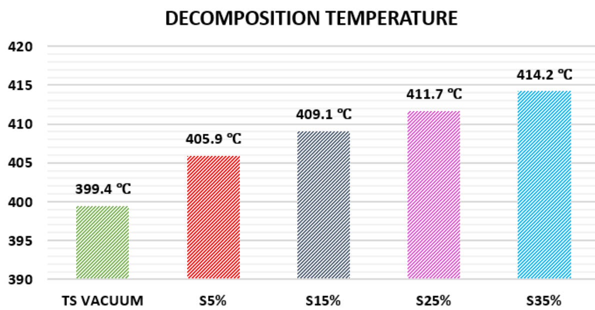
Next, in Fig. 10(b), in terms of mass change percentage, CFRP without silica has a mass change percentage of up to 65.02% of mass, while the addition of silica can reduce mass change by up to 42.88% mass. Likewise at the decomposition temperature shown in Fig. 10(c), a significant increase in thermal resistance can be seen in the difference of CRFP without silica with the highest value of 399.4 °C to 414.2 °C.



(a)



(b)



(c)

Fig. 10. Data analysis results. (a) Extrapolated onset temperature (b) Mass changes (c) Decomposition temperature.

V. Conclusion

Based on testing with TGA and the analysis from Fig. 10, it is concluded that the addition of silica to the CFRP composition can enhance the thermal resistance. This characteristic is important in applications where the material must be able to resist temperature fluctuations without structural damage. The addition of up to 35 g of silica has been shown to enhance thermal resistance compared to CFRP without the addition of silica. This can maintain mass with a difference of up to 22% at high temperatures. This indicates that CFRP can be used to protect the internal parts of the robot, especially the battery layer, and maintain the function of the robot to work on heat exposure for a long time, However CFRP requires good temperature management.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Himawan Hadi Sutrisno contributed to the scheme and testing of CFRP material, Farhah Al Faizah and Yunita Sari contributed to TGA testing while the , Layla Najwa Husaini and Anissa Intan Audrya contributed to data analysis. All authors had approved the final version.

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