VOL. 10, NO. 17, SEPTEMBER 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

ELECTRICAL AND MECHANICAL PROPERTIES OF FLY ASH FILLED SILICONE RUBBER FOR HIGH VOLTAGE INSULATOR

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ABSTRACT

Electrical and mechanical properties of fly ash filled silicone rubber for high voltage insulator are investigated in this paper. The fly ash studied is taken from subbituminous coal combustion which contains high amount of Silica (SiO_2) and Alumina (Al_2O_3), majority in form of glass and quartz. In many literature, Silica and Alumina have been proven can enhance electrical and mechanical performance of silicone rubber insulator. Measurements are conducted on various amount of fly ash in RTV (Room Temperature Vulcanization) silicone rubber to find electrical and mechanical characteristics of fly ash and RTV silicone rubber composite such as dielectric strength, volume resistivity, surface resistivity, dielectric constant (relative permittivity), tensile strength, and hydrophobicity. Test performed according to ASTM (American Society for Testing and Materials) standard. Test results showed that, on average, the dielectric strength of materials are increase with increasing fly ash content. Maximum value of the dielectric strength achieved in 40% fly ash content in silicone rubber. Volume resistivity of the materials are increase with addition of fly ash. The maximum volume resistivity value is achieved in 30% fly ash content. Surface resistivity and dielectric constant also increase with increasing content of fly ash up to 80% in the silicone rubber. Tensile strength of the materials, on average, are increase with addition of fly ash content. The maximum increase in tensile strength, reached on the 30% fly ash content. Hydrophobicity test by contact angle measurement of the materials are increase with addition of fly ash in the silicone rubber, with maximum contact angle is reached in 30 % of fly ash content.

Keywords: silicone rubber, fly ash, electrical properties, mechanical properties.

INTRODUCTION

Environmental conservation, one of which is the waste treatment is one topic that concerns many countries today. Advances in technology achieved today quite encouraging on the one hand, but on the other hand the technology industry produces waste, which in this case must receive attention how to manage it. While the raw materials for industrial technology derived from natural resources are limited in number, it is necessary to setup and maintenance of over-exploitation, or by searching for industrial raw materials derived from the processing of waste as an alternative material selection.

One of the popular waste researched at present, to be used as an industrial raw material some of which is fly ash. Fly ash is derived from burning coal and mostly generated by coal-fired power plants [1]. In Indonesia, the average production of fly ash is relatively high, because many coal-fired power plants have been operated, considering the power plant of this type, have operating costs per kwh which is relatively low compared to power plants that use oil.

Fly ash has been widely studied in the field of civil engineering, especially in the manufacture of concrete. Where the provision of fly ash to concrete mixtures have been shown to increase the strength of concrete. Several investigation also have been studied, showed that the content of silica (SiO_2) which is dominant in the fly ash increases the strength of concrete [2]. In addition to silica, in the fly ash are also contain other compounds, which possess a relatively large percentage such as alumina (Al_2O_3), Fe_2O3 and CaO especially on fly ash derived from subbituminous coal combustion or known as Type F fly ash. These compounds, some of them forming minerals such as quartz and mullite which has a high percentage in the fly ash. In addition, there are also minerals such as magnetite, hematite, etc which have a small percentage in the fly ash [1] [3].

On the other hand in the field of electrical insulating material, compounds such as silica and alumina has been widely studied as a filler in the polymer insulators. Filler is one of the many additives in the compounding techniques, added to the polymeric material to modify or improve certain mechanical or electrical characteristics of the polimer insulating material [4].

Associated with the filler of the polymeric material, one type of polymer that is popularly used today one of which is polydimethylsiloxane, or commonly known as silicone rubber. Electrical insulators made from silicone rubber material are known to have superior resistance to weather. Silicone rubber is known to have Si-O backbone that provides resistance to ultraviolet (UV) radiation coming from the sun. Beside that, CH_3 groups in silicone rubber has water-repellent properties, which make silicone rubber material has excellent hydrophobic properties. Hydrophobicity is known to have a correlation with leakage current flowing on the surface of the insulator [5-7]. This material also has a low density and high elasticity compared to other materials such as glass and ceramics, which is currently a material that is often used as a high voltage insulator. These advantages, makes the silicone rubber material is suitable for electrical insulator application, especially for outdoor use, where the influence of the weather will be the main obstacle that can accelerate aging polymer insulator other than silicone rubber [5] [6].

Besides the advantages mentioned above, there are some disadvantages of this material when used as an outdoor insulator. Silicone rubber known to have a low tear resistance and hardness, wherein the application as transformer bushings and pin type insulators, this parameters are indispensable. To improve the performance of silicone rubber, so that it can be used in outdoor applications, the provision of additives such as filler, performed. As for the most popular type of filler used in silicone rubber some of which are silica and alumina. Silica and furned silica are known to improve the resistance to tracking and erosion. It can also improve the mechanical properties of silicone rubber through molecular bonds beetwen them. Alumina also known can increase resistance to tracking and erosion [8-11].

Silica and alumina which are known to have high percentage in fly ash, can be expected to improve the mechanical and electrical characteristics of silicone rubber material. Silica in the form of quartz that is dominant in the fly ash is also known to have a high electrical resistivity, so that if it is applied as a filler for silicone rubber, it can be expected to increase resitivity of polymeric material such as silicone rubber [12] [13]. This increase in resistivity can also bring to the reduction of the dimensions of the insulator which will provide an advantage in high voltage applications. The size and mass of insulator will affect the dimensions of the transmission poles. It will affect the number of conductors that can be installed which would determine the power transmission capacity on the transmission network.

Based on these considerations, the use of fly ash as filler for silicone rubber material for high voltage insulator is very possible to be studied which is expected can improve the electrical and mechanical performance of silicone rubber. In Indonesia, fly ash is classified by the government as B3 waste, which means hazardous and toxic materials. If fly ash can be used to improve the quality insulator then it will reduce the negative impact of fly ash waste to environment

This paper describe the experimental result of electrical performance by conducting some test based on ASTM standard such as dielectric strength, dielecric constant (relative permittivity), surface and volume resistivity, tensile strength and hydrophobicity on various composition of fly ash content in RTV silicone rubber. The objective of this experiment is to find characteristic of fly ash content in RTV silicone rubber, which is expected can improve electrical and mechanical performance of RTV silicone rubber as high voltage insulator.

EXPERIMENTAL PROCEDURE

Material

Silicone rubber material supplied by PT Matapel Chemical. Type of silicone rubber is RTV 683 which is easily found in market. According to the manufacturer, the silicone rubber material is not given any additional filler that can affect experimental results. The silicone rubber has a catalyst or hardener in form of liquid acetoxysilane. RTV 683 is condensate type which require humidity expose in curing process.

Fly ash material is taken from PT. Semen Tonasa coal based power plant, which is taken directly from coal plant silo. The fly ash, based on ASTM known as tipe F fly ash which contain low content of lime (CaO) and high content of SiO_2. Fly ash mineralogy and compound content has been examined using XRF (X-ray Fluoroscence) and can be seen on table below.

Table-1. Typical chemical compound content of fly ash.

No.	Chemical compound	Percentage (%)
1	Na_2O	2,4
2	MgO	3,8
3	Al_2O_3	19,48
4	SiO_2	40,16
5	P_2O_5	0,15
6	SO_3	1,33
7	K_2O	1,75
8	CaO	8,35
9	TiO_2	1,3
10	Cr_2O_3	0,05
11	MnO	0,29
12	Fe_2O_3	20,22
13	CoO	0,06
14	SrO	0,12
15	ZrO_2	0,06
16	BaO	0,19
17	Pr_6O_{11}	0,05
18	Nd_2O_3	0,08

Material preparation

Fly ash obtained from the plant is filtered with a sieve size 50. Sieve selection is based on studies which shows that the size of fly ash particle range between 0,5 and 300 pm [1]. Silicone rubber resin is mixed with fly ash in a container by using a manual mixing technique. Stirring is stopped when the mixture is homogenized. The catalyst is then poured into the mixture and then stirred again until homogenous.Then the mixture is put into a

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vacuum chamber to eliminate / minimize the trapped air bubbles. The mixture is poured into a mold with a depth of 2 mm and pressed so that the material with a uniform thickness is achieved. In the curing process, material is placed in a room with a humidity of 80%. Curing process runs for 24 hours. After the curing process is complete, to remove residual moisture / water in the materials, material is placed in an oven with a temperature of 80ºC for 24 hours. Furthermore, the material is ready for electrical and mechanical testing. Cured materials are placed in an airtight container to prevent contamination of humidity and other contaminants in air.

Materials are made with different contents of fly ash to investigate the effects of fly ash addition as filler, on the electrical and mechanical characteristics of silicon rubber materials. The composition of the fly ash and silicone rubber can be seen in the table below:

Table-2. Sample code and percentage of fly ash content.

No.	Sample code	Percentage of fly ash content (by Weight of Silicone Rubber)
1	SF0	0
2	SF1	10
3	SF2	20
4	SF3	30
5	SF4	40
6	SF5	50
7	SF6	60
8	SF7	70
9	SF8	80

Each composition made with 3 samples to give more acurate data. Letter a, b, and c is used to mark each sample in one composition, like SF1a, SF1b, etc. Final value of each composition measurement is the average value of 3 times measurement at each sample.

CHARACTERIZATION

Testing procedure based on ASTM standards. The testing standards can be seen in the table below:

Table-3. Test method.

Test name	Test method
Dielectric Strength	ASTM D 149
Volume and Surface Resistivity	ASTM D 257
Relative Permittivity	ASTM D 150
Tensile Strength	ASTM D 412

All test conducted at 3 different samples on the same material composition. The final value of each test in each composition is the average value of measurement on 3 samples. The measurements on 3 samples of each composition are performed, because the homogeneous level of each test sample can be different, so the more samples tested, the more accurate the data will be obtained.

Type of electrode used in all test is made from copper. The selection of copper as an electrode, because this material is easy to obtain and can be made in precision sizes easily, which is required in the measurements. Copper also does not react chemically and physically with the silicone rubber, so it does not diminish the validity of the data.

Dielectric strength test is conducted in accordance with ASTM D 149 standard. Electrode used in the measurement are needle electrode on the top and electrode plate on the bottom. Materials are placed between the electrode and voltage from transformator will be set to slow rise of rate. Voltage frequency 60 Hz is used in this test. Breakdown at the materials are determined when there is an high increase of electric current on the secondary side of the transformer or the occurrence of flash over on the insulator. Test performed under room temperature 27 ºC and humidity 80%.

Volume and surface resistivity performed using Kyoritsu insulation tester with electrode configuration and procedure based on ASTM D257 standard. Humidity when volume and surface resistance measurement conducted is about 83% and the temperature is 27 ºC. Test voltage from the instrument is 5670 V DC for volume resistivity measurement and test voltage 2730 V DC is used for surface resistivity measurement. To make uniform measurement, resistance value at each measurement will be taken in 3 second. This is done because, the resistance measured on the instrument seems change every second that can be caused by polarization in the material.

Relative permittivity or dielectric constant is obtained by the capacitance measuring of the materials with capacitance meter. Materials placed between round paralel plate (paralel plate method) and measurements conducted with frequency 800 Hz. Capacitance measurements performed under room temperature 26 ºC and humidity about 85%. Capacitance values obtained then converted into relative permittivity corresponding with :

$$C = \frac{k.\varepsilon_0.A}{d} \qquad (1)$$

Where C is capacitance, k is relative permittivity, ε_0 is vacuum permittivity, A is area of material tested (in this measurement is equal to the area of electrode). d is electrode separation distance (material thickness) [14]. In order to reduce measurement inaccuracies due to stray capacitance, calibration of measurement modules is

ARPN Journal of Engineering and Applied Sciences

required. Calibration is conducted by holding capacitance measurements on soda lime glass and acrilic sheet. If permittivity obtained from the measurements of glass and acrylic sheet capacitance in accordance with the data of the tested material datasheet, then measurements on silicone rubber materials prepared.

Hydrophobicity test is performed with a static contact angle measurements. Several suspected factors which can affect the results of measurements such as temperature, air precipitation and pollution will be maintained properly. To produce accurate data, parameters such as temperature must be maintained properly. Pollution on the surface of the materials are cleaned by using ethyl alcohol 80%. Measurements are conducted in a closed room with the aim that air flow will be maintained constant, so that the air cleanliness can be properly maintained. Test is performed under room temperature about 26 ºC and humidity 85%. Provision of water droplets are done by using micropipette with volume droplets 20 microliter. Aqua water used in this experiment is sterile bidestilata i.e. water with a high degree of purity. Water droplets picture then taken in 3 second at each measurement to make uniform measurement. All parameter that can affect contact angle value have been cultivated and maintained constant so that each measurement is considered to have done in a uniform condition. Water droplets image is then processed using image processing software ImageJ to get the value of the contact angle.

RESULT AND DISCUSSIONS

Dielectric strength

Dielectric strength measurements are done by breakdown voltage test and the results can be seen below.

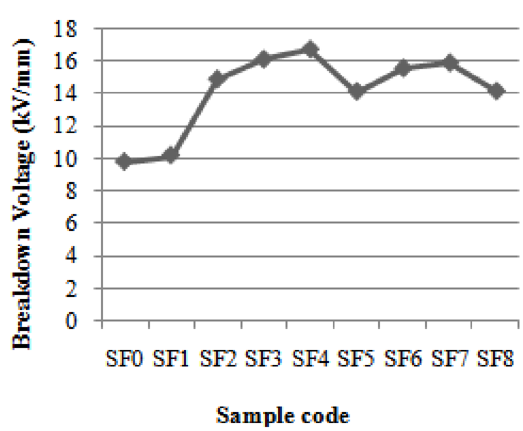

Figure-1. Effect of fly ash content on dielectric strength of fly ash filled silicone rubber.

From the Figure-1, it can be seen that, on average, dielectric strength of fly ash filled silicone rubber materials are increase with addition of fly ash content. Maximum breakdown voltage is achieved in 40% fly ash content in silicone rubber. Breakdown voltage on the composition increased by 71% compared with the silicone rubber without filler.

Breakdown voltage of the tested materials can be affected by the intrinsic properties of the material and extrinsic properties such as the type of applied voltage. The presence of air bubbles in the material being tested can be one of many intrinsics factors that cause the decrease in the dielectric strength of the materials. In the filler content above 40%, the materials are difficult to mold, because the mixture with such composition have a high viscosity. To eliminate the air bubbles to the maximum, vacuum process should be longer. But because of the type of silicone rubber used has a rapid curing process, the removal of air bubbles become not optimal in higher filler content. To overcome this problem, one of the ways that can be used is to change the type of silicone rubber used. Silicone rubber with platinum catalyst is known to have relatively long curing time compared to silicone rubber that use acetoxy as catalysts. Further research is expected to use a silicone rubber with a longer curing time.

Another factor which can influence dielectric strength of materials being tested is the volume resistance. If the volume resistance is low, current flow in the material will raise, which at certain levels can trigger the breakdown mechanism in material [15]. Further studies are needed in this investigation.

Relative permittivity

Relative permittivity of the materials with various fly ash content has been investigated and can be seen in Figure-2.

Figure-2. Effect of fly ash content on relative permittivity of silicone rubber composite.

Figure-2 shows that the relative permittivity of the material, in general, increases with increasing filler content up to 80%. An increase in the value of permittivity

ARPN Journal of Engineering and Applied Sciences

at 80% fly ash content, reaching 68,8% compared to silicone rubber without filler. Relative permittivity is a parameter to determine the dielectric losses of the material according to this equation:

$$W = \omega.E.\varepsilon_0.\varepsilon_r \tan\sigma \quad (2)$$

Where W is power losses on material, ω is radian frequency, E is elecric field, ε_0 is free space permittivity, ε_r is relative permittivity and $\tan\sigma$ is loss tangen of material [15].

From the data in Figure-2, the permittivity of the materials increases with the addition of fly ash content. According to the equation (2), the dielectric losses or power dissipation of the material will increase. Many factor can affect increasing of permittivity in fly ash filled silicone rubber. With regards to the measurement of resistance (volume and surface), it is known that the resistance value read on the instrument, changing every second. The rapid change of resistance value, indicating that the material has a high degree of polarization. According to this equation:

$$\chi_e - \varepsilon_r = 1 \quad (3)$$

Where χ_e is electric susceptibility, ε_r is relative perrmittivity [15], the larger the electric susceptability, the permittivity of the material will be greater. Alumina also known have high permittivity [16]. High alumina content in fly ash also can be suspected as a cause of increasing in permittivity of silicone rubber composite materials.

Volume resistivity

Volume resistivity of the materials has been measured and the result can be seen below :

Figure-3. Effect of fly ash content on volume resistivity of fly ash filled silicone rubber.

In the Figure-3 shows that increasing in fly ash content makes the volume resistivity of the material becomes higher. Critical point of the resistivity achieved in 30% fly ash content, giving an increase of 356% compared with the material without filler.

There are several factor that may affect the surface resistivity of the materials especially if materials are tested with high voltage DC impulse from insulation tester. Filler mineralogy, chemical bond, distribution of molecule and many other chemical factor will contribute to the resistivity value of the materials. Mineralogy of the filler may be a strong candidate to be the main cause of decrease in volume resistance when the content of fly ash is above 30%. Hematite and magnetite known as semiconductor minerals. The resistivity of such minerals varies depending on the voltage applied. Further investigation are needed to understand this characteristic.

Surface resistivity

Surface resistivity of the materials has been investigated and the result can be seen in Figure-4 below :

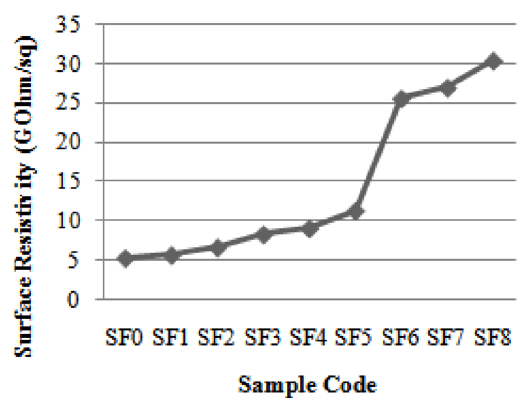

Figure-4. Effect of fly ash content on surface resistivity of fly ash filled silicone rubber.

In the Figure-4. shows that increasing in fly ash content makes the surface resistivity of the materials becomes higher. At the composition with 80% fly ash content, resistivity increased by 466% compared to the material without filler.

Surface resistivity is different with bulk resistivity. Some of surface resistance can be some part of its bulk resistivity. Data accuration can be affected by the thick of the material, more thin the material, the more accurate data will be achieved. Surface resistivity also can be influenced by surface treatment. Further investigation is needed in this study.

Tensile strength

Tensile strength of the material being tested can be seen in the figure below.

ARPN Journal of Engineering and Applied Sciences

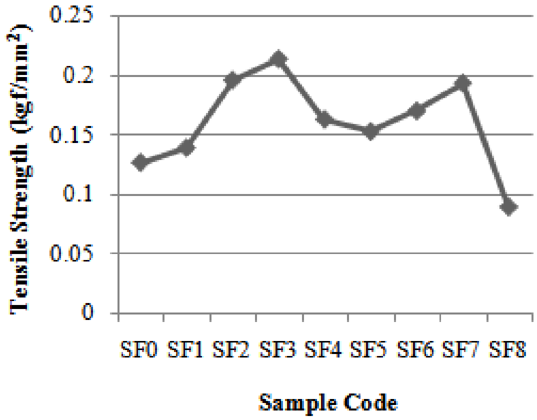

Figure-5. Effect of fly ash content on tensile strength of fly ash filled silicone rubber.

Elongation at break of the materials has been tested and the data can be seen at Figure-6:

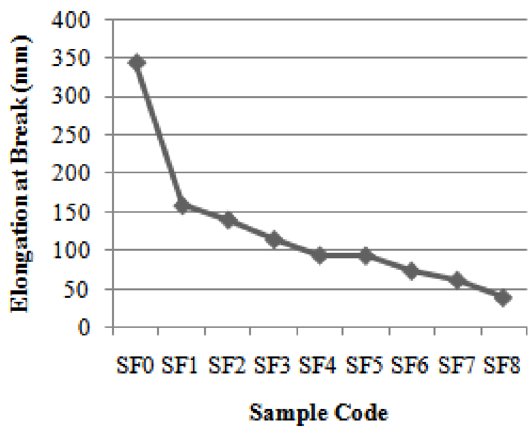

Figure-6. Effect of fly ash content on elongation at break of fly ash filled silicone rubber.

From the Figure-5 shows that the tensile strength of the materials has a maximum increase in 30% filler content. The tensile strength of the composition is increased by 50% compared with the material without fillers.

Tensile strength of the materials are influenced by the bonds strength between the particles of fly ash and silicone rubber. Another factor that can influence tensile strength is the rate of curing of the material. Ununiform mixing process between the catalyst and silicone rubber resin can make irregularities in the material, making the bonds strength between the particles in the material becomes non-uniform. This lack of uniformity makes random weak point in the material. When the testing data are obtained, it will be difficult to achieve good accuracy. In the tests performed, only three samples are tested for each composition. Testing more samples for each composition can provide better data accuracy with good statistical analysis. So the inaccurate data due to defects in the solid materials being tested can be minimized.

Hydrophobicity

Hidrophobicity test by contact angle measurement of various composition of the material can be seen in Figure-7:

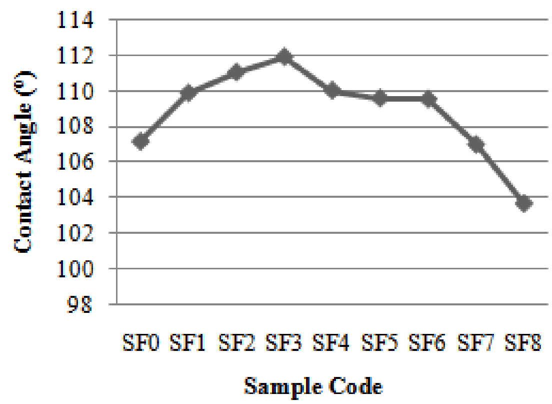

Figure-7. Effect of fly ash content on surface contact angle of fly ash filled silicone rubber.

From the figure above shows that with addition of fly ash, the contact angle of the material initially increases until the fly ash content in the silicone rubber reaches 30%. Contact angle on the composition increased by 4% compared with the silicone rubber without fly ash filler. Fly ash content higher than 30% in the silicone rubber, shows a decrease in the contact angle of the materials.

Contact angle of solid material is affected by many physical and chemical factors such as purity of liquid used, surface topography, surface homogenity, temperature, equilibrium time, surface impurities, size of drop, and thermodynamic stability of solid interface. Some of the factors mentioned above had been kept constant at the measurement such as temperature, purity of liquid used, equilibrium time, and size of droplet. The topography of the material surface will be influenced by the contours of the mold used. Interspacial distance between fly ash filler and silicone rubber also will affect the surface contour of the materials [17] [18].

Moreover, the the contact angle value of the materials are difficult to obtain precise results due to many factors: the resolution of the measuring instrument, also environmental parameters such as temperature and other factors.

CONCLUSIONS

Silicone rubber materials were developed with various composition of fly ash content. The effect of fly ash content on dielectric strength, relative permittivity, volume and surface resistivity, tensile strength and hydrophobic properties have been investigated. The result shows that dielectric strength of the materials is increased with the addition of filler. The biggest dielectric strength value is at 40% filler composition, which increase dielectric strength by 70% compared with the material without filler. Volume and surface resistivity of the materials, on average, are increased by the addition of filler. The maximum increase in volume resistivity is 340% compared with the material without filler and occurs in 30% filler content, the addition of a larger filler seen lowered the volume resistivity. The surface resistivity and relative permittivity of the materials are increased with addition of filler up to 80 %. On average, materials still retain their hydrophobic properties with increased fly ash content. Maximum contact angle achieved in 30% filler content and provides increased contact angle of 4% of the material without filler. Tensile strength of material, on average is increase with addition of filler. Biggest increase is on 30% filler content. Further filler addition seems lower the tensile strength of material. Experimental result shows that fly ash is feasible to use as filler for silicone rubber material due its ability to enhance volume resistivity, surface resistivity, dielectric strength, hydrophobicity, and tensile strength. On average, recommended filler content is between 30-40 %, which can give better improvement on electrical and mechanical properties of silicone rubber material. Fly ash utilization as silicone rubber filler also can reduce environmental impact of coal waste especially fly ash.

ACKNOWLEDGEMENT

The authors gratefully acknowledge Ministry Oof Research And High Education for financial support of this research. We are also grateful for the help of PT. Semen Tonasa for the supply of fly ash used in this study.

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