

Article **E**ff**ect of Silicone Rubber of a Waste Composite Insulator on Cement Mortar Properties**

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Abstract: Due to the rapid growth of the electric power system, the silicone rubber composite insulator is so widely employed around the world. However, the aging damage and decommission of it inevitably generates plenty of waste silicone rubber. It takes up large amounts of land for non-degradation, which is becoming a serious environmental issue. In this paper, the effort has been made to reuse the silicone rubber of composite insulator by peeling, breaking and adding it into the cement mortar to partly replace river sand by 5%, 10%, 15%, 20% and 30% in volume. Moreover, the surface modification of silicone rubber particles with H_2O_2 and KOH is explored to improve hydrophilicity. The mechanical strength of silicone rubber mortar and modified silicone rubber mortar are measured in detail, and the effects of particle size, content and modification of silicone rubber on the properties of mortar are investigated. This study shows that at least a 5% addition of silicone rubber can reduce the strengths, while the 15% addition is obviously favorable for increasing the toughness. Furthermore, the mortar strength gets promoted due to the surface modification. Lastly, the superior thermal insulation and noise reduction of the mortar are obtained as the addition of silicone rubber particles, and an equation between dry apparent density and thermal conductivity of mortar has been developed.

Keywords: waste silicone rubber; composite insulator; cement mortar; thermal insulation; noise reduction

1. Introduction

The silicone rubber based composite insulators (Figure [1\)](#page-1-0) have been widely used all over the world for ultra-high and extra-high voltage transmission lines in recent years [\[1](#page-12-0)[–3\]](#page-12-1). In China, by the end of 2018, the statistical data from the State Grid Corporation of China shows that the number of composite insulators for more than 66 kV levels has exceeded 10 million. The composite insulators are aging gradually because of the long service time (10–15 years) and the natural deterioration due to the electric field, mechanical stress, atmospheric environment and thermal radiation [\[4\]](#page-12-2). The aged composite insulators cannot meet the requirements of electricity transmission, and will be discarded [\[5,](#page-12-3)[6\]](#page-12-4). The cladding material of composite insulator is silicone rubber, and the discarding will result in resources waste and vast expanses of land occupied (Figure [2\)](#page-1-1). Moreover, the combustion disposal is inappropriate as its combustion gases are very contaminative and highly toxic. Therefore, it is an urgent and complicated problem to deal with the plenty of waste silicone rubber based composite insulators. toxic. Therefore, it is an urgent and complicated problem to deal with the plenty of waste toxic. Therefore, it is an urgent and complicated problem to deal with the plenty of waste silicone

Figure 1. Silicone rubber based composite insulators**. Figure 1.** Silicone rubber based composite insulators. **Figure 1.** Silicone rubber based composite insulators**.**

Figure 2. Landfill site of waste composite insulators. **Figure 2.** Landfill site of waste composite insulators. **Figure 2.** Landfill site of waste composite insulators.

The same challenge for dealing with the waste tire rubber has existed since the development of The same challenge for dealing with the waste tire rubber has existed since the development of the auto industry. Afterwards the problem deserves attention, and the recycling of waste tire rubber the auto industry. Afterwards the problem deserves attention, and the recycling of waste tire rubber is chosen to reduce the adverse impact on the environment. The construction and concrete can be is chosen to reduce the adverse impact on the environment. The construction and concrete can be considered as one of the best alternatives to consume recycled rubber [7]. The studies on waste tire considered as one of the best alternatives to consume recycled rubber [7]. The studies on waste tire rubber mortar and concrete have been carried out since the 1990s. Owing to the low specific gravity of tire rubber particles, the apparent density of rubber mortar is less than plain mortar and decreases with the increase of the tire rubber content [8]. The compressive strength and flexural strength tests indicate that the tire rubber mortar and concrete have lower mechanical strength, but fine ductility [7,9–13]. The tire rubber mortar and concrete exhibit the superior thermal insulation in comparison with the plain ones due to [hi](#page-13-4)[ghe](#page-13-5)r air content and porosity [14,15]. Acco[rdi](#page-13-6)[ng](#page-13-7) to previous durability research [16-21] it can be concluded that the tire rubber mortar and concrete possess improved durability to the aggressive environment, such as the resistance to freezing and thawing, permeability resistance, anti-carbonation
and anti-penetration of chlorine. and anti-penetration of chlorine. That we have and anti-penetration of chlorine. The same challenge for dealing with the waste tire rubber has existed since the development of
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The hydrophobic nature of tire rubber is liable to cause the weak bonding strength between The hydrophobic nature of tire rubber is liable to cause the weak bonding strength between The hydrophobic nature of tire rubber is liable to cause the weak bonding strength between tire
rubber and cement paste, so a lot of research has been performed to enhance hydrophilicity through surface modification of tire rubber, and then improve the whole performance of tire rubber mortar surface modification of tire rubber, and then improve the whole performance of tire rubber mortar
and concrete [\[22](#page-13-8)[–24\]](#page-13-9). Mohammadi et al. reported in 2016 that the tire rubber treated by NaOH could observably improve the concrete mech[anic](#page-13-10)al strength [25]. Rivas-Vázquez et al. in 2015 discovered observably improve the concrete mechanical strength [25]. Rivas-Vázquez et al. in 2015 discovered
that the tire rubber concrete mechanical strength increased after the tire rubber was treated with acetone [26]. The tire rubber was firstly oxidized [wit](#page-13-11)h KMnO₄ and then sulfonated with NaHSO₃ in the with NaHSO3 in the research by He et al. in 2016, and the mechanical property of the mechanical property of the tire rubber

research by He et al. in 2016, and the mechanical property of the tire rubber concrete was significantly improved [\[27\]](#page-13-12). Onuaguluchi reported in 2015 that the limestone power pre-coated tire rubber and silica fume could improve the mechanical strength of rubberized mortar [\[28\]](#page-13-13).

The studies on tire rubber and modified tire rubber for mortar and concrete have already achieved many useful results, and the rubberized mortar and concrete have been applied in the engineering field. Nevertheless, the recycling process of the waste tire rubber is complex and of high cost [\[29\]](#page-13-14) and the component system is complicated due to waste tire composed of rubber, tire cord (steel cord, nylon cord, etc.), carbon black, adhesive substance and so on. In contrast, the waste silicon rubber of composite insulators has a simple composition, consisting of the basis material of polydimethylsiloxane, which possesses the molecular chain structure comprising the Si-O main chain and $-CH_3$ side group, and about 55 wt% aluminum hydroxide particle filler [\[1,](#page-12-0)[30\]](#page-13-15). The silicone rubber, even the waste one, still has better abrasion resistance, preferable chemical resistance, more excellent high and low temperature resistance, and is less adverse to health and the environment, compared with waste tire rubber [\[31](#page-13-16)[–33\]](#page-14-0). According to our knowledge, a rare study on the application of silicone rubber in mortar or concrete has been reported. In one study carried by Richardson et al. in 2012, the high silicone content rubber crumb of waste tire was added into concrete and only 0.6% rubber crumb content by weight could provide significant freeze-thaw protection [\[21\]](#page-13-7). Other slightly related studies were carried out on liquid-type silicone rubber used in polymer concretes [\[34](#page-14-1)[,35\]](#page-14-2). Therefore the study on the application of waste silicone rubber in construction materials is necessary and significant. This paper attempts to explore the recycling approach and provide an application basis of the waste silicone rubber of the composite insulator in cement mortar. Firstly, the effect of silicone rubber on mortar mechanical strength was studied. Then the H_2O_2 and KOH were used to enhance the hydrophilicity of silicone rubber, and the mechanical strength between silicone rubber mortar and the modified ones was compared. The thermal conductivity of silicone rubber mortar was measured considering its great application value as a thermal insulation mortar. Besides, the potential utilization of silicone rubber mortar as noise reduction ground was investigated. This study can not only provide a useful reference for silicone rubber applying to thermal and noise insulation mortar, but also contributes to alleviating the adverse impact on environment brought by the waste composite insulator.

2. Materials and Methods

2.1. Materials

 \overline{a}

The cement is Ordinary Portland cement of Grade 42.5 (P.O 42.5) manufactured according to the Chinese Standard GB175-2007. The physical properties of the cement are presented in Table [1.](#page-2-0)

Property	Specific Density (kg/m^3)	Normal Consistency (%)	Initial Setting Time (min)	Final Setting Time (min)	Compressive Strength (MPa)		Flexural Strength (MPa)	
					7 days	28 days	7 days	28 days
Cement	3100	28.35	235	305	30.2	46.7	5.8	7.3

Table 1. Physical properties of cement.

The fine aggregate is graded natural river sand, and its apparent density and fineness modulus are 2580 kg/m^3 and 2.69, respectively.

The silicone rubber is peeled off from the reclaimed composite insulator, which are supplied by State Grid Henan Electric Power Company, China, and then broken to certain size particles (Figure [3\)](#page-3-0). The apparent density and size distribution of the silicone rubber particles are 1436 kg/m³ and 5–50 mesh, respectively.

Figure 3. Silicone rubber particles **Figure 3.** Silicone rubber particles.

2.2. Silicone Rubber Modification 2.2. Silicone Rubber Modification

The modifiers for silicone rubber include H_2O_2 and KOH. In the H_2O_2 instance, the silicone rubber particles were soaked in H_2O_2 for 24 h at room temperature, and then dried naturally. In the KOH instance, firstly, the silicone rubber particles were soaked in saturated KOH solution for 24 h at room temperature. Then, the particles were washed by water several times until the pH value of the washing water approached neutral. Finally, the silicone rubber particles were dried in an oven at 60 °C to obtain the KOH modified silicone rubber particles.

2.3. Mix Proportions 2.3. Mix Proportions

The experiments included two stages. The first one was the exploratory test, in which the effect of silicone rubber on the mechanical strength was studied. The particle sizes of silicone rubber were 5, 10, 10, 20 and 50 mesh. It was mixed into the mortar by equal volume substitution of sand, and the 20 and 50 mesh. It was mixed into the mortar by equal volume substitution of sand, and the contents were 5%, 10%, 15%, 20% and 30%, respectively. The detailed mix proportions are show[n](#page-3-1) in Table 2. The expanded test at the second stage was based on the results of the exploratory. The modified silicone rubbers were added in the mortar with particle size of 5 mesh and volume replacement rate of 5%, 15% and 30%, respectively. The mix prop[orti](#page-4-0)ons are listed in Table 3 in detail. The mechanical strength, thermal conductivity and noise reduction of the modified silicone rubber mortar were measured, and were compared with the original silicone rubber mortar. In the two stages tests, the mix proportion for the cement mortar was 1:0.5:3 (cement:water:fine aggregate).

Description of Mortar	Cement	Water	River Sand	Silicone Rubber
Plain	503.68	251.84	1511.04	$\mathbf{0}$
Replacing 5%; 5 mesh	503.68	251.84	1435.49	42.05
Replacing 10%; 5 mesh	503.68	251.84	1359.94	84.10
Replacing 15%; 5 mesh	503.68	251.84	1284.38	126.15
Replacing 20%; 5 mesh	503.68	251.84	1208.83	168.20
Replacing 30%; 5 mesh	503.68	251.84	1057.73	252.30
Replacing 5%; 10 mesh	503.68	251.84	1435.49	42.05
Replacing 10%; 10 mesh	503.68	251.84	1359.94	84.10
Replacing 15%; 10 mesh	503.68	251.84	1284.38	126.15
Replacing 20%; 10 mesh	503.68	251.84	1208.83	168.20
Replacing 30%; 10 mesh	503.68	251.84	1057.73	252.30
Replacing 5%; 20 mesh	503.68	251.84	1435.49	42.05
Replacing 10%; 20 mesh	503.68	251.84	1359.94	84.10
Replacing 15%; 20 mesh	503.68	251.84	1284.38	126.15
Replacing 20%; 20 mesh	503.68	251.84	1208.83	168.20
Replacing 30%; 20 mesh	503.68	251.84	1057.73	252.30
Replacing 5%; 50 mesh	503.68	251.84	1435.49	42.05
Replacing 10%; 50 mesh	503.68	251.84	1359.94	84.10
Replacing 15%; 50 mesh	503.68	251.84	1284.38	126.15
Replacing 20%; 50 mesh	503.68	251.84	1208.83	168.20
Replacing 30%; 50 mesh	503.68	251.84	1057.73	252.30

Table 2. The detailed mix proportions of mortar in the first stage test (kg/m³).

Description of Mortar	Cement	Water	River Sand	Silicone Rubber
Replacing 5%; 5 mesh	503.68	251.84	1435.49	42.05
Replacing 15%; 5 mesh	503.68	251.84	1284.38	126.15
Replacing 30%; 5 mesh	503.68	251.84	1057.73	252.30
Replacing 5%; 5 mesh; KOH treated	503.68	251.84	1435.49	42.05
Replacing 15%; 5 mesh; KOH treated	503.68	251.84	1284.38	126.15
Replacing 30%; 5 mesh; KOH treated	503.68	251.84	1057.73	252.30
Replacing 5%; 5 mesh; H_2O_2 treated	503.68	251.84	1435.49	42.05
Replacing 15%; 5 mesh; H_2O_2 treated	503.68	251.84	1284.38	126.15
Replacing 30% ; 5 mesh; H_2O_2 treated	503.68	251.84	1057.73	252.30

Table 3. The detailed mix proportions of mortar in the second stage test (kg/m³).

2.4. Sample Preparation and Test Methods

2.4.1. SEM and EDS Tests

A scanning electron microscope (SEM, Merlin Compact, Carl Zeiss NTS GmbH, Oberkochen, Germany) was used to observe the surface morphology of silicone rubber. The surface element content of silicone rubber was determined by an energy dispersive spectrometer (EDS).

2.4.2. Contact Angle Test

A video-based optical contact angle measuring device (Shanghai Zhongchen Digital Technology Equipment Co. Ltd., Shanghai, China) was employed to detect the contact angle between silicone rubber (including original silicone rubber and the modified ones) and deionized water, in order to analyze the polarity change of the silicone rubber surface after modification.

2.4.3. Sample Preparation

Silicone rubber, river sand, cement and water were weighed accurately according to the mix proportions. The mixing process was performed according to the Chinese Standard JGJ/T70-2009. All the molds were lubricated previously with mineral oil to prevent the mortar from adhering to the mold walls. For each mixture, the mortar specimens with the dimensions of $40 \text{ mm} \times 40 \text{ mm} \times 160 \text{ mm}$ was fabricated to measure the compressive strength and flexural strength at 7 days and 28 days. The specimens for thermal conductivity and noise reduction tests were plate-shape with the size of 200 mm \times 200 mm \times 15 mm. All the mortar specimens were applied ambient curing for the first day. After demolding, they were cured to a certain curing period under the standard conditions with a temperature of 20 ± 2 °C and relative humidity of higher than 90%.

2.4.4. Mechanical Strength Test

The compressive strength and flexural strength measurements were performed in accordance with ASTM C 348-02 and C 109-02 by a universal testing machine (WDW-20, Hengruijin Testing Machine Co., Ltd., Jinan, China), and the loading rates were 3 and 150 kN/min, respectively.

2.4.5. Thermal Conductivity Test

To evaluate the effect of the silicone rubber and the modified one on the heat transfer ability of the cement mortars, the thermal conductivity test was carried out by means of a rapid thermal conductivity measurement system (Jiantong Environmental Technology Co., Beijing, China) with the temperature of 30 °C and the humidity of 47%. The mortar specimens were dried at 60 °C for 2 days before testing.

2.4.6. Noise Reduction Test

A self-made rubber ball impact test device was used to measure the noise reduction of the mortar specimen as shown in Figure [4.](#page-5-0) The rubber ball fell freely from a specified height above the mortar plate (0.5, 1.5 and 2.5 m), and a noise meter (Sigma Technology Co., Ltd., Qingdao, China) was used to measure the noise level at different distances (0.1, 2.5 and 5.0 m). The rubber ball was 70.5 g and its measure the noise level at different distances (0.1, 2.5 and 5.0 m). The rubber ball was 70.5 g and its diameter was 48.4 mm. diameter was 48.4 mm.

Figure 4. Self-made rubber ball impact test device **Figure 4.** Self-made rubber ball impact test device. **Figure 4.** Self-made rubber ball impact test device

3. Results 3. Results

3.1. Characterization of Silicone Rubber 3.1. Characterization of Silicone Rubber

3.1.1. SEM and EDS

 $\frac{1}{2}$ Among them, C and Si were mainly from the polydimethylsiloxane matrix of the silicone rubber, and
Al and O stemmed mainly from the aluminum hydroxide filler The SEM images (Figure [5\)](#page-5-1) show that the silicone rubber powder was uneven in surface and $\ddot{}$ irregular in shape, and there was no obvious agglomeration among them. The EDS spectrum of silicone
in the contract of the contract of the matter of the contract of the contract of the contract of the contract o rubber (Figure [6\)](#page-6-0) shows that the main elements of silicone rubber surface included C, O, Al and Si. Al and O stemmed mainly from the aluminum hydroxide filler.

Figure 5. SEM images of silicone rubber powder. (a) 5000x magnification; (b) 300x magnification.

Figure 6. Energy dispersive spectrometer (EDS) spectrum of silicone rubber powder.

3.1.2. Contact Angle 3.1.2. Contact Angle 3.1.2. Contact Angle

In order to analyze the surface property change of the modified silicone rubber, as exhibited in In order to analyze the surface property change of the modified silicone rubber, as exhibited in Figure [7](#page-6-1) the water contact angles of original silicone rubber (96°) , H_2O_2 modified silicone rubber (74°) and Koh modified since $\frac{1}{2}$ modified silicone rubber (79°) $\frac{1}{2}$ g modified since rubber the since $\frac{1}{2}$ and KOH modified silicone rubber (79°) were measured, respectively. That is, through the modification, the surface property of silicone rubber changed from hydrophobic to hydrophilic as a small number of the surface property of since the rubber changed from hydrophobic to hydrophilic as a single rubber of the hydroxyl groups exist on its surface after modification by H_2O_2 or KOH [\[27](#page-13-12)[,36\]](#page-14-3). she signally groups exist on he existed after modification by H_2O_2 or KOH $[27,369]$.

3.2.1. Effect of Silicone Rubber on the Mechanical Strength of Mortar treated; (**c**) KOH treated. treated; (**c**) KOH treated. Figure 7. Testing photographs of the water contact angle of silicone rubber. (a) Original; (b) H_2O_2

MPa. The compressive strengths variations of 7-days and 28-days on account of the size and the *3.2. Mechanical Strength 3.2. Mechanical Strength*

3.2.1. Effect of Silicone Rubber on the Mechanical Strength of Mortar

 $T_{\rm c}$ instance, as the 10 mesh silicone rubber for instance, as the \sim 30, the 7-days to 30% to 30%, the 7-days to 30% to 30%, the 7-days to 30% to 30%, the 7-days to 30%, the 7-days to 30%, the 7-days to 30% to 30%, The 7-day and 28-day compressive strengths of the plain mortar were 30.2 MPa and 46.68 MPa. The compressive strengths variations of 7-day and 28-day on account of the size and the content changes of silicone rubber particles are illustrated by Figure [8a](#page-7-0),b, respectively. Similar to the tire rubber \overline{a} mortar, the compressive strength decreased with the silicone rubber content increasing. Take the 10 mesh silicone rubber for instance, as the content improved from 5% to 30%, the 7-day compressive strength of mortar decreased from 27.6 MPa to 10.1 MPa and the 28-day' decreased from 38.95 MPa to 15.88 MPa. Compared with the plain mortar, the 7-day compressive strength dropped by 8.61% and dropped by 8.61% and 66.56%, and the 28-days' dropped by 16.56% and 65.98%, respectively. Within 66.56%, and the 28-day' dropped by 16.56% and 65.98%, respectively. Within the ranges of this study, the compressive strength tended to rise slightly with the increase of silicone rubber size. Moreover, they all were below the compressive strength of the plain mortar.

Figure 8. The compressive strength of the silicone rubber mortar. (a) 7-day; (b) 28-day.

The 7-day flexural strength of the plain mortar was 5.8 MPa and the 28-day' was 7.3 MPa. Figure 9a,b show the effect of silicone rubber on the 7-days and 28-days flexural strength of the Figure [9a](#page-7-1),b show the effect of silicone rubber on the 7-day and 28-day flexural strength of the mortar. mortar. As can be seen, the flexural strength decreased gradually with the increase of silicone rubber As can be seen, the flexural strength decreased gradually with the increase of silicone rubber content regardless of the particle size. Taking 10 mesh silicone rubber powder as an example, with the silicone rubber content increase from 5% to 30%, the 7-day flexural strength decrease from 5.3 MPa to 3 MPa and the 28-day' decrease from 7 MPa to 3.9 MPa. In comparison with plain mortar, the 7-day flexural strength declined by 8.62% and 48.28%, and the 28-day' declined by 4.11% and 46.58%, respectively. In addition, similar to the compressive strength, a less obvious increasing trend for the flexural strength can be observed accompanying the increase of particle size.

Figure 9. The flexural strength of silicone rubber mortar. (**a**) 7-days; (**b**) 28-days. **Figure 9.** The flexural strength of silicone rubber mortar. (**a**) 7-day; (**b**) 28-day.

The reasons of reduction in the mechanical strength of the silicone rubber mortar are related to the properties of silicone rubber [\[12,](#page-13-17)[16,](#page-13-6)[37\]](#page-14-4). Compared with the fine aggregates like river sand, the but the state of the street tends of the 30 km and the presence of the silicone rubber in the value of the stiffness and lowers its load bearing capacity. In addition, the silicone rubber is hydrophobic, which causes the weak bond between silicone rubber and cement paste. Therefore, the degree of weakness increases, which leads to the declined strength. Previous research has shown that the rubber has the air-entraining ability in the process of adding and stirring in the cement paste as its rough surface stiffness of the silicone rubber is low. Hence the presence of the silicone rubber in mortar reduces the morphology and hydrophobic surface [\[38,](#page-14-5)[39\]](#page-14-6). Based on it, the mode pore diameter and the total

porosity in the mortar gradually increases as a result of the improvement of the rubber particle content. The pore will become harmful even disastrous pores as pore diameter larger than 100 nm [\[39\]](#page-14-6), bringing (**a**) (**b**) about a harmful effect on mechanical strength. The more silicone rubber the mortar contains, the lower the mortar strength is. As for the elevating trend of strength accompanying the increase of particle size, it can be explained that the interfacial transition zone between the cement paste and the silicone rubber particles reduces as the bigger particle possessing smaller total surface area.
The content of silicone rubber was seen the content of silicone rubber was 5%, when the content of silicone ru

The failure modes of the mortar in the compressive test are shown in Figure [10.](#page-8-0) The plain mortar specimens exhibited brittle failure (Figure [10a](#page-8-0)). When the content of silicone rubber was 5%, the brittle failure obviously reduced (Figure [10b](#page-8-0)). There was no brittle failure of the 30% silicone rubber mortar under compressive loading (Figure 10 c). This phenomenon proved that [the](#page-8-0) addition of silicone rubber could improve the toughness of mortar, coinciding with the previous studies [\[10,](#page-13-18)[27\]](#page-13-12). [10,27].

Figure 10. Failure modes of the mortar specimen in the compressive test, (a) plain (b) 5 mesh silicone rubber, 15% content, and (**c**) 5 mesh silicone rubber, 30% content. rubber, 15% content, and (**c**) 5 mesh silicone rubber, 30% content.

3.2.2. Effect of the Modified Silicone Rubber on the Mechanical Strength of Mortar 3.2.2. Effect of the Modified Silicone Rubber on the Mechanical Strength of Mortar

The effects of H_2O_2 and KOH modified silicone rubbers on the 28-day mechanical strength of mortar are displayed in Figure [11.](#page-8-1) The silicone rubber treated by H_2O_2 or KOH solution has an enhancing effect compared with the original silicone rubber, especially the compressive strength. For example, when the content of silicone rubber was 15%, compared with original rubber, the 28-day compressive strengths treated by H_2O_2 and KOH improved by 10.56% and 12.44% respectively, and the 28-day flexural strengths improved by 1.82% and 7.27% respectively.

Figure 11. The 28-day mechanical strength of modified silicone rubber mortar. (a) Compressive strength; (**b**) Flexural strength. strength; (**b**) Flexural strength.

The possible reasons for this effect are shown as follows. H_2O_2 can remove the impurities on the surface of silicone rubber and improve its surface hydrophilicity, which ameliorates the interface between silicone rubber and cement paste, further increases the mechanical strength of mortar. Similarly, after treatment with KOH solution the hydrophilic property of the silicone rubber increases according to the contact angle result. In addition, the KOH can provide a weak alkali condition around the silicone rubber particles, which is conducive to the cement hydration around it, so a higher hydration degree and lower porosity of transition zone can be realized [\[36\]](#page-14-3), by virtue of which the mechanical

3.3. Thermal Insulation

3.3.1. Thermal Conductivity

strength of silicone rubber mortar has an obvious improvement.

In order to fulfill the increasing demands of indoor comfort and energy efficiency requirements of building, the innovative material with high thermal insulation, for example, the rubber mortar has attracted more and more attention. The thermal conductivity is an important characteristic to evaluate the thermal insulation performance.

In the study, the thermal conductivity of plain mortar was 1.09 W/(m·K). As shown in Figure [12,](#page-9-0) when the silicone rubber content was 5%, 15% and 30%, the thermal conductivity was approximately 77.71%, 68.81% and 60.64% of the plain mortar, respectively. The thermal conductivity of mortar declines as a consequence of the increase porosity due to the heat preservation of air in the pores. As hereinbefore discussed, the air-entraining ability of rubber leads to the increase of the total porosity, including the interface porosity and the porosity in cement paste [\[39\]](#page-14-6). Hence the thermal conductivity decreases accompanying the increase of silicon rubber content. Moreover, pure silicon rubber usually has poor thermal conductivities of 0.165 W/m·K [\[40\]](#page-14-7), which is another factor for the better thermal insulation of mortar [[41\]](#page-14-8).

Figure 12. Thermal conductivity of the original and modified silicone rubber mortar **Figure 12.** Thermal conductivity of the original and modified silicone rubber mortar.

In addition, it can also be seen that the modified silicon rubber mortar showed a slightly higher modified silicone rubber by H_2O_2 and KOH, the thermal conductivities enhanced by 1.21% and 2.42%, respectively. This also shows that the compactness of KOH modifying silicon rubber mortar was slightly higher than the H_2O_2 modifying one, meaning the former possessing lower porosity, and this was in agreement with the mechanical strength results, also known as mortar containing 30% modified the dry approached with the mortalistic of exhibiting the 16.24% and 4.36% higher compressive strength, and silicone rubber by H₂O₂ and KOH exhibiting the 16.24% and 4.36% higher compressive strength, and $\frac{1}{100}$ increased by $\frac{1}{2}$ replacement of the reasons for the reasons the 10.42% and 6.52% higher flexural strength, respectively, in Section [3.2.2.](#page-8-2) The air-entraining ability is on account of the rough surface morphology and hydrophobic surface. Whereas, the rough surface thermal conductivity compared with the original one. For instance, the mortars containing 30% morphology hardly changes through the modification treatment, so there is little change of the porosity **0.2** especially in cement paste, resulting in the thermal conductivities to be quite close between the original **0.0** silicone rubber mortar and the modified ones. n
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3.3.2. Dry Apparent Density **12. I**n the original and models are original and models and models are rubber more rubber more rubber more rubber models and more rubber more rubber more rubber more rubber more rubber more ru

The dry apparent density of mortar is of great significance to the cost and convenience of the construction, especially mortar pouring and repairing. It is affected by many factors, such as material density, water cement ratio and air content. The apparent density of silicone rubber is 1436 kg/m³, which is quite lesser than 2570 kg/m 3 of fine aggregates of river sand. As can be seen in Figure [13,](#page-10-0) the dry apparent density of mortar was from 2175 to 1996 kg/m³, which decreased with the increasing percent of the replacement of river sand by silicone rubber. One of the reasons for the reduction in mortar density is due to the lesser apparent density of silicone rubber, besides, another reason lies in the silicone rubber entrapping air effect and subsequent higher porosity [\[13](#page-13-3)[,38,](#page-14-5)[39,](#page-14-6)[42\]](#page-14-9). However, the modification of silicone rubber had no obvious effect, which was consistent with the thermal conductivity. $\frac{1}{3}$, the drive dry apparent density of mortar was from 2175 to 1996 kg/m3, which decreased with the contract with the contrac thermal conductivity.

Figure 13. Dry apparent density of the original and modified silicone rubber mortar. **Figure 13.** Dry apparent density of the original and modified silicone rubber mortar.

With the silicone rubber content increased, the thermal conductivity of silicone rubber mortar With the silicone rubber content increased, the thermal conductivity of silicone rubber mortar showed a similar variation trend with the dry apparent density according to the test results. As showed a similar variation trend with the dry apparent density according to the test results. As shown $s = 14.4$ the points in Figure 14, the theory approximately increased with the dry approximately increased wit by the points in Figure [14,](#page-10-1) the thermal conductivity increased with the dry apparent density and a good correlation was recognizable. Therefore, the functional relationship between them was established as:

$$
\lambda = -2.22 \times 10^{-6} \rho^2 + 0.0106\rho - 11.6729 \text{ (R}^2 = 0.9862),\tag{1}
$$

where ρ is the dry apparent density of the silicone rubber mortar, kg/m³ and λ is the thermal conductivity of silicone rubber mortar, W/(m·K).

Figure 14. Fitted curve between thermal conductivity and dry apparent density **Figure 14.** Fitted curve between thermal conductivity and dry apparent density.

3.4. Noise Reduction

The noise reduction of the mortar is an essential performance when it is used for indoor ground.
 In this study, the rubber ball impact method was used to simulate the noise generated by hitting the ground of the sole. As shown in Figure [15a](#page-11-0),b, the noise level of the mortar decreased with the increase of silicone rubber content. For example, it was 73.5 dB (A) for the plain mortar with 1.5 m falling height, when 5% and 30% original silicone rubber was added, it reduced to 71.04 dB (A) and 70.65 dB (A), respectively. It also can be seen that the noise level for the mortar containing modified silicon rubber was slightly higher than the original ones, which might be connected with the little smaller porosity. Besides, the noise level increased with the increase of falling height from 0.5 m to 2.5 m, and the noise reduction brought by silicone rubber also became more significant at the same time. The effect of measuring distance on the noise level was exhibited in Figure [15c](#page-11-0) with the falling height of 1.5 m. The curves of different measuring distances were almost parallel straight lines with fixed spaces, and the noise level of 0.1 m measuring distance was about 2.86 dB (A) and 6.73 dB (A) higher than that of 2.5 m and 5 m, respectively. Besides, as the silicone rubber content increased by 5% to 30%, the noise $h = \text{reduction was about } 0.4 \text{ dB} (A).$ vas siightiy higher than the original ones, which hiight be connected with the inti measuring abstract on the noise reduction by significant by significant at the same. $\frac{1}{2}$ was about 0.4 dB (A).

Figure 15. Effect of test conditions on the noise level of silicone rubber mortar. (a) Modification method method (measuring distance: 0.1 m; falling height: 1.5 m); (**b**) Falling height (original silicon rubber; (measuring distance: 0.1 m; falling height: 1.5 m); (**b**) Falling height (original silicon rubber; measuring distance: 0.1m); (**c**) Measuring distance (original silicon rubber; falling height: 1.5 m).

The principle of the noise reduction improvement is similar to the air-entraining effect of the silicone rubber. The porosity of mortar increased along with the addition amount of silicone rubber as discussed above, which could increase the frequency of acoustic reflection caused by the rubber ball reduced after adding elastic silicone rubber, which increased the adaptability of stress diffusion and impact, achieving the energy dissipation. At the meantime, the elastic modulus of mortar reduced absorption*,* and consumed more sound energy. after adding elastic silicone rubber, which increased the adaptability of stress diffusion and stress

4. Conclusions

In this paper a novel approach to reuse waste silicone rubber of composite insulator applying to the cement mortar was developed. In addition, a valid attempt to modify the silicone rubber surface by KOH and H_2O_2 was carried out.

The silicone rubber was proved to be a good substitute for fine aggregate to enhance the mortar toughness according to the failure modes. The compressive strength and flexural strength decreased with the silicone rubber content increasing. However the strength of modified silicone rubber mortar improved compared with the original one.

As the silicone rubber increased, the mortar porosity went up resulting from the air-entraining ability and the expanding loose interfacial transition zone, and the thermal insulation and noise reduction performances of the silicone rubber mortar enhanced as a result. Moreover, the low thermal conductivity of the silicone rubber was favorable for the thermal insulation of mortar, and the high elasticity of the silicone rubber was beneficial for the noise reduction of mortar. The thermal conductivity of 30% silicone rubber content mortar remarkably decreased to 60.64% of the plain mortar. Furthermore, as to the silicone rubber mortar there was a good correlation between thermal conductivity and dry apparent density, and a quadratic function was obtained to describe the relationship. A self-made rubber ball impact test device was used to measure the noise reduction when the measuring distance was 0.1 m and falling height was 1.5 m, the mortar noise level reduced by 2.46 dB (A) and 2.85 dB (A) with the 5% and 30% silicone rubber content, respectively.

This study not only contributes to reuse waste silicone rubber in thermal and noise insulation mortar, expanding the cement mortar application field, but also helpfully reduces solid waste, providing valuable reference for environment protection. Moreover, further research on mechanical strength improvement of silicone rubber mortar, as well as silicon rubber addition to concrete will be carried out for the next stage.

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