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Sustainable sulfur composites with enhanced strength and lightweightness using waste rubber and fly ash

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HIGHLIGHTS

- The highest strength was achieved when 50% of modified sulfur was replaced by fly ash.
- With more than 40% fly ash, the microstructure of sulfur matrix was completely changed.
- At a low ratio of fly ash, the use of 5–10% rubber powder enhanced the strength of sulfur composites.
- Sulfur mortars with 5–10% sand showed lower strengths than sulfur composites with rubber powder.
- The sulfur composites had very low porosities, and the use of fly ash reduced the porosity.

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ABSTRACT

Sulfur polymer concrete (SPC) is a thermoplastic composite that is generally composed of modified sulfur polymer binder and aggregate. This study proposed a new approach for developing sustainable sulfur composites by using only hazardous industrial wastes without aggregate. The industrial wastes used in this study were sulfur, fly ash, and rubber powder from waste tires. The proposed method may have several major advantages compared to using cement-based concrete as well as traditional SPC: less CO_2 emissions, lower life-cycle cost, and superior durability. To examine the effects of waste rubber powder and fly ash on the strength and microstructure of sulfur composites after three days of curing, a series of characterization analyses were conducted based on the tests of compressive strength, powder X-ray diffraction, scanning electron microscopy with energy dispersive spectroscopy, and mercury intrusion porosimetry. The test results suggested that the replacement of sulfur with fly ash up to about 45% generally improved the compressive strength of sulfur composites, and rubber powder effectively substituted fine aggregate or a portion of sulfur without significant strength reduction. This study also revealed that the microstructure of sulfur composites was significantly affected by varying the amounts of fly ash or rubber powder, despite no change in reaction products.

1. Introduction

The recycling of industrial wastes and byproducts is a common practice in the construction field today. The main materials used in this study, such as sulfur from petroleum refineries, rubber from waste tires, and coal-fired fly ash, fall into this category.

Large amounts of elemental sulfur have recently been generated from mining or as a byproduct of petroleum refining processes around the world. Due to its thermoplastic characteristics, sulfur can be mixed with aggregates or fillers at a high temperature, and they can be bound in hardened sulfur concrete at room temperature.

As for fly ash, it is reported that more than 750 million tons are produced annually worldwide. Despite various attempts to recycle fly ash in the construction industry, almost one-half of all fly ash is deposited in landfills [1]. Fly ash contains a considerable amount of leachable toxic trace elements (e.g., As, Cd), which may cause serious environmental issues if air, water, and soil are directly exposed to them. Thus, suitable utilization methods for fly ash should be developed to avoid such problems.

Also, about 1.4 billion automobile tires are traded worldwide every year, and subsequently, most of them turn into wastes after their lives [2]. Increasing amounts of waste tires are generally piled

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in landfills [3]; they are usually not buried in landfills due to their low density and poor biodegradation even after long periods. Therefore, reutilization methods are needed. Earlier attempts [3–8] were made to apply tire rubber in the production of Portland cement concrete. The researchers investigated using sliced rubber particles of various sizes and shapes, and they reported that the rubber particles could be utilized as lightweight aggregates while enhancing the properties of concrete (e.g., toughness, plastic energy absorption).

Many countries involved in the petroleum and natural gas industries have been aware of the environmental harms of sulfur and have enacted necessary regulations on the related industries. China is an exemplary country that recently mandated compulsory desulfurization at all petroleum refineries [9]. Canada also set the allowable quantities of sulfur in gasoline and diesel and limited the emissions of SO_2 from petroleum refineries. These actions have led to a considerable increase of surplus sulfur in solid form around the world. Currently, the global generation of sulfur is approximately 10–20% larger than the worldwide demand, which is about 57 million tons per year [10]. The oversupply of sulfur has dramatically reduced the market price of sulfur. Therefore, the current situation can be an attractive opportunity for other industrial fields to utilize sulfur at a cheaper price. On the other hand, the disposal of excess sulfur has emerged as a serious problem due to the shortage of temporary storage spaces at petroleum refineries. Therefore, new recycling methods of surplus sulfur should be developed.

Global warming is a critical issue that may jeopardize the entire human society unless it is properly addressed. Cement production in the world yields about 7% of the total CO_2 emissions [11]. Several previous studies on sulfur polymer concrete (SPC) were conducted in past decades [12–16]. These studies suggested sulfur as an innovative material in civil engineering. In particular, it was

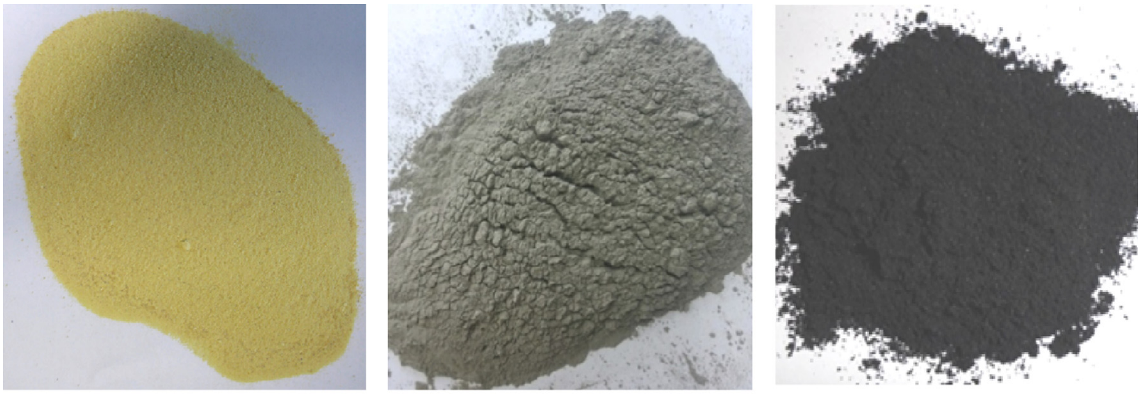
(a) (b) (c)

Fig. 1. Raw materials: (a) modified sulfur, (b) fly ash, and (c) rubber powder.

Table 1
Mix proportions of tested sulfur composites.

Mixture Label	Binder precursors						Sand	
	Modified sulfur		Fly ash		Rubber powder			
	Vol.%	kg/m^3	Vol.%	kg/m^3	Vol.%	kg/m^3	Vol.%	kg/m^3
0–0	100	1910	–	–	–	–	–	–
0–10	90	1719	10	222			–	–
0–15	85	1624	15	333			–	–
0–40	60	1146	40	888			–	–
0–45	55	1051	45	999			–	–
0–50	50	955	50	1110			–	–
5–0	95	1815	–	–	5	56	–	–
5–10	85	1624	10	222			–	–
5–15	80	1528	15	333			–	–
5–40	55	1051	40	888			–	–
5–45	50	955	45	999			–	–
5–50	45	860	50	1110			–	–
10–0	90	1719	–	–	10	112	–	–
10–10	80	1528	10	222			–	–
10–15	75	1433	15	333			–	–
10–40	50	955	40	888			–	–
10–45	45	860	45	999			–	–
10–50	40	764	50	1110			–	–
15–0	85	1624	–	–	15	168	–	–
15–10	75	1433	10	222			–	–
15–15	70	1337	15	333			–	–
15–40	45	860	40	888			–	–
15–45	40	764	45	999			–	–
15–50	35	669	50	1110			–	–
S5	95	1815	–	–	–	–	5	133
S10	90	1719	–	–			10	265
S15	85	1624	–	–			15	398