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The Effect of Sulfur Salts on Concrete

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Abstract: It is anticipated that the constant need for concrete will rise as a result of the rapid advancements in global construction. Due to this need, a significant amount of cement must be produced, which could have negative ecological effects like raising atmospheric CO2 emissions. This prompted a number of researchers to look for cement substitutes, and sulfur salts -based concrete is one such substitute. The amount of cement needed to manufacture regular concrete is decreased because to this concrete composite In order to produce Ordinary Portland Cement (OPC) can be partially substituted with sulfur in sulfur salts -based concrete. It is a composite matrix of building materials composed primarily of sulfur and aggregates. In terms of exceptional durability resistance, low heat conductivity, little shrinkage, quick early strength rise, and improved adhesion, sulfur-modified concrete performs better than regular concrete. Due to the exceptional qualities indicated above, sulfur salts -based concrete can be used as a primary building material for offshore projects, underground utility networks, and dams. This study provides a thorough understanding of the possible uses of sulfur salts -based concrete in the modern construction industry by analyzing the sources, emissions from construction companies, and compositions of sulfur; describing the properties and processes of sulfur production; and highlighting relevant literature.

Keywords: concrete, sulfur salts, compositions, properties.

1. Introduction

Large-scale waste from oil and gas producing plants produces sulfur as a byproduct. Given the estimated global sulfur output (based on data from the US Geological Survey (USGS)), the entire usage (disposal) of sulfur and its many other uses need to be carefully studied [1]. Due to a rise in refineries and gas processing facilities, China has emerged as the world's largest producer of sulfur as a by-product in recent years, with 17 million tons produced in 2018 [2]. In 2018, the world's second-largest producers of sulfur were, Kazakhstan, and the United States (9.7 million tons) (each = 3.5 million tons). [2]. Sulfur salts has several possible applications in construction, including the incorporation of sulfur into sulfur-based concrete. Sulfur-based concrete has several advantages over Portland cement concrete, including, and the ability to concret at negative ambient temperatures [7]. The great capacity of sulfur's atoms to join to create ring or chain molecules causes it to exhibit a wide spectrum of allotropic alterations. Sulfur allotropes come in two varieties. [13]. Combining sulfur atoms to create cyclic rings (cyclo-Sn: where n is the number of atoms) and chains (catena/polycatena sulfur) allows for the creation of millions of intramolecular sulfur allotropes (taking into account all possible combinations of sulfur atoms). Remember that whereas Sn molecules with six to twelve sulfur atoms are rather stable and exist as rings, those with fewer or more sulfur atoms can exist as either a ring or a chain, which is unstable.

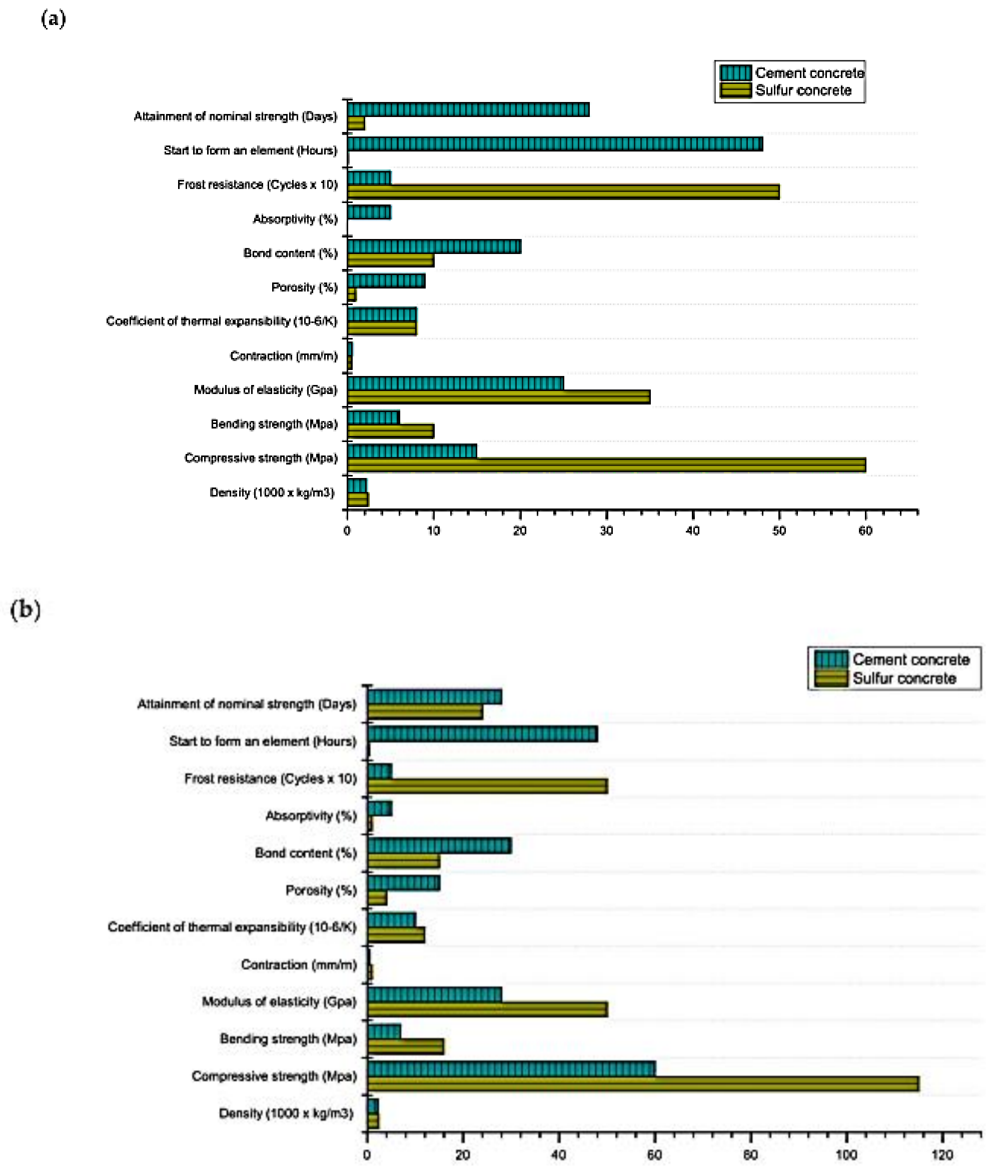

Figure 1: Durability and mechanical characteristics of concrete based on sulfur and cement Data taken from Reference [14] shows the (a) maximum (grade M60) and (b) minimum (grade M15).

2. Background and Literature Review

Allotropes differ in their physical qualities, although most of their chemical properties are relatively similar [13]. In certain ratios, they can coexist in equilibrium based on pressure and temperature. The thermal history determines the physical and chemical characteristics of solid sulfur, as well as the existence and concentration of each allotrope. The rhombic (α), plastic, and monoclinic (β) allotropic changes are the three most significant [15].. molecules of cyclo-S8. Sulfur in liquid form, which is produced by polymerizing and opening S8 rings, is with uneven spacing between them above 159 °C.

[3]. Furthermore, several studies have looked at sulfur-based concrete since the 1970s, initially in North America [16–21]. The primary findings of previous research led to the conclusion that Concrete with a sulfur basis was environmentally safe. The amount of sulfur collected rose during the 1980s and 1990s as hydrocarbon output expanded [22–24]. OPC can create sulfur-based concrete by using sulfur as a partial binder substitute. Mostly composed of aggregate and sulfur, sulfur-based concrete is a composite matrix of building components. Due to its many advantages over conventional concrete, sulfur-based concrete is strongly advised, dam, and

offshore systems, as shown in Table 1.. Emissions from construction companies and sulfur compounds are discussed after a review of sulfur's natural and artificial sources. A detailed analysis of the characteristics and procedures of sulfur manufacture is followed by a discussion of possible avenues for further research.

Table 1. Comparison between Ordinary Portland Cement (OPC)-based concrete and sulfur-based concrete properties (grade M15 and M60).

Property	Unit	OPC-Based Concrete	Sulfur-Based Concrete	Refs
Time of strength gain	Time	28 days	3 h	[7]
Compressive strength	MPa	15–25	55–65	[14]
Tensile strength	MPa	3–4	5–7	[25]
Wearing capacity	%	17	3	[26]
Flexural strength	MPa	6–9	10–15	
Freezing resistance	%	50	300	[4]
Acids resistance	at 100/cent humidity	23	84	[27]
Water resistance	%	0.8	1.0	[28]

3. Source of Sulfur salts

can be found in both natural and artificial sources, yet it is exceedingly challenging to measure the amount of sulfur that is produced globally from either source. For example, sulfur from mining and environmental byproducts (such as oil refineries, natural gas processing facilities, and nonferrous metal smelters) may be measured with reasonable accuracy. Sulfur from electric power plants and businesses, however, is exceedingly hard to define. Furthermore, due to the variety of sources, emissions, and chemicals involved, it is challenging to measure sulfur emissions derived from natural sources [1].

3.1. Sulfur's Natural Sources

It is challenging to measure the complexity of the natural sources of sulfur production. The earth's crust contains a variety of minerals that contain sulfur, which makes it among the very few elements that exist in an elemental condition in the crust of the earth. In addition, it can be found in natural gas, coal, and oil in different forms and concentrations. Furthermore, all living things, including plants and animals, require sulfur [1,29]. Some of the sulfates produced by weathering sulfide minerals found in the lithosphere are released into the oceans through a variety of mechanisms, including erosion and runoff from rivers. By reacting with microorganisms, the remaining weathered sulfate creates a number of chemicals that are eventually absorbed by plant/soil systems. Plants that contain sulfur components are used or consumed by animals, and following consumption, these plants eventually create sulfates [29]. The most spectacular and well-known naturally occurring sulfur sources are volcanoes. Both during eruption and non-eruptive periods, sulfur compounds are released during volcanic activity. Additionally, the sulfur content of seawater is such that 2.56 milliliters of sulfate are present in every gram of water. Sulfur is present in water bodies because of weathered minerals and the decomposition of marine life. Salt particles are created and released into the sky when water bubbles (molecules) rupture, especially at sea, rivers, oceans, or any other body of water. Figure 2.

3.2. Man-Made Sulfur salts Sources

illustrates the sulfur input from naturally existing sources. Although the amount of sulfur released into the sulfur resources are caused by the burning of fossil fuels. Up until the 1970s, when sulfur emissions were regulated by environmental laws in both Europe and America, the rising trend continued [35]. Sulfur emissions were decreased via environmental controls, however the problems were not entirely resolved.

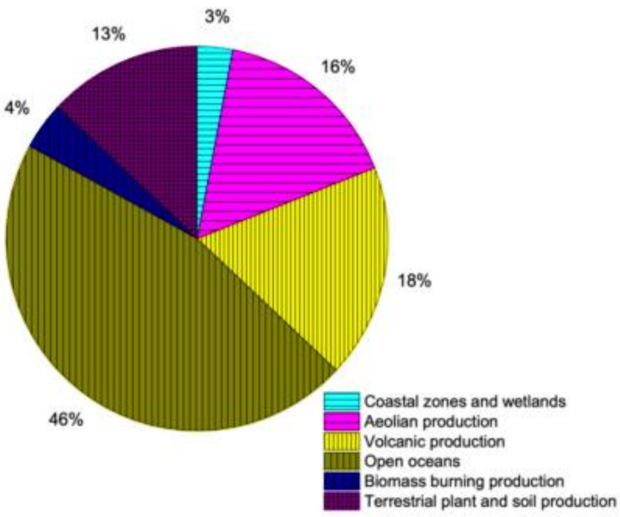

Figure 2. Sulfur's contribution through natural resources (information taken from Reference [36]).

3.2.1. Natural Gas

$H2S$ separation is the first step in the recovery of sulfur from natural gas. Because of its corrosive and poisonous properties, H2S must be separated. Sour gas is the natural gas that makes up H2S. It is designed to pass through a solvent, such as amines, in which H2S dissolves but the necessary proportion of natural gas stays insoluble [37, 38]. H2S is then extracted from the solution by heating the solvent [37, 38]. Following the separation of various natural gas components, procedures transform H2S into sulfur salts.

3.2.2. Petroleum

In general, crude oil is composed of 84% carbon, 14% hydrogen, 1-3 percent sulfur, and less than 1% nitrogen, oxygen, metals, and salt. [39]. Sulfur separates from the different organic components as H2S during the petroleum refining process. H2S, which was produced during the refining process, was utilized as refining fuel until the environmental legislation of the 1970s. This procedure was constrained because sulfur dioxide is released into the atmosphere when H2S is burnt. Generally speaking, elemental sulfur can be created by further processing the H2S generated in oil and petroleum refineries [40].

3.2.3 Sands of Oil

The increase in sulfur and nitrogen deposition in that area is one of the issues with the development of oil sand reserves. [41].. A major source of sulfur is sands, which are mostly found in Canada, where there are about 300 billion barrels of extractable oil with 3.5–5% sulfur [43,44]. Bitumen, clay, water, and sand are typically mixed to create oil sands. 10% and 7% bitumen in oil sands are regarded as rich and not economical [43]. To get a sizable amount of sulfur, the oil sand refinery needs to be improved. One may argue that H2S production in particular is receiving extra attention since, on the one hand, it contributes to the partial desulfurization of oil and, on the other [42].

3.2.4. Smelting Sulfides

Smelting nonferrous metals can yield combined sulfur. Smelter gases containing SO2 are converted to liquid sulfur and H2SO4. H2SO4 from the smelting of nonferrous metals produced around 11% of the sulfur in the United States in 1990 [45]. SO2 emissions are another source of sulfur salts. The desulfurization process, is depicted in Figure 3, where slag is combined with sulfate mineral concentrate before being injected with enhanced oxygen to create oxidation reaction forms [46]. Following that, the molten matte and [46]. SO2 and other toxic pollutants are produced by this process. The gas released during the operation is transformed into sulfuric acid, a useful byproduct. [47].

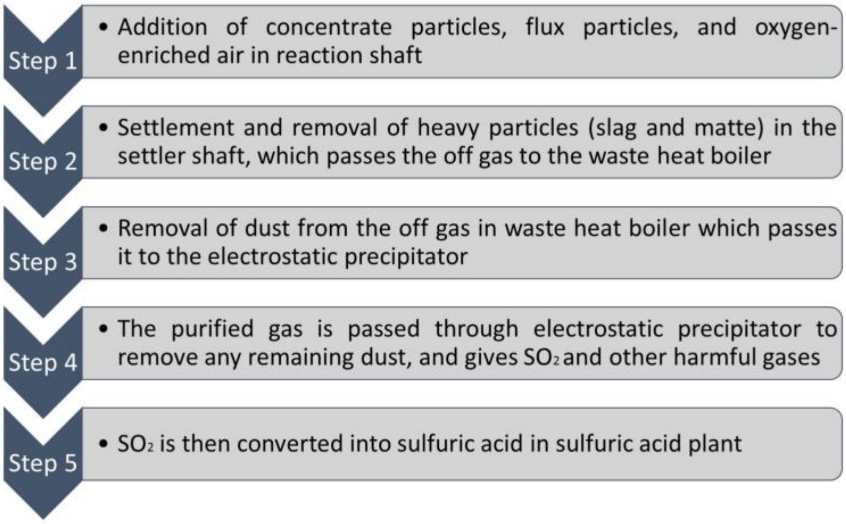

Figure 3. Flash Smelting Furnace Schematic (information taken from Reference [46]).

4. Methods and Material

More than 5 billion tons of sulfur are found in natural deposits, comprising sulfur ores with sedimentary and magmatic origins. Approximately 1.2 billion tons of native sulfur can be found in the explored deposits. The two sectors of the sulfur mining business are attentive and specialized. The primary goal of the [48], 200 million tons in the United States [49], 100 million tons in Chile [50], and 100 million tons in Mexico [51]. The Japanese islands [56], , and Turkmenistan have also been the sites of extensive deposits. [55]. Sulfur is created in the attendant sector as a byproduct of processing hydrogen sulfide; the amount of sulfur produced is determined on the amount of natural gas and refined oil as well as the amounts of sulfur salts consumed. There are three forms of sulfur produced commercially: lump, granulated, and liquid. Technologies for producing sulfur include the extraction and refinement of naturally occurring sulfur [57], the extraction of sulfur from pyrites [58], the production of sulfur from H2S [59,60], and the creation of sulfur from SO2. [61].

4.1. Claus Procedure

Every source of sulfur, particularly artificial ones, releases H2S, which can be transformed into sulfur by a variety of global processes. Claus, named for its creator Carl Friedrich Claus, is one such technique [30,62]. The Claus procedure has an overall efficiency of 94–97% [63,64]. The following is how the conventional Claus method (shown in Figure 4) is executed: [64]

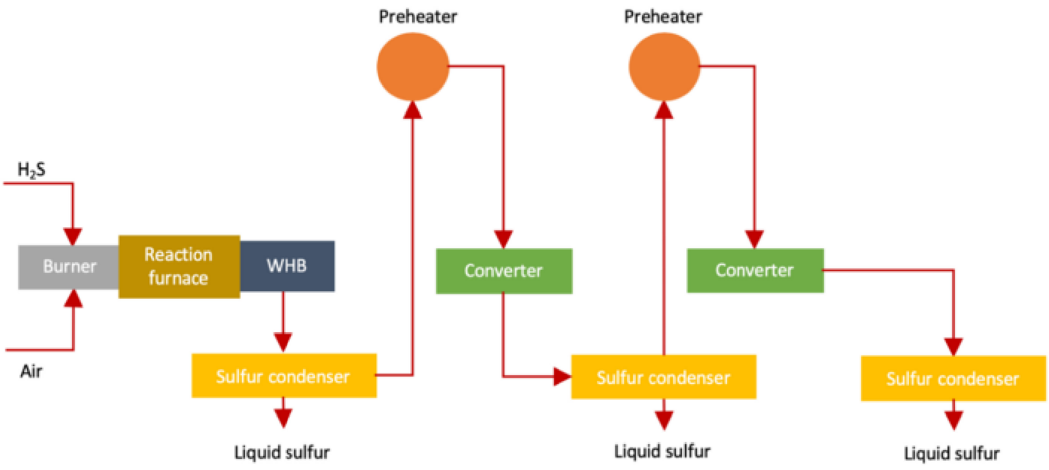

Figure 4. Claus method for producing sulfur (derived from Reference [64]).

SO2 is created when H2S reacts with the oxygen (O2) present in the air. While H2S and SO2 mix to produce 3/2 S2, the reaction described above generates a lot of heat. Up to 75% less equilibrium transformation occurs in this highly reversible exothermic process. Reaction furnace effluent gas is moved to a waste heat boiler (WHB) to generate high-pressure steam and recover heat. WHB with effluent gas is delivered to a condenser for condensing sulfur after the S2 in the gas transforms into hexasulfur (S6) and octasulfur (S8). After being heated, condensed effluent gas is transported to two or three catalytic reactors. As the converted effluent gas cools in the condenser, sulfur is produced at each stage of the catalytic reaction.

4.2. Mining Frasch

In 1984, Dr. Herman Frasch developed a method for recovering sulfur that involved pumping it to the surface after it had melted underground [1]. In 1903, this method was first applied commercially at Sulfur Mine in Louisiana [65]. Typically, frasch mining (as seen in Figure 5) follows these steps: [37]:

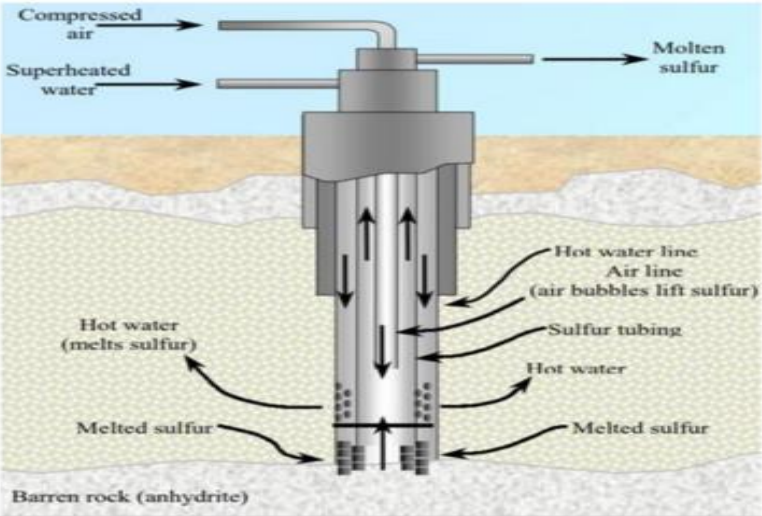

Figure 5: Frasch pump schematic shape (source: USGS [1])

5. Sulfur salts Properties

A Frisch pump is placed in the earth where sulfur deposits are found. In sulfur-containing mineral strata, hot water (165 °C) is added. Sulfur is melted by hot water and then pumped to the surface by pressurized air. Frasch mining, particularly in sulfur-rich nations like the US, Iraq, and Mexico, recovered over 90% of sulfur from man-made sources; nonetheless, this mining process necessitates the following requirements [66]: • Massive sulfur deposits that are rich and permeable. • The overlying rock above the deposit is impermeable. • A steady and enough supply of water. • Economical fuel source needed to heat vast amounts of water to melt the sulfur deposit and supply sufficient power for the process's energy-intensive machinery to operate properly. If geological requirements are met, the deposits should be either salt domes with permeable sulfur (packed in impermeable strata) or bedded evaporite [67]. Even though this method is widely used to extract sulfur, tiny and shallow sulfur deposits cannot be recovered using it.

5.1. Point of Melting/Freezing

lists the various melting and freezing temperatures of sulfur, which are typically based on the solid allotrope being considered (melted). The dissociation (automatic) of the melt to create sulfur utilizing other solid allotropes, which have a lower freezing point than cyclo-S8, causes a natural decrease in the freezing point of sulfur [68]. As a result, the entire mixture has a lower freezing point. Sulfur can reach its maximum intensity or concentration at a specific temperature, also referred to as the natural melting point or low freezing point. Sulfur's freezing point is determined by the mixture's or melt's temperature and pressure. [13,69,70]

Table 2. Melting point of various allotropes of sulfur.

Allotrope of Sulfur	Melting Point (°C)	Refs.
α-sulfur	110.06	[36]
	115.1	[13]
	112.8	[36,69]
β-sulfur	114.6	[69]
	119.6	[71]
	120.4	[13]
	133	[69]
γ-sulfur	106.8	[72]
	108	[73]
	108.6	[13]
δ-sulfur	160	[13]
ω-sulfur	77	[73]
	90	
	160	
Fibrous	104	[69]
	75	[73]
	104	[72]
Hexasulfur	50	[74]
Heptasulfur	39	[75]
Cyclo-S_{12}	148	[74]
Cyclo-S_{18}	128	[76]
Cyclo-S_{20}	124	

5.2. Viscosity

Sulfur's viscosity is strongly affected by temperature. The viscosity of sulfur, for example, can drop by as much as 7 to 8 centipoises at 160 °C. It rises a lot (by roughly 930 poise) at 190 °C before falling once more. Additionally, determine how much the viscosity increases or decreases. Thus, the decrease in viscosity (at 160 ◦C) can be explained by the growth.

5.3. Density

Similar to viscosity, sulfur density is temperature dependent. Figure 6 illustrates how the density of sulfur rises as the temperature drops. According to reports, the polymerization form changes from eight-membered rings of sulfur atoms to a long chain with about 106 million atoms as the temperature rises. This new polymerization shape is said to lower the density of sulfur [77]. Sulfur polymerization, however, alters a number of its characteristics (such as density and viscosity) at a fixed temperature. The Lambda Temperature is the name given to this temperature [69]. One of the elements with the greatest number of solid allotropes is sulfur, and the majority of these feature cyclic molecules with ring sizes ranging from 6 to 10 [78]. The density in the Figure 6

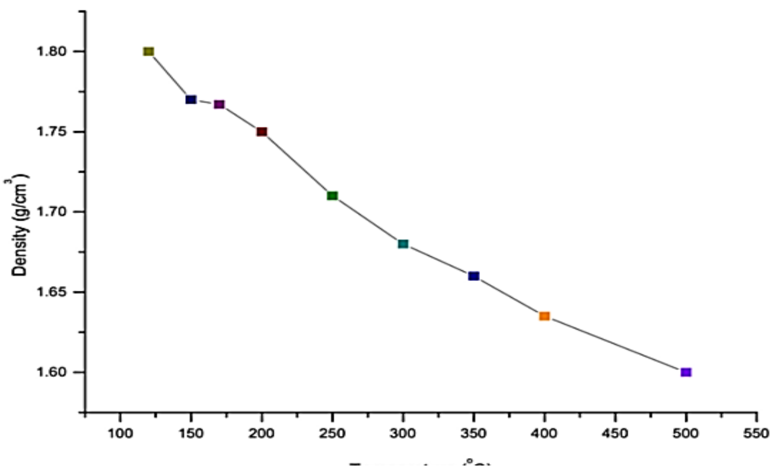

Figure 6. Sulfur density according to temperature and allotropes (information taken from References) [15,36,69,79–86].

5.4. Color

Table 3 illustrates how the colors of sulfur's various allotropes and melts vary [87]. Pure sulfur, for example, is clear and bright yellow at its melting point and gradually turns deep or opaque red at its boiling point [88]. The cooling rate is a significant factor in determining the color of sulfur since it is recovered in the molten or melted condition [89]. When molten sulfur is cooled to -80 °C (the boiling point), for instance, it will be yellow; when it is cooled to -209 °C (in liquid nitrogen), on the other hand, red sulfur will be produced. [69].

Table 3. Colors of various allotropes of sulfur.

Allotrope of Sulfur	Color	Refs
Octasulfur alpha	Bright yellow	
Octasulfur beta	Yellow	
Octasulfur gamma	Light yellow	
Hexasulfur	Orange to red	[15,76,80–86]
Heptasulfur	Light yellow	
Anneasulfur	Deep yellow	
Decasulfur	Yellow to green	
Octadecasulfur	Lemon to yellow	

5.5. Thermal Conductivity

The polymerization at the Lambda Temperature causes discontinuities in sulfur's thermal properties, similar to those of density and viscosity [69]. Temperature and thermal conductivity have a linear relationship. The thermal conductivity of sulfur first falls as the temperature rises until it approaches the phase transition [90]. Sulfur has a lower thermal conductivity than the majority of rocks and is almost as thermally conductive as insulators like mica and asbestos. Furthermore, temperature affects the solid/liquid sulfur's thermal conductivity at a certain air pressure [91]. It is determined that solid sulfur has a higher heat conductivity than liquid sulfur. [91].

5.6. Strength

The purity and thermal history of sulfur determine its strength. In 1965, two researchers (Dale and Ludwig) conducted a thorough investigation on sulfur's compressive and tensile strength [25]. Sulfur's compressive strength is said to be between 1800 and 3300 psi (12.41 and 22.75 MPa), whereas its tensile strength is primarily determined by temperature, cooling rate, and thermal histories [6,26,92]. For example, Figure 8 illustrates how a high beginning temperature and quick cooling rate [26]

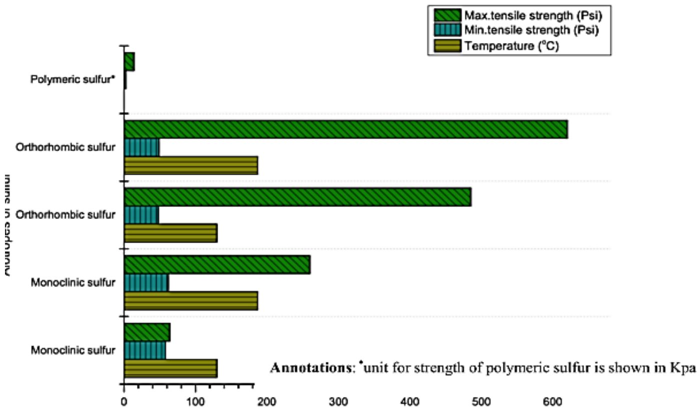

Figure 7. Range of sulfur's tensile strength at different temperatures (information taken from Reference [25])

6. Results

As seen in Figure 9 [93], sulfur has been used in a number of industries, including the pharmaceutical, petroleum, and agricultural sectors. As cement production has become more environmentally conscious and material resources for cement ingredients are running low, sulfur has emerged as a valuable binding material. Sulfur has also been utilized to produce bitumen, a necessary component for building roadways. Roadblocks, sidewalks, drainage/sewerage pipes, foundation covering, railroad ties, bridge decks, and acid tanks can all be constructed with sulfur-based concrete [50,94]. Meanwhile, streets, roads, and highways can be built using sulfur asphalt. Due to its qualities (such as increased strength, impermeability, quick strength development, resistance to corrosion, and recyclability), sulfur-based concrete is growing in popularity and may be a dependable cementitious alternative..

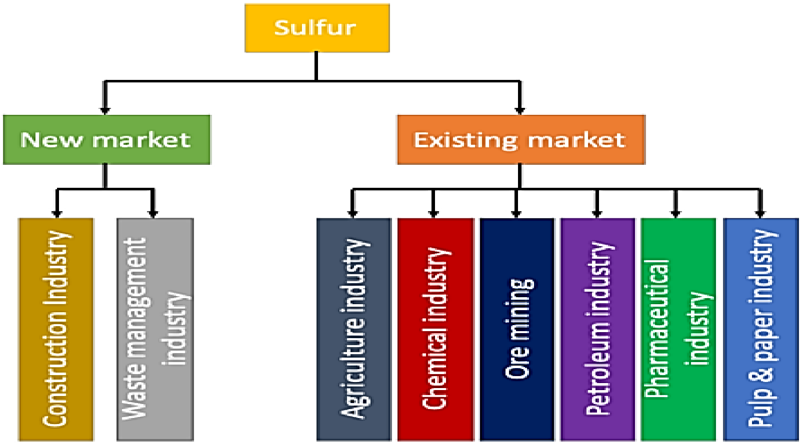

Figure 8. Global sulfur markets, both new and established (information taken from Reference [36]).

6.1. The composition and mixing of concrete based on sulfur

In sulfur-based concrete, sulfur is used as a binder in its molten state [7], taking the place of cement and water, two components of traditional concrete. Molten sulfur is created by heating sulfur, and then it is cooled to create cemented concrete [92]. Compared to regular concrete, sulfur-based concrete requires a different mixing process. Sulfur-based concrete is mixed with extra caution for the following reasons [96]:

- To lessen the absorption of moisture and improve resistance to acid and salt. • To limit drying shrinkage after hardening, preserve workability, and retain (improve) the mechanical qualities of sulfur-based concrete in comparison to ordinary

6.2. Emissions of Sulfur from Construction Companies

During the cement-making process, the amount, the energy fuel's quality are the main factors influencing sulfur dioxide emissions [32,97]. Sulfur dioxide emissions are higher in raw materials that include a lot of organic sulfur or pyrite (FeS). In 2015, China alone emitted 18.6 million tons of sulfur dioxide, of which: • utilizing vertical grinding machines and allowing waste gases to flow through the mill [97]. • selecting low-sulfur fuel [98] and adding adsorbents to the exhaust fumes that are routed to the filters [99], like hydrated lime, calcium oxide, or fly ash with a high CaO content. • the application of scrubbers, either dry or wet. Due to its higher cost compared to wet gas cleaning, dry gas cleaning is typically employed when sulfur dioxide emissions surpass 1500 mg/m3 [100]. • Sulfur dioxide emissions while choosing low volatile quarry minerals [101]. • Adding bicarbonate or hydrated lime to the waste gas stream before to the filters [102] and injecting slaked lime or highly dispersed quicklime into the kiln furnace cap [103]. Sulfur, a corporate waste product, can also be effectively used to create building materials because it helps with environmental.

since flue gases contain significant levels of anthropogenic sulfur which are released into the atmosphere (170 to 180 million tons per year) [104]. Within the concrete business, it might be the best substitute for cement.

6.3. Concrete with Sulfur

Modifications According to the 2002 theory by Gracia et al. [50], using unmodified sulfur shows promise in achieving the required properties of special concretes. Nevertheless, there are no further continuations in this version. According to the scientific [105], and Korolev [54], it is improbable that sulfur could be used unchanged at this point in the evolution of building materials research. To prevent sulfur from changing from its monoclinic to its orthorhombic form, the most widely employed modifiers [5,106]. Due to the exothermic nature of the sulfur-dicyclopentadiene interaction, which necessitates precise temperature control, and because the sulfur [107]:

6.3.1. The Microstructure of Different Composites Modified with Sulfur

By polymerizing a cyclic hydrocarbon, sulfur at 120 to 140 ◦C for 30 minutes, and then rapidly freezing and curing the resulting sulfur polymer, McBee [115,116] states that sulfur can be added.

Table 5. Modifiers and fillers for sulfur-based concrete

Inorganic Additives		
Modifier	**Concentration % of the Mass of Sulfur**	**Result**
Talk [3,110]	26	Acid resistance
Heavy metals and mercury [36]	6	Durability
Alumina [3]	20–26	
Fly ash [3]	22–23	Acid resistance
Silica [3]	22–25	
Organic additives		
Dicyclopentadiene [5,9,12,117,118]	0.1–50	Increased strength in corrosive chemical environments, increased fire resistance
Dicyclopentadiene + cyclopentadiene + dipentene [5,9,12]	1–30	Rapid development of compressive strength
Olefin polysulfide additives [12,110]	5–25	Improving the strength characteristics
Epoxy resin [119]	2–6	Improving the strength characteristics
Polyolefin [7]	2.5–5	Plasticizer
Bitumen [6,12,110]	1–4	High corrosion resistance, high physical strength
Additive STX (Starcrete) [120]	2–7	High fatigue strength
Styrene [6,110]	2–30	Low water permeability
Ethylidene norbornene [121]	1–5	Provides, with smaller quantities of the modifier, an increase in the resistance of sulfur-based concrete in acidic and basic environments, has high strength, high frost resistance and also eliminates the toxicity of the material obtained

6.3.2. Mobility of the Mixture and Melt Viscosity

Liquid sulfur's dynamic viscosity, which ranges from $(6.5–11) \times 10^{-3}$ Pa•s for temperatures between 120 and 155 ◦C, suggests that sulfur is a fluid that moves easily. This allows for the modification of the rheology of materials containing sulfur while they are heated [77]. The polymerization of cyclo-octa sulfur starts at 187 ◦C when catena-polymers are formed and the viscosity increases several thousand times to 93.3 Pa•s [121]. Sulfur demands a maximum temperature of 159 °C to work with. Plasticizers such as polysulfides are used to improve the plastic qualities of sulfur-based mortars and raise the hardening concrete's resistance to cracking. Citing [118], The concrete made of cast self-compacting sulfur has flexural and compressive strengths of 12 and 20 MPa, respectively.. The surface contact of molten sulfur and asphalt granulate particles produced the flexibility of these concrete compositions. The kind and modifying additives, the amount of sulfur-based concrete..

6.3.3. Hardened Properties

How strong sulfur-based concrete is depends on a number of factors, including the strength and composition of its materials, the technology used for molding, preparation, and other processes, and the extent [117]. As the amount of aggregate in sulfur-based concrete increases, the concentration of sulfur binder, the most powerful component of concrete, which is made by mixing sulfur, filler, and modifying chemicals, steadily falls [110] (Table 5). After the sulfur binder solidifies (Table 6), sulfur-based concrete provides quick acquisition of compressive and flexural strength [18,36,122]. In order to reach 90% of its final strength, conventional concrete needs to hydrate for 28 days, taking into account the required moisture and temperature conditions. Nevertheless, sulfur-based concrete produces the intended effects without the need for certain moisture or [123]. Additionally, the compressive strength of ordinary concrete increases with increasing strain and then falls after reaching its maximum (till 0.17 mm/mm and 20 MPa). However, at higher levels (such as 40 MPa and 0.025 mm/mm), the compressive strength of sulfur-based concrete likewise exhibits a linear relationship with strain [122]. The strength development of sulfur-based concrete can be investigated using X-ray diffraction testing and analysis..

Table 6. Characteristics of strength of various sulfur-based concretes.

Authors	Content	Compressive Strength, MPa	Flexural Strength, MPa	Tensile Strength, MPa
Vlahovich et. al. [3]	Sulfur—30 wt. % Sand—63 wt. % Fillers—7 wt. %	55	8	3
Dehestani et. al. [6]	Sulfur—98 wt. % styrene—2 wt. %	54	8	3
Al-Otaibi et al. [7]	modified sulfur—1 wt. % granulated sulfur—11 wt. % sand—40 wt. % coarse aggregate, 42 wt. % fly ash—6 wt. %	30	2	1
Gracia et. al. [50]	Sulfur—25 wt. % Sand—70 wt. % slag—5 wt. %	70	12	5
Bae et. al. [88]	modified sulfur—15 wt. % fly ash—13 wt. % sand—32 wt. % coarse aggregate—40 wt. %	83	13	6
Choura et. al. [92]	Sulfur—50 wt. % Phosphogypsum—50 wt. %	41	5	2
Gwon et al. [118]	modified sulfur—40 vol. % sand—35 vol. % binary cement—25 vol. %	62	9	4
Anyszka et. al. [119]	modified sulfur—30 wt. % sand—70 wt. %	115	16	7
Lopez et. al. [120]	Sulfur—17 wt. % Polymer—2 wt. % Sand—49 wt. % coarse aggregate—24 wt. % soil—8 wt. %	60	13	6
Dugarte et. al. [123]	modified sulfur—30 vol. % sand—70 vol. %	43	5	2
Sabour et. al. [124]	Sulfur—25 wt. % Sand—70 wt. % slag—5 wt. %	52	8	3
Yeoh et. al. [125]	Sulfur—1 wt. % Cement—14 wt. %S and—30 wt. % coarse aggregate—40 wt. % water—15 wt. %	42	5	2

The mineralogical composition that might emerge during the hardening process is identified using this technique [16, 25].

6.3.4. Durability Properties

Sulfur composites' resistance to acids in severe liquid environments is determined by the extent to which an acid penetrates their structure, according to a number of studies [110,117]. How well sulfuric materials absorb water depends on a number of elements, including the type and concentration of modifying agents, the amount of sulfur and filler, and other considerations. Sulfur composites' water resistance properties are greatly influenced by the type and quantity of filler and modifying additives used [110,117]. For instance, kerosene, barite, and thiokol result in a minor drop in water resistance, while paraffin and stearic acid result in a slight rise [49,110]. [88,110,117], It was discovered that dicyclopentadiene significantly improved the sulfur composite's chemical resistance under organic (0.95–0.98), acid (0.78–0.90), and salt (0.90–0.98) conditions. Papers [89,110,117,126,127] suggested using kerosene solutions of liquid rubbers as a dressing additive to alter. The resistance of sulfur-based concrete against a range of chemical and biological agents is demonstrated. in Table 7.

Table 7. Resistance of sulfur-based concretes.

Author	Lost Weight, %					
	H_2SO_4	HCl	NaCl	$SO_4(NH_4)_2$	Kerosene	Thiobacillus Thiooxidans Bacterium
Sabour et. al. [124]	5	1	-	-	-	2.25
Gwon et al. [117]		0	-	1	-	-
Vlahovich et. al. [3]	0	−1	2	-	-	-
Dehestani et. al. [6]	-	0	-	-	3	-
Dugarte et. al. [123]	1	−1	3	1	-	-
Gracia et. al. [50]	-	-	-	-	3	-
Yeoh et. al. [125]	4	-	2	-	-	-
Choura et. al. [92]	2	-	-	-	-	-
Bae et. al. [88]	3	-	3	1	-	-
Anyszka et. al. [119]	2	-	-	-	-	-
Lopez et. al. [120]	5	-	2	-	3	-
Al-Otaibi et al. [7]	4	-	-	1	-	-

6.3.5. Deformative properties

The deformative characteristics of sulfur-based concrete are taken into account while measuring the structural rigidity and resistance to cracks. Table 8 enumerates the deformative properties of concrete based on sulfur [3,8,11,125]. Low-temperature creep can be either higher or lower than normal concrete creep, depending on product compositions and usage scenarios. This could cause additional issues. [5]. In crystal structure, the existence of extraneous (amorphous) phases and flaws are the main causes of creep, which is adversely affected by the addition of organic plasticizers to sulfur binder [3,110]. Compaction can minimize creep and drastically cut down on the quantity of sulfur binder used in plasticized sulfur-based concrete, which leverages the binder's movement to compensate for shrinkage, according to computer models of the material's behavior [10,58].

Table 8. Sulfur-based concretes' deformative qualities

Properties	Concrete on Sulfur and Aggregates		Refs
	Dense	Porous	
Poisson's ratio	0.19–0.21	0.24–0.31	[3,8,11,125]
Thermal expansion coefficient, 10^{-6} °C^{-1}	9–14	7–9	
Linear shrinkage, %	0.9–1.5	0.7–1.1	

Concrete hardened by sulfur is essentially impervious to shrinking. By the end of 120 days, the indicators' signals were negligible and proportionate to the linear thermal expansion coefficient, or similar in magnitude to the deformations caused by temperature changes [48,125]. During the first 50 cycles, sulfur-based concrete's resistance to frost deteriorates dramatically, but over the next 500 cycles, this decline is negligible.

7. Discussions

10–30% sulfur binder and 70–90% mineral fillers (aggregates) make up sulfur-based concrete [3, 5–12]. The porosity of compacted filler mixtures is calculated and tested to establish the material's ideal sulfur concentration. The creation below the optimal sulfur content. It is important to remember that the sulfur binder serves as the matrix that transfers stress to the high-modulus component, or grain-reinforcing filler. are shown in Figure 10.

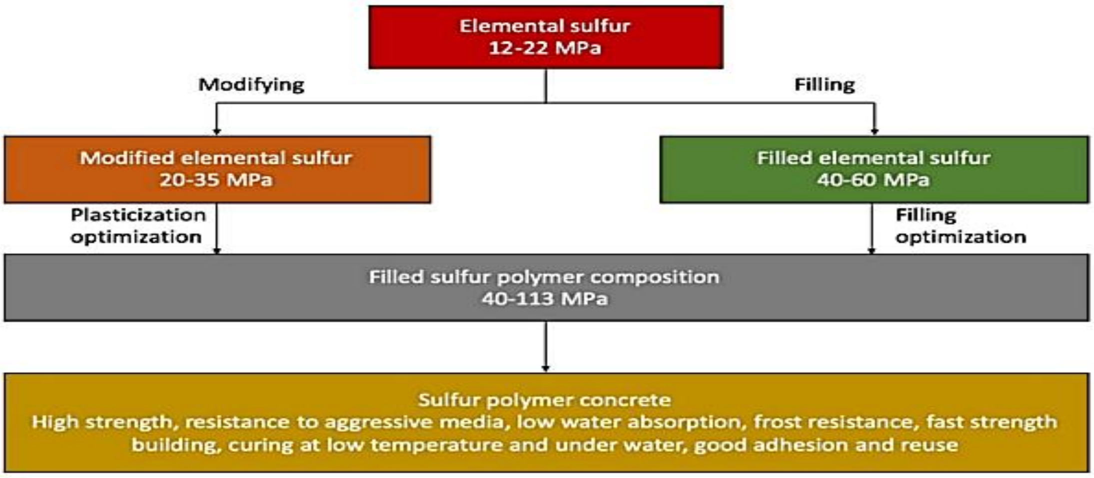

Figure 10. The stages of obtaining sulfur polymer concrete (data extracted from

8. Future Works

Numerous studies have been conducted to improve the efficiency of sulfur in the manufacturing of concrete, and it has been established that this waste has practical uses in a number of fields [35,127]. Sewage pipes constructed of concrete based on sulfur were examined by Sabour et al. in 2011 [124]. The findings demonstrated that sulfur-based concrete was less resistant to the effects of microbiological corrosion but considerably more resistant to severe acid impacts (chemical corrosion) than cement concrete. The manufacturing of concrete blocks using sulfur polymer concrete offers promising prospects [124]. Precast concrete structures can be made using. Furthermore, sulfur is a component found on t [10,104,128]. In order to reduce the negative effects of the moon, samples of lunar concrete were created to aid in the design of structures [10]. To overcome the drawbacks of sulfur-based concrete, more study may be conducted. Thermal stabilizers are required because sulfur-based concrete has drawbacks, such as high production technology requirements and the need to maintain the solution at 140 ◦C [102] [128]. The second drawback is that sulfur-based concrete's polymer sulfur content gradually drops, which can cause it to become monoclinic and necessitate chemical stabilization [107]. The third disadvantage is that sulfur has biophilic qualities. Certain bacteria, like sucrose, may consume sulfur when there is moisture and organic materials present [129,130,131].

9. Conclusions

The creation of efficient cementless building materials is pertinent to today's modern construction sectors. One cementitious substance that can be utilized as a partial substitute for OPC is sulfur salts. According to earlier research, sulfur modification is required before sulphur may be added to concrete. Furthermore, the structure of sulfur-based concrete is greatly influenced by workability, which is mostly determined by the sulfur salts concentration, melt viscosity, filler characteristics, aggregate type, and modifying additive type and concentration. The properties of bending, tension, deformation, and compressive strength for several sulfur-based concrete compositions were covered in detail. The ability of sulfur-based concrete to withstand a variety of harsh conditions demonstrated that it is superior to OPC concrete in terms In order to achieve this, this study reviewed the sources, emissions from construction companies, and compositions of sulfur salts; explained the properties and methods of sulfur production; and examined relevant literature to produce thorough insights into the possible uses of sulfur in the construction sector. Thus far, the following observations have been made in light of this extensive review: Sulfur production has seen a significant growth in consumption, making it more useful in the global building industry. Due to waste disposal and environmental protection benefits, sulfur is an efficient waste material used by businesses to produce building materials. The melting and freezing points of sulfur vary depending on depending on the mixture's temperature, pressure, and the solid allotropes being considered (melted). To enhance the engineering and microstructural qualities of sulfur-based concrete, various modifiers may be used. Concrete based on sulfur reaches its maximum strength in a few hours (three to six hours), and it doesn't require any special moisture or temperature conditions, especially when it's at room temperature. Theoretical and experimental estimates of the porosity of compacted filler mixtures are frequently used to calculate the ideal sulfur concentration in the material. When it comes to strong acid effects, sulfur-based concrete is more resilient than OPC-based concrete. By lowering cement output and reducing sulfur emissions from other businesses (by absorbing them), the addition of sulfur to concrete promotes sustainability.

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