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Integrated mixing machine for sulfur concrete production

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The production of sulfur concrete (SC) from its ingredient materials requires controlled heating and mixing conditions at a temperature level of 130°C–150°C. Although this process considered to be common and applicable at the industrial level, it is difficult at the laboratory/research level. This paper presents the design and manufacturing details of a relatively inexpensive laboratory machine for heating and mixing sulfur concrete. The different components of the machine are described in detail to help researchers to produce high-quality sulfur concrete. In this work, the quality of the machine is verified through experimental testing of the physical and mechanical properties of different prepared SC mixtures. Thus, the homogeneity and mixing efficiency required a certain level of workability, and the full controlling of temperature during the production process has been realized. The machine is proven to be efficient, safe, and durable. The comparative study on the physical and mechanical properties of the prepared SC relative to other SC of the same ingredients but heated and mixed through other small-scale machines, showed the superiority of the mixing machine in the production of high strength concrete.

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1. Introduction

Sulfur’s world production and consumption have been gradually increasing. The United Arab Emirates (UAE) has proved to be one of the main exporters of sulfur in the global market since it has invested a lot of effort, technology, and financial resources to fabricate and operate the sulfur handling terminals in Ruwais, UAE. Hence, any increased world consumption of sulfur will be an advantage to the UAE. This may explain the fact that the UAE is producing higher value sulfur products than other countries such as Canada and Kazakhstan [1] and its researchers showed a high interest in this field as early as 1989 [2]. In the past, the research boom in sulfur applications has held up in filling the gap between supply and demand of sulfur. Because of the thermoplastic properties of sulfur, it has been considered as a possible cementing agent for different aggregates. However, recently, near-term oversupply concerns have been raised again, which contributed more interest and need for new applications of sulfur, especially in the construction industry as it is considered an excellent outlet for sulfur consumption [1,3–9].

Sulfur concrete (SC) has emerged as a solution for the excessive elemental sulfur by-product from petroleum refineries. It is considered a sustainable and cost-effective product that has a strong chemical resistance as a construction material [6,9–
Thermoplastic material, such as the SC, is produced through heating a mixture of both mineral aggregates and sulfur. To control the mechanical properties of SC, different proportions of its components are to be specified and then the mixture should be processed through heating at a specified temperature within 130–149 °C with continuous mixing. The previous procedure produces a semi-liquid viscous mixture that can be casted into a preheated metal mold to ensure no temperature difference between the mold and the prepared mixture. When the liquefied sulfur in the mixture solidifies, as it cools down, the aggregates are bonded, and the shaped sulfur concrete is produced. The generated SC demonstrates good compression strength, controllable shrinkage, and good durability [5]. One of the major advantages of SC is that no water is required for mixing and placement, which makes it a preferable choice in arid and semi-arid environments where water is scarce. Another sustainable aspect that adds to the sustainable value of SC is that it resembles a solution that is cost-effective, has a high resistance to severe environmental conditions, and characterized by its high strength [6,12–14]. Hager et al., have proposed the use of SC in 3D-printing in construction applications due to its fast hardening and rapid strength gaining properties [15], while Khoshnevis et al., investigated the possibility of using SC as a building material on Mars as it is mixed and casted under relatively elevated temperatures (140–150 °C) [16]. On the other hand, Vlahovic et al., have reported the superiority of SC to standard cement in the sense that it has the advantage of low water permeability, which makes it gain a considerable resistance and increase the life expectancy under severe environmental conditions [17].

Keeping in mind these advantages, SC can be utilized in many applications such as, but not limited to, sewer pipe, dams, and water breakers [6,18]. Other applications such as irrigation canals, concrete piles, piers, and beach walls were also proposed [12]. Currently, SC is used in the commercial fabrication of many construction items including wastewater pipelines, wave energy-dissipating blocks, and chemically resistant floor tiles. The production of SC on a large scale is simple, available in most of the large-scale factories, well-reported and explained [19]. On the other hand, producing SC on the laboratory scale, for experimental evaluation and testing, was not presented clearly in literature and a lack of information was noticed in respect to the used machines and selected designs. The authors together with Nippon Oil Corporation, have analyzed the properties of lab-produced small sulfur polymer concrete (SPC) cylinders produced from UAE-local sulfur, fly ash, desert sand and olefin hydrocarbon obtained from petroleum refineries. In addition to lab-produced SC, some commercial products exist like STARcreteTM [20], Sulfurcrete [21], Sulfur Cements; Ergon Armor [1], and Shell Thioccrete: Royal Dutch Shell plc. [22]. In spite of all this, sulfur concrete is still a niche application that needs more research in the area of testing systems and production equipment.

However, for research purposes it is not an easy task as the manufacturing process requires special machines and conditions for the different stages: heating, mixing and casting. Such lab-size machine is unavailable in the market and hence each researcher or research team needs to manufacture his small-scale system that can be operated efficiently within the lab constraints. The main objective of this paper is the documentation of the design and manufacturing process of an efficient laboratory-size machine to be used for the heating, mixing, and preparation of SC with preferable mechanical properties such as superior workability and high compressive strength properties.

2. Design of laboratory-size SC production machine

The heating/mixing machine was designed and manufactured in the UAE. The design went through many cycles of refinements to ensure the best compatibility between the design requirements and manufacturing limitations. Fig. 1 shows a real photo of the heating and mixing machine and Fig. 2 shows the schematic sketch of its main parts.

The desired machine should realize the following features: (i) heating the mixture components and maintaining the temperature between 130 °C and 149 °C, (ii) mixing hot SC components with variable blending speed for an approximate volume of 0.035m³ (35 L), it is suitable to produce the targeted pipe segment of 600-mm external diameter, 900-mm length, and 30-mm wall thickness, (iii) pouring the molten mixture to its mold with minimum effort, (iv) allowing the monitoring of the mixture consistency and temperature during casting, and (v) minimizing the temperature losses by insulating the mixture from the ambient temperature.

The main parts of the mixing machine are listed as follows: (a) stainless-steel double-walled cylinder to circulate the hot oil for heating the mixture, (b) steel stairs and platform to support the operator of the machine, (c) mold used for casting the SC pipe segment, (d) vibrating table used for compaction of the SC hot mixture in the mold, (e) steel base to support the machine, (f) oil bath heater/circulator, and Teflon hoses (PTFE) reinforced with outer steel braids, (g) electric heating stove (electric power of 5000 W), (h) rotating stirrers/blades used for mixing, (i) electric motor used in rotating the mixing blades, (j) vertical moving shaft used for moving the electric motor and the mixing blades up and down, and (k) post to support the mixing cylinder and the mixing motor.

3. Detailed specification of the SC production machine

Details of the main parts of the SC production machine are provided herein as a functional and descriptive illustration to have a clear vision of the sulfur concrete manufacturing process at the laboratory scale:
3.1. Stainless steel double-walled cylinder

A double-walled mixing cylinder with an outer diameter of 462-mm, an inner diameter of 370-mm and an internal height of 380-mm is mainly used to contain and thermally stabilize the mixture components of the SC during the mixing process. The cylinder material is made from stainless steel (ASTM240 grade 316) and the double-wall layers consist of a jacket with a total internal volume of 14 L that allows the circulation of hot silicon oil to heat the inner cylinder content. Each wall has a thickness of 3-mm and a gap in-between of 40-mm. Stainless steel tubes as an inlet and outlet for the circulating hot oil, are connected/welded to the internal void between the cylinder walls as shown in Fig. 3(a). To increase the heating efficiency and uniformity, the internal part of the inlet tube was located to discharge the oil at a level close to the top of the cylinder to have efficient circulation for the oil as shown in Fig. 3(b). Two Teflon hoses were connected to the oil circulation tubes, and the heating sources of the mixing cylinder, during the mixing process, are provided by the circulating hot oil.

The mixing cylinder is also equipped with few features to facilitate the mixing and pouring processes as illustrated in Fig. 4(a, b). The cylinder has a circular cover, which is attached to the mixing blades, and has a movable door that can be opened to inspect the consistency and temperature of the mixture during mixing and heating processes. The cylinder has also a projecting tongue to facilitate the pouring of the mixture into the casting mold. A wheel handle is designed to facilitate the tilting of the cylinder while pouring the hot mixture.

3.2. A platform with associated steel stairs

The mixing cylinder is located at a suitable height to allow appropriate pouring of SC into the casting mold which, in turn, is placed on the top of a vibrating table as presented in Fig. 5(a). Steel stairs and platform allow the machine’s operator to inspect the progress of the mixing process and to use the wheel handle for tilting the mixing cylinder and pour the mixture once it is ready for casting. The steel stairs and the platform are welded together to form one piece, which is bolted in-turn into the rest of the machine to enable their assembly and/or dismantling during machine transportation and installation.
3.3. Machine supporting basement

Since the SC heating/mixing machine involves a lot of mechanical movements during each operational cycle, a rigid support is allocated and designed to be a major part of the machine to ensure a stable and successful operational environment. The supporting base is composed of a couple of welded hollow steel rectangular members as shown in Fig. 5. The rigid base extends to a suitable distance to provide the desired stability during the main post/shaft operational conditions. One important feature of the steel base is to allow the user the ability to stand on the ground close to the heating/mixing cylinder and the casting mold with no obstruction.

Fig. 2. 3D Schematic of the main parts of the SC heating, mixing and casting machine.

Fig. 3. (a) A real photo and (b) schematic sketch of the double-walled mixing cylinder with a vertical cross-section showing the internal inlet and outlet tubes.

3.3. Machine supporting basement

Since the SC heating/mixing machine involves a lot of mechanical movements during each operational cycle, a rigid support is allocated and designed to be a major part of the machine to ensure a stable and successful operational environment. The supporting base is composed of a couple of welded hollow steel rectangular members as shown in Fig. 5. The rigid base extends to a suitable distance to provide the desired stability during the main post/shaft operational conditions. One important feature of the steel base is to allow the user the ability to stand on the ground close to the heating/mixing cylinder and the casting mold with no obstruction.
3.4. Oil bath heater/circulator unit

Production of homogenous SC requires mixing of the hot aggregate with modified sulfur in the temperature ranged from 127 °C to 149 °C. The composition and properties of the produced SC are very critical to the heating processes. As mentioned earlier, two heat sources are used to heat the SC mixture; the electrical stove, and the oil bath heater/circulation system. The oil recirculation thermostat system of model “Ultraterm-200” with adjustable temperatures feature from ambient 5–200 °C was used. Silicon oil is heated and circulated through the walls of the mixing cylinder by an oil heater/circulator unit; the heater/circulator unit has a storage capacity of 20 L and heating limit of up to 200 °C. It is worth noting that the temperature in the mixing cylinder is controlled by a built-in thermostat inside the oil circulator unit, and accordingly, the overall temperature from both heating sources (hot oil and electrical stove) is controlled via the oil heater/circulator unit as shown in Fig. 6.

3.5. Teflon hoses (PTFE) reinforced with outer steel braids

Super quality stainless steel braided hose, with tight double braiding, PTFE with good bend radius, and pressure rating were used for circulating the constant heat around the mixing cylinder. Two flexible hoses are necessary to convey the hot silicon oil from the circulator unit through the inlet and outlet tubes of the mixing cylinder as indicated in Fig. 7(a). Different hoses types were used and tested for oil spills, the most appropriate and robust ones were found to be the Teflon hoses which are reinforced with outer steel braids. Quick connectors as shown in Fig. 7(b) were used to connect/disconnect the hoses to the inlet/outlet tubes of the mixing cylinder.
3.6. Electrical heating stove

As a main source of heating, an electrical stove, with a power of 5000 W is used. The electrical stove is placed on a swinging tray and locked in place underneath the steel mixing cylinder during the mixing process. Heat transfers from the stove to the mixing cylinder through the direct surface contact. Different screening experiments were typically conducted to adjust the heating level to ensure complete sulfur melting during the mixing process. It is important to note that the stove is unlocked from the mixing cylinder and swung freely to allow the easy tilting of the mixing cylinder during the pouring of the SC mixture as shown in Fig. 8. Below the heating zones of the stove, there is a coil of metal, and when it is turned on, current flows through the coil, creating an invisible magnetic field. If a stainless-steel mixing cylinder is placed on the top, the magnetic field penetrates the cylinder with electrical currents, making it hot. The ultimate benefit of this is that the heating top is always cool to the touch. This advantage makes this heater a safe choice for the SC production process, fast heating up with no wasting of heat energy.

3.7. Rotating mixing stirrers/blades

Steel stirrers/blades were used to ensure a proper and efficient mixing process for the SC components inside the steel mixing cylinder. The option of using different shapes of the steel blades is considered with keeping the vigorous and uniform mixing process inside the steel cylinder, as indicated in Fig. 9. The main shaft of the steel blades is connected to a rotating shaft through a snap-tight connection to enable blades connection/disconnection for a possible maintenance or replacement procedure.
3.8. Electrical motor

A 3-phase powerful electric motor is used to rotate the stirrers/blades during the mixing phase. The motor is capable of rotating in two opposite directions to facilitate the mixing process and eliminate any agglomeration inside the SC mixture. The rotary motion of the motor is transferred to the stirrer’s shaft through a pulley and V-belt to control the shaft’s rotary speed. At the early stages of mixing, a slow speed is needed while higher speeds are applicable when the sulfur is completely molten. Fig. 10 shows a real photo of the electrical motor that is used in the presented SC mixing machine.

3.9. Vertical moving shaft

The main support/spine of the machine and mixing cylinder is a hollow square steel post as tagged in Fig. 11. The steel post holds inside another sliding steel post, with less diameter, that supports and moves the mixing head (motor and stirrers) up
and down. The movement of the inner sliding post is maintained and controlled by an AC electrical motor located close to the
base of the machine. The AC motor is connected to a gearbox (controlling the up/down movement speed of the mixing head) using bevel gears to convert the motion from a horizontal shaft to a vertical screw and threaded steel shaft installed inside the steel post. The threaded shaft is attached to the mixing head to transfer its up/down motion. Such mechanism converts the rational motion of the AC motor to axial motion, up and down, for the mixing head.

As shown in Fig. 11, the main supporting hollow steel post of the machine is designed to carry the total weight of the different machine components. It is welded to the supporting base and has a steel door bolted to one of its sides, to facilitate any required maintenance procedure. In addition, all the insulated electrical wiring and control units are attached to the proper place on the sides of the post.

4. Integrated safety of the SC production

The safety aspects of the designed testing machine are:

a) Sulfur concrete has been produced within its recommended mixing temperature range of 127° to 149 °C to ensure proper preparation, handling, and casting procedure.

b) As shown in Fig. 12, an overhead exhaust/ventilation device was fixed above the mixer machine to ventilate the harmful gases and dust produced during the preparation and handling of sulfur concrete.

c) As a part of the safety system, a gas detector, with an alarm, for detecting the presence of harmful gases in the lab area, has been installed.

d) Proper protective clothing, eye protection, gloves, helmets, and safety shoes are used in the lab area.

5. Power consumption of SC mixing machine

Power consumption is a basic integral quantity in a mixing operation that determines the cost operation. In this paper, a theoretical model is proposed to better estimate the electricity consumption of the SC mixing machine. In studying the power consumption and distribution in the presented SC mixing machine, Eq. 1 is used for power usage.

\[
P_{\text{Total}} = P_{\text{Motor1}} + P_{\text{Motor2}} + P_{\text{Elec. Stove}} + P_{\text{Oil-Path}}
\]  

(1)

The power consumed in the two motors, \(P_{\text{Motor1}}\) & \(P_{\text{Motor2}}\) are considered to be independent of the other power consumption terms in Eq. (1) [23] and [24]. Fig. 13 shows the energy consumed by each mentioned unit with time, wherein the power consumed by first motor, second motor, electrical stove and oil circulation bath was found to be 0.29862 kW, 4.357 kW, 6.25 kW, and 3.605 kW, respectively. The resulted total power consumption of one SC production run of 14.52 kW. The value of power consumption considered to be reasonable and practical compared to the power consumption of a Twin-Shaft mixing machine, which was reported to be in the range of 5–25 kW [24].

![Fig. 12. Exhaust ventilation unit installed over the mixer machine.](image-url)
6. Preparation of sulfur concrete

Sulfur concrete is prepared using the new laboratory mixing machine, described above, and according to the procedure described in ACI 548.2R-93 for mixing and placing sulfur concrete [25]. The preparation process was completed through different continuous steps as represented in (Fig. 14). Pre-mixing; all aggregates have been heated in an electrical oven in a temperature above the melting point of sulfur (120–125 °C) to reach a constant weight for complete dryness and to maintain the required mixing temperature. The time of drying depends on the total moisture content. Mixing processes was completed through three stages. Stage I: Sulfur modification: elemental sulfur is modified by mixing with the modifying agent at 120–130 °C for 30 min to form a sulfur-containing polymer, where the polymer acts as a compliant layer between the sulfur crystals, thus overcoming the drawbacks of using elemental sulfur, like shrinkage and cracks [6,26]. Stage II: Sulfur cement preparation; the preheated filler like (fly ash, cement kiln dust (CKD), or ground granulated blast furnace slag (GGBFS), . . . etc.) was added to the molten modified sulfur at 130–140 °C and mixed for 30 min, at a controlled rate. The role of sulfur cement is to bond the aggregate particles together, fill the voids in the mixture and provide sufficient fluidity and workability. Stage III: Sulfur concrete preparation; the preheating fine and coarse aggregate was added to the prepared sulfur cement, described in Stage II, at 140–149 °C and the mixture was mixed for 45 min until a homogeneous mixture is obtained. The power consumption of the stage (I), (II) and (III) was calculated to be 2.35 kW, 4.85 kW, and 7.3113 kW, respectively.

The aggregate types and proportions affect SC workability, physical and mechanical properties. Workability is one of the most important properties of SC, which not only affects the transportation and casting but also the strength and surface quality of the final product. As the workability changing with several fundamental characteristics such as viscosity, mobility, internal friction, pump ability, segregation, bleeding, formability, and finishing ability. By using the newly designed mixer machine, all those characteristics are well observed and controlled to produce a high quality of the finished SC [27]. The time of heating needed prior to the mixing is dependent on the aggregate total moisture content. It is found that heating time decreases with decreasing moisture content. Moreover, the variation in the temperatures of materials and ambient is too small to affect the heat consumed or the heating time. The estimated average time for the whole SC preparation process was found to be around two hours, so long as there were no mishandling or machinery obstruction. The gradual addition of the mixture ingredients is to ensure homogeneity of the mixture and to minimize the efforts on the mixing motor. Initially, the mixing motor is kept at low speed and then the speed is increased when the sulfur in the mixture is completely molten. The temperature was maintained, throughout the mixing process, at the range of 140–149 °C using the electrical stove and the oil

![Fig. 14. A schematic diagram of the thermal processes through SC production.](image-url)
heater/circulator unit. Finally, after completing the mixing step, the hot mixture was poured into the pre-heated mold and compacted on a vibrating table. The mold with its content is then placed in a temperature-controlled oven for curing by decreasing its temperature gradually to approximately 25 °C (room temperature) with a cooling rate of approximately 1 °C/min, then samples were kept at room temperature.

7. Casting of sulfur concrete

Fig. 15(a–d) shows the different steel molds used in casting and shaping of the final SC mixture, which are as follows: (a) single-cavity, two-part, steel cube mold with base plate, and size of 100 × 100 × 100 mm, is used for compressive strength testing of SC cubes, according to ASTM C39-01 [28], (b) cylinder mold vertically split into two parts, with the diameter of 100 mm and height of 200 mm, is used for splitting tensile strength according to ASTM C496-96 [29], (c) beam mold of size 152 × 152 × 508 mm, is used to determine the flexural strength of SC beams, according to ASTM C78 [30], and (d) steel pipe mold was designed to produce a pipe segment with internal diameter of 300-mm, thickness of 30-mm, and length of 900-mm for the three-edge-bearing test according to ASTM C497 [31]. The pipe segment mold is basically composed of four parts: base, outer skin, inner skin, and cover. The outer and inner cylindrical skin parts are designed to fit into grooves in the base. The outer skin is made of two halves that are connected through a set of bolts; each half is made of a curved steel sheet reinforced with steel ribs. The inner skin is made of one self-contracting cylindrically curved steel sheet that is pushed in place before casting and is set free to self-contract after curing of the pipe segment. To facilitate the separation of the SC pipe after curing, rubber silicon liners are attached to the SC side of the mold. The rubber silicon is selected for its smooth surface and its ability to stand high temperatures (above 200 °C). The top of the mold has a conical receiver to allow easier pouring of the SC mixture into the mold. The conical receiver has multiple perforations that facilitate the flow of the hot SC mixture into the void between the outer and inner skins of the mold as shown in Fig. 15(d).

To compact the SC inside the steel mold, the preheated mold (to about 150 °C) is placed on a low-height (about 0.8-m high) vibrating table for compaction of the mixture as illustrated in Fig. 16, and then the hot SC mixture is poured gradually in the mold to prevent any formation of air pockets in the pipe segment. The vibration performance is typically applied for about 2–3 min for the previously described molds.

8. Performance evaluation of the mixer machine

The performance and efficiency of the new mixer machine were evaluated, through the preparation of different SC mixes using industrial waste materials like aggregates and mixing with the modified sulfur cement. Table 1 shows the different SC mixes, which were processed using the newly designed machine. It is worth noting that statistical analysis has been carried out using Minitab software 18, based on the central composite design and by following the full factorial methodology [32]. The effect of each additive (modified sulfur, crushed sand, dune sand, fly ash, cement kiln dust (CKD), Ladle furnace slag (LF Slag), and ground granulated blast furnace slag (GGBFS)) on the physical properties of the resulting casted SC was evaluated. From the results we have observed that (a) the highest casted SC density was 2433 Kg/m³, and (b) the best workability, during casting of SC, was for mixes 3, 4, and 5.

Furthermore, Table 2 shows the grain size distribution of the aggregates, which used in the SC mixes; the coarse aggregate is crushed limestone, the fine aggregates are dune sand and Ladle furnace slag (LF slag), while the used fillers are fly ash,
Fig. 16. A real photo of the electrical vibrating table.

Table 1
Sulfur concrete mixes.

| Mix | Composition by Weight (%) | Physical Properties |
|-----|----------------------------|---------------------|
|     | Modified Sulfur | Crushed Sand | Dune Sand | Fly Ash | Cement Kiln Dust (CKD) | Ladle Furnace Slag (LF Slag) | ground granulated blast furnace slag (GGBFS) | Observed workability during Casting of SC | Density of casted SC (Kg/m³) |
| 1   | – | 60 | – | – | – | – | – | – | – | soupy | 2293 |
| 2   | 34.6 | – | 29 | 36.4 | – | – | – | – | – | fluid | 2340 |
| 3   | 32 | – | 30 | – | 38 | – | – | – | – | workable | 2329 |
| 4   | 28 | – | 34 | – | – | 38 | – | – | – | workable | 2417 |
| 5   | 31.25 | – | 31.25 | – | – | 18.75 | – | 18.75 | – | workable | 2433 |
| 6   | 21 | 38 | 24 | – | – | 8 | 9 | – | – | Relatively dry | 2527 |

Table 2
Grading of the aggregates and alkaline solid waste materials used.

| Aggregates   | Passed (%) by Weight from Sieves |
|--------------|----------------------------------|
|              | Sieve size                       |
|              | 10 mm | 5 mm | 2.5 mm | 1.25 mm | 850 μm | 450 μm | 300 μm | 180 μm | 150 μm | 125 μm | 75 μm | 38 μm |
| Crushed limestone | 100 | 96 | 68 | 39 | 8 | 3 | – | – | – | – | – | – |
| Dune Sand     | –   | –   | –   | –   | 100 | 93 | 85 | 66 | 56 | 40 | 19 | – |
| LF slag       | –   | –   | –   | –   | 99  | 97 | 86 | 74 | 50 | 35 | 16 | 2 |
| Fly ash       | –   | –   | –   | –   | –   | –   | –   | 100 | 96 | 95 | 87 | 73 | 64 |
| CKD           | –   | –   | –   | –   | –   | –   | –   | 96  | 80 | 50 | 20 | 18 | 10 |
| GGBFS         | –   | –   | –   | –   | 98  | 92 | 79 | 62 | 30 | 19 | 4 |

cement kiln dust (CKD) and ground granulated blast furnace slag (GGBFS). Additionally, the chemical composition of used components was determined using the inductively coupled plasma optical emission spectroscopy (ICP-OES) technique. Fig. 17 shows the major chemical components of the used aggregates with a standard error deviation of (0.001–1.71).

In fact, the SC mixes reported in Table 1, had been used by the authors in a previous study to prepare cubes and cylinders, using the standard lab asphalt-mixing machine [8,11,26]. In those studies, optimization of SC mix proportions to produce the highest compressive strength was performed through applying a statistical experimental design using Minitab software. Different SC mix proportions were designed. The proportions of the mixture components were selected in terms of the mass fraction. The lower and upper limits of the proportions were chosen based on pre-laboratory (screening) experimental results, the experimental design and statistical evaluation of experimental results in additional SC mixtures was conducted to test the validity of the proposed mixture models. The design of experiments was targeted to find the composition of SC that maximize their physical and mechanical properties. Using the newly designed machine, the optimum mixes were reproduced but in bigger quantities with an approximate volume of 0.035 m³. Table 3 shows the optimum mechanical properties of the prepared SC using the new mixer machine which shows a significant superiority in the mechanical properties compared to those prepared by the asphalt mixer machine. The standard deviations for each test are also presented to indicate the variability of the results. As shown in Table 3, low standard error of deviation has been reported for each average mechanical property, and this reflected the reliability of the considered averaged data and the accurate reflection of each mix average property.
9. Conclusions

Sulfur concrete is a thermoplastic material prepared by hot mixing of sulfur cement and mineral aggregates. Mixing, working, casting, and finishing of sulfur concrete are sensitive to the heating process. The best practices in producing sulfur concrete have been incorporated in the newly designed laboratory-size machine. The mixing machine was used in producing sulfur concrete samples (e.g., cylinders, cubes, and pipe segments) with superior characteristics, that have been subsequently confirmed by their admirable mechanical properties and evenhanded power consumption. The newly designed laboratory-size machine is anticipated to help other researchers in developing their own heating/mixing machine which is expected to improve the quality of the research in this area.

Declaration of Competing Interest

The authors report no declarations of interest.

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