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Laboratory studies on the mechanical properties of sulphur-based construction material at simulated Martian temperatures

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ABSTRACT

Mars is the next destination for further exploration and the hypothetical establishment of humanity's frontier. However, the planet offers very harsh environmental conditions particularly the very cold temperature in the Martian environment. Knowing that the sulphur-based construction material is perceived as one of the ideal Martian construction materials based on the identified abundant source of sulphur on Mars, its behaviour when subjected to the very cold Martian temperature is yet to be fully clarified. Therefore, this study intends to investigate the behaviour of the Martian sulphur-based construction material subjected to the simulated very cold Martian temperature whilst being compared with the simulated hot Martian temperature. Two mixture compositions of 50/50 and 60/40 comprising of sulphur and Mojave Mars simulant 1 (MMS-1) respectively were fabricated in this study characterising the simulated Martian temperature. The workability at 50 % and 60 % sulphur content was initially investigated. Subsequently, the overall mechanical properties characterising the sulphur content and simulated Martian temperature were investigated via unconfined compression, three-point bending and tensile splitting tests. Necessary factors that influence the overall mechanical properties including the internal structure and microstructural characteristics were also performed via ultrasonic pulse velocity (UPV) and scanning electron microscopy (SEM) respectively. X-ray diffraction (XRD) was also conducted to identify the chemical composition of the end product. The comparisons between this study and other previous related studies within the state-of-the-art Martian sulphur-based construction materials were also outlined. Prospects for future construction on Mars are also presented. It was found that the 60 % sulphur content exhibited higher workability due to the high amount of unreactive sulphur. The 50 % sulphur content recorded the optimal overall mechanical properties under the simulated hot and very cold Martian temperatures. The simulated very cold Martian temperature triggered non-uniform interparticle distribution and larger cavities thus dramatically reducing its overall strength and triggering higher volumetric inconsistency. The very brittle nature of unreactive crystallised sulphur binder at excessive thickness particularly at 60 % sulphur content in between filler particles also triggered volumetric inconsistency which further worsened at the simulated very cold Martian temperature. The iron sulphate hydrate found was almost in agreement with the related works and another new compound, potassium calcium magnesium sulphate was identified as well. The overall mechanical properties are comparable with the other previous related studies and the residual strength when subjected to the simulated very cold Martian temperature remains adequate in the Martian environment of low gravity. The 60 % sulphur content is suggested for structural elements built internally whereas the 50 % sulphur content demonstrated a high potential in adapting to the harsh Martian environmental conditions. The findings of this study hoped to act as the initial outlook on how such Martian sulphur-based construction material would react upon fabrication on Mars.

1. Introduction

The human civilisation had achieved many evolutions from primitive technologies that could be sustained by establishing an outer space frontier [1]. Also known as 'The Red Planet' for its reddish appearance [2], Mars is regarded as the main space frontier with focused efforts on

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the construction of a human settlement before human arrival. The National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) set their ambitious vision to deploy humanity on Mars by 2030 [3]. However, due to the tremendous amount of material transportation cost from Earth [4–7], implementing in situ resource utilisation (ISRU) for construction on Mars is most certainly inevitable to reduce cost. According to Hadler [8] and Starr and Muscatello [9], ISRU is defined as the utilisation of local Martian resources through the necessary chemical and physical processes to fabricate components that satisfy humanity's needs, such as infrastructure for day-to-day operations, artificial oxygen, and human shelters. It is of the utmost importance that the ISRU-based construction materials should be able to withstand the apparent harsh Martian environmental conditions [10–18] i.e. temperature fluctuation including the very cold temperature, low gravity and minimal pressure. More specific requirements of the ISRU-based construction materials to fabricate a human settlement subjected to the harsh Martian environmental conditions are elaborated in Section 3.6. Over the last few years, there have been various kinds of unique ISRU-based construction materials proposed by researchers such as polyimide-based [19,20], geopolymer-based [21–24], magnesium-based [25–29] and sulphur-based [30–34].

Sulphur-based construction material is proposed based on the identified rich source of sulphates and sulphides that could be extracted and processed into elemental sulphur [35,36]. Furthermore, other advantages are it does not require water, hardens rapidly, exhibits high early strength, can be incorporated into additive manufacturing or also known as 3D-printing and no mandatory shipping is needed [37–44]. It also demands a heating temperature not more than 150 °C in order to turn molten state, indicating that the energy requirement is very low. In molten state, the Martian regolith simulant is added into the mix, bound by the molten turned hardened sulphur and gained high early strength instantly upon casting, thus requiring no further mandatory curing and additives. To conclude, the identified rich source of sulphur and the aforementioned several advantages further justify that sulphur-based is one of the ideal construction materials to be utilised on Mars. The state-of-the-art Martian sulphur-based construction materials has been progressing well ever since its feasibility was initially tested for lunar application specifically subjected to sublimation [45] and temperature cycle [46]. For instance, Toutanji et al. [47] demonstrated the superiority of sulphur-based construction material utilising a lunar regolith simulant with a higher compressive strength than the conventional cement-based construction material. Although initially meant for lunar application, it can be incorporated on Mars as well but with less criticality; the presence of thin atmospheric layers and minimal highest temperature on Mars which closely resembled by the room temperature on Earth [48,49]. Therefore, a Martian sulphur-based construction material was developed while investigating the effects of varying composition of sulphur and JSC Mars-1a, a Martian regolith simulant on the overall mechanical properties [30]. An optimum sulphur/JSC Mars-1a mixture composition of 50/50 was concluded. Brinegar [50] incorporated 60 % sulphur composition and found that the initial strength further enhanced upon recast. Li et al. [31] integrated sulphur and magnetite with the latter represented one of the major components of Martian regolith [51]. They achieved an initial compressive strength of 12.63 MPa and further improved up to 17.41 MPa with the addition of silica sand. Shahsavari et al. [32] studied in depth the individual function of sulphur and the two most individual components of Martian regolith, iron oxide and aluminium oxide on the mechanical properties. Akono et al. [33], elaborated the effects of distinct Martian regolith simulants on the microstructure and strength via indentation and scratch tests. Contrary to Wan et al. [30], Snehal et al. [34], increased the Martian regolith simulant content up to 70 % and investigated the effects of varying temperature of 0 C, 40 C and 50°C on the overall strength. Giwa et al. [44], investigated the influence of vacuum condition on the 3D-printed sulphur-based material. Most importantly, it is also noted that several sources have highlighted the harsh Martian environment encountered by humanity upon arrival particularly the very cold average temperature on Mars ranging between −57°C and −73°C [10,48,52–55]. Based on the aforementioned state-of-the-art Martian sulphur-based construction materials, except the work done by Snehal et al. [34], most previous related studies were only conducted in the room temperature that resembled the hot temperature on Mars ranging between 17°C and 35 C [48,56]. On the contrary, Snehal et al. [34], noted that the simulated cold Martian temperature at 0 C enhanced the overall strength. However, the effect of the simulated very cold Martian temperature on the mechanical properties is yet to be fully clarified. In short, the fundamental breakthrough on the mechanical properties of the Martian sulphur-based construction material utilising Martian regolith simulant subjected to the very cold Martian temperature is not well established.

Unparallel to the advancement in terms of technological development for future Mars missions, the studies on the Martian construction material utilising sulphur-based binder system need to progress properly and a better comprehension on its fundamental properties subjected to the environmental conditions on Mars should be achieved as well. In order to address the aforementioned gaps while also acting as the extension study based on the findings illustrated in Figs. 1 and 2 recorded by Wan et al. [30], the effects of the simulated Martian temperatures on the Martian sulphur-based construction material are the main purpose of this study. Such effects are evaluated in terms of the overall mechanical properties along with contributing factors such as internal structure and microstructural characteristics via ultrasonic pulse velocity (UPV) and scanning electron microscopy (SEM) respectively. The workability and the chemical composition characterising the sulphur content were also investigated via mini slump flow test and X ray diffraction (XRD) respectively. As far as the influence of sulphur content is concerned, only 50 % and 60 % were taken into account in this study with the former perceived as the optimal sulphur content and the latter chosen based on the apparent highest dispersion of data recorded by the previous study, see Fig. 1. Other sulphur contents in Fig. 1 i.e. 40 %, 45 %, 47.5 % and 52.5 % were not considered in this study due to the limited supply of Martian regolith simulant owned by the authors. However, such sulphur contents are believed to be feasible to be utilised on Mars according to specific needs which will be elaborated in Section 3.6. Based on the identified temperature range for both hot and very cold Martian temperatures based on previous references, the average simulated hot and very cold Martian temperatures of 25 C and −65°C respectively for this study were chosen with the former assumed to be the ambient room temperature in laboratory condition. The findings of this study hoped to provide a clear overview on the behaviour of the Martian sulphur-based construction material characterising the subjected Martian temperature.

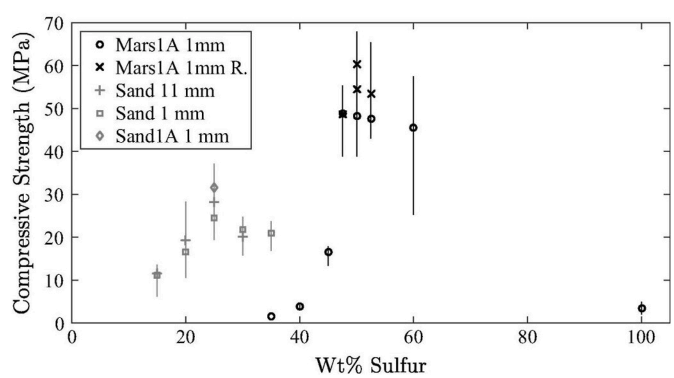


Fig. 1. Compressive strength [30].

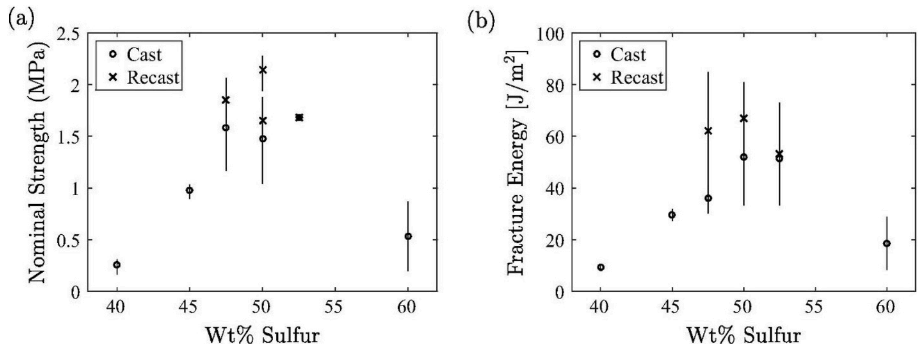


Fig. 2. Flexural strength and fracture energy variation [30].

2. Methodology

2.1. Materials

As the binder system of the Martian sulphur-based construction material to be fabricated in this study, a commercially available 99.8 % pure sulphur was used in this study. On the other hand, the Martian regolith simulant used in this study was Mojave Mars simulant 1 (MMS-1) available for purchase from the Martian Garden [57]. Specifically, the MMS was fine-sized grain at 0.5–1.27 mm with density 1290 kg/m^3 according to the Martian Garden. It is noted that the limitation of this study is the MMS-1 used in this study did not resemble the authentic MMS developed by Peters and his colleagues [58] as the MMS-1 was based on the highly modified cinder material instead of the unmodified basalt that comprised the authentic MMS [59,60]. Table 1 shows the differences between the MMS-1 and MMS in terms of oxide compositions. In spite of that, it is also evident that the actual Martian regolith varies chemically and mineralogically across Mars [51,61]. These were evidenced by the reported oxide compositions of the actual Martian regolith in Table 1. Since the authentic MMS was unavailable but the MMS-1 was readily available to be purchased along with the apparent variation on the oxide compositions of the actual Martian regolith, the MMS-1 was utilised in this study as the primary filler. Moreover, both MMS-1 and JSC Mars-1a were almost identical to the actual Martian regolith investigated by roaming rovers and orbiters thus making the former regolith simulant practical to be utilised as one of the components of the Martian sulphur-based construction material.

2.2. Mini slump flow test

As the preliminary work for this study, the workability of the molten Martian sulphur-based construction material characterising the two distinct sulphur content was investigated through the mini slump flow test in accordance to ASTM C1437 [62] and C230 [63]. The mini slump flow test was conducted to determine the workability in the form of spread flow diameter based on the previous work done on the modified sulphur [64]. The mini slump cone and tamping rod were preheated at approximately 150°C prior to adding and tamping the molten Martian sulphur-based construction material. Subsequently, the cone was slowly lifted upward and the spread diameter was measured at five directions. The average spread diameter indicated the fluidity defined as the flowing ability of the molten Martian sulphur-based construction material. It was calculated using equation (1) stated below where F is the fluidity expressed in percentage, D_1 is the calculated average spread diameter and D_0 is the constant base diameter of the mini slump cone at 100 mm.

$$F = \frac{D_1 - D_0}{D_0} \times 100\% \tag{1}$$

2.3. Preparation of the Martian sulphur-based construction material

Two sets of hardened specimens differentiated with two mixture compositions of 50/50 and 60/40 comprised of sulphur and MMS-1 respectively were prepared. The method of casting was conducted in accordance to the guidelines provided by Fontana et al. [65]. The pure sulphur was initially heated in a melting pot at temperature 120°C–150°C and allowed to fully crystallise when lowering the temperature. This was to ensure an optimum melting without a trace of residual powdered sulphur. Then, the temperature was raised again to re-melt the crystallised sulphur prior to adding the MMS-1 gradually until it turned into a flowable state. The mixture was thoroughly mixed before being added into the moulds fabricated in accordance to BS EN 12390–1:2012 and left to cool for 24 h. Post-cooling, the specimens were de-moulded and divided into two groups; the first group was being left exposed at room temperature at approximately 25°C to simulate the hot

Table 1
Comparison between Martian regolith simulant and actual Martian regolith.

Oxide	Martian regolith simulant			Actual Martian regolith			
	JSC Mars-1a[c]	MMS-1[a]	MMS[b]	Mars Pathfinder[b]	Viking Landers 1[b]	Chryse[d]	Utopia[d]
SiO_2	34.50–44.00	57.30	49.40	42.00	43.00	44.00	43.00
TiO_2	3.00–4.00	1.10	1.09	0.80	0.66	0.62	0.54
Al_2O_3	18.50–23.50	12.90	17.10	10.30	7.30	7.30	7.00
Fe_2O_3	9.00–12.00	9.10	10.87	21.70	18.50	17.50	17.30
MgO	2.50–3.50	4.10	6.08	7.30	6.00	6.00	6.00
CaO	5.00–6.00	4.90	10.45	6.10	5.90	5.70	5.70
Na_2O	2.00–2.50	4.20	3.28	2.80	n/a	n/a	n/a
K_2O	0.50–0.60	2.10	0.48	0.60	<0.15	<0.50	<0.50
P_2O_5	0.70–0.90	0.20	0.17	0.70	n/1	n/a	n/a

[a] [59].
[b] [58].
[c] [30].
[d] [54].

temperature on Mars. On the other hand, the second group was surrounded by blocks of frozen carbon dioxide, CO_2 or also known as dry ice to simulate the very cold Martian temperature as the dry ice was able to provide the desired very cold temperature at approximately −65°C. Both groups were cured for another 24 h prior to mechanical properties testing. The simulated hot and very cold Martian temperature were consistently monitored using the digital thermometer with probe sensor. In order to maintain the simulated very cold Martian temperature, the blocks and the hardened specimens were arranged in a styrofoam box as illustrated in Fig. 3(a) prior to being confined inside the cooler box, see Fig. 3(b) in order to prevent an instant sublimation of the blocks and provide a better simulation on the very cold Martian temperature. After 24 h of being subjected to the simulated very cold Martian temperature, it was found that the specimens were coated by the thin layer of white frozen CO_2, see Fig. 4(b) that eventually condensed around the specimens when taking out from the cooler box for further testing.

2.4. Ultrasonic pulse velocity

The ultrasonic pulse velocity was conducted in accordance to BS EN12504–4:2004 [66] on all specimens to evaluate the internal structure in terms of quality, denseness and homogeneity of the specimen prior to mechanical properties tests. Direct transmission based in Fig. 5 was incorporated. Based on Fig. 5(b), the pulse velocity was recorded along the length of the beam for higher precision as recommended by the standard BS EN12504–4:2004 [66]. As for the specimens subjected to the simulated very cold Martian temperature, the longitudinal pulse velocity was recorded before and after they were being surrounded by blocks of dry ice in order to identify changes on the longitudinal pulse velocity.

2.5. Mechanical properties tests

Unconfined compression, three point bending and tensile splitting tests were conducted in accordance to BS-EN-12390–3:2009 [67], BS EN 12390–5:2009 [68] and BS EN 12390-6: 2000 [69] with the loading rate at 1.5 kN/s, 0.03 kN/s and 0.2 kN/s respectively to record the compressive strength, flexural strength and tensile splitting strength respectively. A uniform load was applied on the top of the 50 × 50 × 50 mm cubic specimen to determine the compressive strength. A centre point load was applied during the three-point bending test on the 50 × 50 × 175 mm beam with formula (2) where f_{cf} is the flexural strength in megapascal (MPa), F is the maximum load in newton (N), I is the distance between the supporting rollers in millimetre (mm) and d_i is the lateral dimension of the cross-section in millimetre (mm). Both I and d_i remained constant at 150 mm and 50 mm respectively. On the other hand, the tensile splitting strength test was conducted on the 50 × 50 × 50 mm cubic specimen by applying a compressive force on a narrow region along the length of cubic specimens at 50 mm. Hardboard packing strips were placed between the curved steel loading pieces and the aforementioned narrow region along the length of cubic specimens. Formula (3) was incorporated where f_{ct} is the tensile splitting strength in megapascal (MPa), F is the maximum load in newton (N), L is the length of the narrow region in millimetre (mm) and d is the cross-sectional dimension in millimetre (mm). Both L and d remained constant at 50 mm and 50 mm respectively. At least 3 specimens were tested for all mechanical properties testing.

$$f_{cf} = \frac{3 \times F \times I}{2 \times d_1 \times d_2^2} \tag{2}$$

$$f_{ct} = \frac{2 \times F}{\pi \times L \times d} \tag{3}$$

2.6. Scanning electron microscopy (SEM)

The overall mechanical properties of the Martian sulphur-based construction material were influenced by their microstructural characteristics including the nature of interparticle distribution and the presence of voids. Initially, the hardened specimens were evaluated via UPV test to evaluate the internal structure in terms of quality, denseness and homogeneity. As an in-depth analysis to support the findings on the UPV test, scanning electron microscopy (SEM) was conducted. The SEM test was conducted at Advanced Membrane Technology Research Centre (AMTEC), Faculty of Chemical & Energy Engineering, Universiti Teknologi Malaysia, Johor using TM3000 Hitachi microscope. A total of 8 samples at approximately 5 mm were extracted from the specimens for 50 % and 60 % sulphur content at simulated hot and very cold Martian temperatures. Four of them were the outer chunks that represented the surface of the specimens and the remaining four were the inner chunks that represented the internal structure of the specimens. All 8 samples were initially coated with titanium for higher image resolution and the internal structure of the sample was illustrated.

2.7. X-ray diffraction (XRD)

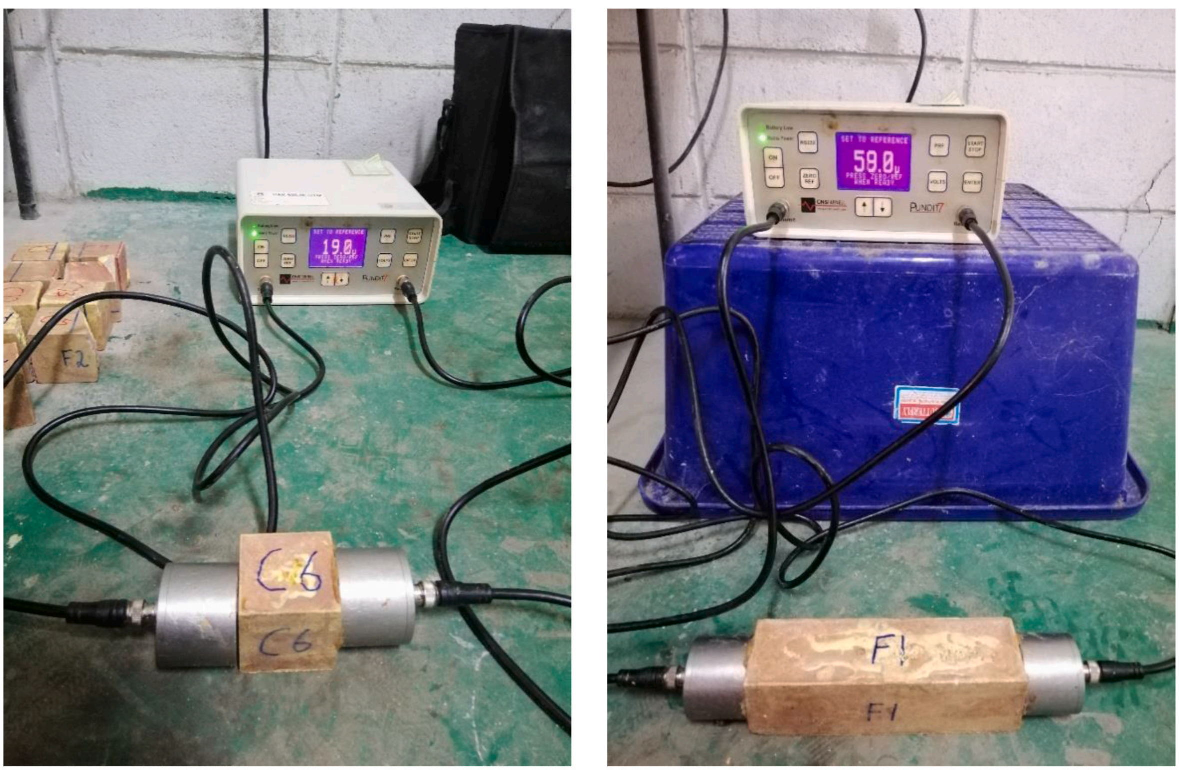
Initially, the previous investigation hypothesised that the unidentified metal sulphates and poly-sulphates were formed upon chemical reaction between the elemental sulphur and the metal elements in the Martian regolith simulants [30]. The authors also highlighted the requirement for subsequent works that further recognise the outputs of

(a) (b)

Fig. 3. (a) Specimens surrounded by blocks of dry ice inside the styrofoam box; (b) The styrofoam box was further confined inside the cooler box.

(a) (b)

Fig. 4. Conditions of the cubical specimens after 24 h of curing under the simulated Martian temperature (a) hot; (b) very cold.



(a) (b)

Fig. 5. Direct transmission on (a) cube and (b) beam.

such chemical reactions. In order to achieve this, X-ray diffraction (XRD) was performed at Department of Geology, Faculty of Science, Universiti Malaya, Kuala Lumpur using the PANalytical Empyrean X-ray diffractometer. One sample of 50 % sulphur content and another sample of 60 % sulphur content were extracted from the specimens and crushed into powder form for XRD analysis. Both samples were limited to being subjected to the simulated hot Martian temperature. The samples that were analysed started from the theta position of 2° and ending at 80°, at a temperature of 25°C and standard generator setting of 40 mA and 45 kV. The peaks were identified using its software generator.

3. Results and discussion

3.1. Workability of molten Martian sulphur-based construction material

The understanding on the workability of Martian sulphur-based construction material is important as it also influenced the overall mechanical properties. According to Khoshnevis et al. [41] and Gamal et al. [70], it is based on criterion such as consistency, portability and executability which subsequently influence the strength and aesthetic quality of the end product. This is due to the fact that molten sulphur undergoes rapid hardening that could affect the overall solidity of the hardened sulphur-based construction material. Hence, the fluidity in terms of flow mechanism may act as the preliminary illustration on the workability of the Martian sulphur-based construction material during extrusion and placement. During mixing, molten pure sulphur reacted with the metal oxides in the Martian regolith simulant to form compounds that made up the solidity of the hardened specimens as reported by Wan et al. [30]. The newly formed compounds were further melted upon heating during casting thus exhibiting higher flowability that also further enhanced by the leftover molten pure sulphur. Fig. 6 illustrates the spread mechanism demonstrated by the molten specimen which then being measured at five different directions. Table 2 shows the measured spread flow diameters at five different directions along with the average diameter. In comparison between both sulphur content, the 50 % and 60 % sulphur content demonstrated distinct fluidity at 149 % and 274 % respectively. This was likely attributed to the higher sulphur content that did not undergo chemical reaction with the metal oxides in MMS thus exhibiting lower viscosity by acting as the fluid that enhanced the overall flowability and potentially being advantageous for extrusion; minimal risks of clogging due to hardened sulphur on extrusion pipe walls [41]. In accordance to the findings by Gwon and Shin [64], the lower fluidity of the latter sulphur content at 50 % was attributed by the increasing powder content that formed higher amount of metal sulphate particles. They eventually triggered higher yield stress between the particles which culminated with lower fluidity. As the authors were focusing on the modified sulphur composites [64], further clarifications describing the yield stress and plastic viscosity of the Martian sulphur-based construction material are required while replicating the authors' methodology i.e through the rheometer test.

Table 2
Spread flow diameter of the specimens.

Mixture composition	Spread flow diameter (mm)	Average (mm)
50/50	252	249
	255	
	245	
	240	
	255	
60/40	377	374
	380	
	385	
	370	
	360	

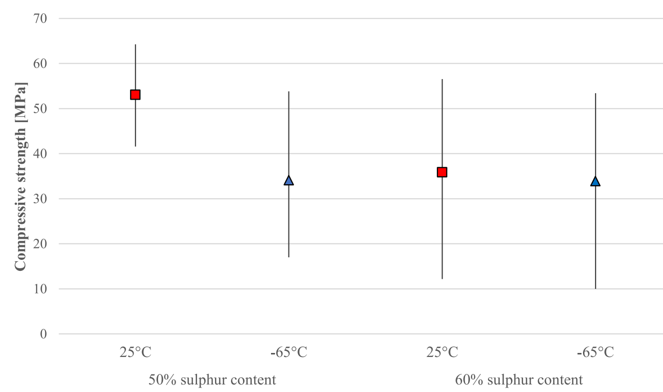


Fig. 7. Compressive strength versus temperature and mixture composition.

3.2. Mechanical properties results

Inspired by the findings describing the Martian sulphur-based construction material utilising JSC Mars-1a [30], this study addressed the previous study by incorporating MMS-1 into the mix. In this study, the Martian sulphur-based construction materials utilising MMS-1 were fabricated and investigated in terms of mechanical properties subjected to the simulated very cold Martian temperature whilst being compared with the simulated hot Martian temperature. More specifically, the simulated hot and very cold Martian temperatures taken in this study were approximately 25°C and −65°C respectively. The overall findings on the mechanical properties are illustrated in Figs. 7–9 and further discussed while characterising the sulphur content, temperature and coefficient of variation (COV).

3.2.1. Comparisons characterising the sulphur content

This section elaborates the findings on the mechanical properties characterising the distinct sulphur content at 50 % and 60 %. As an overall based on Figs. 7, Figs. 8 and 9 for compressive strength, tensile splitting strength and flexural strength respectively, the 50 % sulphur content demonstrated the optimum mechanical properties. According to the standard BS EN 12390-3 [67] as well as the elaboration provided by Bogas et al. [71], satisfactory failures exhibited identical cracking in all four exposed surfaces or crushed into pieces similar to the finding by Wan et al. [30] illustrated in Fig. 10 whereas unsatisfactory failures exhibit non-uniform cracked surfaces or tensile cracks. Post-cube compression test, most cubic specimens utilising 50 % sulphur demonstrated satisfactory failures shown in Fig. 11(a). The 60 % sulphur content was previously found to have a high workability but demonstrated unsatisfactory uniformity and strength [41]. Based on the very brittle nature of sulphur reported by Dugarte et al. [72], adding more sulphur triggered higher amount of hardened sulphur that did not fully react with the lesser metal elements in the Martian regolith simulant. This was evidenced by the visible internal hardened sulphur consolidated post-cube compression test as illustrated in Fig. 11(b). Not just that, the 60 % sulphur content also illustrated bright and yellow-ish internal structure, see Fig. 12(b) unlike the 50 % sulphur content

Fig. 6. The spread diameter was measured in different directions after the cone was slowly lifted upward.

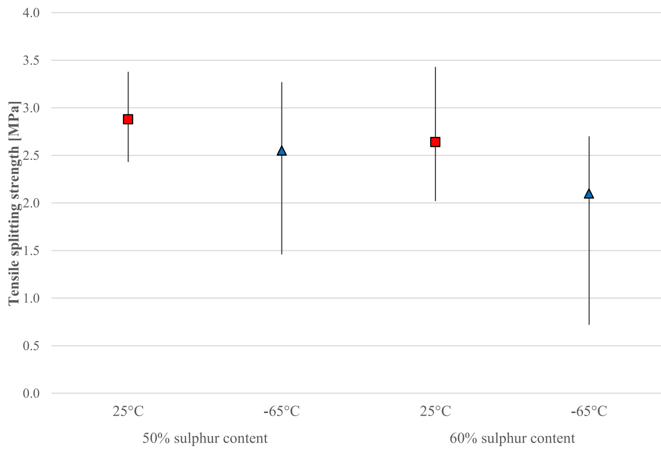


Fig. 8. Tensile splitting strength versus temperature and mixture composition.

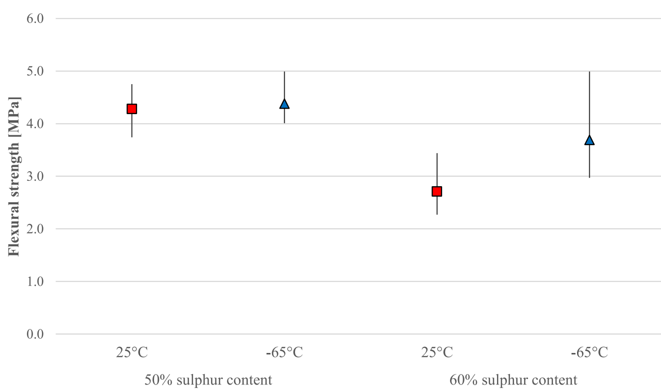


Fig. 9. Flexural strength versus temperature and mixture composition.

which illustrated dark and brown-ish, see Fig. 12(a) instead. This phenomenon clearly indicated that the 60 % sulphur content was comprised of more hardened sulphur matrix that was excluded from the chemical reaction with the metal oxides in the Martian regolith simulant. Consequently, the very brittle nature of sulphur consolidated at excessive thickness further reduced the overall strength [73]. On the contrary, as the sulphur content further reduced and additional Martian regolith simulant being added, an extensive chemical reaction between the pure sulphur and the metal elements in the Martian regolith simulant occurred thus forming higher amount of metal sulphates upon hardening. As a result, the higher amount of metal sulphates further enhanced the overall strength of the Martian sulphur-based construction material with 50 % sulphur content. Additionally, the internal particles were adequately bound by the sulphur with minimal and acceptable thickness thus triggering more compact structure [74].

3.2.2. *Comparisons characterising the temperature*

This section discusses the findings on the mechanical properties with distinct sulphur content at 50 % and 60 % subjected to the simulated hot and very cold Martian temperatures. When the Martian sulphur-based construction materials were subjected to the simulated very cold Martian temperature, the compressive strength further reduced up to 34.1 MPa and 33.9 MPa from the initial hot temperature of 53.1 MPa and 35.9 MPa for 50 % sulphur content and 60 % sulphur content respectively. On the other hand, most cubic specimens for both sulphur contents subjected to the simulated hot Martian temperature demonstrated satisfactory failures whereas the cubic specimens particularly 60 % sulphur content subjected to the simulated very cold Martian temperature exhibited unsatisfactory failures post-cube compression test. The average tensile splitting strength recorded in this study was 2.88 MPa and 2.64 MPa for 50 % and 60 % sulphur content respectively while being subjected to the simulated hot Martian temperature. When being subjected to the simulated very cold Martian temperature, the average tensile splitting strength declined up to 2.55 MPa and 2.10 MPa for 50 % and 60 % sulphur content respectively. Both compressive strength and tensile splitting strength experienced strength reduction but it was identified not the case for flexural strength. The average flexural strength subjected to the simulated hot Martian temperature was 4.28 MPa and 2.71 MPa for 50 % and 60 % sulphur content respectively. When being subjected to the simulated very cold Martian temperature, an increment in strength up to 4.38 MPa and 3.69 MPa for 50 % and 60 % sulphur content respectively was reported. This was almost in agreement with the findings by Grugel [46] who investigated the effects of temperature cycle and testing condition on the overall strength of the lunar sulphur-based construction material. The author found a clear difference between the cycled and non-cycled specimens. However, the compressive strength was found to enhance when subjected to the very cold testing condition. Despite the apparent increase in the flexural strength for both sulphur contents, the coefficient of variation (COV) and longitudinal pulse velocity contradicted such findings and will be elaborated in Section 3.2.3 and 3.2.4 respectively. Additionally, this phenomenon was also attributed to the alteration of the internal structure and microstructural characteristics of the Martian sulphur-based construction material upon exposure to the simulated very cold Martian temperature which will be further discussed based on the SEM findings in Section 3.4.

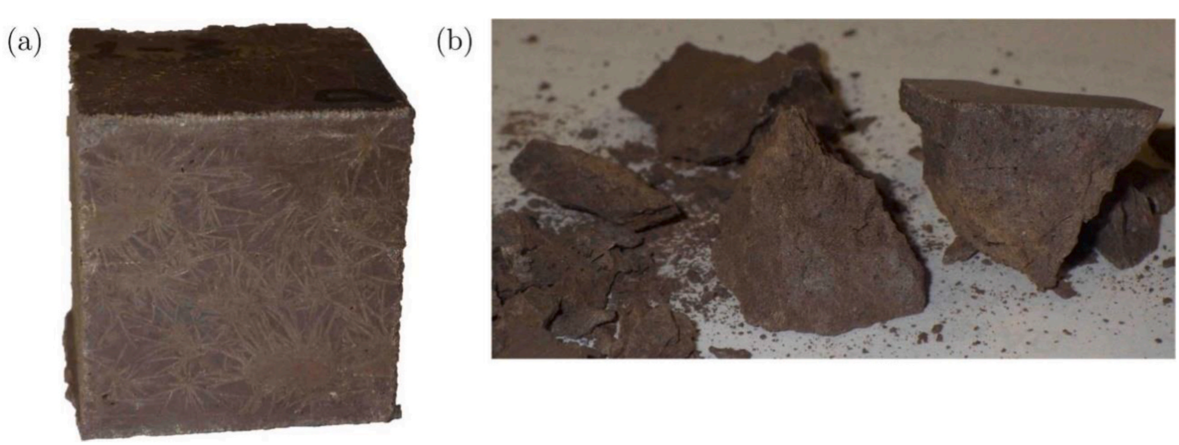
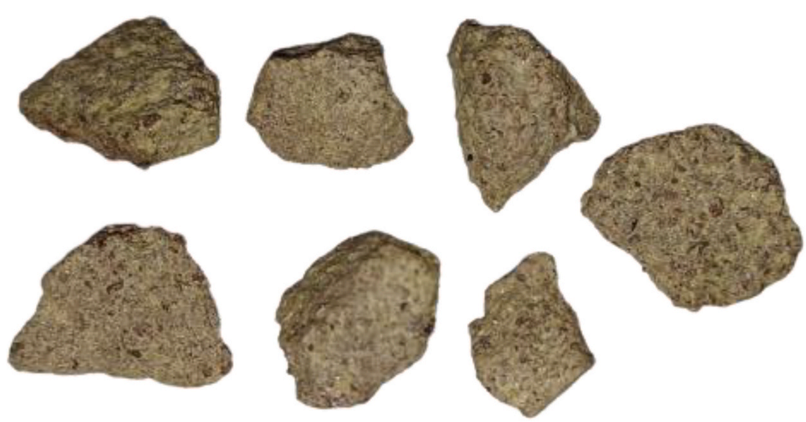


Fig. 10. Failure mechanism (a) before and (b) after cube compression test [30].

(a) (b)

Fig. 11. Failure mechanism (a) satisfactory; crushed into pieces (b) unsatisfactory; failure on one surface of the cube and the internal hardened sulphur.

(a)



(b)

Fig. 12. Chunks of Martian sulphur-based construction material post-cube compression test; (a) 50 % sulphur content (b) 60 % sulphur content.

3.2.3. Comparisons characterising the coefficient of variation (COV)

Last but not least, this section elaborates the comparisons on the mechanical properties based on the reported dispersion of data in this study. Regardless of sulphur content and temperature, a varying dispersion of data among all specimen groups was also observed as illustrated in Fig. 13. Particularly, the 50 % sulphur content demonstrated minimal COV than the 60 % sulphur content for both simulated Martian temperatures. The distinct internal structure of the hardened Martian sulphur-based construction material was inevitably due to the changes in the overall volume during casting into the moulds. This was in agreement with the previous related findings [30,46]. The volumetric alteration and variation were mainly due to the internal stress triggered as a result from the subsequent transformation of the denser orthorhombic sulphur than the initial monoclinic sulphur [30,34]. The molten sulphur crystallised to form monoclinic sulphur (S_β) and subsequently denser orthorhombic sulphur (S_α) during cooling below 96°C [43,72,75]. Furthermore, the interparticle bond between the hardened particles within the hardened specimens was unable to maintain a strong connective bond with each other during placement as sulphur-based construction materials usually harden very rapidly [65]. Consequently, the lack of homogeneity between layers subsequently affected the overall strength of the final product and most certainly provided varying outputs on the mechanical properties. Future studies addressing the aforementioned lack of uniformity in order to provide more precise results on the mechanical properties should be taken into consideration. In order to quantitatively calculate the dispersion of data, all sets of data were calculated and compared using the form of COV. It is defined in (3) where x is the value, μ is the mean value and N is the total number of samples. The lower the COV calculated, the better quality and higher consistency the overall data thus vice versa. Based on Fig. 13, the 50 % sulphur exhibited lower COV regardless of the simulated Martian temperature. Initially, the dispersion of data utilising 50 % and 60 % sulphur content was very minimal. When being subjected to the simulated very cold Martian temperature, the dispersion of data particularly 60 % sulphur content exhibited higher increment. Although demonstrating an increment in flexural strength, the flexural strength for 50 % and 60 % sulphur contents subjected to the simulated very cold Martian temperature were found to exhibit higher COV particularly the latter sulphur content; contradicting the increment in flexural strength. The previous findings by Grugel [46] also reported the variation in strength in very cold testing condition. As a summary, the internal stress due to the sulphur transformation from the less-dense to denser structure and the lack of homogeneity between layers triggered volumetric alteration and subsequently strength variation. Subjecting to the simulated very cold Martian temperature worsened the volumetric alteration. Furthermore, the phenomenon is also due to the previously mentioned alteration on the internal structure of the Martian sulphur-based construction material and will be elaborated in Section 3.4.

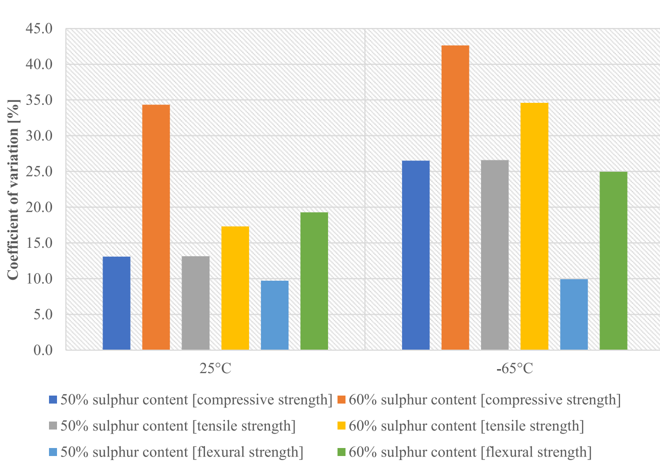


Fig. 13. Coefficient of variation (%) versus simulated Martian temperature.

$$\textit{coefficient of variation}, CV = \frac{\sqrt{\frac{\Sigma|x-\mu|^2}{N}}}{\mu} \times 100\% \tag{3}$$

3.2.4. Correlation with longitudinal pulse velocity

The internal structure most certainly played a role in differentiating both specimens as it indicated the quality, denseness and homogeneity of the specimens during ultrasonic pulse velocity testing. Higher longitudinal pulse velocity indicates lesser and small voids, closely packed internal particles thus high denseness. Fig. 14 shows the comparison between the distinct 50 % and 60 % sulphur content characterising the simulated Martian temperature. The 50 % sulphur content exhibited higher longitudinal pulse velocity than the 60 % sulphur content for both simulated Martian temperatures and demonstrated similar trend with the previously discussed effects of sulphur content and temperature on the mechanical properties. As the Martian sulphur-based construction materials were subjected to the simulated very cold Martian temperature, the longitudinal pulse velocity for both 50 % and 60 % sulphur content experienced reduction. Along with the high COV, the overall longitudinal pulse velocity of the specimens tested on the flexural strength demonstrated a reduction as well. These indicated higher and possibly larger voids, loosely packed internal particles thus lower denseness. As a result, the overall internal structure of the Martian sulphur-based construction material was significantly altered and to be discussed in Section 3.4. Fig. 15 illustrates the correlation between the longitudinal pulse velocity and the recorded compressive strength. The 50 % sulphur content for both simulated Martian temperatures was closely packed with each other particularly the simulated hot Martian temperature whereas the 60 % sulphur content for both simulated Martian temperatures were widely dispersed with each other also particularly the simulated very cold Martian temperature. These demonstrated similar trend with the coefficient of variation characterising the simulated Martian temperature.

3.3. X-ray diffraction analysis

The unidentified metal sulphates and poly-sulphates were formed upon chemical reaction between the elemental sulphur and the metal elements in the Martian regolith simulants [30]. The authors also mentioned the need for subsequent works that further recognise the outputs of such chemical reactions. Subsequently, Shahsavari et al. [32], confirmed the hypothesis by identifying alumino-coquimbite, an iron (iii) sulphate as well. Another work by Snehal et al. [34], investigated the changes on the mineralogical composition of the regolith simulant used comprised of anorthite, albite and olivine at distinct temperatures. This study addressed the said requirement as well as acted as a continuation. The X-ray powder diffraction (XRPD) of the MMS-1 can be found in this reference [76]. Caporale et al. [59], reproduced the XRPD findings on the MMS-1. The rich source of plagioclase (anorthite) and hematite (iron oxides) were identified. The XRD analyses are illustrated in Figs. 16 and 17 for 50 % and 60 % sulphur content respectively. As expected, crystallised sulphur was identified in both 50 % and 60 % sulphur content with the latter revealed to be at higher concentration than the former. This supported the aforementioned justifications on the findings of the workability and the mechanical properties characterising the sulphur content discussed in section 3.1 and section 3.2.1 respectively. Furthermore, the hematite in MMS-1 was found to react with sulphur to form iron sulphate hydrate which was almost in agreement with the previous work [32]. Interestingly, the minor metal oxides in MMS-1 i.e. potassium oxide, calcium oxide and magnesium oxide were found to react with sulphur to form potassium calcium magnesium sulphate. It will also act as the distinct chemical composition found in this study that is based on the state-of-the-art Martian sulphur-based construction materials. Much like the previous findings by Shahsavari

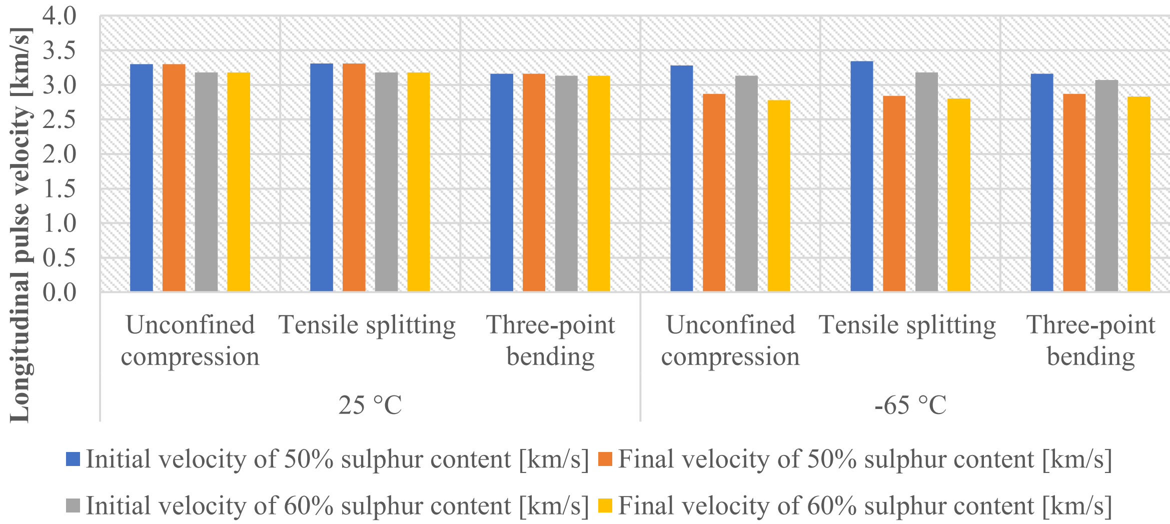


Fig. 14. Longitudinal pulse velocity versus simulated Martian temperature.

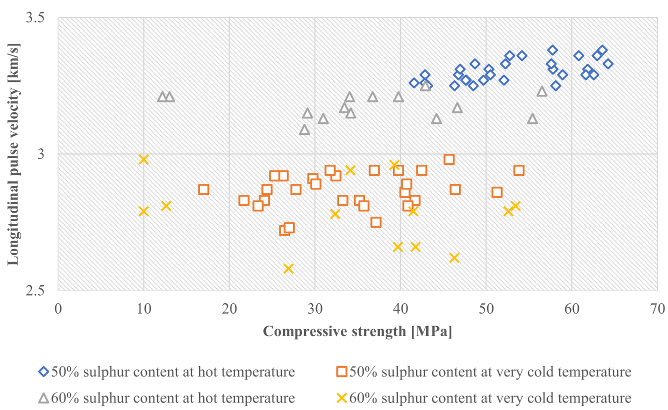


Fig. 15. Longitudinal pulse velocity (km/s) versus compressive strength (MPa).

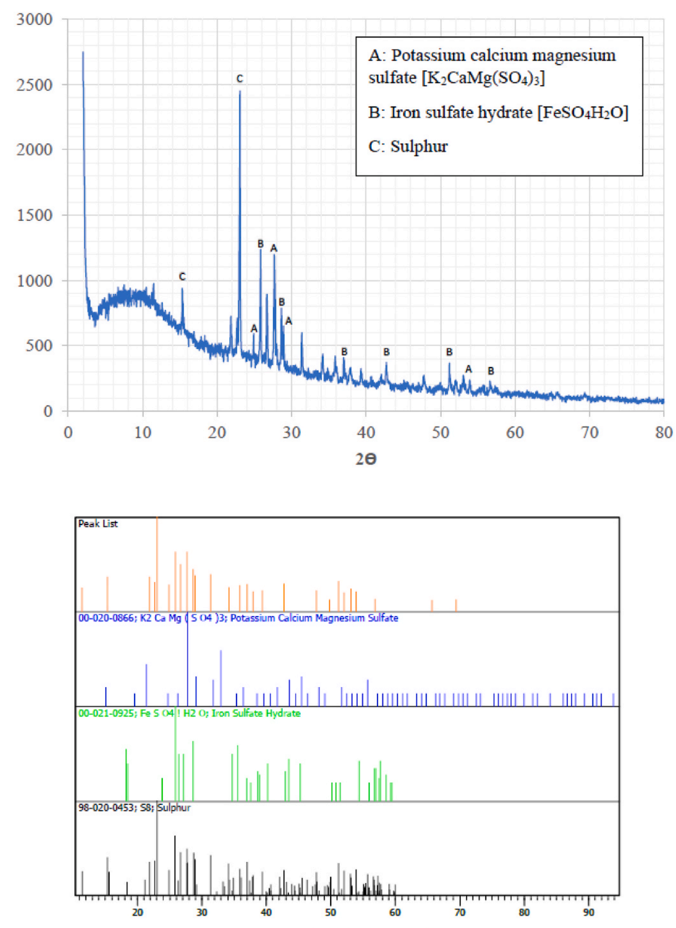


Fig. 16. XRD analysis on 50 % sulphur.

et al. [32], the presence of water vapour in the laboratory condition during mixing led to the formation of the iron sulphate hydrate which contributed to the strength enhancement; almost in agreement with the previous work [32]. This study was unable to identify poly-sulphates as mentioned by the previous study thus subsequent works are essential to potentially identify such compounds. Last but not least, this study was only limited to the identification of the integral chemical compounds in the form of sulphates and poly-sulphates that led to increasing strength. The mineralogical phase transition at very cold temperature i.e. below zero temperature can be further studied in future investigations.

3.4. Microstructural characteristics of the Martian sulphur-based construction material

The microstructural characteristics play a role in determining the structural rigidity of the Martian sulphur-based construction material. As previously discussed, lower longitudinal pulse velocity was recorded that subsequently predicted the declining strength of the Martian sulphur-based construction material when subjected to the simulated very cold Martian temperature. Additionally, higher coefficient of variation was simultaneously recorded based on the declining strength. The microstructural characteristics was initially hypothesised to change dramatically when subjected to the simulated very cold Martian temperature. Therefore, this section elaborates on the SEM findings on the Martian sulphur-based construction material characterising the sulphur content and simulated Martian temperature. Figs. 18–23 illustrate the overall SEM findings in this study that elaborated on the distinct microstructural characteristics of the Martian sulphur-based construction material at distinct sulphur content and/or simulated Martian temperature.

At first, a grainy anatomy was observed with a light-grey matrix as illustrated in Fig. 18. The 60 % sulphur content revealed broader light-grey matrix which indicated the crystallised sulphur as the dominant

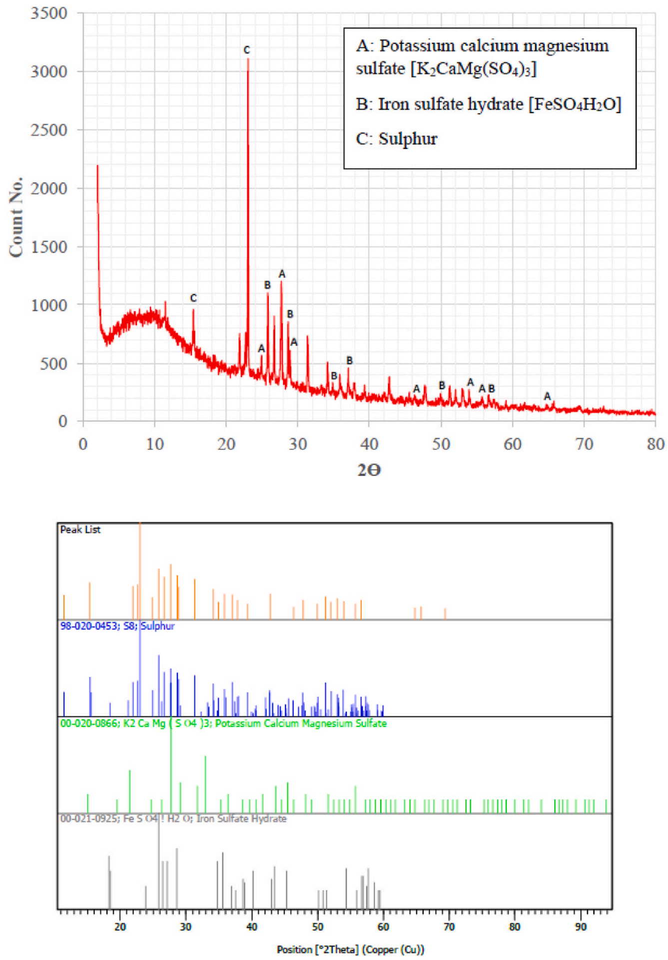


Fig. 17. XRD analysis on 60 % sulphur.

matrix, see Fig. 18(b). This supported the aforementioned justifications on the findings of the workability, mechanical properties characterising the sulphur content and XRD findings discussed in section 3.1, section 3.2.1 and section 3.3 respectively. Subsequently, the samples were closely examined and semi-periodic striations on the surface of the light grey matrix were identified, see Fig. 19. The semi-periodic striations are defined as patterns of lines or grooves along the surface which indicated the micro-passage filled with air. Therefore, the light grey matrix and ultimately the Martian sulphur-based construction material fabricated in this study exhibited a micro-permeable anatomy. This was almost in agreement with the work done by Akono A. T [33]. The author justified that the micro-permeable anatomy was triggered by the directional heat loss; as the temperature declined from 145°C to 20°C post-casting crystals were forged via self-assembly procedure. At 145°C, it was merely seconds after the moulds were completely filled and the specimens were rapidly hardened. Then, the hardened specimens undergone heat loss during cooling that further declined up to 20°C. Based on Figs. 20 and 21, the microstructural characteristics of the Martian sulphur-based construction material subjected to the simulated hot Martian temperature illustrated uniform and homogeneous interparticle distribution apart from least and smaller cavities. Based on Fig. 20, minor cracks were also identified most likely due to the internal stress triggered from the sulphur shrinkage as a result from the difference in density between the initial monoclinic sulphur and the subsequent transformation to denser orthorhombic sulphur based on the observed crystallised sulphur in XRD analysis. As the Martian sulphur-based construction material was subjected to the simulated very cold Martian temperature, a non-uniform interparticle distribution and larger cavities based on Figs. 22 and 23 were evident. As a result, the overall porosity was significantly increased and further degraded the overall strength of the Martian sulphur-based construction material. Such findings were also in agreement with the previously discussed lower longitudinal pulse velocity, see Figs. 14 and 15. To relate, the longitudinal pulse velocity is inversely proportional to the size and rate of internal voids within the Martian sulphur-based construction material. To further support these findings, we will further explore in depth on the microstructure of the Martian sulphur-based construction material comprised of the pore sizes, pore size distributions, etc while characterising the subjected simulated Martian temperature in future studies.

3.5. *Comparisons with other related studies on the Martian sulphur-based construction material*

As previously cited in the beginning of this manuscript, there have been other related studies on the state-of-the-art Martian and lunar sulphur-based construction materials. This section focuses on the

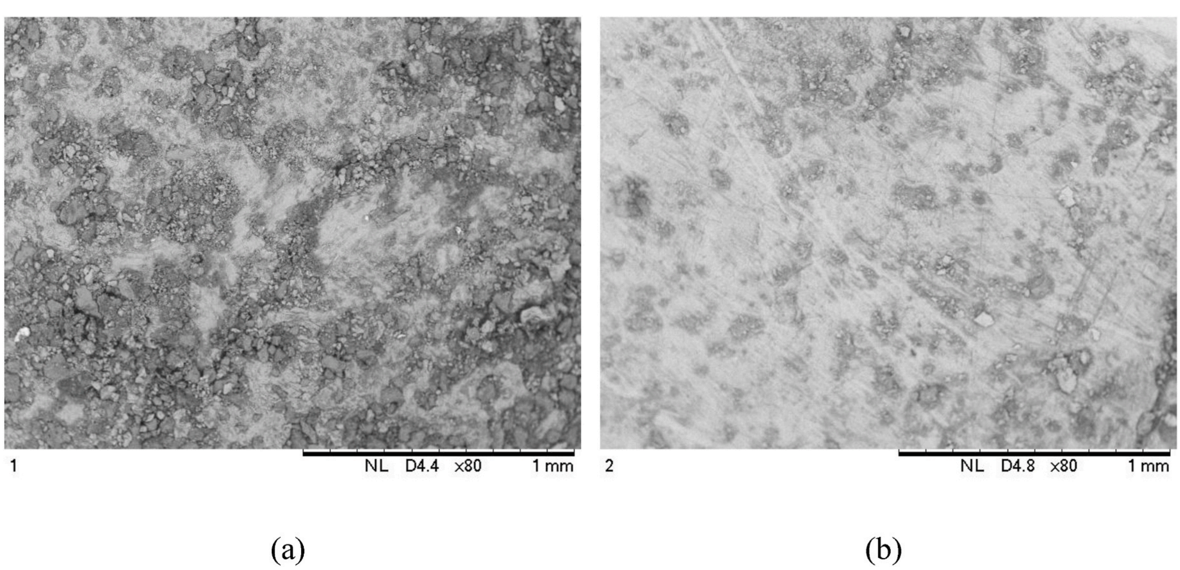
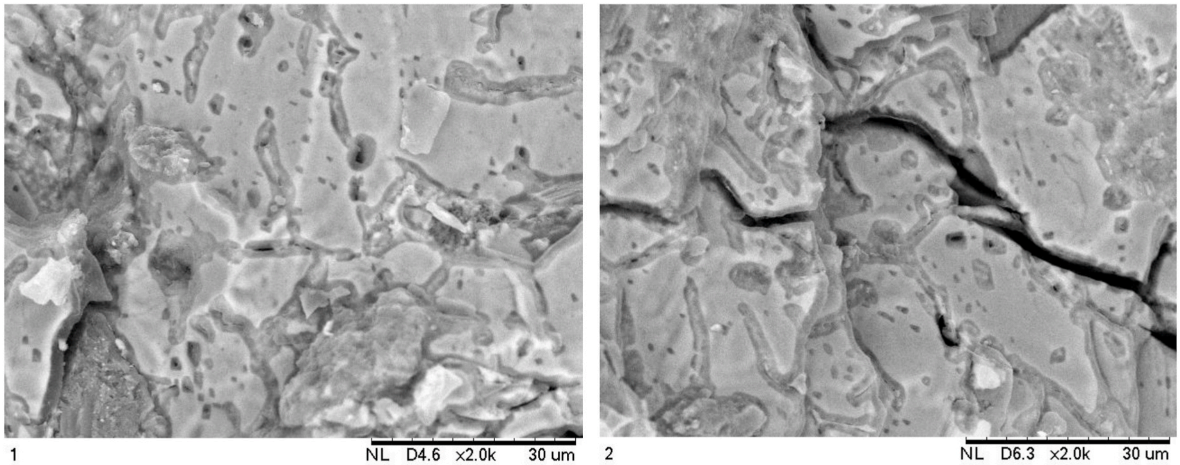
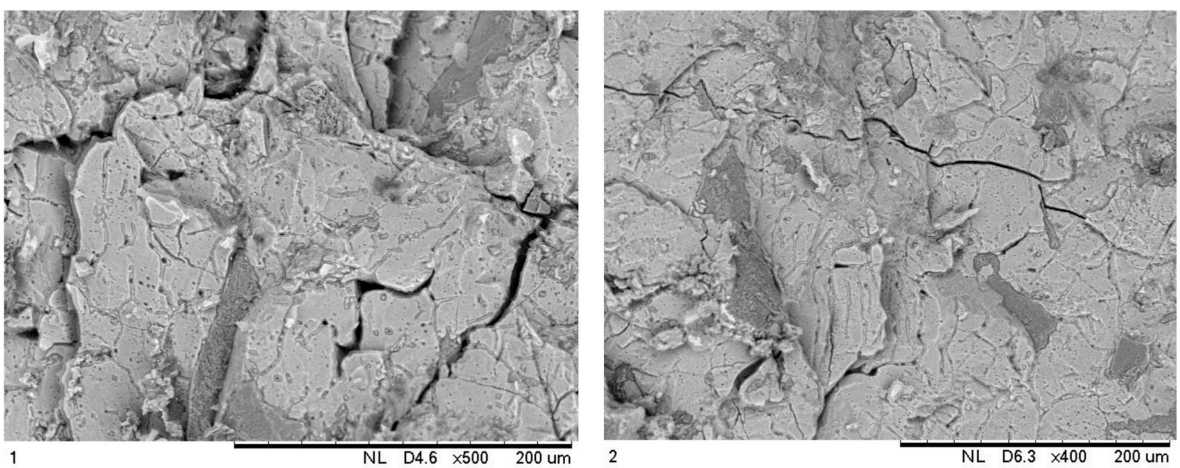


Fig. 18. Light grey matrix at 1 mm scale on Martian sulphur-based construction material at simulated hot Martian temperature utilising; (a) 50 % sulphur (b) 60 % sulphur.



(a) (b)

Fig. 19. Semi-periodic striations at scale 30 μm on Martian sulphur-based construction material at simulated hot Martian temperature utilising; (a) 50 % sulphur (b) 60 % sulphur.



(a) (b)

Fig. 20. SEM findings at scale 200 μm on the of Martian sulphur-based construction material at simulated hot Martian temperature utilising (a) 50 % sulphur (b) 60 % sulphur.

comparisons between the findings of this study with other cited related studies. Fig. 24 illustrates the comparisons with other related studies on the optimal compressive strength. The lunar sulphur-based comprises of Toutanji et al. [47], and Grugel [46] whereas the Martian sulphur-based are represented by Wan et al. [30], Li et al. [31], Shahsavari et al. [32], and Snehal et al., [34]. With the exception of the work done by Snehal et al. [34], other works were conducted in the simulated hot Martian temperature. As an overall based on Fig. 24, the optimal compressive strength of the Martian sulphur-based construction material in this study subjected to the simulated hot Martian temperature is the highest. On the other hand, the strength reduction from 53 MPa to 34 MPa was reported up to 36 % for 50 % sulphur content when subjected to the simulated very cold Martian temperature. With the exception of Wan et al. [30], the reported residual strength is still comparable with the other related Martian sulphur-based construction materials subjected to the simulated hot Martian temperature. Interestingly, the residual strength after being subjected to the simulated very cold Martian temperature would still hypothetically be able to adapt in the Martian environment particularly due to the environment's minimal gravity at 3.71 m/s^2; approximately one-third of Earth's gravity at 9.81 m/s^2 [77, 78]. This indicates that the Martian structure is expected to exert very minimal load thus permitting weaker concrete to be utilised. It is also noted that the minimal gravity may trigger detrimental effects on the microstructure of the final product. Previous investigations conducted onboard the International Space Station (ISS) on the water-based products demonstrated high internal porosity due to inadequate self-weight consolidation and separation of the internal particles [79–81]. Air bubbles were found integrated within the cementitious materials due to minimal buoyancy forces in a low gravity environment [81]. Conversely, sulphur-based construction material is non-hydraulic and hardens rapidly upon placement. However, the low gravity may hinder further self-consolidating during placement thus adversely affecting the overall solidity and bonding strength between layers [82]. Hence, applying pressure during placement may be helpful [30]. On the other hand, the vacuum atmosphere is found to trigger sulphur sublimation particularly at high temperature [45]. As the highest Martian

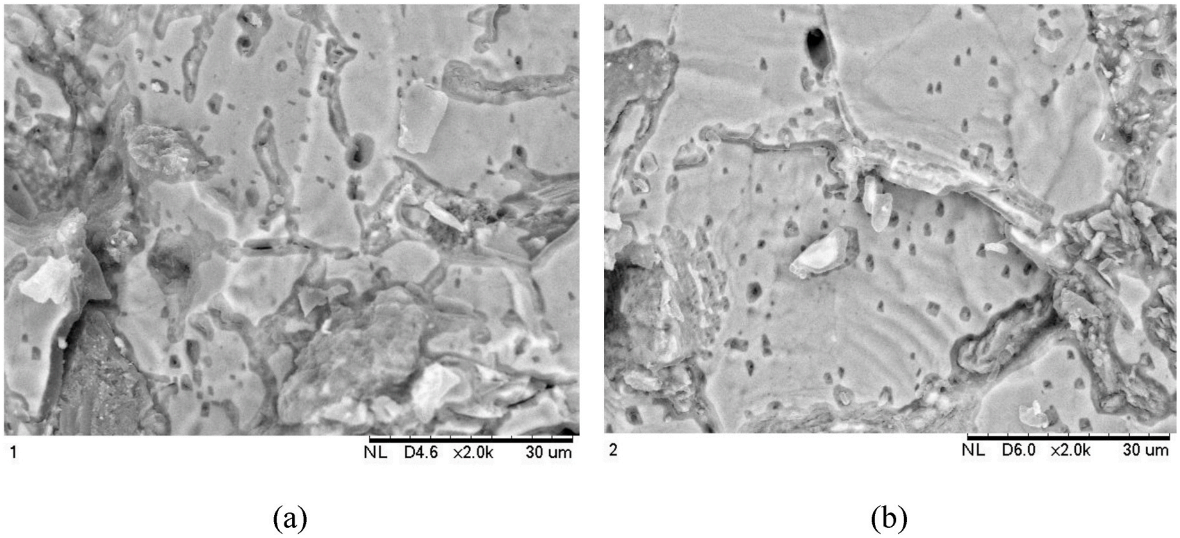


Fig. 21. SEM findings at scale 30 μm on the of Martian sulphur-based construction material at simulated hot Martian temperature utilising (a) 50 % sulphur (b) 60 % sulphur.

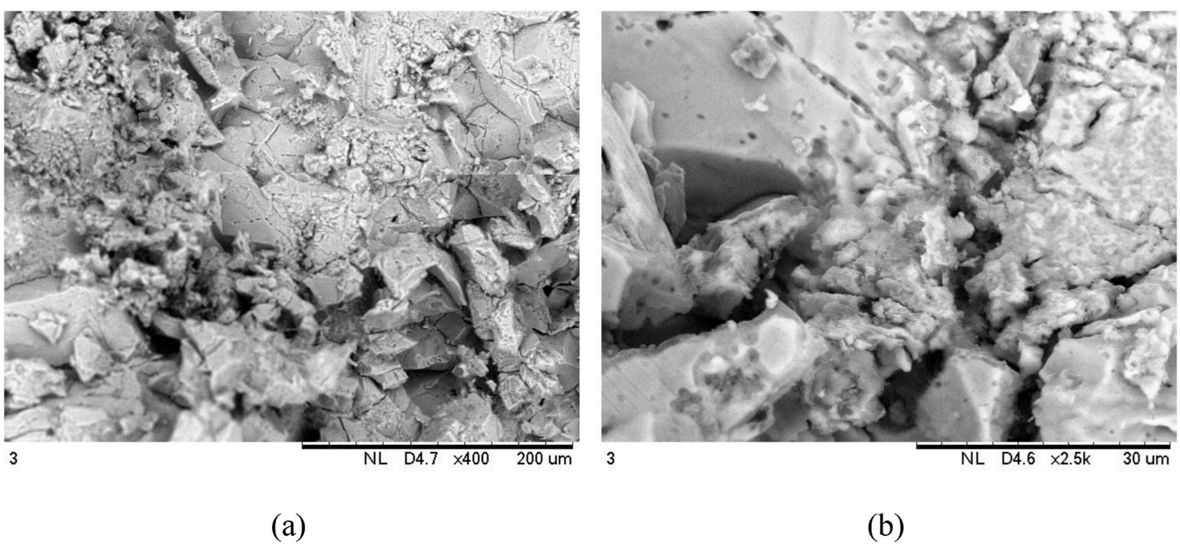


Fig. 22. SEM findings on the of Martian sulphur-based construction material at simulated very cold and CO_2 rich Martian environment utilising 50 % sulphur at scale (a) 200 μm; (b) 30 μm.

temperature almost resembles the room temperature on Earth, the sulphur sublimation is expected to take longer upon exposure unlike being subjected to the very hot lunar temperature up to 120 °C or more which triggers instant sublimation. The very cold Martian temperature further extends the time taken for sulphur to sublimate [32]. These indicate the advantages of sulphur-based construction material for Martian construction. Further recommendations will be outlined in Section 3.6. On the other hand, it is notable that Mars also experiences temperature fluctuation i.e. hot and very cold at daylight and night respectively. Therefore, this study specifically this section recommends that the strength reduction reported above was not too drastic based on the minimal Martian gravity. Thus, further understanding on the influence of the temperature variation on the overall strength may not be essential.

In comparison between this study and the previous notable investigation; Wan et al. [30], strictly for simulated hot Martian temperature as the previous investigation was conducted solely in similar simulated temperature as previously mentioned, the overall mechanical properties is comparable, in agreement and achieved the identical optimal percentage of sulphur at 50 %. It is also noted that the similar previous investigation also investigated the tensile splitting strength and flexural strength with the former being tested upon re-cast; the Martian sulphur-based construction material was re-melted and re-cast after the initial laboratory testing. The flexural strength obtained in this study was 4.28 MPa, almost comparable with 7.24 MPa reported by Wan et al., [30]. On the other hand, this study also illustrated the findings characterising the tensile splitting strength based on Fig. 8. The average tensile splitting strength obtained in this study for 50 % sulphur content subjected to the simulated hot and very cold Martian temperatures were 2.88 MPa and 2.55 MPa respectively. The findings on the tensile splitting strength in this study more or less functioned as the prefatory investigation and comparison for the previous works that investigated the tensile splitting strength of the re-cast specimens utilising 50 % sulphur which demonstrated higher tensile splitting strength but only limited at simulated hot Martian temperature. It was evident in the previous study that re-casting enhanced the tensile splitting strength up to 3.9 MPa, a 35 % increment from the freshly cast specimen at 2.88 MPa recorded in this study. However, the re-casting was again only limited to

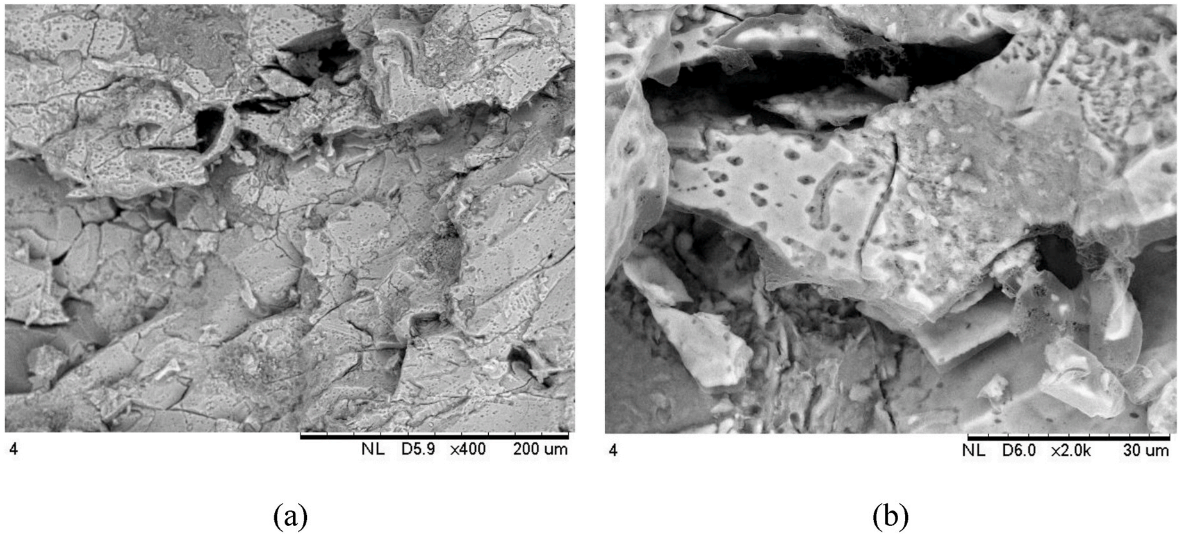


Fig. 23. SEM findings on the of Martian sulphur-based construction material at simulated very cold and CO2 rich Martian environment utilising 60 % sulphur at scale (a) 200 μm; (b) 30 μm.

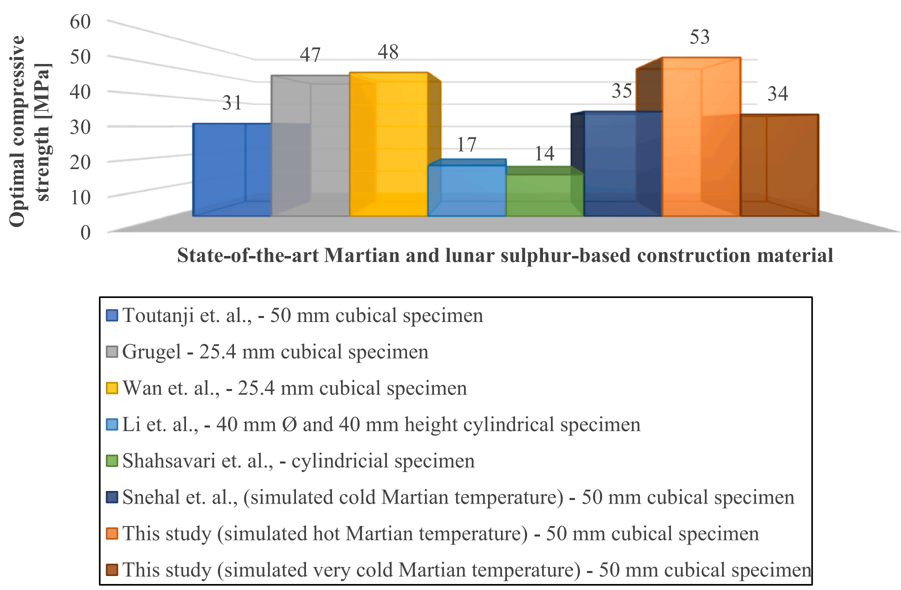


Fig. 24. Comparisons with other related Martian and lunar sulphur-based construction materials.

the simulated hot Martian temperature thus further investigations are required on the simulated very cold Martian temperature. Investigations made by Gulzar and his colleagues [83] found that the initial re-cast promotes enhanced interparticle connection through better mixing and applying pressure. However, subsequent re-cast triggered higher breakage and more interfacial transition zone (ITZ) thus degrading the overall strength of the subsequent re-cast. Hence, further investigations are recommended on the initial re-cast while being subjected to the simulated very cold Martian temperature. Furthermore, the distinct microstructure of the fresh and initial re-cast can also be explored for further understanding on how re-casting alters the overall microstructure of the Martian sulphur-based construction material. Moreover, the Martian regolith simulant used in this study was the 1st generational simulant which was extracted from one particular location. Karl et al. [60], outlined several other types of Martian regolith simulants categorised into 3 groups i.e. 1st generational simulants, 2nd generational simulants and 3rd generational simulants. The 2nd generational simulants are simulants made by integrating distinct minerals while almost replicating the actual Martian regolith whereas the 3rd generational simulants are the successor of the 2nd generational simulants but with improved physical characteristics. As the actual Martian regolith varies chemically and mineralogically across Mars, the state-of-the-art Martian sulphur-based construction materials can be further progressed by utilising varying Martian regolith simulants from all 3 aforementioned groups.

3.6. *Suggestions for future construction on Mars*

First and foremost, the Martian settlement should provide adequate thermal, mechanical and radiation shelter for occupants [54]. It is also subjected to the pressure differential between the pressurised interior up to 1 atm or 101 kPa which is necessary for occupants' comfort and the minimal outer pressure up to 0.636 kPa [77,84]. Additionally, it is also susceptible to high tensile stresses imposed by the pressurised interior [54]. In spite of that, thinner structural components at larger spans while utilising weak construction materials can be opted [3,55].

However, such strategy is recommended to be built internally which is not directly vulnerable to the harsh Martian environmental conditions apart from the minimal gravity. As a result, the mechanical properties would not be the main priority for internal structures thus weak construction materials can be considered as long as ISRU can be fully implemented in order to reduce cost. On the other hand, the apparent harsh Martian environmental conditions require sturdy and resilient barrier between the harsh exterior and the interior. Hence, it is vital to apply construction materials with a rigid bonding mechanism between the binder and the filler which provides the required resiliency. Even a small leakage would trigger freezing, crack distribution, enlargement and eventually wreckage to the Martian settlement [77].

Based on the findings of this study, utilising 60 % sulphur content is suggested for the structural elements built internally as a mean to maximise the usage of abundant sulphur on Mars while not highly considering the mechanical properties and neglecting the dispersion of data. Furthermore, utilising 60 % sulphur content for internal structural elements also potentially avoids sublimation as the more sulphur exposed to the harsh Martian environmental condition, the higher the sublimation rate thus causing more free regolith without proper bonding [45]. Conversely, the 50 % sulphur content demonstrated a high potential to be utilised for the aforementioned barrier based on the reported high strength, minimal data dispersion and acceptable residual strength when subjected to the simulated very cold Martian temperature. The minimal sulphur content reduces the risk of high sublimation rate when being subjected to the harsh Martian environmental condition. Post-sublimation, the free regolith particles may land on the remnants of the sulphur thus blocking them from being exposed to sublimation [45]. This indirectly minimises the risk of high sublimation rate. However, further clarifications are still required. As a few examples, the freshly cast specimens demonstrated minimal tensile strength which further enhanced upon re-casting [30]. As an alternative to re-casting in order to potentially improve the tensile strength, adding fibres enhances fracture and strength as well as hinder tiny cracks [85,86]. Based on the identified source of basalt on Mars, it can potentially be extracted and processed into the required basalt fibres to be added into the mix. Adding appropriate amount of fibres into the mix enhances the tensile and flexural strength due to the bridging mechanism by impeding cracks within the internal particles [87–90]. Higher fibre dosage contributes to fibre clustering that weakens the bonding strength between the fibres and the regolith particles [44,87,89]. As the tensile and flexural strength enhancement were demonstrated by the sulphur polymer based on the investigations by Wang and his colleagues [89], such methodology can be implemented on Martian sulphur-based construction material in future works. However, it is noted that the brittleness of sulphur may be easily disrupted by the addition of fibres thus forming weak spots [38]. Therefore, careful considerations should be taken into account i.e. minimising the sulphur binder thus potentially utilising 50 % sulphur content and adding fibres into the final mix.

4. Conclusion

Based on the experiments and analyses made in this study, the behaviour of the Martian sulphur based-construction material subjected to the simulated very cold Martian temperature at −65 °C has been established. As previously mentioned, the very cold temperature was not considered in the previous notable study [30] and further understanding is required from the investigated simulated Martian cold temperature at 0°C [34]. The effects of the simulated very cold Martian temperature on the mechanical properties i.e. compressive strength, tensile splitting strength and flexural strength were investigated. It has been found that the simulated very cold Martian temperature further worsened the microstructure of the Martian sulphur-based construction material that was previously affected by the sulphur shrinkage by disrupting the interparticle arrangement and triggered larger voids thus contributing to strength degradation and higher volumetric inconsistency evidenced by the reported high dispersion of data. The compressive strength and the tensile splitting strength experienced reduction. Although the flexural strength suggested otherwise, the COV and longitudinal pulse velocity reported for the flexural strength contradicted such findings while also in agreement with the compressive strength and tensile splitting strength. Hence, the reported volumetric inconsistency caused variation in strength thus this issue should be seriously taken into account in future studies. As for this investigation, 2 out of 3 components i.e compressive strength and tensile splitting strength demonstrated strength reduction when being subjected to the simulated very cold Martian temperature. Therefore, this study concludes that the simulated very cold Martian temperature triggered inferior mechanical properties. On the other hand, the residual strength is perceived to remain sufficient in the Martian environment of low gravity. Thus, the findings gained from this study provided a clear simulation on how the Martian sulphur-based construction material would adapt to the simulated Martian temperature. Furthermore, other findings are presented herein.

- Martian sulphur-based construction material utilising 50 % sulphur exhibited the optimal mechanical properties with lower coefficient of variation thus higher consistency upon exposure to the simulated hot and very cold Martian temperatures.
- The workability of the molten Martian sulphur-based construction material is directly proportional to the sulphur content but inversely proportional to the mechanical properties. However, as previously mentioned, the findings related to this matter are relatively basic thus further enrichment on other related parameters including the aforementioned plastic viscosity and yield stress are recommended.
- Based on the clear distinction on the findings of the longitudinal pulse velocity, the ultrasonic pulse velocity exhibited good potential as the non-destructive test (NDT) in evaluating and estimating the mechanical properties of the Martian sulphur-based construction material characterising the sulphur content and nature of exposure.
- The dispersion of data for the findings on mechanical properties was made apparent. This is due to the internal stress from the high sulphur content that demonstrated high brittleness as well as shrinkage and the increasing porosity. The increasing porosity was further worsened by the alteration of the interparticle distribution in the simulated very cold Martian temperature. As a result, the exact conclusions on the mechanical properties of the Martian sulphur-based construction material are unclear. Therefore, future studies are highly advocated on addressing such matter.
- The overall mechanical properties in this study are comparable with the previous related studies within the state-of-the-art Martian sulphur-based construction materials and are predicted to be sufficient for the Martian environment of low gravity.
- The 60 % sulphur content is proposed for structural elements built internally which are not directly exposed to the harsh Martian environmental conditions apart from the minimal gravity thus mechanical properties can be slightly disregarded and the ubiquitous source of sulphur on Mars can be fully utilised. Conversely, the 50 % sulphur content demonstrated a high potential in adapting to the harsh Martian environmental conditions based on the reported high strength, minimal dispersion of data and sufficient residual strength in a Martian environment of low gravity. However, further clarifications are still required and will be addressed in future works in this section.

Next, the limitations and future works of this study are presented herein.

- The MMS-1 utilised in this study is the first generational simulant which was extracted from one particular location. As of now, there have been subsequent generational simulants developed by numerous researchers with improved physical properties and clearer resemblance of the actual Martian regolith. As the actual Martian regolith varies mineralogically, distinct Martian regolith simulants are necessary to be utilised in future studies.

- The workability of the Martian sulphur-based construction materials reported in this study is relatively basic i.e. in the form of spread flow diameter via mini slump flow test. Thus, further enrichment on other related parameters including the aforementioned plastic viscosity and yield stress is recommended.
- The Martian sulphur-based construction materials fabricated in this study are of freshly cast specimens. It has been found that re-casting improves the overall mechanical properties but it is limited to the simulated hot Martian temperature. Future studies are encouraged on the behaviour of the re-cast specimens subjected to the simulated very cold Martian temperature. The difference in terms of microstructure of the fresh and re-cast specimens is advocated to be explored for further understanding on how re-casting enhances the overall strength.
- This study was only limited to the identification of the integral chemical compounds in the form of sulphates and poly-sulphates that led to increasing strength. The mineralogical phase transition at very cold temperature i.e. below zero temperature can be further studied in future investigations.
- The low tensile strength of the Martian sulphur-based construction material is another issue. In order to potentially address this issue, adding fibres into the mix are suggested in future studies. At appropriate amount in order to avoid unexpected clustering, fibres provide a bridging mechanism by preventing further internal cracks thus improving the tensile strength.
- Controlling the hardening of Martian sulphur-based construction materials is difficult. As a result, volumetric inconsistency occurred thus contributing to higher dispersion of data. Future works are encouraged in addressing this issue by potentially incorporating necessary additives as previously suggested [34].

CRediT authorship contribution statement

Muhammad Nazrif Zamani: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **Norhazilan Md Noor:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Sarehati Umar:** Resources, Supervision. **Mohamad Shazwan Ahmad Shah:** Funding acquisition, Resources, Supervision, Writing – review & editing. **Nordin Yahaya:** Project administration. **Jang Ho-Jay Kim:** Resources. **Ng Chiew Teng:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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