Concrete on Mars: Options, challenges, and solutions for binder-based construction on the Red Planet☆

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ARTICLE INFO

ABSTRACT

As humans prepare to colonize Mars, there will be a need for locally-sourced concrete to build durable, habitable structures. However, conventional terrestrial formulations would not be well suited to the unique resources and conditions prevalent on the Martian surface and near-surface. Plaster of Paris or water (which would bind by freezing) would be the most appropriate binders. Water for concrete would be produced from ice or by condensation out of the atmosphere, and local aggregates could be used in a similar manner to those on Earth. Unique mixing, casting, compaction, and curing methods will be required for the low-temperature, low-gravity, low-pressure conditions. Concrete elements could effectively support gravitational, wind, seismic, and micrometeoric loads. Concrete structures would preferably be buried under a 7–10 m layer of Martian regolith in order to counter-balance aerostatic loads and to protect against the hazards of cosmic and solar radiation, wide temperature swings, and deliquescent salts.

1. Introduction

The colonization of Mars is a rapidly-evolving field of research and interest. As part of broader efforts to establish a human presence on the Red Planet, NASA is preparing to launch the Mars 2020 Rover [1], and SpaceX intends to begin manned missions starting in 2024 [2]. One of the crucial needs of a Martian settlement will be the construction of safe and durable structures from locally-produced materials [3,4]. Specifically, concrete has been consistently suggested as an important structural material, and a large variety of formulations and methods have been proposed [4–13]. The successful application of concrete on the Red Planet will require a comparative review of the various options, and an analysis of their suitability to the unique conditions of the Martian environment (illustrated in Fig. 1). This paper examines the options, challenges, and solutions for the production and performance of concrete on the Martian surface and near-surface with respect to the following: binders, availability of water, energy sources, aggregates, handling and properties of fresh concrete, structural and habitability requirements, and durability.

The binders that are examined are plaster of Paris (PoP) [3,7], ordinary Portland cement (OPC) [3–6,12,13], alkali-activated cement (AAC) [5,6,14], geopolymer cement (GC) [15], Mg- and Si-based binder (MSBB) [8], elemental sulfur (ES) [9–12], and water (which would bind by freezing). The synthesis of any of these binders will require considerations of energy and raw material availability. For most of them, the production of concrete will require an abundant and high-quality supply of water, energy, and aggregates.

The Martian environment gives rise to much different conditions than those found on Earth for fresh, curing, and hardened concrete. The Martian gravity is 0.38G, and the average atmospheric pressure is 0.006 atm [16]. The surface is the target of much greater meteoric activity and radiation than Earth [4]. The temperature averages roughly $-63\,°C$, and varies greatly based on location, season, and time of day [16]. These conditions will redefine the processes of mixing, casting, compaction, and curing. The entire built environment will need to be reconfigured to adequately support a different set of loads and weathering mechanisms than on Earth, while protecting inhabitants from the exposure hazards of Mars.

2. Binders

In the simplest sense, "concrete" is defined as a combination of a binder and an aggregate (filler). Most binders also require water as part of the concrete formulation (ES is a notable exception). Additionally, additives or admixtures may be used to modify the properties of the concrete, though they are not strictly required. On Earth, the use of OPC as binder is so universal, that OPC is colloquially referred to simply as "cement." However, any a substance that causes the components of a mixture to cohere is considered a binder [17], and alternative binders to OPC may be appropriate for Martian concrete. Binders which have been proposed or which may have some viability are discussed below and illustrated in Fig. 2, with key characteristics compared in Table 1.

2.1. Plaster of Paris

PoP ($CaSO_4\cdot\frac{1}{2}H_2O$), which has been previously suggested as a
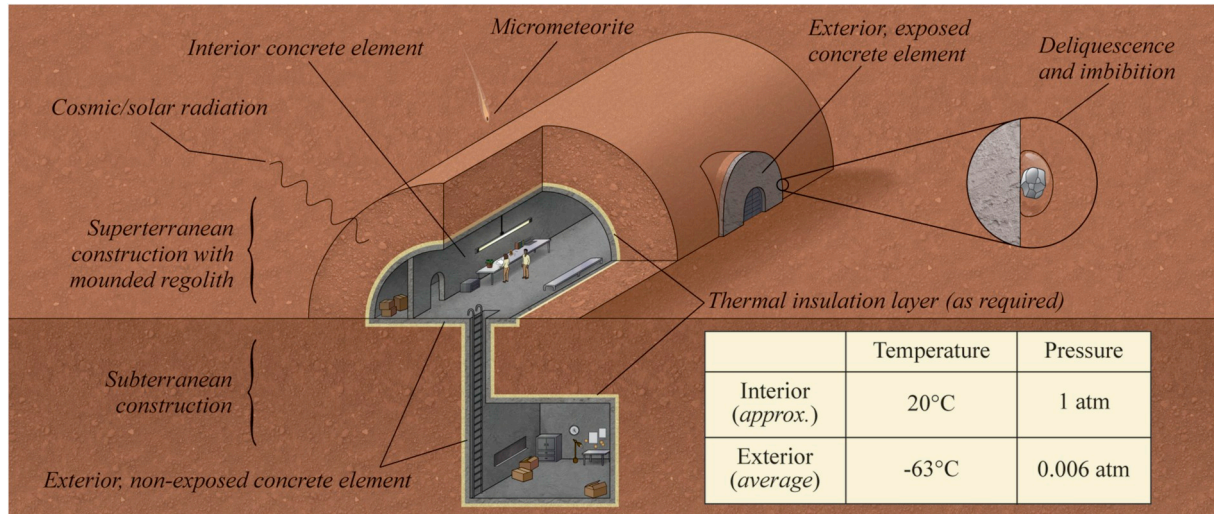

Fig. 1. Concrete structures and conditions that would affect the built environment on the Martian surface and near-surface.

construction material for Mars [3,7], is a commonly-used binder typically made from the calcining of gypsum ($CaSO_4 \cdot 2H_2O$) at around 150–165 °C [18]. When mixed with water with or without aggregates PoP hydrates back into gypsum, thereby setting and hardening into a solid matrix. The process is rapid (on the order of minutes), but may be retarded by chemical additives if necessary.

Bassanite (i.e., naturally-occurring $CaSO_4 \cdot \frac{1}{2}H_2O$) has been observed in a number of locations by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) and Curiosity Rover (Fig. 3a and Fig. 4), and it has been suggested that this mineral may occur at other locations [19]. The preparation of PoP from bassanite would be a very simple, highly energy-efficient process, requiring mining and milling, but no

calcining. If colonization takes place far from a bassanite reserve, an alternative process for PoP production would be the calcination of gypsum, which is a fairly low-energy process. Gypsum is known to be available in deposits in a number of locations on Mars (e.g., Fig. 4) [19], and is especially plentiful as dunes (Fig. 3b) near the North Pole [20].

Mars appears to be more environmentally conducive than Earth for external and load-bearing gypsum construction. On Earth, the use of PoP to fabricate structural elements is limited by the sensitivity of steel reinforcement to the chemical environment of gypsum in the presence of moisture or humidity [21], and even non-structural exterior use is limited by gypsum's sensitivity to liquid water [18]. Since liquid water is not thermodynamically stable on the Martian surface [22], all water in the
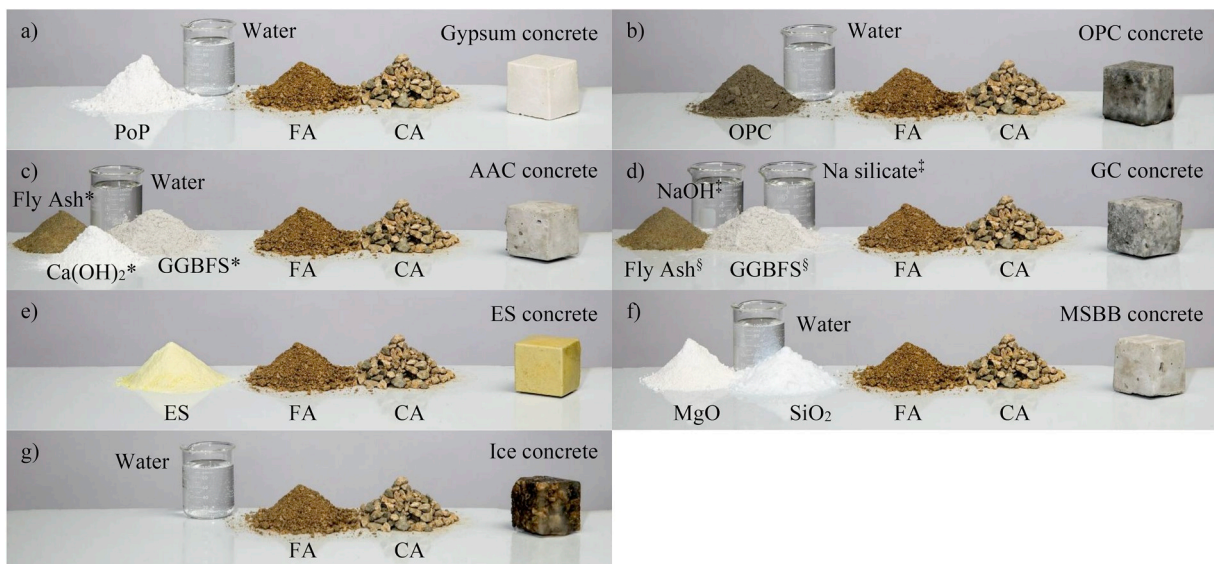

Fig. 2. Terrestrial concrete formulations with potential applicability on Mars (each illustrating the binder, aggregates, and concrete made therefrom). Sorted by binder: a) PoP, b) OPC, c) AAC, d) GC, e) ES, f) MSBB, and g) water. Ratios are not representative of any particular formulation. Admixtures may optionally be used to modify the properties of concrete, but are not shown. *Or other suitable combination of soluble SiO_2/ASP(s), Ca source(s), and alkali activator(s) per [14]. ‡Or other suitable solutions of alkali activator(s) and SiO_2 source(s) per [15]. §Or other suitable source(s) of SiO_2 and/or ASPs per [15].

Table 1
Key properties of the potential binders for construction on Mars (references in text).

Binder	Binder synthesis (temperature)[a]	Binding
PoP	Direct mining of bassanite or $CaSO_4 \cdot 2H_2O \rightarrow CaSO_4 \cdot \frac{1}{2}H_2O + 1\frac{1}{2}H_2O(150°C)$	$CaSO_4 \cdot \frac{1}{2}H_2O + 1\frac{1}{2}H_2O \rightarrow CaSO_4 \cdot 2H_2O + Q$
OPC	$3CaCO_3 + SiO_2 \rightarrow (CaO)_3SiO_2 + 3CO_2 (1,450°C)$	$(CaO)_3SiO_2 + 5.3H_2O \rightarrow (CaO)_{1.7}SiO_2(H_2O)_4 + 1.3Ca(OH)_2 + Q$
AAC	ASPs and Ca source likely recovered from mining or metallurgical waste products	$1.7CaO + SiO_2 + 4H_2O \rightarrow (CaO)_{1.7}SiO_2(H_2O)_4$
GC	Silica and/or ASP precursors mined as-is or calcined from clay (temperature varies from ambient to 700°C).	Restructuring of ASP solid structure through solution into cross-linked polymeric matrix
MSBB	$2Mg_2SiO_4 + 5H_2O \rightarrow Mg_3Si_2O_5(OH)_4 + 2Mg(OH)_2 + H_2(20-50°C)Mg(OH)_2 \rightarrow MgO + H_2O(300-450°C)$	$\alpha MgO + SiO_2 + \beta H_2O \rightarrow (MgO)_\alpha SiO_2(H_2O)_\beta$
ES	$2Fe_2(SO_4)_3 \rightarrow 2Fe_2O_3 + 6SO_2 + 3O_2 (900°C)6SO_2 + 9H_2 + 3CO \rightarrow 6S_{(s)} + 3CO_2 + 9H_2O(20°C)$	$S_{(l)} \rightleftharpoons S_{(s)}$ (transition at ~120 °C)
Water (as ice)	$H_2O_{(s)} \rightarrow H_2O_{(l)}(0°C)$ or $H_2O_{(g)} \rightarrow H_2O_{(l)}$ (ambient)	$H_2O_{(l)} \rightleftharpoons H_2O_{(s)}$ (transition at ~0 °C)

Binder	Raw materials	(availability)	Advantages	Disadvantages
PoP	• Bassanite or gypsum • Water	• (common) • (found as ice)	• Extensive history of terrestrial applications • Compatible with available resources • Low energy • Fast set, harden • Aggregates optional	• Unknown
OPC	• Limestone • Clay/shale • Water	• (rare) • (ubiquitous) • (found as ice)	• Extensive history of terrestrial applications	• High energy • Rare resources required
AAC	• Mine tailings or slag • Water	• (waste product) • (found as ice)	• Extensive history of terrestrial applications • Low energy • Recycled product	• Resources not immediately available • Slow set, harden
GC	• Clay • Optional: amorphous silica • Alkali catalyst • Water	• (ubiquitous) • (local) • (requires synthesis) • (found as ice)	• Compatible with available resources • Low to moderate energy	• Limited knowledge base from terrestrial applications • Slow set, harden
MSBB	• Olivine • Amorphous silica • Water	• (ubiquitous) • (local) • (found as ice)	• Moderate energy • H₂ by-product of synthesis	• Location-limited by resource availability • Limited knowledge base from terrestrial applications • Slow set, harden • High-waste process
ES	• Ferric sulfate or other source of S	• (ubiquitous)	• Compatible with available resources • No water required for casting (however, required for production of H_2 for synthesis)	• High energy • High-waste process • Limited knowledge base from terrestrial applications

Table 1 *(continued)*

Binder	Raw materials	(availability)	Advantages	Disadvantages
Water (as ice)	• Water	• (found as ice)	• Fast set, harden • Compatible with available resources • Very low energy • Good workability • Fast set, harden • Aggregates optional	• Sensitive to melting or sublimation

[a] Nominal reactions are illustrative and idealized. Stoichiometric coefficients for OPC are approximate. The arbitrary stoichiometric coefficients α and β were used for MSBB, as their value is currently unknown.

pores of gypsum elements would be completely desiccated or frozen, thereby vastly expanding the potential applications of PoP concrete. Overall, PoP appears to be particularly well-suited as a binder for Mars.

2.2. Ordinary Portland cement

OPC is a hydraulic binder produced by the inter-grinding of limestone ($CaCO_3$) with Si-rich clay or shale, and firing at temperatures of approximately 1450 °C [18]. OPC is the most commonly-used terrestrial binder, notably due to its high strength and durability to water. The use of OPC as a binder on Mars has previously been proposed [3–6,12,13]. While it has been suggested that Mars may contain reserves of $CaCO_3$ [7], known sources are rare and impure. The Shergotty-Nakhla-Chassigny meteorites, which are thought to be of Martian origin, exhibit a minor content of carbonates (~1% by volume), with Mg and Fe predominating over Ca as counter-cations [23]. Observations by terrestrial telescopes, the Phoenix Lander, and the Spirit Rover (Fig. 4) have identified the presence of $CaCO_3$ at very low concentrations, which would not be adequate for OPC production. Given the shortage of the requisite raw materials and the intense energy demands, OPC would not be a good binder for use on Mars.

2.3. Alkali-activated cement

AAC is a binder made by the combination of soluble silica or aluminosilicate phases (ASPs), a Ca source, and an alkali activator (e.g., $Ca(OH)_2$, NaOH, or KOH) in the presence of water [14], and has been previously suggested as a binder for Mars [5,6]. AACs were essentially the binder that was used in the production of ancient Roman concrete [6,25], where volcanic soil contributed ASPs, and lime functioned as both a Ca source and alkali activator. In modern AAC, waste products from the mineral, metallurgical, or energy sectors are used as raw materials. For example, ground granulated blast furnace slag (GGBFS) or fly ash may be used as sources of one or more of silica, ASPs, or Ca [14].

While still energy-intensive, the production of AAC would require significantly less energy than OPC, both because of the lower firing temperature (e.g., 1200 °C if $Ca(OH)_2$ from a $CaCO_3$ precursor is used as a Ca source and alkali [18]), and because the silica or ASPs are not calcined. Sources of soluble silica (Fig. 3c) and ASPs such as Al smectite clay (Fig. 3d) are known to occur on Mars (Fig. 4). However, the known availability of $CaCO_3$ on Mars is poor (Fig. 4), and this makes AAC an unsuitable binder for construction in the early stages of colonization. AAC may become a viable construction material during later stages of Mars colonization, as the planet is explored for minerals (e.g., production of iron metal), thereby creating mine tailings, slag, or comparable waste products that could be used for AAC production in a similar manner to what is done on Earth.

2.4. Geopolymer cement

GC is made by the combination of soluble ASPs (e.g., fly ash, GGBFS, or calcined clays) with an aqueous solution of alkali silicate (generally produced by reaction of silica or an ASP with NaOH or KOH), and has been researched as a potential substitute for OPC in terrestrial applications [15]. The binding reaction consists of the rearrangement of the solid structure of the ASP(s) into a cross-linked polymer matrix, and is generally catalyzed by the addition of an alkali solution (e.g., NaOH or KOH) [15].

From an energy and resource perspective, GC would be greatly advantageous over OPC or AAC, because it requires little or no calcining of the raw ingredients, and does not require Ca. Al phyllosilicates such as smectite (Fig. 3d) are common on Mars [26–28], and could be used as ASPs. Calcining (presumably in the range of 500–700 °C [29]) may be advantageous, in order to facilitate their reactivity. Amorphous silica (Fig. 3c), which could be used without calcining for the production of alkali silicates, has been identified by the Spirit and Curiosity Rovers (Fig. 4). The synthesis of NaOH or KOH on Mars may prove challenging, and alternative formulations of alkali should be considered. At any rate, only minor quantities of alkali would be required (on the order of 10% of the mass of binder [29], corresponding to ~2% of the total mass of concrete).
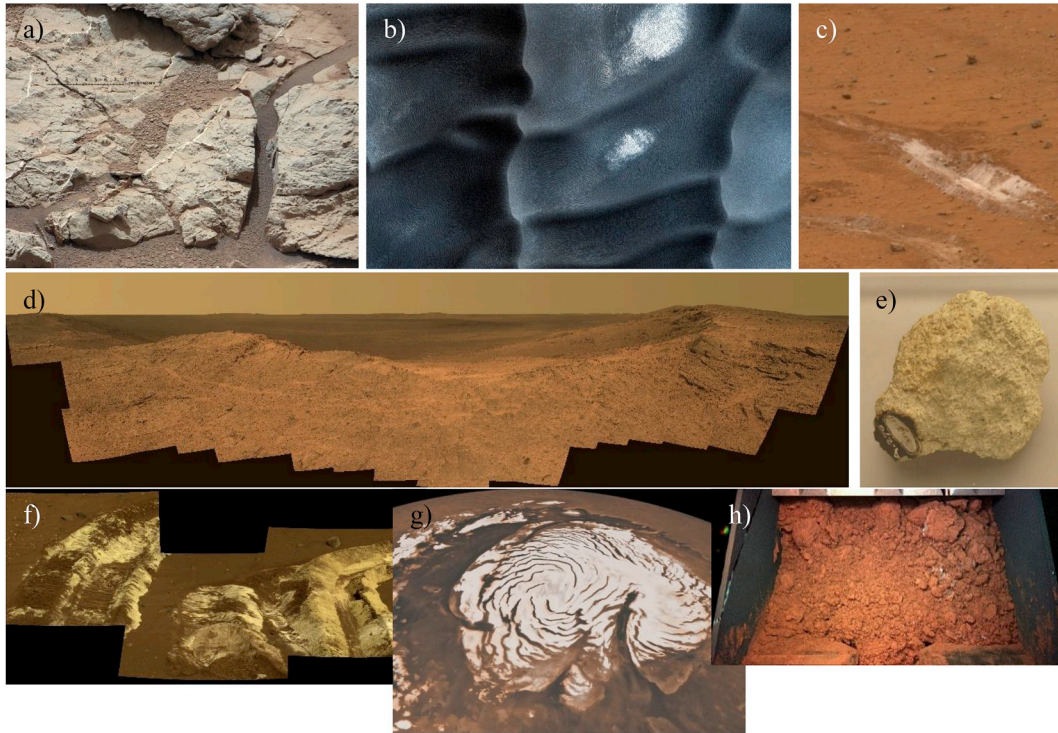
Fig. 3. Potential raw resources for the production of concrete on the Martian surface (images Courtesy NASA/JPL-Caltech unless otherwise noted): a) bassanite or gypsum in Gale Crater, b) aerial view of gypsum dunes in Olympia Undae near the North Pole, c) opal (i.e., amorphous silica, seen as a white streak) uncovered in Gusev Crater by Spirit Rover under a superficial layer of red aeolian soil, d) the rim of Endeavor Crater, which is rich in Al smectite clay, e) the Chassigny meteorite (of Martian origin), which consists primarily of olivine [24], f) ferric sulfate (seen as light-colored streaks) uncovered in Gusev Crater by Spirit Rover under a superficial layer of red aeolian soil, g) aerial view of the North Polar Ice Cap, which is the planet's most abundant source of water (as ice), and h) regolith in the scoop of the Phoenix Lander. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.5. Mg- and Si-based binder

MSBB is a novel binder that has been proposed specifically for use in Martian construction [30], based on previous observations of the hydraulic binding reaction of magnesia and silica [31]. MSBB would be synthesized by the reaction of Mg-based olivine (Mg_2SiO_4) with water at 20–50 °C (Table 1). Out of the total mass of reactants, 68% is wasted as

serpentine ($Mg_2Si_2O_5(OH)_4$), 31% is recovered as magnesium hydroxide ($Mg(OH)_2$, which is calcined at 300–450 °C to make MgO binder), and < 1% is recovered as hydrogen gas (H_2), which could be used as fuel. The MgO would be combined with amorphous silica and water in order to form the binding phase magnesium silicate hydrate ($(MgO)_\alpha SiO_2(H_2O)_\beta$), where the stoichiometric coefficients α and β are presently unknown. The weeks-to months-long setting and hardening process is similar to that of
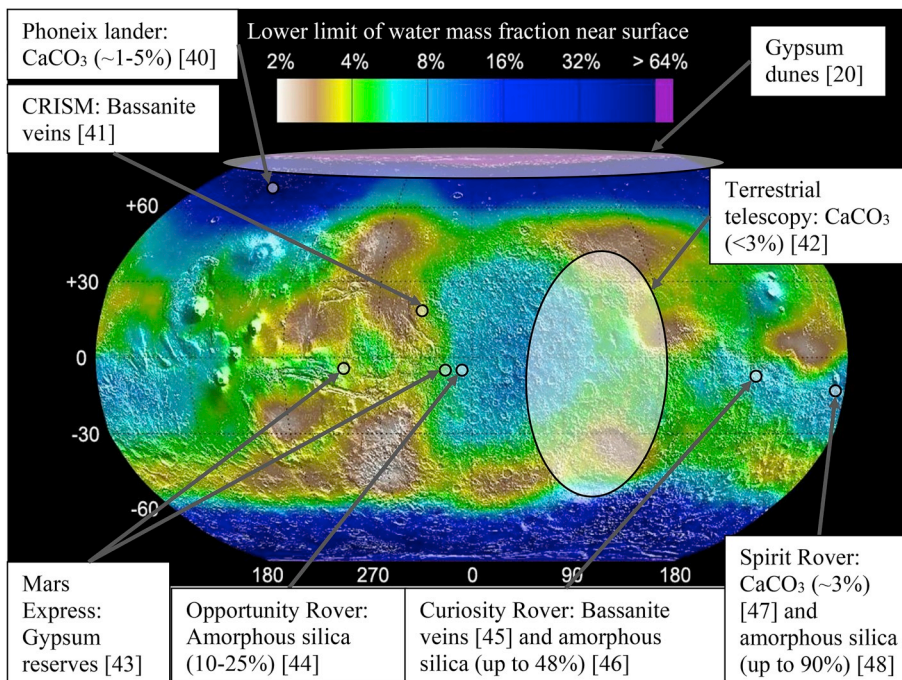
Fig. 4. Selected observations of resources for binder production (bassanite or gypsum for PoP; $CaCO_3$ of any mineralogy for OPC or AAC; amorphous silica for AAC, GC, or MSBB), over a map (courtesy of [39]) of water availability on the Martian near-surface. All %s shown by mass. Ubiquitous raw materials (e.g., olivine and clays) not shown [40–48].

AAC, with Mg substituting for Ca. An alternative synthesis of MgO from $MgCO_3$ is described [30], though this would be a less likely approach, because $MgCO_3$ is rare on the Martian surface [22].

Although MSBB forms a comparatively weak concrete, the use of a Mg-based, rather than Ca-based, binder clearly fits well with the composition of the Martian near-surface, where olivine (Fig. 3e) is ubiquitous [30,32,33], and amorphous silica has been identified (Figs. 3c–4). However, the production of MSBB would be fairly energy-intensive, and would recover only a small fraction of the ore as binder. Moreover, it must be noted that olivine on Mars is not ordinarily found purely as Mg_2SiO_4, but rather with Fe substituting for some of the Mg in the crystal lattice (e.g., $Mg_{1.24}Fe_{0.76}SiO_4$ [32]), and it is not yet clear what effect this will have on the synthesis of $Mg(OH)_2$. MSBB is a novel and unique technology, and may evolve substantially with additional research.

2.6. Elemental sulfur

ES has been examined as a potential binder for Martian concrete [9–12], and would be produced from sulfate minerals, which are common on the Martian surface (e.g., ferric sulfate, $Fe_2(SO_4)_3$, shown in Fig. 3f) [10,33,34]. Table 1 illustrates synthesis by the pyrolysis of ferric sulfate at ~900 °C [35,36], followed by catalytic reduction of the evolved sulfur dioxide gas (SO_2) [37]. In this process, the synthesis of 1 kg of ore requires 22.5 g of H_2, and 105 g of CO, which could be synthesized on Mars from water and CO_2, respectively [3]. The beneficial products of this reaction would be 240 g of ES, 203 g of water, and 120 g of O_2. Waste products would consist of 400 g of Fe_2O_3 (solid) and 165 g of CO_2 (gas). The water and CO_2 could be recycled to regenerate the H_2 and CO reagents.

In order to use ES as a binder, it would be combined with aggregates, melted at > 120 °C and cast [10]. Upon cooling, the mix sets and hardens rapidly into a solid matrix, which can be repaired by localized heating, or recycled by heating and recasting.

ES is an attractive binder for construction on Mars, because it makes use of commonly-found resources, and is unique in that it does not require any water for mixing and casting. From terrestrial applications, it is already known that ES concrete exhibits desirable mechanical and chemical properties.

The most challenging aspect of using ES as a binder appears to be its synthesis. Wan et al., 2016 [10] have suggested the possibility that sulfur may be found in elemental form on or near the Martian surface. If, indeed, large and accessible sulfur reserves are found, then the production of ES would be a low-energy enterprise, and its viability as a Martian binder would be near-certain. However, no such reserves have been found to date, nor are there any indications that they exist near the surface [12]. Based on the profile of known S-containing species near the Martian surface, the energy demands and high waste involved in synthesis appear to be prohibitive against the use of ES.

2.7. Water

In the extremely cold conditions of the Martian surface, it is possible to use water as a binder by casting it in liquid form into a set of molds (with or without aggregate) and allowing it to freeze into ice concrete. Compared to other binders, the use of water would be simple and very low-energy, and the hardening process would be rapid (on the order of minutes to hours). Due to its low viscosity compared to pastes made from the other binders, water would be highly workable. Ice concrete could easily be repaired or recycled by heating and re-freezing.

This material would only be suitable for elements expected to be permanently frozen (e.g., subterranean or near-polar construction), and preferably for those elements whose temperature will never exceed −22 °C (below this temperature, water remains frozen regardless of pressure [38]). Elements constructed in an environment that periodically experiences above-freezing temperatures (i.e., near-equatorial and superterranean), could be prevented from thawing by the addition of thermal mass, such as by mounding regolith over the structure. The external walls, floors, and roofs of climate-controlled structures would require robust insulation on their internal faces in order to prevent thawing. Internal elements (e.g., as shown in Fig. 1) would not be suitable for ice concrete, as they could not feasibly be prevented from thawing. Ice concrete would be potentially vulnerable to sublimation (i.e., transition of water directly from ice to vapor) at any interface with the atmosphere, and may therefore need to be coated or covered.

3. Availability of water

Water is a basic need for all facets of Mars colonization, including the production of concrete. Liquid water is not thermodynamically stable on or near the surface, but might occur and be recoverable from the sub-surface, or could be produced by melting ice [3]. There are substantial and common-place reserves (Fig. 4) of superficial or near-surface ice at latitudes > 50° N or S, particularly near the poles (Fig. 3g). Closer to the equator, ice reserves are more localized and less plentiful, though still known to occur [49]. If it is necessary to produce water where ice or a liquid aquifer cannot be practically accessed, water may be condensed from atmospheric humidity [3].

4. Energy sources

Like water, energy production will be key to many human enterprises on Mars, including concrete production. In fact, Meyer and McKay 1989 [50] suggested that, "Energy sources to power base activities may well be the limiting resource on Mars." Since the Martian surface lacks for both fuel and oxygen, combustion-based energy production would not generally be scalable. Therefore, it has been proposed that energy should be produced from wind, solar, or nuclear sources [3,50]. These could suitably be used to produce electricity for mining, milling, conveyance, etc. Electric heating or focused solar energy could feasibly be used to melt ice (~0 °C), to calcine gypsum for PoP (~150 °C), or perhaps even for somewhat high-temperature binder syntheses (see Table 1 for more details). Still, it is difficult to envision a scalable way to sustain temperatures on the order of 1000 °C, as required to synthesize OPC, $Ca(OH)_2$ (if used for AAC), or ES.

5. Aggregates

Martian regolith (Fig. 3h) would presumably be used as a natural aggregate. The appropriate combination of fine aggregate (FA, defined as having a maximum particle size ≤ 4.75 mm) and coarse aggregate (CA, defined as having a maximum particle size > 4.75) is important for balancing properties such as the workability of the mix and its cost (via the content of binder) [51]. Martian regolith is found in a variety of sizes, and can provide both FA and CA comparable to those on Earth [10,30]. The mechanical properties of regolith are known to be suitable for aggregate, and a simulant of it has been successfully used on Earth for the manufacture of concrete using MSBB [30] and ES [10].

However, the regolith presents new challenges in terms of potential reactivity between aggregates and binder. Salts in the regolith [9,50] may affect the reactivity of binders (e.g., by accelerating or retarding setting and hardening [52]). Depending on the application and circumstances, such effects may be desirable or undesirable. In terrestrial applications (i.e., predominantly OPC as binder) the effects of salts on hydration is usually tested on a case-by-case basis, or estimated based on experience with the particular materials at hand, because the complicated chemistry of fresh concrete makes these difficult to predict in advance. In Martian applications, aggregates with non-negligible salt content should ideally be avoided. If salt-free aggregates cannot be readily found or produced (e.g., by washing), then the effects of salts on the hydration of binders should be tested ad hoc prior to on-site construction.

In the chemical environment of OPC and similar binders (e.g., AAC, GC, and MSBB), aggregates containing pyrite [53], clays [54], or glassy silica [55] are potentially reactive on the time scale of months to years. Wan et al., 2016 [10] observed reaction between ES and Martian regolith simulant, which appeared to consist of the formation of sulfates and polysulfates. These binder-aggregate combinations should be approached with caution, because the reaction of aggregates can

compromise the interface with the binding phase [15,56], and furthermore can cause deleterious internal volumetric changes and stresses [53,55].

6. Handling and properties of fresh concrete

6.1. Mixing and casting

Due to the temperature and pressure conditions of the Martian surface, fresh concrete made with water (i.e., using PoP, OPC, AAC, GC, MSBB, or water as binder) would boil until freezing if directly exposed to the atmosphere [22]. Accordingly, concrete made using these binders will have to be mixed, transported, cast, and compacted in either a pressure-controlled or sealed environment. Molten ES *would be* thermodynamically stable in ambient pressure [10], and therefore could be produced without environmental containment or pressurization.

The low Martian gravity (about 0.38G [16]) may make the casting and consolidation of concrete more difficult. On the other hand, cohesiveness may be improved, as the strong gravity of Earth causes fresh concrete to segregate via the settlement of large aggregates and the bleeding of water and fine particles [57].

6.2. Air content

Air content is an important property of fresh concrete which would be strongly affected by conditions on Mars. Typically, air in the form of fine bubbles is entrapped into terrestrial concrete during mixing to the tune of 0.2–3% of the total volume [51]. The air content must be carefully balanced, as it produces a combination of beneficial and undesirable effects: entrained air bubbles enhance the workability of fresh concrete and increase the durability of the hardened concrete to freeze-thaw cycles, but reduce the strength and other mechanical properties [58]. Generally, compaction by means such as vibration or vacuum [59] is used to induce large bubbles and pockets of air to the surface, where they break and are released into the atmosphere.

The environmental conditions of Mars would cause entrapped air (or, more strictly speaking, entrapped atmospheric gas) to behave differently from Earth. Supposing that a bubble with a volume V_0 (m^3) is entrapped in fresh concrete, near the surface (i.e., at depth $d \approx 0$ m). Then, as the bubble is transported to an arbitrary depth d (e.g., due to casting into formwork), the volume of the bubble will decrease due to the effect of hydrostatic pressure. Assuming that the gas behaves ideally, then the volume and buoyant force acting on the bubble is given by (1)–(4).

$$\frac{V_d}{V_0} = \frac{P_0}{P_d} \tag{1}$$

$$P_d = P_0 + d\rho_c g \tag{2}$$

$$\frac{V_d}{V_0} = \frac{P_0}{P_0 + d\rho_c g} \tag{3}$$

$$F_d = V_d \rho g = V_0 \frac{P_0}{P_0 + d\rho_c g} \rho_c g \tag{4}$$

where.

V_d = volume of the bubble at depth d (m^3),
P_0 = pressure at the surface of the concrete (i.e., atmospheric pressure: 1.013×10^6 Pa on Earth; 600 Pa on Mars),
P_d = pressure at depth d (Pa),
ρ_c = density of concrete (typically on the order of 2400 kg/m^3 [51]),
g = gravitational acceleration (9.81 m/s^2 on Earth; 3.71 m/s^2 on Mars),
F_d = buoyancy force acting on the bubble at depth d (N).

Per Fig. 5a, the size of air bubbles in terrestrial concrete is fairly insensitive to their depth. However, on Mars bubbles would shrink noticeably with depth (thereby reducing the volumetric content of air), as the hydrostatic pressure of the concrete ($d\rho_c g$) strongly predominates over the low pressure of the Martian atmosphere (P_0) in (2). This volumetric air content would be close to zero (a reduction of > 80%) at depths > 30 cm, so that consolidation may not be required at these depths (e.g., for most foundations, columns, and deep beams).

Per Fig. 5b, the buoyant force acting on bubbles near the surface of concrete on Mars would be about one-third that on Earth. Furthermore, due to the aforementioned shrinkage of bubbles (Fig. 5a), the buoyant force would decrease rapidly with depth. Therefore, terrestrial buoyancy-based consolidation methods (i.e., various forms of vibration [59]) would be generally ineffective at evacuating small bubbles. If higher-than-terrestrial air contents are deemed to be problematic, new methods for design and control of air content will need to be developed.

6.3. Curing

The temperature of the Martian surface averages $-63\,°C$ [16], but varies with time and location. Spirit and Opportunity experienced temperatures generally in the range of $-80\,°C$-20 °C each sol (Martian day) [60]. The low temperatures would be advantageous for concrete made using ES [10] or water as binder, as these harden by cooling. In the case of PoP [18], whose hydration is quick and exothermic, cold temperatures would not be a significant obstacle. However, for OPC [4], AAC [14], GC [15], and MSBB [30], hardening requires weeks or months, during which the material must be maintained in a humid condition and circa terrestrial room temperature. Existing technologies for casting in cold climates include the pre-heating of concrete components, insulation, supplementary heating, and the use of set-accelerating admixtures [61], and these technologies would be viable on Mars.

Ensuring the presence of liquid water for an extended period of time in the cold, dry Martian conditions would place significant technical complications on concrete work. Fundamentally, curing requires one of two approaches: water curing (i.e., exposing concrete surfaces to wet or humid conditions, such as by ponding or irrigation), or sealed curing (i.e., preventing the loss of mix water by sealing the surfaces with moisture barriers) [62]. Water curing would not be practical in the thin Martian atmosphere, so that barriers will be crucial to maintain the moisture of elements until curing is substantially complete. Still, moisture in external concrete elements would not and could not be indefinitely maintained. Given that barriers are imperfect and that they may be deliberately removed (e.g., the retrieval of formwork for future use), the pressure differential between the porewater vapor and the atmosphere would eventually drive a complete desiccation of any unfrozen water in the pores. This is not problematic, so long as the element is given sufficient time and adequate conditions for a satisfactory degree of hydration.

7. Structural and habitability requirements

7.1. Static loads

Structures must bear static loads, which are primarily gravitational in nature (e.g., structure self-weight, weight of furniture/equipment, loads from dust/ice deposited during weather events). Due to the weak Martian gravity, comparable objects would exert a load 62% smaller than on Earth. This could open possibilities for using weaker concrete mixes than are normally used on Earth (e.g., using PoP, MSBB, ES, or water as binders, which tend to be weaker than comparable OPC-based formulations), for constructing smaller elements, and/or for using fewer elements in a comparable structure. Such a savings in the number and/or size of elements would further reduce structural self-weight.

Unlike Earth, any structure that is designed for human occupation on Mars will be stressed by an aerostatic pressure differential on the order of 1 atm between the pressurized interior and the thin surrounding atmosphere. Thus, structures would need to be able to handle substantial flexural loads, or alternatively this pressure differential

could be counter-balanced by underground construction or mounding of regolith over structures (Fig. 1). The thickness that has been proposed for such a pressure-balancing layer has varied on the range of 2–11 m [6,63], depending on assumptions related to pressurization and the degree of regolith compaction.

7.2. Transient loads

Wind and seismic loads are minor on Mars [4], and could be accommodated using much lighter and weaker construction than is used on Earth. Similarly, transient gravitational loads (e.g., weight of occupants and mobile equipment) would be lower.

A unique type of transient load that has been suggested for construction on Mars has been micrometeoric impact (Fig. 1) [4,13], given that the thin Martian atmosphere is much less effective than Earth's at burning up micrometeorites [64]. Let us therefore consider the likelihood and consequences of micrometeoric impact.

Likelihood of micrometeoric impact: Flynn 1990 [65] estimated a frequency of 10^4 impacts $m^{-2}yr^{-1}$ by micrometeorites on size range 10^0–10^3 μm, with the dependence on size shown in Fig. 6. For all intents and purposes, micrometeroic impact on structures is therefore a certainty (and a frequent one).

Consequences of micrometeoric impact: The model of Chen and Li 2002 [66] (5)–(7), which was developed for projectile impacts on concrete, can be used for a first-order estimate of the destructive power of micrometeorites.

$$I = \frac{Mv^2}{l^3 f_c A N_1} \tag{5}$$

$$A = 72 f_c^{-0.5} \tag{6}$$

$$X = \frac{1}{2} lI \tag{7}$$

where.

- M = mass of micrometeorite (kg),
- v = impact velocity of micrometeorite (m/s),
- l = dimension of the micrometeorite (m),
- f_c = compressive strength of concrete (MPa),
- N_1 = nondimensional shape constant for micrometeorite,
- X = penetration depth of impact into concrete (m).

Assuming f_c = 40 MPa, a spherical micrometeorite (N_1 = 1.16) [66], a micrometeorite density of 1 g/cm³ [65], and an upper bound for v of 1 km/s [65], the penetration depth X of a particle would be roughly one-half its diameter l. Even supposing a large micrometeorite (l = 4 × 10³ μm), whose probability of impact is extremely small (on the order of 10^{-5} particles $m^{-2}yr^{-1}$), the consequences would be the spalling of concrete on the order of 2 mm, which would not substantially affect structure serviceability. Therefore, it appears that concrete would be a good

choice of material to protect from micrometeoric loads. If, per 10.1 and per previous proposals [3,50,63], concrete structures would be covered with regolith (illustrated in Fig. 1), then the concrete could be protected even from spalling due to micrometeorite impact.

7.3. Temperature

The generally-cold and highly-variant temperature conditions of Mars have been noted in 9.3. Concrete is a highly thermally-conductive material (with a thermal conductivity on the order of 1–2 W/mK if conventional concrete is used [67]), and is potentially sensitive to freeze-thaw cycling [68], which occurs almost daily in the near-equatorial regions [60]. On Earth, common approaches to reducing the thermal conductivity of concrete is the use of highly porous aggregates or the entrainment of air [67]. Natural (e.g., pumice or vermiculite) or artificial (e.g., polystyrene foam or expanded perlite) aggregates that are used for this purpose do not appear to be compatible with the raw materials and energy resources available on Mars, and the entrainment of air would not be a feasible approach due to the low atmospheric pressure (see 9.2). Therefore, insulation of structures by modifying the properties of the concrete itself would not be a viable approach, and one or more distinct insulation layers should be provided.

One approach to insulation could be by the mounding of native regolith or by subterranean construction, which has already been suggested above for other reasons and is illustrated in Fig. 1. Supposing the thermal conductivity of Martian regolith is comparable to that of terrestrial sand (on the order of 0.15–0.27 W/mK [69]), regolith as an insulator would be more efficient than concrete by approximately an order of magnitude. This approach would also provide a great thermal inertia, which would moderate the effects of temperature fluctuations.

Let us estimate the insulating effects of the regolith to the first order using steady-state heat flow (8)[67].

$$q = K \frac{\Delta T}{\Delta x} \tag{8}$$

where.

- q = heat flux (W/m²),
- K = thermal conductivity (W/mK),
- ΔT = temperature differential between environment and interior (K),
- Δx = thickness of medium (m).

Consider a 0.2 m thick exterior concrete wall (suppose thermal conductivity of 1.5 W/mK), enclosing a temperature-controlled (20 °C) space, with a static outside temperature of −63 °C. The wall conducts 620 W/m² of heat out to the environment. If a 10 m (per 10.4) thick layer of regolith (suppose thermal conductivity of 0.2 W/mK) is used, then the heat flux would be reduced to 1.7 W/m². Thus, the temperature control for 60 m² of wall area (perhaps a large room) would require about as much energy as a single incandescent light bulb. If it is still desirable to provide additional insulation, then a non-structural insulation layer (e.g., of mineral wool [67]) may be used, as illustrated in Fig. 1.
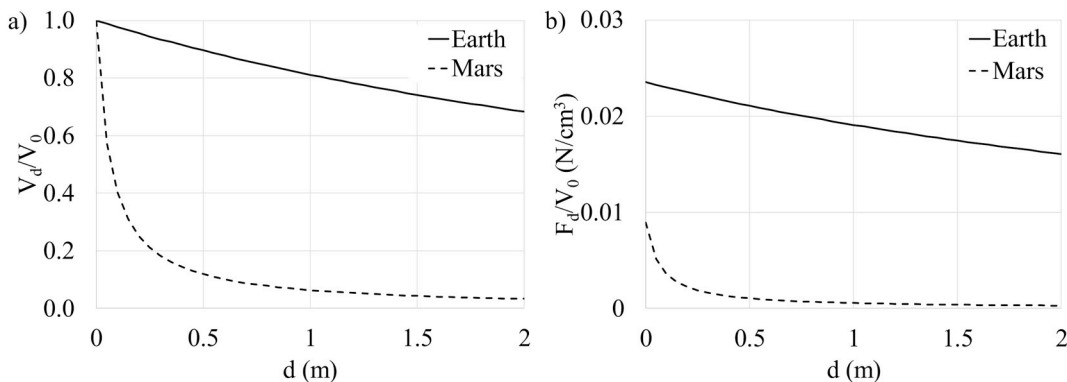

Fig. 5. The effects of depth d in fresh concrete on (a) the volume of a bubble (V_d), and (b) the buoyancy force acting on the bubble (F_d), normalized to the bubble's volume at the surface (V_0).

7.4. Radiation

Due to its thin atmosphere and the absence of a magnetosphere, Mars experiences much greater solar and cosmic radiation than Earth. Solar radiation varies greatly based on solar events, and may produce particles with energies of $< 1.5 \times 10^8$ eV, which cannot penetrate the Martian atmosphere, or particles with greater energies, which reach the Martian surface [70]. In either case, solar radiation may generate secondary neutron radiation, which would impact the surface [70]. Cosmic radiation on the planet's surface exhibits per-nucleus energies from 10^7 eV to $> 10^{10}$ eV, and consists of 85–90% protons, 10–13% helium ions, ~1% electrons, and ~1% heavier nuclei [70]. The dose rate of cosmic radiation (180–225 μGy/day) [70] would not be expected to be dangerous to the durability of concrete [71,72], but could pose hazards to human health [3,7].

Stoker and Emmart 1996 [7] suggested that ~6 m of Martian regolith should be piled over structures to provide comparable protection to the Earth's atmosphere. The Bethe formula (9)-(13) can be used per [73] for a more rigorous estimate of the required thickness of shielding materials against protons, as the predominant form of cosmic radiation on the surface of Mars. Per Fig. 7, the stopping distance against protons (i.e., the depth of the material required to achieve a particle energy of $E = 0$) is comparable for regolith and for all potential binders (in their hardened form), except for water. In order to protect inhabitants from radiation at energy up to 10 GeV, approximately 7–10 m of material (20 m in the case of ice) would be required (Fig. 7a). The construction of such large concrete elements would be cost-prohibitive and impractical, and this suggests that regolith should be used as the primary material for radiation shielding. This again indicates the advantage of subterranean construction or mounding of native regolith onto structures.

$$\frac{dE}{dx} = -\frac{4\pi}{m_e c^2} \frac{nz^2}{\beta} \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \left\{ ln\left[\frac{2m_e c^2 \beta^2}{I(1-\beta^2)}\right] - \beta^2 \right\} \tag{9}$$

$$E(x) = \int_0^x \frac{dE}{dx} dx \tag{10}$$

$$\beta = \frac{v}{c} = \sqrt{1 - \frac{1}{\left(1 + \frac{E}{m_p}\right)^2}} \tag{11}$$

$$n = \sum_{i=1}^k \frac{f_i N_A Z_i \rho}{A_i M_U} \tag{12}$$

$$I = \sum_{i=1}^k I_i f_i \tag{13}$$

where.

- E = energy of the particle (eV),
- x = distance traveled by particle into medium (m),
- m_e = mass of electron (9.109×10^{-31} kg),
- c = speed of light (299,792,458 m/s),
- z = particle charge (+1 for proton),
- e = elementary charge (1.602×10^{-19} C),
- ε_0 = permittivity of free space (8.854×10^{-12} F/m),
- I = excitation energy of the medium (eV),
- v = velocity of radiation (m/s),
- m_p = energy-equivalent mass of proton (9.38×10^8 eV),
- k = number of elements nominally used to describe material composition,
- f_i = mass fraction of element i (per Table 2),
- N_A = Avogadro's number (6.022×10^{23} mol^{-1}),
- Z_i = atomic number of element i,
- ρ = bulk density of material (kg/m^3),
- A_i = relative atomic mass of element i,
- M_U = molar mass constant (1 g/mol),
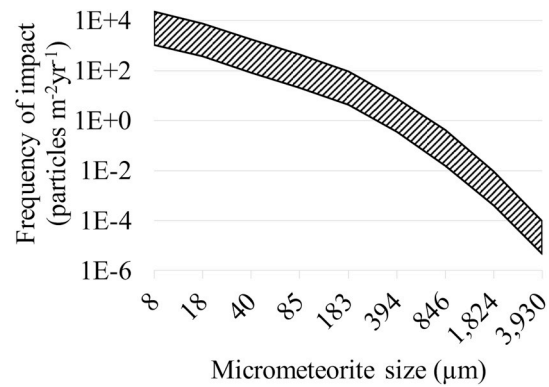- I_i = excitation energy of element i (eV).

Fig. 6. Frequency band for impact of micrometeorites by size estimated by Ref. [65].

8. Durability

8.1. Mass transfer and freeze-thaw

On Earth, the predominating weathering mechanisms for concrete made using OPC or comparable materials (e.g., AAC or GC) consist of reactive mass transfer phenomena, notably oxidation of the steel reinforcement, chloride attack, carbonation, sulfate attack, acid attack, leaching, and alkali-aggregate reactions [15]. Specifically, the weathering mechanism of carbonation has been suggested [4,5] as particularly important on Mars, because the partial pressure of CO_2 there is about 5X greater than on Earth [16]. However, carbonation and other mass transfer phenomena require the presence of some liquid porewater, which is typical in terrestrial concrete. Freeze-thaw cycling, though it is not a mass-transfer phenomenon, is likewise only damaging if liquid porewater is present [68]. Many (not all) of these or comparable phenomena could affect concrete made using PoP, MSBB, ES, or water as binder. Since water in the pores of Martian concrete would be expected to completely evaporate or freeze (see 9.3), the durability of concrete to all of these weathering mechanisms would be functionally indefinite.

8.2. Deliquescence and imbibition

Highly deliquescent salts (i.e., salts which tend to draw moisture from the atmosphere into a concentrated brine) such as calcium perchlorate ($Ca(ClO_4)_2$) and magnesium sulfate ($MgSO_4$) are known to occur on the surface of Mars [9,79]. These present a unique durability challenge for concrete. If a grain of salt is carried (such as by the wind) onto the face of a concrete element, the brine produced by its deliquescence (Fig. 1) could be imbibed by the concrete's capillary pores [79]. Unlike pure water,

Table 2
Nominal bulk density and composition of regolith and binders (in hardened form) with associated values of I_i.

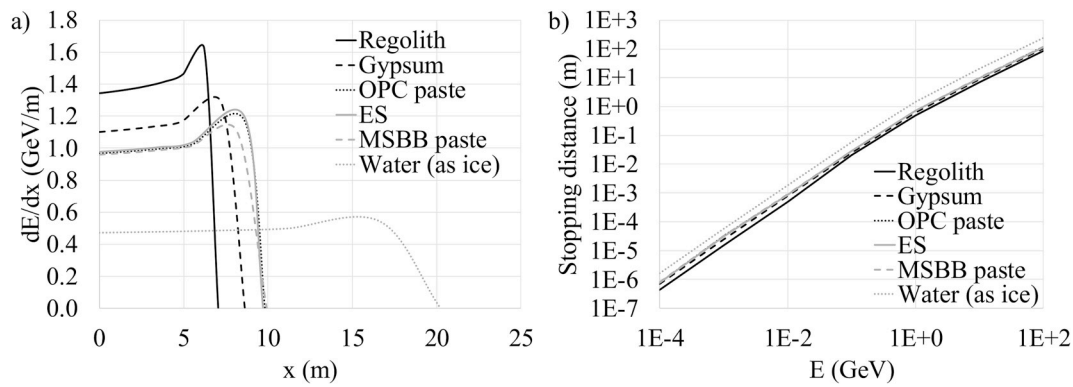|	Regolith	Gypsum	OPC paste	ES	MSBB paste	Water (as ice)	I_i (eV)
Source	[74]	[75]	[76]	[77]	[30]	[78]	[73]
ρ (g/cm^3)	1.6	2.3	2.0	2.1	2.0	0.92	
f_i (%)							
H		2	3		3	11	19.2
O	50	56	52		60	89	95.0
Na	2		0.2				149
Mg	2		0.9		17		156
Al	11		2				166
Si	18		7		20		173
P	0.3						173
S		19	0.5	100			180
K	0.5		0.5				190
Ca	4	23	33				191
Ti	2		0.1				233
Mn	0.2						272
Fe	10		2				286

Fig. 7. For a proton passing through a structural medium consisting of regolith or binder (in hardened form), a) the energy loss profile given E = 10 GeV, and b) the stopping distance for variable E. Note that OPC paste is compositionally comparable to AAC paste and GC paste, and therefore the latter two were not shown.

these brines are thermodynamically stable as liquids on the Martian surface, and could therefore facilitate deleterious reactive mass transfer phenomena (see 11.1). These brines are sometimes inherently reactive with one or more components of the concrete, and may generate damaging chemical reactions such as sulfate attack [80]. Additionally, cycles of deliquescence and subsequent drying could lead to the gradual accumulation of salts within the pore network, causing potentially harmful internal volumetric changes [81]. In the case of ice concrete, such salts could cause melting due to freezing point depression.

The afore-proposed underground construction or mounding with native regolith may help to protect concrete from the weathering effects of deliquescence. However, some concrete surfaces will inevitably be exposed to the environment (Fig. 1), and for these an impermeable and chemically durable coating or paint is advised.

9. Terrestrial simulation of Martian concrete

In order to maximize the preparedness of Martian missions, any concrete formulation intended for use there would first be produced and characterized on Earth. Terrestrial simulants exist for all materials that may need to be used on Mars, including regolith [74]. In order to study binder-based materials in pressures, atmospheric composition, and temperature cycles representative of those found on Mars, a likely approach would be mechanized handling of the materials in a sealed chamber with atmospheric control. Naturally, this or comparable approaches introduce great complexity and cost, but will be necessary in laying the groundwork for successful construction efforts on the Red Planet.

One particularly difficult environmental condition to replicate is low gravity. Experiments on cement hydration in microgravity have previously been conducted in aircraft by the use of a parabolic flight sequence [82]. A similar approach could be used to simulate Martian conditions for the mixing and handling of cement products. However, this approach can only maintain microgravity for less than a minute at a time, so that curing and long-term performance cannot be feasibly examined. Another approach may be casting and analyzing materials in near-Earth Space, such as aboard the International Space Station, where the effective gravity is zero.

10. Conclusion

A number of binders, methods, and construction styles were considered for the Martian environment. For structures or elements which are permanently subjected to freezing conditions, water (cast into formwork and allowed to freeze) would constitute a highly efficient and appropriate binder. For elements periodically or permanently exposed to temperatures > -22 °C, PoP (produced from native bassanite or gypsum) would be the best fit from known binders, due to the high availability of the requisite raw materials, as well as the relative simplicity and the low energy requirements for production. Depending on local resources and exposure conditions, the use of AAC, GC, MSBB, or ES as binders may also be appropriate in certain cases. Although OPC

has previously been suggested as a binder for Mars colonization, its production would be prohibitively resource- and energy-intensive.

Specialized technologies will be required for the handling of fresh concrete in the low-gravity, low-pressure, low-temperature Martian environment. Slow-hardening binders (e.g., AAC, GC, and MSBB) would be particularly challenging for application in these conditions.

Concrete would certainly be a good construction material for supporting the gravitational, wind, seismic, and micrometeoric loads of Mars. However, exposed concrete (and especially ice concrete) might be vulnerable to temperature swings and the effects of wind-carried deliquescent salts, and moreover would not be cost-effective for protection from radiation and weather conditions. A 7–10 m layer of native regolith would be a good medium (e.g., by subterranean construction or mounding) for insulating structures and their inhabitants from these hazards of the Martian environments, as well as for counter-balancing aerostatic stresses in concrete elements.

On the Martian surface, liquid water is not thermodynamically stable, so that the porewater in concrete would eventually completely desiccate or freeze. Therefore, the durability of concrete, especially to mass transfer phenomena, would be expected to be much greater than on Earth. Additionally, the dry conditions would enable the use of a wider variety of materials in a greater number of applications (such as exterior or structural use of gypsum concrete from PoP, and especially the reinforcement of gypsum with steel rebar).

Mars colonization represents an exciting combination of challenges and opportunities for the development of construction materials. As additional information is discovered by exploration of the planet, solutions can be better honed for design of materials and methods. Concrete as we have known it on Earth would not be viable there. Still, if concrete is appropriately adapted to meet the unique demands of the Martian environment, it would appear to be an excellent choice of material for construction on the Red Planet.

References

[1] J. Mustard, M. Adler, A. Allwood, D. Bass, D. Beaty, J. Bell, W. Brinckerhoff, M. Carr, D. Des Marais, B. Brake, Report of the Mars 2020 Science Definition Team, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 2013.
[2] E. Musk, Making life multi-planetary, New Space 6 (2018) 2–11.
[3] D. Barker, G. Chamitoff, G. James, Resource Utilization and Site Selection for a Self-Sufficient Martian Outpost, (1998).
[4] D.S. McKay, C.C. Allen, Concrete—A Practical Construction Material for Mars, Engineering, Construction, and Operations in Space, (1996), pp. 566–570 V.

[5] T. Lin, S. Bhattacharja, Lunar and Martian resources utilization: cement, Space 98 (1998) 592–600.
[6] G. Scheerbaum, In-Situ manufacture of martian construction materials, Space 2000 (2000) 934–940.
[7] C.R. Stoker, C. Emmart, Strategies for Mars: a Guide to Human Exploration, Strategies for Mars: A Guide to Human Exploration, (1996).
[8] C. Oze, A. Scott, Cement and Hydrogen Production from Serpentinization on Mars, EGU General Assembly Conference Abstracts, 2018, p. 3133.
[9] R. Boyd, P. Thompson, B. Clark, Duricrete and Composites Construction on Mars, the Case for Mars III: Strategies for Exploration- General Interest and Overview(A 90-16651 05-12), Univelt, Inc., San Diego, CA, 1989 1989.
[10] L. Wan, R. Wendner, G. Cusatis, A novel material for in situ construction on Mars: experiments and numerical simulations, Constr. Build. Mater. 120 (2016) 222–231.
[11] B. Khoshnevis, X. Yuan, B. Zahiri, J. Zhang, B. Xia, Construction by Contour Crafting using sulfur concrete with planetary applications, Rapid Prototyp. J. 22 (2016) 848–856.
[12] M.J. Werkheiser, M. Fiske, J. Edmunson, B. Khoshnevis, On the Development of Additive Construction Technologies for Application to Development of Lunar/ martian Surface Structures Using In-Situ Materials, AIAA SPACE 2015 Conference and Exposition, 2015, p. 4451.
[13] T. Lin, S. Bhattacharja, L. Powers-Couche, S. Skaar, T. Horiguchi, N. Saeki, D. Munaf, Y. Peng, I. Casanova, Lunar and Martian Resource Utilization: Cement and Concrete, Using in Situ Resources for Construction of Planetary Outposts, (1998), p. 12.
[14] S.-D. Wang, K.L. Scrivener, Hydration products of alkali activated slag cement, Cement Concr. Res. 25 (1995) 561–571.
[15] J.S. Van Deventer, J.L. Provis, P. Duxson, Technical and commercial progress in the adoption of geopolymer cement, Miner. Eng. 29 (2012) 89–104.
[16] D.R. Williams, Mars Fact Sheet, (2004) http://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html.
[17] S.B. Flexner, L.C. Hauck, Random House Unabridged Dictionary, Random House, New York, 2018.
[18] J. Karni, E.Y. Karni, Gypsum in construction: origin and properties, Mater. Struct. 28 (1995) 92–100.
[19] K. Robertson, D. Bish, Constraints on the distribution of CaSO4· nH2O phases on Mars and implications for their contribution to the hydrological cycle, Icarus 223 (2013) 407–417.
[20] M. Massé, O. Bourgeois, S. Le Mouélic, C. Verpoorter, A. Spiga, L. Le Deit, Wide distribution and glacial origin of polar gypsum on Mars, Earth Planet. Sci. Lett. 317 (2012) 44–55.
[21] F. Blakey, Cast gypsum as a structural material, Architect. Sci. Rev. 4 (1961) 6–16.
[22] P.B. Niles, D.C. Catling, G. Berger, E. Chassefière, B.L. Ehlmann, J.R. Michalski, R. Morris, S.W. Ruff, B. Sutter, Geochemistry of carbonates on Mars: implications for climate history and nature of aqueous environments, Space Sci. Rev. 174 (2013) 301–328.
[23] J.C. Bridges, D. Catling, J. Saxton, T. Swindle, I. Lyon, M. Grady, Alteration assemblages in Martian meteorites: implications for near-surface processes, Space Sci. Rev. 96 (2001) 365–392.
[24] Météorite de Chassigny, Wikimedia Commons, (2014).
[25] D.M. Roy, Alkali-activated cements opportunities and challenges, Cement Concr. Res. 29 (1999) 249–254.
[26] F. Poulet, N. Mangold, D. Loizeau, J.-P. Bibring, Y. Langevin, J. Michalski, B. Gondet, Abundance of minerals in the phyllosilicate-rich units on Mars, Astron. Astrophys. 487 (2008) L41–L44.
[27] J.F. Mustard, S.L. Murchie, S. Pelkey, B. Ehlmann, R. Milliken, J.A. Grant, J.-P. Bibring, F. Poulet, J. Bishop, E.N. Dobrea, Hydrated silicate minerals on Mars observed by the Mars reconnaissance orbiter CRISM instrument, Nature 454 (2008) 305.
[28] J.L. Bishop, E.Z.N. Dobrea, N.K. McKeown, M. Parente, B.L. Ehlmann, J.R. Michalski, R.E. Milliken, F. Poulet, G.A. Swayze, J.F. Mustard, Phyllosilicate diversity and past aqueous activity revealed at Mawrth Vallis, Mars, Science 321 (2008) 830–833.
[29] A. Elimbi, H. Tchakoute, D. Njopwouo, Effects of calcination temperature of kaolinite clays on the properties of geopolymer cements, Constr. Build. Mater. 25 (2011) 2805–2812.
[30] A.N. Scott, C. Oze, Constructing Mars: concrete and energy production from serpentinization products, Earth Space Sci. 5 (2018) 364–370.
[31] H. Tran, A. Scott, Strength and workability of magnesium silicate hydrate binder systems, Constr. Build. Mater. 131 (2017) 526–535.
[32] D.L. Bish, D. Blake, D. Vaniman, S. Chipera, R. Morris, D. Ming, A. Treiman, P. Sarrazin, S. Morrison, R. Downs, X-ray diffraction results from Mars science laboratory: mineralogy of rocknest at Gale Crater, Science 341 (2013) 1238932.
[33] N. Demidov, A. Bazilevskii, R. Kuz'min, Martian soils: varieties, structure, composition, physical properties, drillability, and risks for landers, Sol. Syst. Res. 49 (2015) 209–225.
[34] P.L. King, S.M. McLennan, Sulfur on Mars, Elements 6 (2010) 107–112.
[35] V. Petkova, Y. Pelovski, Comparative DSC study on thermal decomposition of iron sulphates, J. Therm. Anal. Calorim. 93 (2008) 847–852.
[36] T. Rosenqvist, Principles of Extractive Metallurgy, Tapir academic press, 2004.
[37] Y. Jin, Q. Yu, S. Chang, Catalytic Reduction of Sulfur Dioxide to Elemental Sulfur, American Chemical Society, Washington, DC (United States), 1994.
[38] M. Chaplin, Water Structure and Science, London South Bank University, 2018.
[39] Water Mass Map from Neutron Spectrometer, National Aeronautics and Space Administration, 2008.
[40] W. Boynton, D. Ming, S. Kounaves, S. Young, R. Arvidson, M. Hecht, J. Hoffman, P. Niles, D. Hamara, R. Quinn, Evidence for calcium carbonate at the Mars Phoenix landing site, Science 325 (2009) 61–64.
[41] J.J. Wray, S.W. Squyres, L.H. Roach, J.L. Bishop, J.F. Mustard, E.Z.N. Dobrea, Identification of the Ca-sulfate bassanite in mawrth vallis, Mars, Icarus 209 (2010) 416–421.
[42] D.L. Blaney, T.B. McCord, An observational search for carbonates on Mars, J. Geophys. Res.: Solid Earth 94 (1989) 10159–10166.
[43] A. Gendrin, N. Mangold, J.-P. Bibring, Y. Langevin, B. Gondet, F. Poulet, G. Bonello,

[43] C. Quantin, J. Mustard, R. Arvidson, Sulfates in Martian layered terrains: the OMEGA/Mars Express view, Science 307 (2005) 1587–1591.
[44] P. Christensen, M. Wyatt, T. Glotch, A. Rogers, S. Anwar, R. Arvidson, J. Bandfield, D. Blaney, C. Budney, W. Calvin, Mineralogy at meridiani planum from the mini-TES experiment on the opportunity rover, Science 306 (2004) 1733–1739.
[45] W. Rapin, P.-Y. Meslin, S. Maurice, D. Vaniman, M. Nachon, N. Mangold, S. Schröder, O. Gasnault, O. Forni, R. Wiens, Hydration state of calcium sulfates in Gale crater, Mars: identification of bassanite veins, Earth Planet. Sci. Lett. 452 (2016) 197–205.
[46] S.M. Morrison, R.T. Downs, D.F. Blake, D.T. Vaniman, D.W. Ming, R.M. Hazen, A.H. Treiman, C.N. Achilles, A.S. Yen, R.V. Morris, Crystal chemistry of martian minerals from bradbury landing through naukluft plateau, Gale Crater, Mars, Am. Mineral.: J. Earth Planet. Mater. 103 (2018) 857–871.
[47] R.V. Morris, S.W. Ruff, R. Gellert, D.W. Ming, R.E. Arvidson, B.C. Clark, D. Golden, K. Siebach, G. Klingelhöfer, C. Schröder, Identification of carbonate-rich outcrops on Mars by the Spirit rover, Science 329 (2010) 421–424 1189667.
[48] S.W. Squyres, R.E. Arvidson, S. Ruff, R. Gellert, R. Morris, D. Ming, L. Crumpler, J. Farmer, D. Des Marais, A. Yen, Detection of silica-rich deposits on Mars, Science 320 (2008) 1063–1067.
[49] M. Carr, J. Head, Martian surface/near-surface water inventory: sources, sinks, and changes with time, Geophys. Res. Lett. 42 (2015) 726–732.
[50] T.R. Meyer, C.P. McKay, The resources of Mars for human settlement, J. Br. Interplanet. Soc. (JBIS) 42 (1989) 147–160.
[51] A.C. Institute, 211.1-91: Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete, 2009.
[52] P. Rosskopf, F. Linton, R. Peppler, Effect of various accelerating chemical admixtures on setting and strength development of concrete, J. Test. Eval. 3 (1975) 322–330.
[53] T. Schmidt, A. Leemann, E. Gallucci, K. Scrivener, Physical and microstructural aspects of iron sulfide degradation in concrete, Cement Concr. Res. 41 (2011) 263–269.
[54] C. He, B. Osbaeck, E. Makovicky, Pozzolanic reactions of six principal clay minerals: activation, reactivity assessments and technological effects, Cement Concr. Res. 25 (1995) 1691–1702.
[55] C.F. Dunant, K.L. Scrivener, Effects of aggregate size on alkali–silica-reaction induced expansion, Cement Concr. Res. 42 (2012) 745–751.
[56] C.F. Dunant, K.L. Scrivener, Micro-mechanical modelling of alkali–silica-reaction-induced degradation using the AMIE framework, Cement Concr. Res. 40 (2010) 517–525.
[57] N. Roussel, A theoretical frame to study stability of fresh concrete, Mater. Struct. 39 (2006) 81–91.
[58] Y. Reches, Nanoparticles as concrete additives: review and perspectives, Constr. Build. Mater. 175 (2018) 483–495.
[59] A.C. 309, Guide for Consolidation of Concrete, American Concrete Institute, 2005.
[60] N. Spanovich, M. Smith, P. Smith, M. Wolff, P. Christensen, S. Squyres, Surface and near-surface atmospheric temperatures for the Mars Exploration Rover landing sites, Icarus 180 (2006) 314–320.
[61] Cold Weather Concreting, Portland Cement Association.
[62] K. Kovler, O.M. Jensen, Novel techniques for concrete curing, Concr. Int. 27 (2005) 39–42.
[63] G.I. Petrov, A Permanent Settlement on Mars: the First Cut in the Land of a New Frontier, Massachusetts Institute of Technology, 2004.
[64] G. Flynn, D. McKay, Meteorites on Mars, Mars Sample Return Science, 1988.
[65] G.J. Flynn, D.S. McKay, An assessment of the meteoritic contribution to the Martian soil, J. Geophys. Res.: Solid Earth 95 (1990) 14497–14509.
[66] X. Chen, Q. Li, Deep penetration of a non-deformable projectile with different geometrical characteristics, Int. J. Impact Eng. 27 (2002) 619–637.
[67] I. Asadi, P. Shafigh, Z.F.B.A. Hassan, N.B. Mahyuddin, Thermal conductivity of concrete-A review, J. Build. Eng. 20 (2018) 81–93.
[68] P. Prado, B. Balcom, S. Beyea, T. Bremner, R. Armstrong, P. Grattan-Bellew, Concrete freeze/thaw as studied by magnetic resonance imaging, Cement Concr. Res. 28 (1998) 261–270.
[69] I.N. Hamdhan, B.G. Clarke, Determination of thermal conductivity of coarse and fine sand soils, Proceedings of World Geothermal Congress, 2010, pp. 1–7.
[70] D.M. Hassler, C. Zeitlin, R.F. Wimmer-Schweingruber, B. Ehresmann, S. Rafkin, J.L. Eigenbrode, D.E. Brinza, G. Weigle, S. Böttcher, E. Böhm, Mars' surface radiation environment measured with the Mars Science Laboratory's Curiosity rover, Science 343 (2014) 1244797.
[71] F. Sanchez, D. Kosson, K. Brown, R. Delapp, R. Teising, R. Gonzalez, J. Lewis, L. Brown, Y. Reches, M. Helbing, Development of Nano-Modified Concrete for Next Generation of Storage Systems, Vanderbilt University, Nashville, TN, 2018.
[72] K. Field, I. Remec, Y. Le Pape, Radiation Effects in Concrete for Nuclear Power Plants–Part I: Quantification of Radiation Exposure and Radiation Effects, Nuclear Engineering and Design, 2014.
[73] M. Berger, M. Inokuti, H. Andersen, H. Bichsel, Stopping Powers and Ranges for Protons and Alpha Particles ICRU Report vol. 49, (1993).
[74] C.C. Allen, R.V. Morris, D.J. Lindstrom, M. Lindstrom, J. Lockwood, JSC Mars-1 Martian Regolith Simulant, Lunar and Planetary Science Conference, 1997.
[75] D. Barthelmy, Gypsum Mineral Data, Mineralogy Database.
[76] Y. Reches, K. Thomson, M. Helbing, D.S. Kosson, F. Sanchez, Agglomeration and reactivity of nanoparticles of SiO2, TiO2, Al2O3, Fe2O3 and clays in cement pastes and effects on compressive strength and thermal durability, Constr. Build. Mater. 167 (2018) 860–873.
[77] D. Barthelmy, Sulfur Mineral Data, Mineralogy Database.
[78] D. Barthelmy, Ice Mineral Data, Mineralogy Database.
[79] A. Leventis, D. Verganelakis, M. Halse, J. Webber, J.H. Strange, Capillary imbibition and pore characterisation in cement pastes, Transport Porous Media 39 (2000) 143–157.
[80] A. Neville, The confused world of sulfate attack on concrete, Cement Concr. Res. 34 (2004) 1275–1296.
[81] E.M. Winkler, P.C. Singer, Crystallization pressure of salts in stone and concrete, Geol. Soc. Am. Bull. 83 (1972) 3509–3514.
[82] M.R. Meier, M. Sarigaphuti, P. Sainamthip, J. Plank, Early hydration of Portland cement studied under microgravity conditions, Constr. Build. Mater. 93 (2015) 877–883.