Communication

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StarCrete: A starch-based biocomposite for off-world construction

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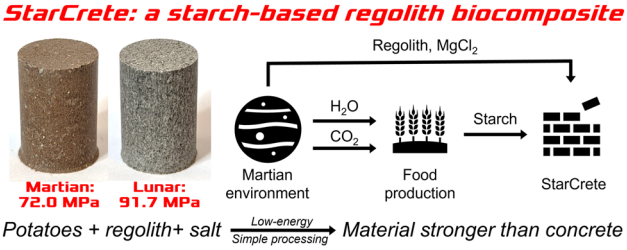
Abstract: Robust and affordable technology capabilities are needed before a sustained human presence on the lunar and Martian surfaces can be established. A key challenge is the production of high-strength structural materials from *in situ* resources to provide spacious habitats with adequate radiation shielding. Ideally, the production of such materials will be achieved through relatively simple, low-energy processes that support other critical systems. Here, we demonstrate the use of ordinary starch as a binder for simulated extraterrestrial regolith to produce a high-strength biocomposite material, termed StarCrete. With this technique, surplus starch produced as food for inhabitants could be used for construction, integrating two critical systems and significantly simplifying the architecture needed to sustain early extraterrestrial colonies. After optimisation, lunar and Martian StarCrete achieved compressive strengths of 91.7 and 72.0 MPa, respectively, which is well within the domain of high-strength concrete (>42 MPa) and surpasses most other proposed technology solutions despite being a relatively low-energy process. The flexural strength of the lunar and Martian StarCrete, at 2.1 and 8.4 MPa, respectively, was also comparable to ordinary concrete (2.5–4.5 MPa).

Keywords: starch, biocomposite, *in situ* resource utilisation, space, biopolymer–bound soil composites, design of experiments



Graphical abstract

List of abbreviations

ERB	extraterrestrial regolith biocomposite
DoE	design of experiments
DSD	definitive screening design
UCS	ultimate compressive strength
LHS-1	lunar highlands simulant 1
MGS-1	martian global simulant 1
FE-SEM	field-emission scanning electron microscopy

1 Introduction

A sustained human presence on the lunar and Martian surfaces will require habitats with thick walls and ceilings for protection against radiation exposure and meteor strikes [1–3]. Due to the high cost of transporting mass from Earth to space, bulk construction materials will be produced from locally available resources – a concept known as *in situ* resource utilisation (ISRU) [4–7]. The stabilisation of loose, unconsolidated regolith (i.e., dust and soil) into a solid concrete-like material would not only provide radiation- and micrometeoroid-shielding, but could also allow the deployment of relatively lightweight, inflatable habitats by countering the extreme thermal and pressure differences between indoor and outdoor environments [7,8]. Although there have been several proposed solutions to the stabilisation of regolith for extraterrestrial construction, most have major drawbacks such as extremely high energy or water use, or the need for additional high-mass mining, transportation,

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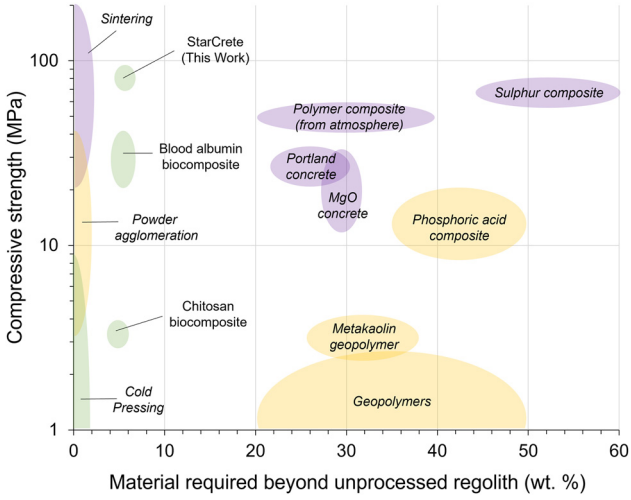

Figure 1: Comparison of proposed ISRU technologies for the stabilisation of extraterrestrial regolith into solid materials. Ultimate compressive strength (UCS) range of materials plotted against the proportion of material required beyond unprocessed regolith. Purple, yellow and green colours indicate high-, medium- and low-energy processes, respectively. Figure adapted from Karl et al. [9].

processing or fabrication equipment which would add to the cost and complexity of any mission (Figure 1) [9–13].

One potential solution is the use of naturally occurring biopolymers as regolith binding agents to produce extraterrestrial regolith biocomposites (ERBs) [14–17]. Since biopolymers are produced under relatively mild, low-energy conditions, they could potentially overcome many of the shortcomings faced by other techniques. Recently, Shiwei et al. proposed a technique to stabilise Martian regolith using a chitosan-based biopolymer binder derived from arthropod cuticle [14]. This ERB, termed Martian Biolith, achieved an UCS of up to 3.6 MPa. In another series of reports [15,16], D. Loftus and co-workers demonstrated that a protein obtained from cow blood plasma (bovine serum albumin, BSA) could also act as an effective binder to produce ERBs with UCSs as high as 22.2 MPa – which is about as strong as ordinary brick. Since it is not convenient to transport cows into space, we expanded on this concept by investigating the human equivalent of BSA (human serum albumin, HSA) as a binder to produce ERBs [17]. Here, HSA obtained from human blood plasma could be combined with urea (abundant in human urine) and regolith to produce ERBs with compressive strengths as high as 39.7 MPa. Although the notion of considering humans as an *in situ* resource has some advantages, the fact that the technique could compromise the health of the crew is a significant drawback.

Starch (amylum) is an abundant plant-based carbohydrate and is the main source of calories in the human diet [18]. In addition to food, starch is also employed industrially as an adhesive/binder for various applications – including paper, cardboard, and textile manufacture [19,20]. Starch has been extensively investigated as a binder for plant fibre-based biocomposite materials [21–28]; however, relatively poor mechanical properties (compressive strengths <2.5 MPa) and moisture sensitivity limit their applicability. Recently, corn starch was employed as a binder for inorganic aggregates such as sand and limestone powder [29,30]. Termed CoRncrete, these materials displayed impressive compressive strengths as high as 30 MPa; however, moisture sensitivity remained a key weakness for practical Earth-based applications [31].

Having extremely limited amounts of water, the issue of moisture sensitivity is irrelevant for the Lunar and Martian environments – meaning a CoRncrete-like material could be well-suited for extraterrestrial construction. Furthermore, since starch is the primary constituent of staple foods such as rice, potatoes, and maize (corn), any sustained off-world habitat will likely have the capability to produce starch as food for inhabitants. To mitigate risks such as crop failure or poor yields, a surplus of starch will likely be produced under ordinary conditions: the use of surplus starch as a binder for regolith would therefore avoid the need for additional construction

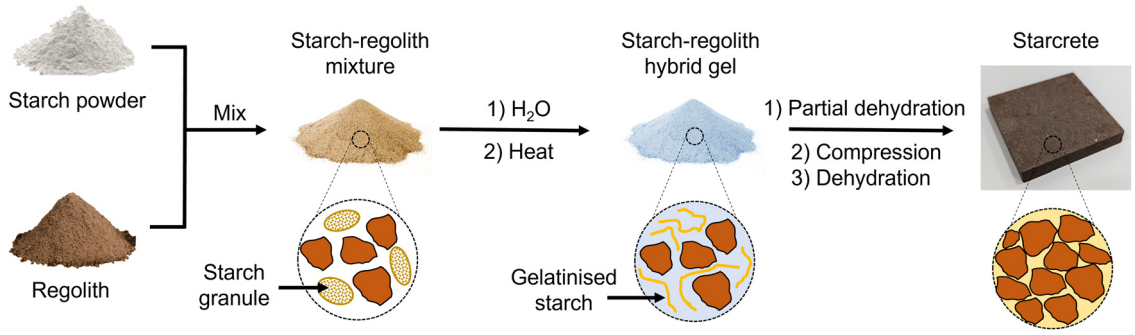

Figure 2: Scheme depicting the steps taken to produce StarCrete.

Table 1: Properties of native starch from various sources (data reproduced from refs. [19,20,41,42]) along with UCS values of resulting ERBs

Starch source	Granule diameter (µm)	Lipid (wt%)	Protein (wt%)	Phosphorous (wt%)	Amylopectin (%)	Amylose DP	Gel. temp (°C)	Paste viscosity	UCS (MPa)
Maize	3–26	0.6	0.35	0.02	28	800	75–80	Medium	2.28 ± 0.80
Waxy maize	3–26	0.15	0.25	0.01	>99	–	65–70	Medium-high	3.69 ± 0.33
Tapioca	4–35	0.1	0.1	0.01	17	3,000	65–70	High	1.43 ± 0.07
Potato	5–100	0.05	0.06	0.08	21	3,000	60–65	Very high	17.7 ± 2.1
Wheat	1–40	0.8	0.4	0.06	28	800	80–85	Medium-low	11.5 ± 1.6
Rice	3–8	0.01	0.06	–	19	–	70–80	Medium	1.36 ± 0.13
Waxy rice	3–8	0.01	0.06	–	>99	–	70–80	Medium	8.35 ± 0.59

Samples are tested in triplicate. DP denotes degree of polymerisation.

material fabrication equipment and supporting infrastructure. This integration of the food- and construction-material-production systems would therefore reduce launch mass, energy use, and technology development costs, whilst also improving system robustness and flexibility.

In this work, we further developed and investigated the CoRncrete concept for use as an extraterrestrial construction material (Figure 2). Since our materials use potato starch rather than corn starch, we renamed this adaption StarCrete (starch-concrete). By employing a statistical Design of Experiments (DoE) methodology to develop and optimise the formulation and process parameters, UCS's as high as 72.0 and 91.7 MPa were obtained for Martian and lunar regolith, respectively. This is within the domain of high-strength concrete (>42 MPa), despite being a relatively simple, low-energy approach.

2 Results and discussion

Starch gelatinisation occurs through a complex multi-phase transition, which is influenced by factors such as starch source, concentration, temperature profile, pH, and the presence of metal salts, enzymes and other additives [32,33]. Moreover, the size, shape, and crystallinity of the starch granules, as well as the molecular weights and ratios of amylose to amylopectin, have a strong effect on starch gelatinisation and vary significantly between plant species. Selective breeding has also resulted in significant differences within species, such as high-amylopectin (waxy) varieties of maize, rice, and potatoes [19,32]. Due to the high complexity of this process and the likelihood of complex multi-factor interactions, a statistical DoE methodology was employed in this study.

For time efficiency, a single Martian regolith simulant (Mars Global Simulant, MGS-1) was employed to optimise the system before translation of the optimised conditions to a lunar regolith simulant [34]. After developing a basic procedure for the fabrication of starch-based ERBs adapted from published methods (see SI for details) [29,30], several starch sources were screened to identify the most promising type (Table 1). The results from this screening experiment indicated that potato starch was by far the most effective source, having an UCS of 17.7 MPa. Potato starch differs from most other grain-derived starches in that it has relatively large starch granules (up to 100 µm), a relatively low gelatinisation temperature (60–65°C), minimal fat and protein content, and relatively high phosphate content [19]. Potato starch also produces a relatively viscous paste upon gelatinisation, which may be the reason it acted as a

relatively strong binder. Due to its clear superiority over other starch sources, potato starch was carried forward for subsequent optimisation experiments.

The next experiment involved screening a range of additives that could feasibly be obtained from the Martian surface and were deemed to potentially have a beneficial effect on the properties of the resulting ERBs. The selected additives were as follows: $MgCl_2$, acetic acid, Na_2CO_3, $FeSO_4$, urea, and human saliva. Metal chloride salt deposits have been detected on the surface of Mars [35] and are known to affect the gelatinisation of starch [36]. Acetic acid can also be produced from starch *via* anaerobic fermentation (e.g., rice vinegar or malted grain vinegar) and can also affect starch gelatinisation [37]. Na_2CO_3 has been employed as an additive in starch adhesives [20], and iron and sulphate salts (e.g., $FeSO_4$) could be obtained from the Martian surface and could promote ionic bridging. Urea can form strong hydrogen bonding interactions and is available in abundance from human urine, and human saliva contains amylose – a starch-active enzyme that has been used to produce starch-based adhesives [38]. These additives were incorporated into the ERBs by replacing the addition of DI water with high-concentration aqueous solutions of these substances. The resulting ERBs were then evaluated for UCS with results presented in Table 2.

The results found that urea and acetic acid had a strong positive effect on the resulting UCS of the ERBs (about 50% stronger), whereas human saliva had little effect and the other additives were detrimental to UCS. However, it was observed that $MgCl_2$ substantially altered the viscoelastic properties of the mixture after gelatinisation (i.e., the mixture was "stickier" than others) and was therefore included out of curiosity – along with urea and acetic acid – for subsequent investigation.

Having accumulated a substantial number of process variables and formulation parameters, a statistical Definitive Screening Design (DSD) DoE experiment was next conducted. A DSD experiment is a highly efficient way to rapidly screen variables in a complex system to determine which factors and factor interactions are significant and should therefore be the focus of subsequent optimisation [39]. In this experiment, ten input variables were screened, namely, starch-regolith ratio, effective starch concentration, urea concentration, $MgCl_2$ concentration, acetic acid concentration, gelatinisation temperature, gelatinisation time, compression force, drying temperature, and drying time. The measured output variable (or response) was UCS.

Table 2: Effect of additive incorporation on UCS of ERBs. UCS presented as a % relative to no additive

Additive	Concentration	Relative UCS (%)
None	n.a.	100
Urea	Saturated	152.5 ± 19.6
$MgCl_2$	Saturated	69.1 ± 24.4
Acetic acid	24 vol%	150.2 ± 42.6
$FeSO_4$	Saturated	10.6 ± 0.9
Na_2CO_3	Saturated	59.4 ± 3.5
Human saliva	Pure	97.2 ± 6.6

Samples tested in triplicate.

Details of the experiment are given in the SI, but to summarise, 25 experimental runs were conducted which revealed that gelatinisation temperature and gelatinisation time were highly significant factors whose ranges (70–90°C and 10–60 min, respectively) had been set too low. This meant that the effects of other factors were eclipsed by these dominating effects, but that significantly better performance could be obtained by simply increasing gelatinisation temperature and gelatinisation time.

In order to find more optimal conditions for gelatinisation temperature and time, another statistical DoE experiment was conducted. This time, a two-factor central composite design (CCD) with one centre point was employed, the details of which are given in the Supporting Information. This experiment found a higher gelatinisation temperature and time did improve the UCS as indicated by the previous DSD experiment, with a UCS as high as 53.5 MPa being achieved. Moreover, the results suggested that even higher gelatinisation temperatures and times would continue to improve the compressive strength of the materials.

A further CCD experiment was then conduced, pushing the gelatinisation time and temperature even higher (120–180 min and 120–180°C, respectively). However, these higher temperatures resulted in the thermal decomposition of urea with the liberation of ammonia and isocyanic acid – the latter being a poisonous gas. Since the generation of poisonous gasses should ideally be avoided in confined environments such as off-world habitats, the gelatinisation temperature was limited to 120°C while urea was included as an additive.

While conducting the above experiment, a serendipitous finding revealed that – after starch gelatinisation – the materials could be fully dehydrated and rehydrated without a detrimental effect on the UCS. This allowed the decoupling of the extent of hydration needed for the gelatinisation step – where a relatively high amount of water seemed to be beneficial – with the extent of hydration needed for the final forming/compression step – where a relatively low about of water seemed to be beneficial.

This modification to the process (i.e., full drying after gelatinisation before controlled rehydration) was incorporated into subsequent experiments.

Having now established a clearer idea of the relevant process parameters and suitable ranges, another DoE experiment was conducted with the aim of mapping the experimental space through a Response Surface Model (RSM). This custom DoE design, the details of which are given in the SI, consisted of 54 runs grouped into six blocks. To summarise the results, the following conclusions were drawn: 1) a starch-regolith ratio of about 4.5% appeared to be optimal, 2) a lower effective binder concentration (i.e., more water during the gelatinisation step) increased UCS, 3) a higher compression force increased UCS slightly, 4) a longer gelatinisation time increased UCS, 5) a lower rehydration extent increased UCS, and 6) both urea and acetic acid were detrimental to UCS, whereas $MgCl_2$ was beneficial. The latter point was both surprising and interesting, since urea and acetic acid had a strong positive effect from the initial additive screening experiment, whereas $MgCl_2$ initially had a detrimental effect (Table 2). This highlights the importance of pursuing interesting observations – otherwise the beneficial effect of $MgCl_2$ incorporation could have been missed. The highest compressive strength achieved in this experiment was 71.10 MPa.

Having further refined our understanding of significant process factors and factor ranges, a subsequent custom DoE experiment was conducted to explore the experimental space that the abovementioned RSM was

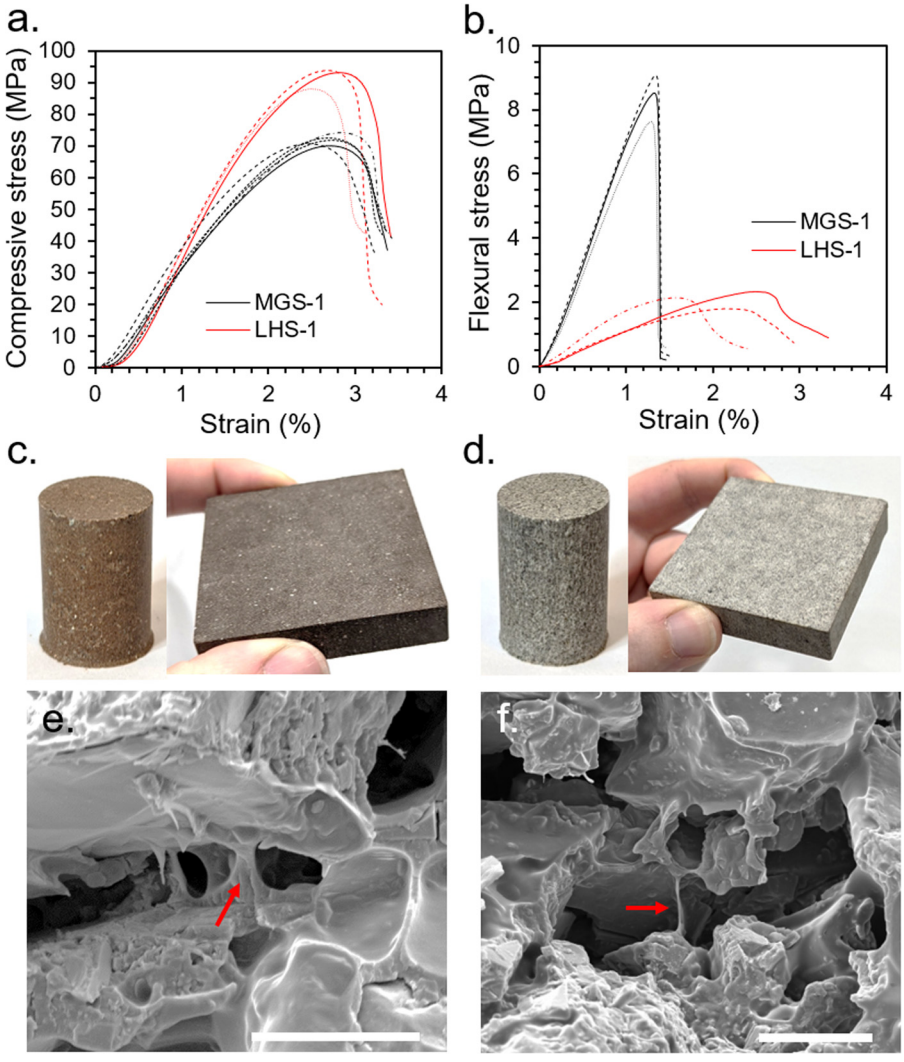

Figure 3: Stress–strain profiles for Martian (MGS-1) and lunar (LHS-1) Starcrete undergoing (a) uniaxial compression tests and (b) three-point flexural tests. (c) and (d) Camera images Martian and lunar Starcrete, respectively. (e) and (f) SEM images of Martian and lunar Starcrete, respectively. Scale bars = 20 µm.

Table 3: Summary of the mechanical property data of MGS-1- and LHS-1-based Starcrete following optimisation

Regolith	UCS (MPa)	Compressive modulus (GPa)	Flexural strength (MPa)	Flexural modulus (MPa)
MGS-1	71.95 ± 1.45 (5)	4.12 ± 0.27 (5)	8.41 ± 0.60 (3)	658.4 ± 43.7 (3)
LHS-1	91.68 ± 2.69 (3)	5.66 ± 0.09 (3)	2.14 ± 0.22 (3)	137.3 ± 37.7 (3)

indicating as being more optimal. Urea and acetic acid were dropped from the formulation since their incorporation was found to be detrimental. This allowed higher gelatinisation temperatures to be employed without the risk of producing poisonous isocyanic acid gas from urea decomposition. In addition to higher gelatinisation temperatures – higher gelatinisation times, lower effective starch concentrations and higher $MgCl_2$ concentrations were investigated in this design. Rehydration extent was fixed at 5% because a lower value of 4% was found to be insufficient and resulted in materials with poor mechanical properties. The results from this experiment are again detailed in the Supplementary Information, but to summarise – it was found that lower effective starch concentrations, higher $MgCl_2$ concentrations and higher gelatinisation temperatures all decreased the UCS, which was the opposite of the prediction of the prior experiment. This suggested that the optimal conditions had already been identified, and pushing the variables to further extremes was detrimental. The conditions that resulted in a UCS of 71.10 MPa from the previous DoE experiment were therefore taken as optimal, with specific conditions presented in the experimental details section of the Supplementary Information.

Having optimised the fabrication procedure and formulation, five further replicates were produced and tested to evaluate the reproducibility of the system (Figure 3, Table 3). The average UCS of these replicates was 71.95 ± 1.45 MPa, which was remarkably similar to the previous 71.10 MPa figure obtained from the DoE experiment. This low variance between samples suggested that there were no significant hidden variables influencing the results. The compressive elastic modulus also displayed low variance, with an average value of 4.12 ± 0.27 GPa.

The optimised process was then translated to a lunar regolith simulant (Lunar Highlands Simulant, LHS-1), which gave a remarkably high UCS of 91.68 ± 2.69 MPa. Given that the system had specifically been optimised for MGS-1, such a high value for LHS-1 was surprising. This increased UCS was attributed to the particle size, shape, distribution, and chemical composition of LHS-1 being better suited than MGS-1 for ERBs – supporting the observations made in our previous study [17]. The compressive elastic modulus was also remarkably high at 5.66 ± 0.09 GPa.

Three-point flexural tests were also conducted on Martian and lunar StarCrete to determine flexural strength and modulus (Figure 3b, Table 3.). Here, tile-like specimens (55 mm × 55 mm × 12 mm) were prepared following the optimised procedure and tested. The results found that Martian (MGS-1) samples had a flexural strength of 8.41 ± 0.60 MPa and flexural modulus of 658.4 ± 43.7 MPa, whereas Lunar (LHS-1) samples were weaker with a flexural strength of 2.14 ± 0.22 MPa and flexural modulus of 137.3 ± 37.7 MPa. For comparison, ordinary concrete typically has a flexural strength between 2.5 and 4.5 MPa [40].

Finally, scanning electron microscopy (SEM) images were taken to probe the structure and morphology of StarCrete. This revealed some evidence of ligament-like bonding between particles as has previously been observed for protein-based binders (Figure 3e and f) [15,17].

3 Conclusions and outlook

Future habitats on the lunar and Martian surfaces will need robust and affordable technology capabilities to produce substantial quantities of construction materials *in situ*. In this work, we demonstrate that ordinary plant-derived starch can serve as an effective binder for extra-terrestrial regolith to produce ERBs with compressive strengths within the domain of high-strength concrete (>42 MPa). The advantages of StarCrete over other proposed technology options include the following: 1) *risk reduction*: having an edible binder means it could be consumed in the event of an 'Apollo 13' type emergency where the ship or habitat enters 'lifeboat mode', 2) *practicality:* unlike many other proposed technology options, StarCrete is a relatively simple solution with a high technology readiness, 3) *system integration:* the production of starch could be integrated with food and oxygen production systems (i.e., plant growth), simplifying mission architecture and lowering costs, 4) *resourcefulness:* unlike many other technology options, starch production doesn't require high energy processing, and most water can be recovered since the mechanism is driven by dehydration, 5) *resource locality*: starch will be produced on-site, which is an advantage over some other technology options that

would require mining and transportation of sparse mineral deposits, and 6) *architectural flexibility:* being an exceptionally high-strength material, habitats can be designed with fewer architectural constraints.

Although StarCrete displays significant potential as an extraterrestrial construction material, further studies will be needed to evaluate its full potential and limitations. We suggest the following studies as avenues for future work: 1) screening a broader range of starch sources and additives, 2) further investigation into the bonding mechanism and adhesion strength of the starch binder with regolith, 3) further testing of StarCrete under simulated off-world conditions (i.e., repeated thermal swings, high radiation, and low pressure) with a focus on durability and longevity of the materials 4) hypervelocity impact testing to evaluate resistance to meteor strikes, 5) regolith particle size optimisation, 6) tailoring the biosynthesis of starch for further optimisation (e.g., directed evolution of the gene corresponding to starch synthase), and 7) investigating the potential of StarCrete for additive manufacturing (3D-printing). Also, since starch granule formation in plants is dependent on various environmental conditions, such as sunlight exposure and circadian rhythms, [32] plants grown under reduced gravity and controlled lighting could form differently from those grown on Earth and hence produce StarCrete with differing properties – therefore, validation of the results under expected operating conditions would be needed before its practical application.

Finally, it is worth noting that since cement and concrete account for about 8% of global CO_2 emissions, further development of StarCrete could result in a relatively sustainable alternative for Earth-based construction. For this to be achieved, the moisture-sensitivity of starch binder needs to be overcome. This could be achieved through the incorporation of covalent crosslinking agents, heat-induced crosslinking, or other biopolymer additives such as proteins, waxes, or terpene-based resins.

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Conflict of interest: Authors state no conflict of interest.

Data availability statement: The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials, and any additional data is available on request.

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