StarCrete: a starch-based regolith biocomposite for extraterrestrial construction

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

List of abbreviations:[1]

[1]Extraterrestrial Regolith Biocomposite (ERB), Design of Experiments (DoE), Definitive Screening Design (DSD), ultimate compressive strength (UCS), Lunar Highlands Simulant 1 (LHS-1), Martian Global Simulant 1 (MGS-1), Field-emission Scanning Electron Microscopy (FE-SEM)

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, StarCrete achieved compressive strengths as high as 91.7 MPa – 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.

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 micrometeoroid strikes.[1–3] Since it's not economically feasible to transport bulk construction materials from Earth, the only practical option is to employ 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, processing or fabrication equipment which would add to the cost and complexity of any mission (Figure 1).[9–13]

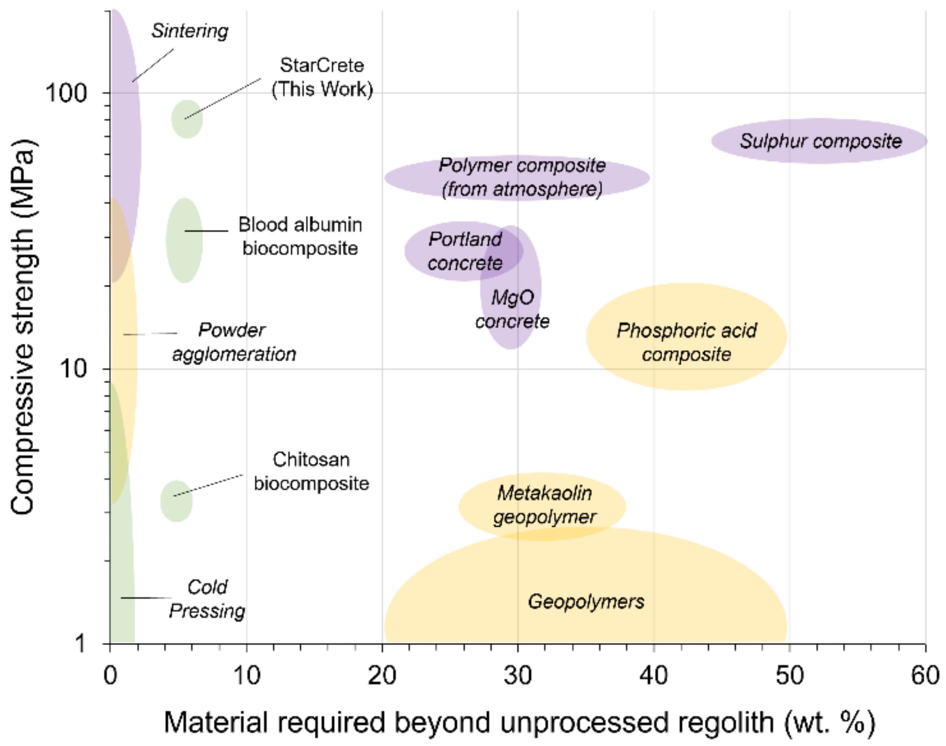

Figure 1. Comparison of proposed ISRU technologies for the stabilisation of extraterrestrial regolith into solid materials. Ultimate compressive strength (UCS) range of materials plotted against the proportion of material required beyond unprocessed regolith. Purple, yellow and green colours indicate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

One potential solution is the use of naturally-occurring biopolymers as regolith binding agents to produce extraterrestrial regolith biocomposites (ERBs).[14–18] Since biopolymers are produced under relatively mild, low-energy conditions, they could potentially overcome many of the shortcomings faced by other techniques. Recently, N. 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 ultimate compressive strength (UCS) of up to 3.6 MPa. In another series of reports,[15–17] 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 the it's 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.[18] 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 crew is a significant drawback.

Starch (amylum) is an abundant plant-based carbohydrate and is the main sources of calories in the human diet.[19] In addition to food, starch is also employed industrially as an adhesive/binder for various applications – including paper, cardboard, and textile manufacture.[20,21] Starch has been extensively investigated as a binder for plant fibre-based biocomposite materials,[22–29] 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.[30,31] 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.[32]

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 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 didn’t rely on corn starch *per se*, 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.

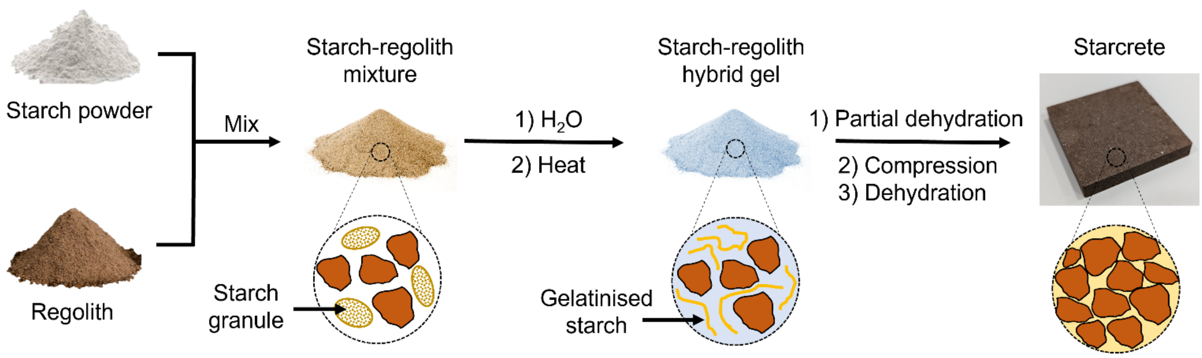

Figure 2. Scheme depicting the steps taken to produce StarCrete

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.[33,34] Moreover, the size, shape, and crystallinity of the starch granules, as well as the molecular weights and ratios of amylose to amylopectin, has a strong effect on starch gelatinisation and varies 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.[20,33] Due to the high complexity of this process, and likelihood of complex multi-factor interactions, a statistical Design of Experiments (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.[35] After developing a basic procedure for the fabrication of starch-based ERBs adapted from published methods (see SI for details),[30,31] 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 ultimate compressive strength (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.[20] 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.

Table 1. Properties of native starch from various sources (data reproduced from[20,21,42,43]) along with UCS values of resulting ERBs. Samples tested in triplicate. DP denotes degree of polymerisation.

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	3000	65 - 70	High	1.43 ±0.07
Potato	5 - 100	0.05	0.06	0.08	21	3000	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

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,[36] and are known to affect the gelatinisation of starch.[37] 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.[38] Na_2CO_3 has been employed as an additive in starch adhesives,[21] 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.[39] 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.

Table 2. Effect of additive incorporation on UCS of ERBs. UCS presented as a % relative to no additive. Samples tested in triplicate.

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

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.[40] 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.

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 minutes, 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 SI. 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 minutes 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 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 SI, 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 SI.

Having optimised the fabrication procedure and formulation, five further replicates were produced and tested to evaluate 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.

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)

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.[18] The compressive elastic modulus was also remarkably high at 5.66 ±0.09 GPa.

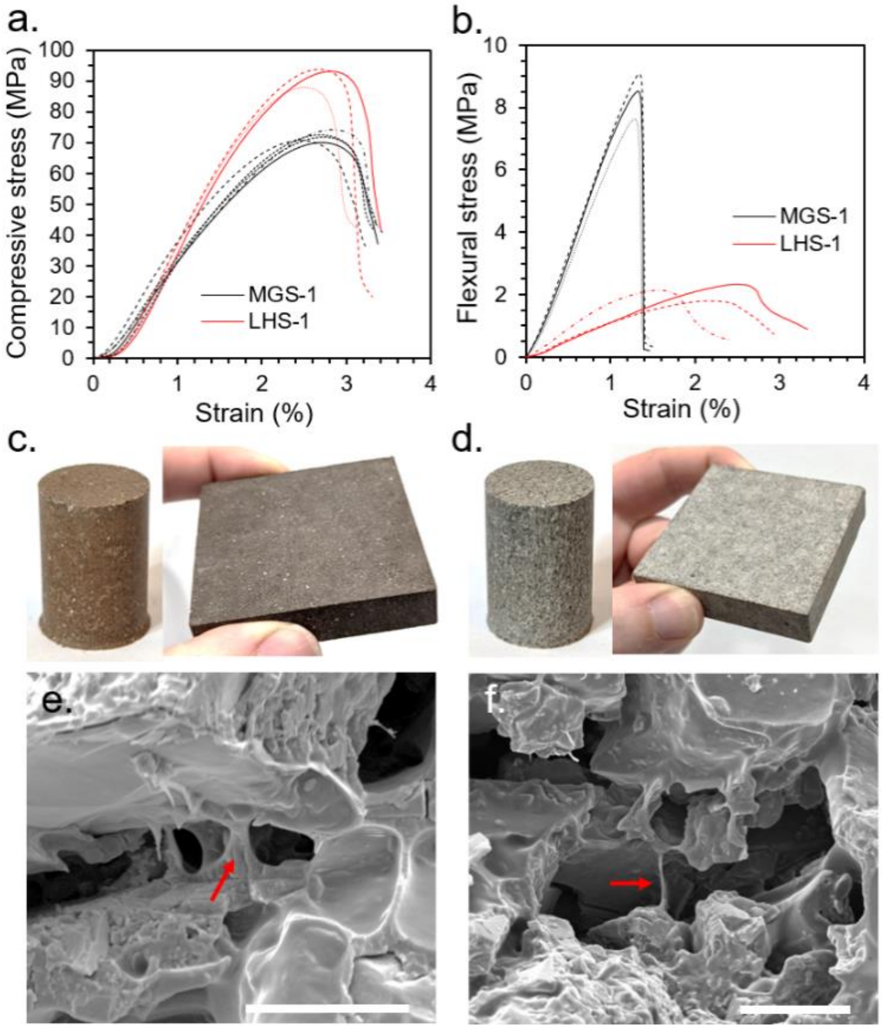

Figure 3. Stress-strain profiles for Martian (MGS-1) and lunar (LHS-1) Starcrete undergoing a) uniaxial compression tests and b) three-point flexural tests. c) and d), camera images Martian and lunar Starcrete, respectively. e) and f), SEM images of Martian and lunar Starcrete, respectively. Scale bars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

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 (55x55x12 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 – 4.5 MPa.[41]

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 3f).[15,18]

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 extraterrestrial 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, and therefore doesn't require heavy mining or transportation equipment to exploit mineral deposits for material production, 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 how this relates to starch source, 3) further testing of StarCrete under simulated off-world conditions (*i.e.*, repeated thermal swings, high radiation, low pressure *etc.*) 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) 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,[33] 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 incorporation of covalent crosslinking agents, heat-induced crosslinking, or other biopolymer additives such as proteins, waxes or terpene-based resins.

Acknowledgements

This work was supported by the Future Biomanufacturing Research Hub (grant EP/S01778X/1), funded by the Engineering and Physical Sciences Research Council (EPSRC) and Biotechnology and Biological Sciences Research Council (BBSRC) as part of UK Research and Innovation (UKRI). We acknowledge the University of Manchester Electron Microscope Centre and Mechanical Testing facility. The authors would like to thank Mr Stuart Morse for assistance with mechanical testing and Dr Will Finnigan for helpful discussions regarding Design of Experiments. We would also like to thank Annie Carpenter and Andrew Wilson as the organisers of the art-science collaboration group Para-lab, and the artists Michelle Harrison and Hannah Leighton-Boyce for the insightful discussions that resulted in the conceptualisation of this concept. We would also like to thank the Year 5 pupils from St Margaret's CoE Primary School (Whalley Range, Manchester) for their contribution to material development and enthusiastic questions.

References

[1] L.C. Simonsen, J.E. Nealy, Radiation Protection for Human Missions to the Moon and Mars, *NASA Tech. Reports Serv.* (1991). https://ntrs.nasa.gov/citations/19910008686 (accessed June 12, 2022).

[2] B.G. Drake, S.J. Hoffman, D.W. Beaty, Human exploration of mars, design reference architecture 5.0, *IEEE Aerosp. Conf. Proc.*, 2010, 1–24.

[3] M. Durante, Space radiation protection: Destination Mars, *Life Sci. Sp. Res.*, 2014, **1**, 2–9

[4] A. Ellery, Sustainable in-situ resource utilization on the moon, *Planet. Space Sci.*, 2020, **184**, 104870.

[5] S.O. Starr, A.C. Muscatello, Mars in situ resource utilization: a review, *Planet. Space Sci.*, 2020, **182**, 104824.

[6] K.R. Sridhar, J.E. Finn, M.H. Kliss, In-situ resource utilization technologies for Mars life support systems, *Adv. Sp. Res.* 2000, **25**, 249–255.

[7] R.W. Moses, D.M. Bushnell, Frontier In-Situ Resource Utilization for Enabling Sustained Human Presence on Mars, *NASA Sci. Tech. Inf.*, 2016. https://ntrs.nasa.gov/citations/20160005963 (accessed June 12, 2022).

[8] D. Cadogan, J. Stein, M. Grahne, Inflatable composite habitat structures for lunar and mars exploration, *Acta Astronaut.*, 1999, **44**, 399–406.

[9] D. Karl, K.M. Cannon, A. Gurlo, Review of space resources processing for Mars missions: Martian simulants, regolith bonding concepts and additive manufacturing, *Open Ceram.* 2022, **9**, 100216.

[10] M.Z. Naser, Extraterrestrial construction materials, *Prog. Mater. Sci.* 2019, **105**, 100577.

[11] M.Z. Naser, Q. Chen, Extraterrestrial Construction in Lunar and Martian Environments, *Sel. Pap. from 17th Bienn. Int. Conf. Eng. Sci. Constr. Oper. Challenging Environ.*, American Society of Civil Engineers, 2021, 1200–1207.

[12] Y. Reches, Concrete on Mars: Options, challenges, and solutions for binder-based construction on the Red Planet, *Cem. Concr. Compos.* 2019, **104**, 103349.

[13] J. Liu, H. Li, L. Sun, Z. Guo, J. Harvey, Q. Tang, H. Lu, M. Jia, In-situ resources for infrastructure construction on Mars: A review, *Int. J. Transp. Sci. Technol.*, 2022, **11**, 1–16.

[14] N. Shiwei, S. Dritsas, J.G. Fernandez, Martian biolith: A bioinspired regolith composite for closed-loop extraterrestrial manufacturing, *PLoS One*., 2020, **15**, e0238606.

[15] H. Roedel, M.D. Lepech, D.J. Loftus, Protein-Regolith Composites for Space Construction, Proc. 14th Bienn. Int. Conf. Eng. Sci. Constr. Oper. *Challenging Environ.*, 2014, 291–300.

[16] M.I. Allende, B.A. Davis, J.E. Miller, E.L. Christiansen, M.D. Lepech, D.J. Loftus, Hypervelocity Impact Performance of Biopolymer-Bound Soil Composites for Space Construction, *J. Aerosp. Eng.*, 2020, **33**, 04020001.

[17] M.I. Allende, B.A. Davis, J.E. Miller, E.L. Christiansen, M.D. Lepech, D.J. Loftus, Hypervelocity Impact Performance of Biopolymer-Bound Soil Composites for Space Construction, *J. Aerosp. Eng.*, 2020, **33**, 04020001.

[18] A.D. Roberts, D.R. Whittall, R. Breitling, E. Takano, J.J. Blaker, S. Hay, N.S. Scrutton, Blood, sweat and tears: extraterrestrial regolith biocomposites with in vivo binders, *Mater. Today Bio.*, 2021, **12**, 100136.

[19] E. Jéquier, Carbohydrates as a source of energy, *Am. J. Clin. Nutr.*, 1994, **59.**

[20] R.P. Ellis, M.P. Cochrane, M.F.B. Dale, C.M. Duffus, A. Lynn, I.M. Morrison, R.D.M. Prentice, J.S. Swanston, S.A. Tiller, Starch production and industrial use, J. Sci. Food Agric., 1998, **77**, 289–311.

[21] L. Kruger, N. Lacourse, Starch Based Adhesives, *Handb. Adhes.*, 1990, 153–166.

[22] G. Bumanis, L. Vitola, I. Pundiene, M. Sinka, D. Bajare, Gypsum, geopolymers, and starch-alternative binders for bio-based building materials: A review and life-cycle assessment, *Sustain.*, 2020, **12**.

[23] U. Benitha Sandrine, V. Isabelle, M. Ton Hoang, C. Maalouf, Influence of chemical modification on hemp-starch concrete, *Constr. Build. Mater.*, 2015, **81**, 208–215.

[24] A. Hussain, J. Calabria-Holley, M. Lawrence, Y. Jiang, Hygrothermal and mechanical characterisation of novel hemp shiv based thermal insulation composites, *Constr. Build. Mater.*, 2019, **212**, 561–568.

[25] A. Kremensas, A. Kairytė, S. Vaitkus, S. Vėjelis, S. Członka, A. Strąkowska, The impact of hot-water-treated fibre hemp shivs on the water resistance and thermal insulating performance of corn starch bonded biocomposite boards, *Ind. Crops Prod.*, 2019, **137**, 290–299.

[26] V. Alvarez, A. Vázquez, C. Bemal, Fracture behavior of sisal fiber-reinforced starch-based composites, *Polym. Compos.*, 2005, **26**, 316–323.

[27] F. Vilaseca, J.A. Mendez, A. Pèlach, M. Llop, N. Cañigueral, J. Gironès, X. Turon, P. Mutjé, Composite materials derived from biodegradable starch polymer and jute strands, *Process Biochem.*, 2007, **42**, 329–334.

[28] G. Balčiunas, S. Vejelis, S. Vaitkus, A. Kairyte, Physical properties and structure of composite made by using hemp hurds and different binding materials, *Procedia Eng.*, 2013, **57**, 159–166.

[29] A.T. Le, A. Gacoin, A. Li, T.H. Mai, M. Rebay, Y. Delmas, Experimental investigation on the mechanical performance of starch-hemp composite materials, *Constr. Build. Mater.* 2014, **61**, 106–113.

[30] Y. Kulshreshtha, E. Schlangen, H.M. Jonkers, P.J. Vardon, L.A. van Paassen, CoRncrete: A corn starch based building material, *Constr. Build. Mater.,* 2017, **154**, 411–423.

[31] G. Mansour, M. Zoumaki, K. Tsongas, D. Tzetzis, Starch-sandstone materials in the construction industry, *Results Eng.*, 2020, **8** 100182.

[32] Y. Kulshreshtha, P.J. Vardon, Y. Du, G. Habert, A. Vissac, J.-C. Morel, S.M. Rao, L. van Paassen, M. van Loosdrecht, N.J.A. Mota, Biological stabilisers in earthen construction: a mechanistic understanding of their response to water-ingress, *Constr. Technol. Archit.*, 2022, **1**, 529–539.

[33] W.S. Ratnayake, D.S. Jackson, Chapter 5 Starch Gelatinization, in: *Adv. Food Nutr. Res., Academic Press*, 2008, 221–268.

[34] Donovan J. W., Phase transitions of the starche-water system, *Biopolymers.*, 1979, **18**, 263–275.

[35] K.M. Cannon, D.T. Britt, T.M. Smith, R.F. Fritsche, D. Batcheldor, Mars global simulant MGS-1: A Rocknest-based open standard for basaltic martian regolith simulants, *Icarus*, 2019, **317**, 470–478.

[36] M.M. Osterloo, V.E. Hamilton, J.L. Bandfield, T.D. Glotch, A.M. Baldridge, P.R. Christensen, L.L. Tornabene, F.S. Anderson, Chloride-bearing materials in the southern highlands of mars, *Science*, 2008, **319**, 1651–1654.

[37] J. -L Jane, Mechanism of Starch Gelatinization in Neutral Salt Solutions, *Starch - Stärke*, 1993, **45**, 161–166.

[38] K. Ohishi, M. Kasai, A. Shimada, K. Hatae, Effects of acetic acid on the rice gelatinization and pasting properties of rice starch during cooking, *Food Res. Int.*, 2007, **40**, 224–231.

[39] Ray Mears, Making A Bow And Arrow And Fire With Stone Age Tools, *Bushcraft*, https://youtu.be/Ik7GbPEqljg?t=560 (accessed June 14, 2022).

[40] B. Jones, C.J. Nachtsheim, A class of three-level designs for definitive screening in the presence of second-order effects, *J. Qual. Technol.*, 2011, **43**, 1–15.

[41] R.C. de Vekey, H.W.H. West, The flexural strength of concrete blockwork, Mag. Concr. Res., 1980, **32**, 206–218.

[42] H. M. Kennedy, in *Adhesives from Renewable Resources*, American Chemical Society, 1989, **385**, 23–326.

[43] B.O. Juliano, A.P.P. Tuaño, Gross structure and composition of the rice grain, *Rice Chem. Technol.*, 2018, 31–53.