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Thermal performance exploration of 3D printed cob

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ABSTRACT

This paper investigates the thermal properties of 3D printed Cob, a monolithic earth construction technique based on robotically extruded subsoil and locally available organic fibres. The relevance of 3D printed earthen construction materials and the transition from vernacular construction towards a digitally-enabled process are critically discussed. The use of robotic manufacturing is outlined and the methodology to produce the necessary samples for thermal measurement is detailed. The results of the 3D printed samples are compared with traditionally-constructed Cob material of the same dimensions. The assessment has revealed strong potential for 3D printed cob as compared to its manually constructed counterparts in terms of thermal conductivity. Moreover, the testing process has helped in identifying several challenges in the 3D printing process of cob and the assessment of its thermal properties, which will ultimately bring the work closer to full-scale applications.

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Robotics; 3d printing; cob construction; parametric design; thermal analysis; vernacular architecture

Introduction

Conventional monolithic (e.g. concrete) construction has several associated shortcomings such as high CO₂ emissions, high embodied energy of construction process and depletion of natural resources (Goodhew and Griffiths 2005). In contrast, this paper presents cob construction as a viable alternative. Cob stands as the most used construction material around the world (Figure 1), and consists of subsoil (earth), water, fibrous material (typically straw) and sometimes lime. Other mixtures can use an addition of sand and/or clay, if required, in order to improve the physical properties of the material mix (Hamard et al. 2016). Given the reliance of this material on localized modes of construction, its application in built elements can be found in a series of material configurations including adobe bricks or 'quinchas' (clay-based soil mix applied onto a woven pattern of fibrous materials). Likewise, a series of geometric and formal configurations can be found in vernacular architecture which illustrate the versatility and structural characteristics of cob construction, including circular configurations in China and ovoid configurations in African vernacular architecture.

Cob is a sustainable material as compared with concrete, requires very limited resources to be sourced, mixed and constructed (Benardos, Athanasiadis, and Katsoulakos 2014). Moreover, Hamard et al. (2016) and Wanek, Smith, and Kennedy (2015) have demonstrated that re-using cob will have building performance and financial benefits, while it complies with modern UK building regulations.

In terms of design opportunities, cob provides higher freedom of design and ease of construction, while also it allows design modifications (cutting or adding material) easily at any

time when the building element's cob is still wet or dry (Melià et al. 2014; Hamard et al. 2016). This malleability, low cost and building performance suggest further work is required in order to understand the opportunities offered by cob in the new digital age, and particularly on novel and emergent frameworks of digital practice and design, such as robotic fabrication. Within this research territory, this paper explores the suitability of raw-earth in the research territory of robotically-assisted 3D printing. It is acknowledged that the consideration of raw-earth for 3D printing applications can reveal a series of potential lines of enquiry, such as mechanical and structural properties, new design and formal opportunities, new local economies and skilled labour, or environmental and geological considerations. This report stems from the project 'Computing craft' which aims at scoping the feasibility for robotically 3D printed cob structures at early stages of the technology development cycle, and further work is required to determine properties of larger scale cob construction. In response to this project's life cycle, we specifically introduce this area of enquiry by assessing the thermal performance of 3D printed cob in comparison with handmade cob samples.

In order to critically situate this research within the broader area of 3D printing, cob must be defined in relation to its vernacular constructive expression, and particularly on how it can be adopted and modified in the context of emergent digital practices. Here, vernacular architecture and construction are not seen as primitive or historical, but instead as a series of local sophisticated material practices which engage with and address local environmental and material conditions. It is acknowledged, then, that the perception of vernacular architecture has been

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Figure 1. Cob building in Totnes, UK (Veliz Reyes et al. 2018).

evolving to reflect different environmental, technological and cultural contexts (Niroumand, Barceló Álvarez, and Saaly 2016). Aligned with this, earthen materials have received renewed interest within the modern construction industry for the past few years (Chandel, Sharma, and Marwah 2016; Veliz Reyes et al. 2018). As a result, it can be claimed that despite its vernacular development, cob is currently being subjected to a series of studies aiming at incorporating this local, material-based knowledge within established frameworks of practice and academic research and development (e.g. Veliz et al. 2018).

Much of the material performance outside the confines of life-cycle assessment relates to the thermal properties of earthen building techniques and subsequent materials (Houben and Guillaud 1994; Hurd and Gourley 2000; Walker et al. 2005). This has been assessed in a number of different design configurations, including different sequences of material layers and the inclusion of natural insulation (Steven Goodhew and Griffiths 2005; Griffiths and Goodhew 2012). Many of these proposed or measured material configurations specify appropriate thermal characteristics, such as thermal conductivity (W/mK) or specific heat capacity ($J/kg/degC$). Thermal conductivity is a property that is used to calculate (whether in the more raw form of a spreadsheet or more complex and animated use of dynamic thermal simulations) the ability for a building built from the material to perform as expected. This performance might be associated with the thermal comfort of the occupants or the energy use of the building (CIBSE 2015). Therefore, much interest is centred on the ability for an earthen material, that can be made from different subsoil types and mixed at different ratios with a range of different fibres, to fulfil technical and legislative requirements.

In the present era, cob construction techniques operate under established frameworks of practice often based on notions of hand-making, hand-assembling and localized material intelligence. This operational knowledge has been developed over many years outside the boundaries of academic, technological and professional disciplinary frameworks (Crysler, Cairns, and Heynen 2012). At the same time, the construction industry has been demanding more complex forms, faster processes, and lower labour costs, which are making traditional construction methods increasingly obsolete (Veliz Reyes et al. 2018). Hence, Digital construction of earthen materials could be instrumental to promoting the use of locally available natural construction materials as it expands the range of sustainable construction solutions that are adapted to local contexts (Hamard et al. 2016; Veliz Reyes et al. 2018), following the key precepts of vernacular architecture such as local, material-driven knowledge and practices.

The benefits of digitally augmented crafts have been examined broadly only on small-scale applications, yet the greater benefits for the design and construction industry are poorly explored. An early study that was conducted at ETH Zurich by Gramazio, Kohler, and Willmann in 2008 has revealed the ability of robotic technology to directly create informed design solutions based on materials and manufacturing restraints (Veliz Reyes et al. 2018). This early experimentation has raised the awareness of digital fabrication, and particularly additive manufacturing, within the AEC industries worldwide (Hague, Campbell, and Dickens 2003; Wu, Wang, and Wang 2016). The continuous experimentation with digital fabrication methods in recent years has created substantial enhancements to large-scale 3D printing techniques (Baumers et al. 2016; Ishak, Fisher, and Larochele 2016).

This dramatic increase in the amount of research on implementing 3D printing into large-scale processes has revealed several potential applications for architecture and the construction industry (Agustí-Juan and Habert 2017; Wu, Wang, and Wang 2016), such as reductions in waste, material usage, and transportation costs in the supply chain. In this respect, both Hamard et al. (2016) and (Agustí-Juan et al. 2017) highlight that the integration of digital fabrication techniques into vernacular architecture has revealed sustainability potentials for construction applications. However, this research has also revealed further challenges to be addressed that include not only the development of novel 3D printing robotic applications, but more broadly their implications for the AEC industry such as the need for skilled labour, new material configurations, or new design and geometric opportunities.

Methods and materials

Prototypes design

This study is mainly assessing the thermal conductivity of four scaled prototypes of 3D printed cob specimens. Then the research compares the result to seven cob specimens of nearly the same dimensions that were constructed using manual techniques. The prototypes are scaled down to one fourth ($1/4$) the average real cob walls thickness. The geometries of prototypes are modelled in Rhinoceros via Grasshopper, while kuka PRC was

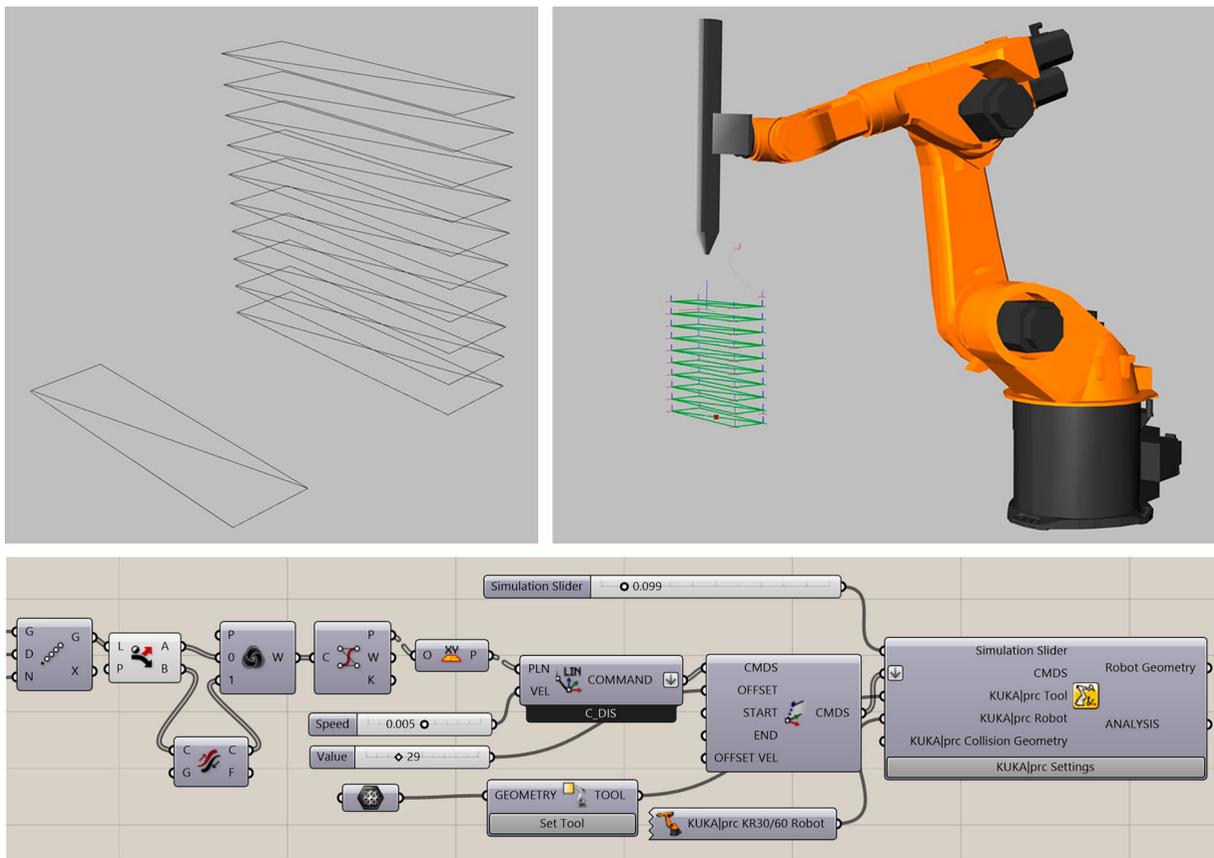


Figure 2. Creating the toolpath for cob prototypes in Rhino via Grasshopper and KUKA PRC.

the used tool for robotic simulation (Figure 2). Each model is designed on the basis of unidirectional tool paths then arrayed vertically to create the full height of the specimen. Some of the geometric constraints for toolpath design have been outlined as:

- The layer heights have been set to 18 mm, and the diameter of the nozzle in all experiments was 25 mm, yet, due to the fluid nature of the material, it was expected that a 35–40 mm thick cob path would be created.
- Printing speeds has been set at 10 mm/sec
- Initially all toolpaths have been created following a standard 3-axis contour crafting approach (X, Y, Z).

Virtual prototypes were then 3D printed at Cardiff University using a Kuka KR60HA robot and a custom designed material extrusion system (Figure 2). The extrusion system utilizes a stepper motor with a worm gearbox and acme screw that pushes the wet cob mix through a tube with a 25 mm nozzle at its end. Each 3D printed sample consumed nearly two hours for production (including the time to replace the cob cartridge). The designed geometries are converted into multi-layered path lines of which the robotic arm can follow in a layer by layer fashion (Figure 3). Each of the four prototypes was designed to represent a different solution for better thermal insulation of walls (Figure 4).

- (1) The first prototype was designed as a solid wall (CF1).
- (2) The second prototype was design as a double-layered wall with a single continuous air gap (CF2).

- (3) The third prototype was designed as a triple-layered wall with air pockets (CF3).
- (4) The fourth prototype was designed as double-layered wall with pockets filled with straw (CF4).

The 3D printed samples have dimensions of (300 × 300 × 90 mm), while the manually constructed samples (Figure 5) are (300 × 300 × 70 mm), both formed into blocks of a suitable size for the heat flow metre (Figure 6). The air gaps in the 3d printed cob samples is a natural result of the 3D printing technique and design workflow, while they are created without the use of form-work. This eventually leads to a reduction in time, the overall weight and used raw material while maintain the same volume as compared to conventional cob.

Materials

As stated earlier, cob basically is a mix of subsoil, fibre, and water. Weismann and Bryce (2006) recommended a generic ratio of water to subsoil as one part water to every five parts of dry ingredient. By converting this to weight, it means 2.0 Kg of water is added to each 8.0 Kg of subsoil. As for the straw, it is recommended to be 2% by weight. Hamard et al. (2016) supported the previous statement in his extensive systematic review on cob by affirming the proportions of cob mixture (averages) to be 78% subsoil, 20% water and 2% fibre (straw).

According to both Weismann and Bryce (2006) and Hamard et al. (2016), the recommendation for the subsoil formula itself is 15–25% clay to 75–85% aggregate/sand. Harrison (1999)



Figure 3. The 3D printing set up in Cardiff University; KUKA KR60 HA robot with a custom designed material extrusion system.



Figure 4. The Layer by layer technique of printing.

also stated similar recommendation of 20% clay to 80% aggregate/sand. Testing the subsoil properties is a critical step for the right determination of the cob formula. Testing occurs on the subsoil before water content is added. Subsoil contains different amount of clay, sand, silt and aggregate. This depends on the

sourcing location and where the subsoil is being dug within that location. Based on several field testing of the subsoil, besides using a trial and error method, amendment to sand and clay ratios could be identified to achieve the right ingredient for cob. After examining the subsoil, the next step is to add the water and fibres, which is straw for this study. Other bindings fibres can be used such as seaweed and alginate (Perrot, Rangeard, and Courteille 2018).

3D Printed cob samples

The subsoil for the 3D printed samples for this study was sourced from farmland near Barry in Cardiff, UK. Three subsoil specimens from three locations within the same field were examined according to the recommended testing methods that are found in the literature (Goodhew, Grindley, and Probeif 1995; Harrison 1999; Weismann and Bryce 2006). These tests included simple field tests and in-depth laboratory tests. Both testing methods have revealed that the ingredients of the subsoil are matching the general recommendations for cob mixture without applying any additional aggregates or clay. The subsoil samples from Cardiff were found to have an average aggregate to clay ratio as 79.5 to 21.5% respectively.

Since cob is typically mixed in a nearly dry state, the previous proportions do not fit the purpose of 3D printing. The relatively low water content of the mix creates massive friction in the extrusion circuit, which then generates enormous pressure on the extrusion system joints. This continues pressure leads to the destruction of the holding parts and it increases the wear rate of the electric actuators. Hence, a more viscous mix is required. However, the increase of water content can affect negatively other material properties including shrinkage, drying time and mechanical/structural stability during the 3D printing process, leading consequently to limitations in the layering heights and the overall quality of a printed prototype (Veliz Reyes et al. 2018).

Several 3D printing tests were conducted to reach a modified proportions of cob mixtures for 3D printing purposes. These tests mainly examined how the cob mix rheology is influenced by the following factors:

- (a) Water content in the cob mix
- (b) Extrusion speed (relative to the robot speed)
- (c) Layer height (relative to the nozzle diameter)

Testing process included systematic alteration of each factor. Water content was tested as 22, 24, 26, and 28%. Extrusion speed was tested on a range from 0.01 to 0.1 m/sec, while layer height was tested as 30, 60 and 90% of the nozzle size. Worth mentioning that the layer height always preferred to be less than the used nozzle diameter in order to create a flat surface that can support the following layer. The new mixture has an increase in the water content to 25–26%, a subsoil ratio of 72–73% and a straw ratio to 2%. In all cases, field tests of the subsoil properties are always recommended and required prior to determining the appropriate cob mix.

Manually constructed cob samples

The manually constructed cob samples were prepared at Plymouth University as part of the Interreg project 'The CobBauge'



Figure 5. Samples of the 3d printed cob. From left to right; solid, single gap with straw filling and double gap.



Figure 6. Samples of the manually constructed cob specimen in Plymouth University. The cob sample to the left uses UK subsoil in the mix, while the right one uses French subsoil.

(The CobBauge Project 2018). These samples were prepared in the lab using a variety of sub-soils that had been identified as being suitable for use in cob construction without additional aggregates. The soils were then analyzed for particle size distribution. These tests were carried out by wet sieving for the fraction greater than 80 μm and by laser granulometry for elements smaller than 80 μm . The soils are identified as FR4, a sandy yellow French soil with a low clay content and UK3, a heavy red clay soil from mid Devon (UK). The subsoils had a variety of fibres added to them in different proportions based on the literature (Hamard et al. 2016), and the accumulated experience on several actual cob building projects.

The fibres used in these tests were hemp shiv, chopped reed and chopped straw in proportions of 8%, 4%, 2% and none (% by dry weight of soil). The soils were first oven dried at 40°C until they reached an equilibrium weight, where 3 subsequent weighings at 24 hour intervals were within 1% of each other, then a percentage of water was added: 28% to the FR4, and 31% to UK3 (the different amounts of water were added to give the same viscosity to the final mix). After allowing the clays to soak, the fibres were added and mixed manually.

Thermal performance testing

To establish the thermal performance of the material, a series of conductivity tests were undertaken using a Heat Flow Meter at Plymouth University (Figure 7). The four 3D printed cob samples were compared to seven manually-constructed cob samples.

The heat flow metre used for the conductivity tests was a Netzsch HFM 446 (NETZSCH 2018). This machine is based on ASTM C518, ASTM C1784, ISO 8301, JIS A1412, DIN EN 12664, and DIN EN 12667 Method and Technique for the Characterization of Insulation Materials. The Netzsch was chosen because it takes a larger sample size and uses additional external thermocouples in conjunction with the hot and cold plates. This makes it suitable for measuring denser, more random materials like cob.

The thermal measuring process requires samples of a certain size and geometry. Thus, the results are influenced by the thermal measurement technique and the geometry produced via the 3d printing process. Comparability of samples could be improved by using the same cob mix in both conventional and 3d printing technique. Yet, the cob mix used for 3d printing purposes needs to combine a higher water content at 25–26% and low straw ratio at 2% as compared to conventional cob mix.

Results

Table 1 shows all the tested cob samples, listed in order of their conductivities. The close relation between density and conductivity could be also seen (Volhard and Reisenberger 2016). The graph in Figure 8 shows the relationship between conductivity and density of all the cob samples. Walls with lower conductivity and lower density, towards the left bottom corner of the figure, are more desirable due to their higher insulation value and lighter weight. The conductivity results show that all specimens conform to within 10% of each other. The dotted line

Table 1. Results of the Conductivity analysis of the cob samples in relation to their density.

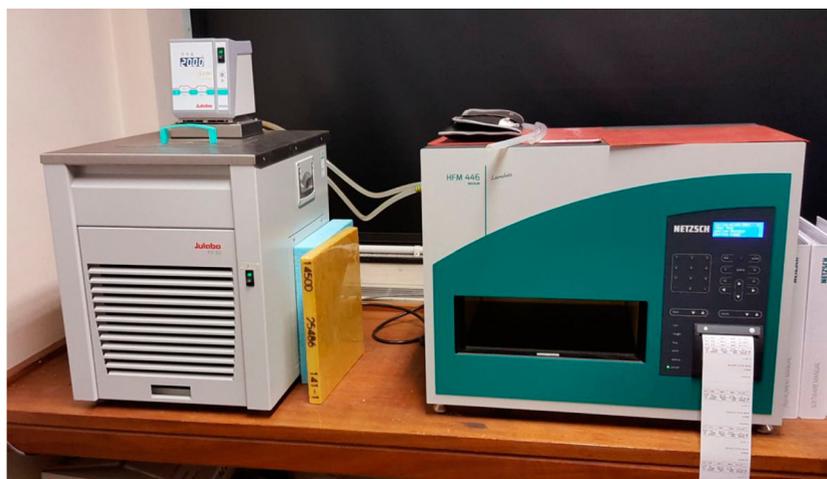
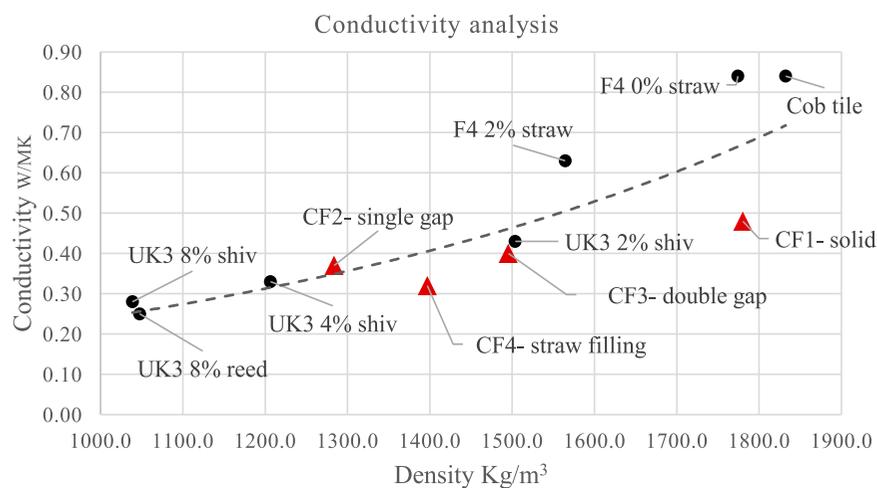
Sample	Method	Density (kg/m ³)	Conductivity (W/mk)
UK3 8% reed	Manual	1047.6	0.25
UK3 8% shiv	Manual	1038.7	0.28
CF4 Straw fill	3d printed	1397.0	0.32
UK3 4% shiv	Manual	1206.5	0.33
CF2 Single-Gap	3d printed	1283.7	0.37
CF3 Double-Gap	3d printed	1495.5	0.40
UK3 2% shiv	Manual	1503.8	0.43
CF1 Solid	3d printed	1780.3	0.48
F4 2% straw	Manual	1564.5	0.63
F4 0% straw	Manual	1774.3	0.84
Cob Tile	Manual	1832.3	0.84

shows an exponential trend in the relationship between the density and conductivity of the samples (Dominguez-Muñoz et al. 2010). Of the four printed samples, the three that are not solid are all below this line. This indicates that the cavities in the samples are affecting their performance, and giving a relatively better conductivity in relation to their density).

The percentage of straw in the cob mixture of the 3D specimens was kept constant at 2%. The differences were in the

design of the specimen cross-section and the addition of loosely packed straw in air cavities. The analysis indicates that the use of air cavities combined with the addition of straw into them significantly improves the conductivity of the 3D printed samples relative to their density. Specifically, CF4 (Air gap with straw) showed an improvement of 15.0% in conductivity and an increase of 8.0% in density when compared to CF2 (Air gap without straw). In terms of absolute conductivity, sample CF4, with the straw filling, gives the best result among the 3D printed samples due to its lower conductivity regardless of density. Within manually constructed samples, the higher percentage of fibres in the mix lead to lower density and consequently a lower conductivity.

Compared to all samples, CF4 represented the third best result. The significant thermal performance of the 3D printed samples is immediately recognized among their manually-structured counterparts. Even when comparing solid samples, the CF1 specimen out-performed approximately half the manually-constructed samples. The relationship between density and conductivity is plotted for a range of conventionally mixed soil and fibre mixes. There is no reference for an extruded material, so further work will be needed to establish the appropriate relationship.

**Figure 7.** Heat flow metre (HFM 446) at Plymouth University.**Figure 8.** Conductivity of all the cob samples in relation to their density.

Conclusions

the results detailed above reveal that 3D printed cob is comparable with hand-made counterparts. While the 3D printed samples do not outperform the hand-made samples significantly, the results suggest that 3D printing can be utilized for cob construction without compromising the building performance of the construction, thus revealing further opportunities for research by exploring additional benefits of robotic fabrication, including (among others):

- Novel geometric and design opportunities.
- Higher precision and accuracy of the built element when compared to manual labour, specially in producing complex geometries
- Exploring emerging opportunities in the field of robotics in terms of skills automation, as well as to develop new skills in the construction workforce.
- Scoping new opportunities afforded by recent development in the fields of robotics and material sciences including human-robot collaboration, artificial intelligence and data-driven design processes.

This study, on the other hand, has exposed major challenges of cob 3D printing during the early stage of experimentation. Three main challenges were specified: extrusion speed, consistency of extrusion, and continuity of extrusion. Hence, the project team has been developing an innovative bespoke large-scale cob extruder that has improved dramatically the preceding challenges. The new extrusion system is capable of achieving variable high speeds up to 0.3 m/sec, while combining an enhanced cartridges system that allows a continuous extrusion of material. The details of the new system will be introduced as part of a future study. Another line of future studies will focus on establishing a viable business model, utilizing robotically fabricated building components for small-scale building solutions.

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