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3D printing polyurethane foam structures for aerial additive building manufacturing

Barrie Dams[1*]
Sina Sareh[2]
Ketao Zhang[2]
Paul Shepherd[1]
Mirko Kovac[2]
Richard J Ball[1]

[1] BRE Centre for Innovative Construction Materials, Department of Architecture & Civil Engineering, University of Bath, Claverton Down, Bath, BA2 7AY.

[2] Aerial Robotics Laboratory, Department of Aeronautics, Imperial College London, South Kensington Campus, London, SW7 2AZ.

* corresponding author:
b.dams@bath.ac.uk
(0044) 7443566080
BRE Centre for Innovative Construction Materials
Department of Architecture and Civil Engineering
University of Bath
Bath
BA2 7AY

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Abstract

This paper describes the first aerial additive manufacturing system developed to create and repair civil engineering structures using polymeric materials 3D extrusion-printed by aerial robots. The structural potential of three commercially available expanding polyurethane foams of varying density (LD40, Reprocell 300 and Reprocell 500), and their feasibility for deposition using an autonomous dual-syringe device is described. Test specimens consisting of one and two layers, with horizontal and vertical interfaces, were mechanically tested both parallel and perpendicular to the direction of expansion. LD40 specimens exhibited ductile failure in flexural tests and provided evidence that interfaces between layers were not regions of weaknesses. Hand-mixed specimens of Reprocell 500 possessed compressive strengths comparable with concrete and flexural strengths similar to the lower range of timber, though exhibited brittle failure. There are challenges to be faced with matching the performance of hand-mixed specimens using the autonomous dual-syringe deposition device, primarily concerning the rheological properties of the material following extrusion. However, the device successfully imported and deposited two liquid components, of varying viscosity, and maintained correct mixing ratios. This work has demonstrated the structural and operational feasibility of polyurethane foam as a viable material for extrusion-printing from aerial robots.

Keywords chosen from ICE publishing list

Materials technology; Resins and plastics; Strength and testing of materials.

List of Notations

ABM	Additive Building Manufacturing
DC	Direct current
G’	Elastic modulus
G’’	Viscous modulus
kg	kilograms
kN	kilonewtons
LE	Linear Encoder
SEM	Scanning Electron Microscopy
V	Volts
δ	Phase angle

1. Introduction

Additive manufacturing in the construction industry currently consists of large, ground based processes (Lim et al. 2012; Kreiger et al. 2015) which are reliant upon favourable topography, soil conditions and climate. The size of an additive manufactured, or ‘3D printed’, building is restricted by the size of the deposition machinery. Structures have been created without the need for formwork, using both cementitious materials with the contour crafting, concrete printing and D-shape printing methods (Lim et al. 2012; Le et al. 2012; Labonnote et al. 2016) and polymeric materials, an example of which is the ‘canal house’ in Amsterdam, which consists of bio-plastic elements (Frearson 2016; Labonnote et al. 2016). Additive manufacturing technologies currently being investigated for applications in the construction industry broadly fall into three categories: fused filament fabrication, powder bed printing and extrusion printing (Kreiger et al. 2015; Stansbury and Idacavage, 2016). The latter method extrudes fluid from a nozzle one layer at a time. The interface between these layers is of critical importance, as factors such as the adhesive, rheological and curing properties of the material, height of layer and speed of deposition all affect the interface and whether it may become an area of weakness in the ensuing structure (Lim et al. 2012; Krieger et al. 2015).

Aerial robots have been established in a variety of applications including remote sensing (Sugiura et al. 2003), agriculture (Sugiura et al. 2003), aerial photography (Schutte et al. 2001) and surveillance (Wright 2005), and are being considered in other areas such as courier delivery (Siciliano and Khatib 2008). Within the Aerial Additive Building Manufacturing (Aerial ABM) project, it is envisaged that a coordinated swarm of aerial robots, each equipped with a 3D printing device depositing viscous liquid with suitable mechanical properties, can construct or repair buildings free from constraints concerning size, soil conditions and topography. This would be particularly applicable where faced with hazardous or inaccessible environments. The feasibility of 3D printing using a single aerial robot was demonstrated by co-authors at the Aerial Robotics Laboratory of Imperial College London (Hunt et al. 2014).

This paper investigates the feasibility for autonomous 3D extrusion printing of buildings and infrastructure repair applications using polyurethane foam. Expanding polyurethane foam is established in the construction industry as a method of insulating buildings (Wu et al. 2012) due to its low coefficient of thermal conductivity (Zhang et al. 2014). To the authors' knowledge, expanding polyurethane foam has not previously been used as a structural material in either residential or commercial construction projects. This study compares low density LD40 foam used for thermal insulation (Isothane 2016a) to higher density foams Reprocell 300, marketed as a substitute for timber in prop and set design, and Reprocell 500, which is used for deep sea buoyancy applications (Isothane 2016b).

A feasibility study of the two low density polyurethane foam liquid components (Hunt et al. 2014) demonstrated that these liquids could be carried by an aerial robot capable of mixing and extrusion 3D printing the material during controlled, coordinated flight. Quadcopters capable of depositing foam within a defined 10 cm radius circle have been developed (Hunt et al. 2014) and Figure 1 illustrates the robot in flight with an attached, deployed dual syringe device and mixing nozzle of preliminary design.

2. Experimental Methodology

The mechanical, morphological and rheological properties of the foams were laboratory tested to determine structural and operational feasibility.

2.1 Polyurethane foam

The liquid components of LD40, Reprocell 300 and Reprocell 500 consist of a polyol resin and an isocyanate hardener (Alaa et al. 2015), with the resulting rigid foam a product of polymerisation, as two isocyanate groups per molecule chemically react with the polyol (Trovati et al. 2009). The mixing ratio was 1:1 by volume for all three foams.

Foam specimens were made using three methods:

- ‘cut-edged’: pouring liquid components into a tray and hand mixing to create a bulk of material, which was subsequently cut into specimens using an electric band saw
- ‘moulded’: pouring hand mixed liquid into wooden moulds which had been sealed and pre-sprayed with Macsil releasing agent
- deposition of mixed liquid on to a plastic modelling mat by an autonomous, powered dual-syringe device

It was necessary to determine whether a closed porosity moulded edge provided significantly different properties to an open porosity cut edge. Test specimens were created both in one cycle of deposition, forming a single layer, and in two deposition cycles, forming either horizontal or vertical interfaces in the material. Interfaces are illustrated in Figure 2, which also shows images of the moulded, one layer specimens for all three foams created for compressive strength tests.

2.2 Mixing by Hand

The Reprocell 500 liquid components required heating to a temperature of 35˚C ±5˚C and once poured together, required constant stirring to cream at 30 ±10 seconds due to the isocyanate and polyol resin not initially being entirely miscible. At ≈90 seconds, the light honey coloured cream began to change to a darker brown, thinner liquid as the polymerisation process began, resulting in an exothermic reaction increasing the temperature to over 100˚C. Expansion occurred at 135 seconds with the isocyanate reacting with the water in the polyol resin. Pouring took place between 140-160 seconds with solidification at 180 seconds. Reprocell 300 specimens were created using a similar method, however the exothermic reaction reached ≈80°C. LD40 required minimal stirring at room temperature to cream and exothermic reactions, below 50°C, did not produce a visible change in the creamed liquid colour or viscosity.

LD40 specimens, with an average density of 45 kg/m^3, possessed a high expansion ratio during polymerisation of 20:1. Reprocell 300 specimens averaged a density of 345 kg/m^3 and expanded significantly less, with a ratio of 2:1. Reprocell 500, had a density averaging 685 kg/m^3 and displayed minimal expansion of 1.5:1. During specimen creation, the laboratory temperature was 20.3˚C ± 0.5˚C with 52% air humidity ±5%.

2.3 The syringe deposition device

To autonomously deposit the foam material, a motorised syringe device was developed as shown in Figure 3. The device employed a miniature high-power 6V DC brushed motor with a 298:1 metal gearbox (Pololu, 2016) powered by a PL155

Aim TTI bench supply. The rotary motion of the motor’s shaft was translated to linear motion using a leadscrew mechanism, which moved the two syringes’ plungers simultaneously. Currently, the aerial robot carrying capacity is 0.6 kg, therefore the amount of material capable of being lifted was accommodated by two BD Plastipak 50 ml concentric luer lock syringes. Attached to the luer lock was a mixing device consisting of two 3 mm internal diameter silicone rubber tubes joined to a single 5mm internal diameter silicone tube with a plastic connector. The single 5mm tube contained one (for LD40) or two (for Reprocell 500 and 300) 3M 5.3mm static epoxy mixing nozzles.

The motor was driven at a constant Voltage of 5.95 V thereby allowing the power requirements for the three foams to be determined by the current. With Reprocell 300 and 500, foam deposition on a level surface was attempted with two static mixers, the first followed by 34 cm of tubing (theoretically a two minute flow duration) and the second, 17 cm (one minute flow duration), to accommodate the different stages of reaction. For the LD40 foam, a single static mixer and a subsequent 17 cm length of 5mm diameter tubing was used.

The syringe device was suitable for integration into the 3DR ArduCopter Quad aerial robot (as shown in Figure 1) equipped with an ArduPilot on-board processor, three axis accelerometer, three axis magnetometer and four brushless motors with speed controllers. For this study, stationary positioning of the extrusion nozzle was assumed. The deposition of foam on to a free surface served to confirm the feasibility of 3D printing the material, rather than producing rectangular parallelepiped specimens required for British standards mechanical tests.

2.4 Mechanical Tests

Three-point bending and compression tests were conducted on cut-edged and moulded specimens in accordance with the rigid cellular plastics standards BS 4370-4:1991 and BS EN ISO 844:2014 respectively. The mechanical properties were tested both parallel and perpendicular to the direction of expansion using a 50 kN Instron Universal 2630-120/305632 for the flexure tests of all three foams, along with LD40 compressive strength tests. An Automax 5 50-C46W2 was used for Reprocell 300 and 500 compressive tests due to a greater force than 50 kN being required.

Deformation due to long-term loading was analysed using a bespoke creep rig (Figure 4), fitted with Solartron LE12 linear encoders as optical gauges. The device accommodated eight specimens measuring 30 mm high x 20 mm x 20 mm. There were two samples each of LD40, Reprocell 300 and Reprocell 500 hardened foams (one sample with a vertical interface and one without an interface) along with a solid pine whitewood timber sample, perpendicular to the grain direction (a weaker timber) and an oak sample parallel to the grain (a stronger timber) for comparison. Appropriately sized weights were suspended from the horizontal lever arms at a distance of 630 mm from the samples (Figure 4). The pivots were 35mm from the samples, providing a mechanical advantage of 18. The weights were relative to the average compressive strength of the material at a ratio of 32:1. This corresponded to 1kg, 0.25kg and 0.025kg for the Reprocell 500, Reprocell 300 and LD40 foams respectively. The pine sample was assumed to have a compressive strength >4 MPa and the Oak sample >8 MPa (WoodworkWeb 2017), therefore these were conservatively subjected to 0.125 kg and 0.25 kg respectively. 2 mm thick steel plates measuring 25 mm wide x 40 mm long were placed on top of the samples to ensure force was applied uniformly to each specimen.

The eight Solartron LE12 linear displacement transducers formed an Orbit 3 network with a Solarton USBIM Mk2 USB controller connected to a Solartron PIM supplementary power supply, to ensure power to all eight linear encoders. Measurements were recorded every 15 minutes over a period of 14 days. Temperature and humidity were monitored for the duration of the test period to ascertain the effect of differing environmental conditions; these readings were synchronised with the orbit network.

2.5 Rheological Tests

The liquid components of the foam – all three resins and the M27 Isocyanate, were tested to determine viscosity using a Bohlin C-VOR 200 rotational Rheometer with torque rebalance software and temperature controlling water bath. The geometry was of the 4°/ 40mm specification, with a gap of 150 microns between upper and lower plates. Shear stress was controlled and shear rate was kept constant. Applied stresses ranged from 0.02 Pa to 20 Pa, with 50 samples taken within the range and a 5 second delay specified between samples. Each liquid was tested three times over the stress range and at temperatures of 26°C, 30°C, 34°C, 38°C and 42°C to determine how viscosity changed as temperature increased.

The mixed creamy, viscous liquids of the foams were analysed with a Malvern Kinexus Ultra+ rheometer using a bespoke method which increased the gap between geometry and base plate as the liquid expanded. Diameters of the upper and base disposable plates were 25mm and 60mm respectively. The gap began at 1mm; following the recognition of normal force reaching a level of 0.005 Newtons, the method exercised normal force control, maintaining a constant force to avoid compression of the foam and analyse the vertical expansion of the material. The mixed liquids were hand-stirred for forty seconds prior to placing upon the lower disposable plate and oscillatory stress was applied with a flat geometry at a constant shear strain of 0.1. The method recorded the elastic modulus G’, viscous modulus G’’ and phase angle, δ, over a time period of nine minutes to monitor how the rheological properties changed as the mixed foam solidified.

2.6 Microscopy

Two microscopy approaches were utilised to visualise the solid foam. A JEOL SEM6480LV Scanning Electron Microscope (SEM) was used to obtain images of cuboid samples at a magnification of 70x. A 10 nm gold coating was applied to the samples prior to insertion into the electron microscope chamber to reduce charging. In addition, cuboid samples of the three foams were vacuum impregnated with resin and polished. Images were recorded using a Leica M205C stereo optical microscope and the Leica application suite V3.8 software application at 5x magnification. Images were recorded of cut-edged interiors, moulded exteriors and material interfaces.

3. Results

3.1 Mechanical Tests

The compressive and flexural strengths of the three different types of foam can be seen in Figure 5. The compressive strength achieved with the hand mixed Reprocell 500 specimens exceeded 30 MPa, with one layered specimens almost reaching 40

MPa. This is far in excess of the manufacturer’s specification (11.7 MPa) (Isothane 2016b). Reprocell 300 compressive strengths were <10 MPa for specimens with interfaces, however one layer specimens almost reached 15 MPa. Compressive strengths for LD40 were <1 MPa.

The flexural strength of Reprocell 500 reached 25 MPa, revealing that it is comparable with the lower range of timber, which is 30 MPa (Howard 2003). However, failure with both Reprocell 500 and 300 was universally brittle and vertical interface cut-edge specimens where direction of expansion was parallel to the applied load, were considerably more fragile and failed to reach 5 MPa. Fragility was not evident in moulded specimens with vertical interfaces, where the direction of expansion was perpendicular to the applied load. The flexural strength results provide an elastic modulus range of <0.1 GPa for LD40, 0.2 – 0.6 GPa for Reprocell 300 and 0.4 – 1.4 GPa for Reprocell 500. LD40 displayed ductile failure and the vertical interface moulded specimens, again loaded perpendicular to expansion, performed well in relation to one layered and horizontal interface specimens.

Two samples of each foam were tested in the creep rig. For each foam, the single layered and vertical interface sample strengths were consistent, therefore Figure 6a shows the mean sample deformation for each of the three foams. Reprocell 500 and Reprocell 300 performed competitively with oak. As expected, the low density LD40 was the foam most susceptible to creep. The oak and pine samples were influenced by environmental conditions and fluctuated significantly (Figure 6b); this is particularly evident around one and seven days. The foams were influenced less by temperature and humidity.

3.2 Power, Energy and Syringe Deposition

Table 1 summarises the energy and power required to draw up and deposit 2 x 50 ml of liquid. This represents the energy and power required for a single aerial robot to obtain and expel its maximum carrying capacity. Through the 5mm internal diameter tubing, the velocity of liquid foam travel, without expansion, was 17 cm/minute. There was negligible variation observed in time between the three types of foam both for drawing up and deposition. The syringe device took 15 minutes to draw up 2 x 50 ml of liquid, and 15 minutes to deposit, operating at a rate of 3.33 ml per syringe per minute. The influence of the visibly greater viscosity of the Reprocell foam resin components had been mitigated by prior heating to a temperature of 35˚C ±5˚C. Reprocell 500 deposition required approximately twice as much energy as LD40.

3.3 Rheology

The Rheometer results are presented in Figure 7. All liquid components behaved in a Newtonian manner and experienced shear thinning with increased stress and reduced in viscosity as temperature increased (Figure 7 a-d). At 2000 – 4000 centiPoise, Reprocell 300 displayed the greatest viscosity. All three mixed foams took approximately 9 minutes to change from liquid-like behaviour, where G’’ is dominant, to solid-like behaviour beyond the gelling point where G’ becomes dominant. The gelling point was 529 seconds for Reprocell 500 as shown in Figure 7e. All mixed foams displayed non-Newtonian behaviour and two distinct peaks with the phase angle, δ; Figure 7e shows the phase angle peaks for Reprocell 500. The expansion of the foam was recorded by the normal force control as being 1.9:1 for Reprocell 300 and 1.4:1 for Reprocell 500.

3.4 Microscopy

The SEM images in Figure 8 highlight the difference in porosity between a moulded specimen exterior (Figure 8a, 8c and 8e) and a cut-edge specimen (Figure 8b, 8d and 8f). The exterior image of Reprocell 500 shows an absence of pores at the specified magnification. Material interfaces can be seen running horizontally across Figure 8g (LD40) and Figure 8h (Reprocell 500). Optical microscope images can be seen in Figure 9. The image of an interface within a Reprocell 500 sample shows reduced pore sizes along the edge of the upper layer (Figure 9d). Reprocell 500 exhibited greater variation in cell size than the more uniform Reprocell 300. The Reprocell 500 resin component has a lower viscosity, which makes formation of microcells easier, resulting in uneven diameter sizes and larger cells being present (Zhang et al. 2014).

4. Discussion

The high compressive strength of the moulded specimens of Reprocell 500 was aided by its high density and low expansion ratio. The average density (685 kg/m^3) was the result of extensive and rigorous hand-mixing before, during and immediately following polymerisation. The compressive strengths of the cut-edge specimens were similar to the moulded specimens. The SEM images show significant closed porosity at moulded edges (Figure 8a, 8c and 8e), yet the presence of a significant edge effect enhancing the compressive strength of the material is not evident in one layer, horizontal interface or vertical interface specimens.

Moulded specimens with a vertical interface far outperformed cut-edge vertical specimens in flexure. However, it is reasoned that this gap in performance is due to the stronger adhesion of a vertical interface formed by the pouring of liquid perpendicular to the direction of loading, rather than the edge effect of the moulding.

LD40 exhibited ductile failure in flexural tests. The interface between two layers, intuitively expected to be a weakness, revealed itself to be an area of strength within the material, with specimens containing vertical interfaces not cracking at the interface during flexural tests, but elsewhere within the single layer of the rest of the specimen. Likewise, the horizontal interface provided extra resistance in three-point bending, contributing to a gradual failure with warning cracks rather than catastrophic failure. However, LD40 specimens possessed a bending strength of less than 1 MPa, suggesting suitability for non-structural purposes.

The ductile failure of LD40 contrasted with the brittle failure of the Reprocell foams in flexure, where vertical interfaces parallel to the expansion of the foam in cut-edged specimens did indeed prove to be a weakness, as flexural specimens cracked predominantly at the interface and did not match the performance of one layered or horizontal interfacial specimens. Reprocell 500 is comparable with timber in terms of flexural strength, but it is less stiff; the modulus of elasticity is a maximum of 1.4 GPa. This is similar to timber’s elastic modulus in the weaker axis perpendicular to the grain rather than parallel to the grain, which can be as high as 20 GPa (Howard, 2013). The SEM images show a material which is not homogeneous; the pores differ greatly in size and distribution. The interfaces in Figure 8g and 8h show a clear difference – the LD40 layers have a superior, seamless bond, whilst the Reprocell 500 dense foam material surrounds a distinct line of pores where the layers meet. The deposition of a small amount of material in situ by an aerial robot would result in vertical interfaces. This could be mitigated by a sequence of aerial robots immediately depositing their fluid before the preceding fluid had set, minimising each printed layer to one vertical interface at differing locations. Lateral/wind loading would be a secondary concern, as this would impart loading perpendicular to the rise of the foam. Reprocell 500 represents a viable proposition as a compressive element in a 3D printed structural solution and LD40 a viable insulating material.

The compressive viability of Reprocell 500 is further emphasised by the creep results (Figure 6). Reprocell 500 is competitive with oak and the Reprocell 500 samples were subjected to a heavier weight. It is entirely possible that the oak sample, parallel to the grain, had a compressive strength equivalent to or greater than Reprocell 500 and would have deformed to a greater extent with a 1 kg weight. The timber samples showed clear expansion with increased humidity and contraction with decreased humidity, whereas the Reprocell foams were significantly more stable and resistant to environmental change. Reprocell foams are suitable to resisting deformation from long term loading.

With the rheology results in Figure 7, it can be seen that with all four fluids, the polymer chains have greater freedom to be able to slide past each other as both shear stress and temperature increase, leading to reduced viscosity. The heating of the liquid components of Reprocell 300 and Reprocell 500, and subsequent reduction in viscosity, contributed to the amount of power being required to draw-up and deposit the Reprocell foams being less than double than that required for LD40 (Table 1). Considering that Reprocell 500 has order-of-magnitude superior compressive and flexural strengths to the LD40 foam, the extra energy is justified.

The mixed fluids used in the rheology tests experienced considerably less rigorous hand mixing than the mechanical test specimens due to the logistical requirements of placing and suitably trimming the samples. Tests confirm initial liquid-like behaviour, followed by a reduction in the phase angle as viscosity increases. This is followed by confirmation that the darkening, ‘thinning’ of the liquid as polymerisation occurs results in reduced viscosity and a second clear peak as the mixed foam again becomes more liquid-like (Figure 7e).

The final phase of solidification in the rheometer tests took almost three times as long as hand-mixed specimens. Mixed Reprocell foams deposited by the syringe device also did not react fully within the three-minute hand-mixed timeframe, as the static mixers in the tubing supplied less rigorous mixing than was achieved by hand. The polymerisation stage of the Reprocell foams’ chemical reaction did not take place inside the tubing, but instead post-deposition, after lateral spreading on the free surface had occurred with negligible vertical expansion. Clearly, as the stress applied to the mixed Reprocell foams increased, the rate of reaction increased. LD40 syringe device deposition resulted in the material reacting and expanding exactly as hand mixed samples did; however, expansion on the free surface varied greatly in magnitude and direction, which is undesirable for the given context.

The realisation of 3D printed hardened specimens on a free surface with sufficient shear strength and yield stress to support further layers is a challenge and will involve modifying the rheology of the foam, for example by adding solid particles to increase the shear strength. Two approaches may be investigated further with the syringe deposition device; more rigorous mixing, whether by larger static mixers or introducing mechanical mixers, or increase the tubing length and introduce more static mixers at intervals, so that the liquid may stay within the device for a longer period. The former approach would be preferable to increase the pace of deposition in a construction environment and allow aerial robots to deposit liquid at a greater rate.

This study shows that high density polyurethane foam could feasibly be used as a structural polymeric material. It also demonstrates that a small dual-syringe device light enough to be carried by a quadcopter is capable of depositing and mixing liquids of varying viscosities while maintaining the mixing ratio required for polymerisation. The potential contribution to the construction industry of aerial additive manufacturing is significant. In addition to reducing labour costs, mitigating health and safety issues and reducing waste by using material efficiently, the aerial approach would release autonomous construction from ground-based design and logistical size restrictions. It would facilitate both building repair work involving inaccessible or inhospitable locations, where human labour may be compromised both in terms of accuracy and safety, and the autonomous creation of structures upon unfavourable terrain and in hostile conditions unsuitable for heavy, grounded machinery.

5. Conclusions

It is concluded that Reprocell 500 high density foam has the potential to be both a homogeneous structural material and, particularly, a compressive element in a composite structural solution 3D extrusion-printed by aerial robots. The ability to be printed by an autonomous device requires modification of the foams’ rheology to achieve high viscosity immediately after extrusion and provide sufficient shear strength to support further layers while still liquid. This challenge is being investigated by the authors using particle addition and active mixing. LD40 has the potential to be 3D extrusion-printed for non-structural purposes such as insulation. All three foams were successfully drawn-up, mixed and deposited by the single motor dual-syringe deposition device. By investing approximately twice as much power and energy, the syringe device was capable of depositing material in excess of ten times higher density and with compressive and flexural strengths an order of magnitude higher. The study has demonstrated the feasibility of 3D extrusion-printing a polymeric structural material using an aerial robot.

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Figure Captions

Figure 1: Aerial additive manufacturing - a 3D printing system on-board an aerial robot capable of depositing foam within a defined 10 cm radius.

Figure 2: Moulded compressive test specimens of the polyurethane foams a) LD40 b) Reprocell 300 c) Reprocell 500 and test specimen schematic diagrams d) one layer, e) horizontal interface and f) vertical interface.

Figure 3: The dual syringe deposition device and tubing, a) Concentric luer lock syringes b) 6V DC motor c) 3mm internal diameter silicone tubing d) Plastic interconnector e) 5mm internal diameter silicone tubing f) Epoxy static mixer nozzle.

Figure 4: The creep rig a) Cuboid samples b) metal plates to cover the samples and ensure uniform loading c) suspended weights d) horizontal lever arms e) solar orbit linear encoders f) pivots.

Figure 5: Mechanical test results a) compressive strength at fracture or 10% relative deformation b) flexural strength at fracture or 0.05 tensile strain.

Figure 6: The creep rig results showing deformation due to long term loading along with the temperature and humidity data a) Foam sample mean deformation and timber sample deformation b) Temperature and humidity.

Figure 7: The Rheometer test results showing a-d) the viscosity of the three foam resins and M27 Isocyanate hardening agent liquid components (note the different *y*

axis for a & b) and e) the rheology of the mixed Reprocell 500 liquid: elastic modulus (G'), viscous modulus (G'') and the phase angle (δ) plotted against time.

Figure 8: Scanning electron microscopy images taken at x70, a) LD40 moulded edge b) LD40 cut-edge c) Reprocell 300 moulded edge d) Reprocell 300 cut-edge e) Reprocell 500 moulded edge f) Reprocell 500 cut-edge g) LD40 interface h) Reprocell 500 interface.

Figure 9: Stereo optical microscopy images taken at 5x, a) LD40 cut-edge b) Reprocell 300 cut-edge c) Reprocell 500 cut-edge d) Reprocell 500 interface.

Tables

Table 1: Power and energy consumption of the syringe device for the three foams.