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Functionally graded 3D printed asphalt composites

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ABSTRACT

A new technique for additive manufacture of composites has been developed, capable of 3D printing different compositions of asphalt with magnetic nanoparticles. Variation of the material feed ratio combined with precise fabrication geometries offers a simple avenue to functional grading of the materials properties. The integration of nanomaterials into milli-scale particle feedstock offers a new modality of nanomaterials handling, mixing and processing. We use X-ray computed tomography to quantify the functional grading and magnetic hyperthermia experiments to illustrate the functionalisation of the 3D printed composites. The technique is general and can be applied to a wide variety of materials; it has immediate application for repairing cracks in asphalt roads to modulate their properties and improve the lifetime of the repair.

1. Introduction

Repair of cracks in asphalt roads is a promising way to increase the lifespan of roads through preventing pot-hole formation. In the absence of repair water gets into the cracks which grow rapidly during freeze-thaw cycles and cause de-bonding of the aggregates forming potholes [1]. Once the cracks start it is hard to stop the growth of potholes which cause significant damage to vehicles and shorten the usable lifetime of the road. We have recently demonstrated that 3D printing of asphalt is a viable method for repairing such cracks and could be deployed using an autonomous vehicle to repair small cracks before they turn into potholes [1]. Our practical tests show that cracks in asphalt can be fully filled, and after the crack repair substantial stiffness and strength are recovered. However obtaining specific materials properties within the crack repair will be the key to its success. Specifically, functional grading of elasticity has been shown to increase fatigue life [2]. Implementing functional grading into additive manufacturing processes has been shown in metals, [3] concrete, [4] polymeric nanocomposites, porous structures, [5,6] in the deposition of solution based nanoparticles, [7] as well as lattice-based structures [8]. In this paper we demonstrate a method to functionally grade asphalt composites using 3D printing. Furthermore, we take advantage of the manufacturing platform to deliver functional nanomaterial-modified particles (FNMP) (in this case, magnetic nanoparticles infused into a selective laser sintered printed matrix) to the site of the repair which we demonstrate can be imaged and thermally activated. The method is entirely general and demonstrates a new method to deliver functionality into asphalt repairs. We envisage such additions to be heat activated self-healing capsules which have been shown to increase the lifespan of asphalt composites [9], and radio frequency identification (RFID) devices [10] which would allow the crack repair to be digitally tagged and monitored, as well as a potentially easy path to passive structural monitoring.

2. Experimental

2.1. 3D printer

We used a Mendel90 RepRap frame to control a bespoke auger screw extruder (see [1] for full details of the housing and control systems). Fig. 1 (a) shows the design of the extruder which was fabricated by using a Formlabs Form 2 Stereolithography (SLA) printer using the high temperature acrylic resin for the extruder body, a Trumpf Truprint metal SLS system to print the inner metal chamber and auger screw in 316L stainless steel. Three nozzle diameters were investigated, 1.5, 2.5 and 3.5 mm. A RS PRO hybrid stepper motor giving 1.0Nm torque at 2.8A was used to drive the auger screw. Three Caddock 10 Ω 20 W power film resistors were used to heat the asphalt in the extrusion chamber. The temperature was measured using a 100 k EPCOS B57550G1104F thermistor

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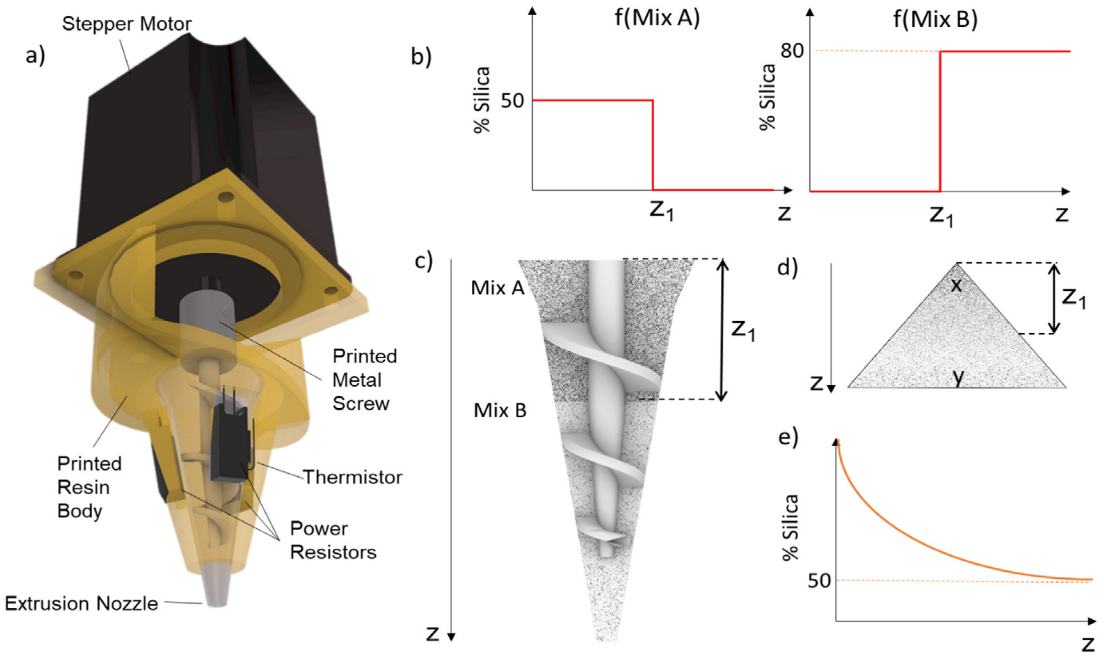

Fig. 1. Design of 3D Printing Functional Grading System: a) Extruder design; b) input fill step functions for two material mixes A and B; c) schematic of filled extruder; d) schematic of resultant graded printed pyramid; e) resultant silica sand concentration profile in print.

affixed to the metal chamber next to a power resistor with superglue. The resistors were bonded to the chamber with MG Chemicals two-part silver epoxy/cold solder, with all components connected to a 15 pin D-Sub connector for connection to the 3D printer.

2.2. Materials

10/20 grade Bitumen, CAS 64742-93-4, was supplied by IKO PLC, Ferrotec EFH1 ferrofluid (10 nm Fe_2O_3 in light hydrocarbon carrier) was obtained from Magnet Expert Ltd, Silica sand 200–300 μm diameter was obtained from Sigma-Aldrich. Composite 2–3 mm pellets of asphalt-sand mixes (25:75, 50:50, 75:25 and 80:20) were manufactured via PDMS cast over FDM printed pellet arrays and cured.

To produce the functional nanomaterial-modified particles (FNMP) we used an EOS Formiga P100 SLS machine to fabricate 3 mm cross shaped nylon inclusions (strut thickness approx. 500 μm), which were then immersed in ferrofluid for 30 min, removed and heated to 90 °C. For full details of this method to create FNMP see [11].

2.3. Functional grading

For the functional grading experiments, the extruder free volume (chamber minus screw volume) was measured to be 6169 mm^3 in the design software. A pyramid of 30 mm square base and 20 mm height (total volume 6000 mm^3) was used as a test printing object in order to maximise the use of the extruder without refilling during printing. For grading between two mixes, equal volumes of the extruder are used to compute an input fill step function, see Fig. 1(b), where the variable z1 represents the fill depth of asphalt-sand mix A, with the remainder of the fill completed with asphalt-sand mix B, see Fig. 1(c). Pyramid test objects (Fig. 1d) were then 3D printed with a volume to match the chamber free volume. Functional grading of pairs of ratios (eg. A = 25:75, B = 50:50) were achieved at print speeds of 1–10 mm/s and temperatures of 150–250 °C creating continuous functional gradients of asphalt sand mix as shown in Fig. 1(e). The print speed was a constant 5 mm/s and a set temperature of 220 °C, leading to an extrusion temperature of 120 °C. Close control of temperature from 150 to 250 °C during the printing process was found to be required in order to print more complex shapes and grading between wider mixes of materials. 3D Printing was also carried out by small (1–3% w/w) additions of FNMP.

2.4. Analysis

The 3D printed objects (Fig. 2b) were analysed using X-ray Computed tomography (CT). Samples were imaged at 55 keV with 500 ms exposure time using a Mediso nanoScan. Data was reconstructed at 73 μm isotropic resolution using Mediso InterView Fusion software. Histogram analysis on the absorbance of samples was obtained using VivoQuant software (inviCRO). Surface plots (Fig. 3f) and line profile analysis (Fig. 2d) were carried out using ImageJ (NIH.gov). Magnetic hyperthermia experiments were performed via a custom system as previously described and imaged using a Testo 875-1i (Fig. 3d) thermal camera, which was also used to monitor and record extrusion temperatures.

3. Results and discussion

3D printing of functionally graded asphalt composites in the shape of a pyramid range of material moduli, (~ 0.1-50GPa), was achieved, see Fig. 2b. Fig. 2c shows the smooth mixing achieved within the extruder, with high contrast sand particles showing no observable localisation. The functional grading was quantified using CT scanning, which showed a correlation between radiopacity and distance (R^2 = 0.41), corresponding to a gradient of sand concentration in the printed object (Fig. 2d). The figure shows that functional grading has been achieved. A range of different gradients have been produced with the key variables being the mixes of the two composites A and B. Through a process of inverse-calculation of the fill volume the functional gradient can also be controlled through variable Z_1.

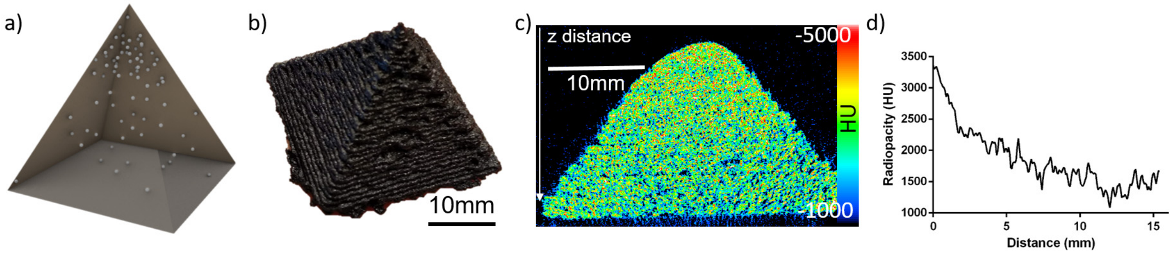

Fig. 2. Functional grading of 3D printed asphalt pyramid: a) schematic of grading in print; b) 3D printed 80:20 to 50:50 sand to bitumen object; c) cross sectional CT analysis; d) quantification of functional grading showing an average of 10 linear profiles from top to bottom of 2C. Linear regression shows correlation of HU with distance through sample (R^2 = 0.41).

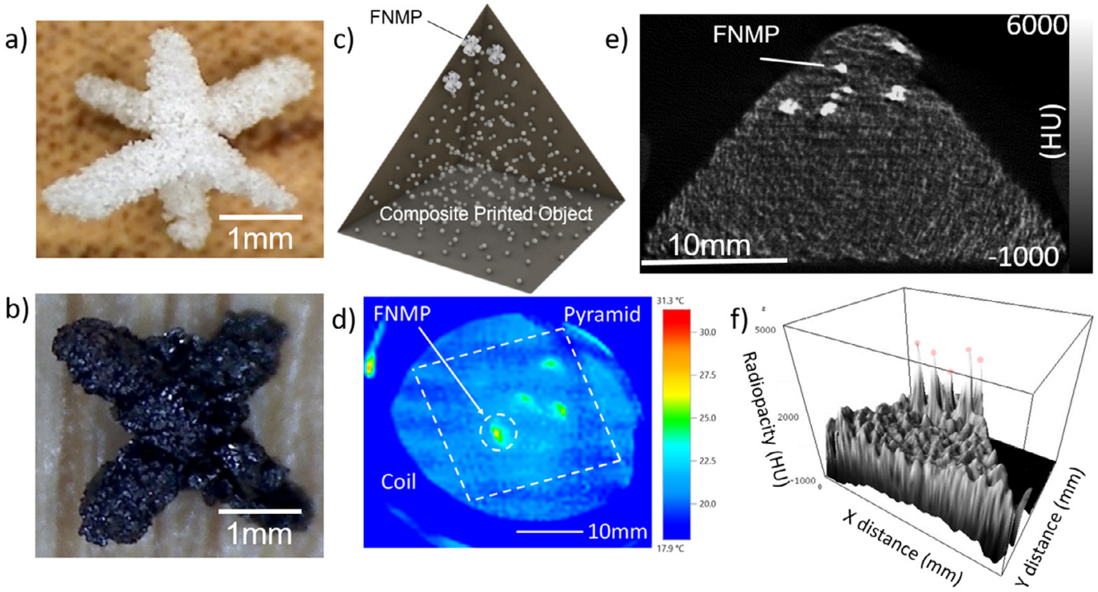

Fig. 3. Functionalisation of Additive Manufacturing: a) SLS printed particle; b) Magnetic nanoparticle modified SLS particle (FNMP) c) HAM schematic; d) thermograph of heated FNMPs in printed object: e) cross sectional CT analysis; f) planar analysis of X-ray attenuation.

We have also demonstrated the ability to successfully print FNMP which survive the temperature and shear forces experienced in the extrusion system. Fig. 3e shows a CT cross-section of a printed pyramid containing FNMP which are visible as high contrast areas in the image. Magnetic hyperthermia experiments were performed on these printed samples which heated up confirming the FNMP had survived the high extrusion temperatures and pressures. The FNMP reached temperatures of 27 °C when the magnetic field was applied as against a background r.t. of 20 °C as shown in Fig. 3d. Fig. 3f shows the surface plot of X-ray attenuation confirming the locations of the FNMP particles.

Asphalt composites have been shown to initiate self-repair when heated [9]. Thus the ability to print a crack repair incorporating FNMP opens the possibility that such repairs can be subsequently inspected and remotely heated using magnetic fields maintaining the viability of repairs. The FNMP could also be a milli-scale protective wrapper for other nanotechnologies to be embedded into crack repairs such as RFID technology, enabling the crack to be monitored using autonomous and remote sensing technology.

4. Conclusion

An additive manufacturing system capable of 3D printing functionally graded asphalt composites has been developed. It is robust and flexible enough to print a wide range of composite mixes at differing speeds and temperatures. We demonstrated the ability to 3D print nanomaterial inclusions within the asphalt composites, which showed functional heating via an applied magnetic field. This opens the possibilities of using such particles to deliver localised heating to 3D printed asphalt repairs to modulate their properties and improve the lifetime of the repair.

Author contributions

Richard Jackson designed, built and tested the 3D printer, he carried out the experiments, tested the samples, and co-wrote the paper. Stephen Patrick carried out the CT scanning and analysis, and gave feedback on the paper. Mark Miodownik conceived the project and obtained the funding; hew gave feedback on the 3D printer design and the experiments, he co-wrote the paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mlblux.2020.100047.

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