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CIVIL INFRASTRUCTURE

3D-Printed Mini-vascular Networks for Self-healing Lime-based Mortars

Climate change is exposing our built heritage to greater and more extreme hazards. Historic masonry repair technologies must evolve in response to these, promoting a new, long-term resilient preservation strategy. Drawing inspiration from the study of mini-vascular networks to develop self-healing in concrete structures, this work proposes the use of biomimetic mini-mini vascular networks (m-MVNs) for repairing cracks in lime-based mortars. The m-MVNs are 3D printed units formed by interconnected channels capable of storing and protecting healing agents that are released when threshold damage is exceeded. In the case where patching is required for restoration of historic masonry wall, m-MVNs are designed to fit completely within the mortar joint. Initial results demonstrated that m-MVNs printed from clear PLA, have a promising design capable of storing healing agents without leaking or premature curing. Future experiments will investigate the appropriateness of this design of m-MVNs to enclose suspensions of bacteria and deliver them to cracks.

Keywords:
3D printing, self-healing, built heritage, lime-based mortars.

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INTRODUCTION

Recent changes in weather patterns expose our built heritage to greater and more aggressive hazards, significantly reducing the service-life of historical structures. A range of traditional intervention strategies are available to address damage in masonry structures (e.g repointing, bed joint reinforcement) [1], although these have not always been successful [2]. A more resilient and durable solution to these problems is urgently needed.

Mini-vascular networks (MVNs) were recently proposed by Cardiff University researchers as a form of biomimetic self-repair system for concrete [3]. The use of MVNs was proposed as an alternative to conventional vascular networks [4]maintenance and replacement of civil engineering infrastructure attracts significant expenditure in the UK. Anecdotal evidence suggests that a significant number of existing and new concrete structures suffer from repair and maintenance problems, but a lack of objective construction industry supported data concerning these problems makes it difficult to establish, with any certainty, the actual problems encountered in current concrete construction in the UK. To address this lack of data, a market research exercise was commissioned by the Materials for Life (M4L, which might cause delays to the concrete casting process caused by their in-situ placement.

As illustrated in Figure 1, 3D PLA-printed regular shaped tetrahedral units (termed TETs hereafter) can be easily introduced to wet concrete during the mixing process. The TET design has been improved to provide good bond properties with the concrete matrix and the ability to store either single (TETs) or bi-components healing agents (d-TETs). Their efficiency to rupture and release sufficient healing agents at a designed crack width has recently been shown by De Nardi et al [5]which employs 3D-printed tetrahedral mini-vascular networks (MVNs. Several healing agents have been tested, such as sodium silicate (SS) solutions, stored individually or in combination with nanosilica (Nsilica) and nanolime (Nlime) solutions.

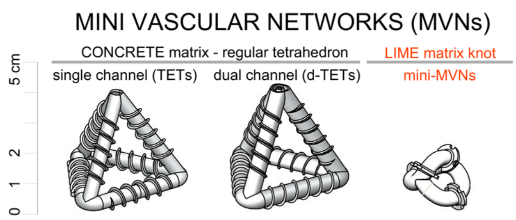

Figure 1. MVNs and m-MVNs design

In particular, TETs filled with SS can produce strength and stiffness recoveries of 20% and 75-80% respectively in prismatic concrete beams.
d-TETs filled simultaneously with SS and either Nlime or Nsilica showed representative increase of strength and stiffness recovery indices of ~10% in comparison to samples containing only SS as healing agent [6].

Recently, the MVN design has been revised and optimised enabling technology transfer from newly constructed concrete structures to historical masonry walls.

Traditionally, if significant sections of masonry have deteriorated to such a degree that mortar joints have lost their function, then patching techniques can be used to restore structural continuity while preserving the original blocks [7]and in some cases were still being, repaired and strengthened. The size and shape of previous MVNs were totally revised allowing mini-mini vascular networks (m-MVNs) to lie entirely within the mortar joint thickness. As with concrete MVNs, m-MVNs are meant to host and protect healing agents that are released when threshold damage is exceeded.

As represented in Figure 2, the concept design was drawn from the idea to manufacture the unit by turning an extruded tube around a spherical shape. The advantages of the proposed new-shaped m-MVNs are that i) they are (almost) directionally invariant with respect to their mechanical behaviour and, (ii) the ribs anchor the unit within the lime matrix, which limits the degree of sliding between the channels and the matrix and means that a channel is likely to fracture when crossed by a crack.

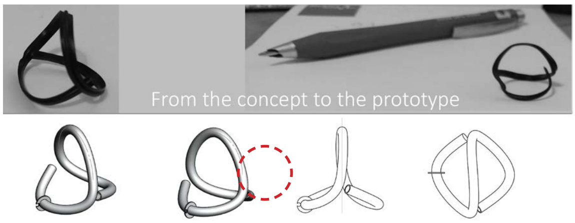

Figure 2. m-MVNs from the concept to the prototype

Regarding the healing agents, much attention will be paid to compatibility criteria, so that the active healing agents are designed to fulfil conservation requirements i.e. be physically, chemically, and mechanically compatible with the host material. In this context, the ability to store healing agents, mainly in the form of aqueous solution have been studied.

MATERIALS AND METHODS

To meet the requirements of the proposed application, m-MVNs were originally created by modifying standard MVN units.

The aim of this first stage was to optimize the design as well as the printing process to satisfy the requirements, namely i) 3D printability of units with reduced geometry and wall-thickness; ii) the ability to be fully watertight when inserted into a lime-based matrix; iii) the ability to prevent any chemical interactions with the healing agent components.

Several variants of m-MVNs were printed from clear PLA, purchased from Verbatim®, using an Ultimaker2+® printer (Utrecht, The Netherlands) with a 0.25 mm nozzle.

In the initial stages of m-MVN development, watertightness tests were conducted to evaluate the ability of thin-wall units to store low-viscosity healing agents over time without premature curing of evident polymer degradation (through longevity tests).m-MVNs were filled with healing agents; either ink, sodium silicate (Na2O3Si) solution - Sigma Aldrich, nanolime (CaOH2) solution, marked as Nanoretsore by the Company CTS Europe produced by CSGI – University of Florence and lithium silicate (Li2O3Si, referred to as LiS herein) marked as Acquacons by CIR Chimica Italiana Restauri.

The longevity tests spanned 4 weeks and consisted of 36 m-MVNs being prepared and filled with SS, Nlime and Nsilica solutions. Three m-MVNs from each solution were opened and examined at 1-7-21-28 days.

The main printing parameters are summarized in Table 1.

Printing parameters	
nozzle	0.25 mm
layer height	0.06 mm
support type	buildplate
bottom_layers	5
cool_fan_speed	80
infill_sparse_density	100
support_infill_rate	2
support_z_distance	0.25
top_bottom_pattern	grid
top_bottom_thickness	0.06 mm
top_layers	5
wall_line_count	16
wall_thickness	0.25 mm
xy_offset	0

Table 1. 3D Printing parameters.

RESULTS AND DISCUSSION

A prototype was successfully 3D printed: the shape was well defined with homogenous surfaces and excellent adhesion between layers. The accuracy and repeatability of printing were also checked, assuring the quality standards in terms of form and dimensional accuracy and stability over printing in separate batches, as can be seen in Figure 3.

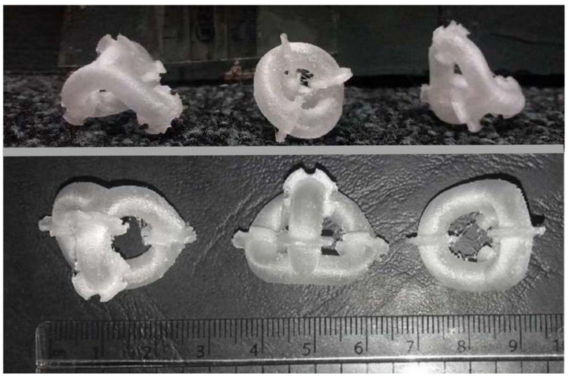

Figure 3. 3D printed m-MVNs from clear PLA.

Following 24 hours of watertightness testing, small quantities of ink were observed. Therefore, in order to ensure complete impermeability, a thin wax coating was externally applied to the m-MVNs. The same coating will provide protection from the alkaline environment to m-MVN units in lime matrices.

The results of longevity tests are summarized in Table 2.

It should be noted that changes in both viscosity of healing agents and PLA polymer were determined through visual inspection and so only provide a qualitative approximation of any change can be reported. The letters l, g, s denote the following: Liquid (l) – no discernible change; Gel (g) – beginning to behave solidly; and Solid (s). The consistency of the polymer was approximately checked by breaking the units and observing if the rupture was brittle (B=brittle) or ductile (D=ductile). The latter was taken as an indication of the initial degradation of the polymer.

clear PLA m-MVNs	Test durations			
	1 day	7 days	21 days	28 days
SS	l/B	l/B	l/B	g/B
Nlime	l/B	l/B	l/D	l/D
Nsilica	l/B	l/B	l/B	l/D
LiS	l/B	l/B	l/B	l/B

Table 2. Longevity tests results.

From the results, it can be seen that SS solution remained liquid for 21 days. After that period the SS appeared similar to transform into a colloidal gel. No changes to the polymer were observed for the SS.

Contrary to this, both Nlime and Nsilica solutions remained liquid throughout the 28 days, without showing any change in viscosity. However, they both caused softening of the PLA. The latter phenomenon was observed in samples ruptured at 21 days in m-MVNs filled with Nlime, and at 28 days in m-MVNs filled with Nsilica. m-MVNs' original mechanical properties are likely to be altered by chemical interactions between the PLA polymer and both Nlime and Nsilica solutions.

CONCLUSIONS

From the analyses of the results presented in the paper, the following main conclusions can be drawn:

- 3D printed MVNs provide a flexible system enabling technology transfer from newly constructed concrete structures to historical masonry walls.
- m-MVNs form the basis of a viable self-healing system for lime-based matrices.
- The 3D printing parameters for m-MVNs need improvement to achieved full watertightness. However, a thin wax coating was able to prevent any leakage and protect the units from the alkalinity of lime.
- SS solution can be stored within m-MVNs with no discernible change in viscosity up to 21 days, after which it forms a gel like substance. No visual changes to the PLA polymer were observed throughout the 28 days.
- Nlime solution remained liquid up to 28 days, but softening effects on the PLA polymer were observed after 21 days. A similar behaviour was observed in m-MVNs filled with Nsilica.

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Conflicts of interest
The authors declare no conflict of interest.

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