A NOVEL 2D VASCULAR NETWORK IN CEMENTITIOUS MATERIALS

Robert Davies, Anthony Jefferson, Robert Lark and Diane Gardner

Cardiff School of Engineering, Cardiff University, Cardiff, Wales, CF24 3AA, United Kingdom

Abstract

An experimental study is presented on a novel 2D vascular network in samples of cementitious materials. This network, described in the present contribution, is formed during the casting process using heat shrink tubing or polyurethane tubing, which is removed after setting to leave permanent channels with no additional materials left in-situ. This paper presents results from a laboratory investigation in which the impact of channel size, length and arrangement, along with supply pressure, different types of healing agents, as well as different bespoke connection joints is assessed. The focus is to maintain a multi-use network that can be re-used over the lifetime of a structure, with the primary aim being to enhance and enable multi-scale healing in cementitious materials.

Keywords: Capillary network, Cementitious, Concrete, Experiment development, Healing agent, Flow network, Self-healing, Vascular network,

1 Introduction

Cracking can be considered one of the major causes of concrete degradation and is typically initiated by thermal effects, early age shrinkage, mechanical loading or a combination of these actions (Concrete Society 2010). One approach to this problem is to include a self-healing component within the material matrix. The state-of-the-art in this field is given in a recent RILEM report on the subject (de Rooij & al. 2013). The focus of this paper is on developing a technique to recover the mechanical properties of cementitious materials and, in particular, to accomplish this through externally supplied healing agents.

Capillary networks have been used in cementitious materials over the last 20 years following the pioneering work of Dry (1994). These networks were initially enclosed capillary capsules but were later developed into systems using glass tubes that form single straight channels extending outside of the prisms (Mihashi & al. 2000, Joseph & al. 2010). Glass tubes have been embedded into frame structures (Dry & McMillan 1996) and cast into bridge decks for full-scale trials (Dry 1999, 2001). However, these techniques have predominantly remained confined to laboratory scale testing and have not been used in practice. A primary reason for this is that these networks comprise brittle individual glass capillary tubes, which tend to break during mixing and casting. To circumvent this problem, glass capillaries have also been replaced with steel rods, which are cast in place and then removed after 24 hours of curing (Dry & McMillan 1996, Pareek & Oohira 2011). It has to be ensured that the steel is removed in a timely manner, which is not always possible in real site situations.

A novel approach developed by Nishiwaki, Mihashi & Okuhara (2010) is a self-repairing system where selective heating at the location of a crack releases healing agent directly to the required location. The glass tube was replaced by a pipe made from spirally twisted wire surrounded by an Ethylene vinyl acetate polymer, which has a melting point of 93 ºC. An alternative mechanism of distributing healing agent into a concrete specimen using an external supply system is to use a concrete with a porous network (Sangadji & Schlangen 2011). In this system, which mimics the human bone structure, porous concrete cylinders are surrounded by standard concrete. These capillary networks in cementitious materials have shown varying degree of success (Dry, Corsaw & Bayer 2003 and Van Tittelboom & De Belie 2013).

In other materials, such polymers and composites, a range of techniques to create flow networks have been developed. Microvascular networks are fabricated using a fugitive scaffold process or sacrificial fibres which are embedded in thermoset resins (Toohey & al. 2007, Esser-Kahn & al. 2011). Multifunctional vascular networks have also been constructed between fibre reinforced plastic composite layers (Boba & al. 2013). Nichrome wires coated with polylactic acid placed in between the composite layers are heated and then removed, leaving behind a network. Hamilton, Sottos & White (2011) investigated pressurised vascular systems in polymers with various static pressures and pumping mechanisms to distribute the healing agent.

The focus of the work described in this paper is to create and maintain a multi-use network that can be re-used over lifetime of a cementitious structure, with the primary aim being to enhance and enable multi-scale healing. The proposed technique aims to overcome the main disadvantages of existing approaches discussed above.

2 Experimental details

An investigation was carried out to find a new way of creating vascular networks in cementitious materials. The most practical approach is to form a network during the concrete casting process. A further criterion considered in the present developments was that any method chosen should be able to be up-scaled from the laboratory to the construction site scale.

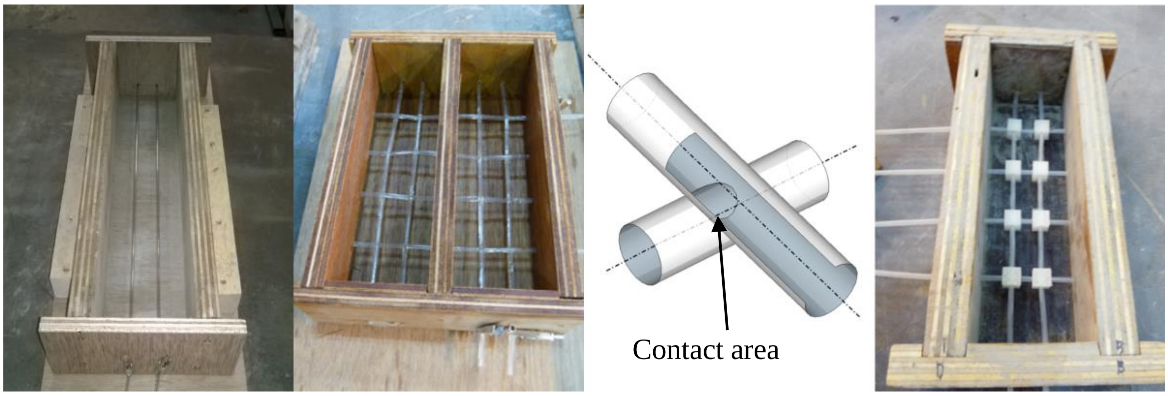
The novel method presented in this paper is to create 1D and 2D networks using plastic tubing, which can be removed to leave permanent channels in the concrete. The approach that proved successful, uses heat shrink tubing or polyurethane tubing. In both cases, the tubing is placed through holes in the concrete prism mould walls. These tubes are aligned with the concrete prism cover zone and held in place with small clamps (crocodile clips) on the outside of the moulds. Fig. 1a and 1b show typical prism specimen moulds prior to casting.

The heat shrink tubing material is polyolefin, which is 3.2 mm in diameter and has a shrinkage ratio of 2:1 at 80 °C. A typical application for this product is to protect electrical wire jointing. This tubing is flexible and compressible and to prevent compression during placement of concrete the network requires pressurisation with water. After casting, curing and de-moulding of the prism specimen, the polyolefin tubing is flushed with hot water. The hot water, having a temperature over 80 °C, causes the tubing to shrink to half of its original diameter, thereby allowing easy removal from the specimen.

The 4 mm diameter polyurethane tubing is commonly used in laboratory air pressure systems. This type of tubing was chosen for its smooth outer surface properties, relatively high stiffness and high tensile strength. The polyurethane tubes are also clamped on the outside of the mould and are robust enough to withstand the casting. After casting, curing and de-moulding, the polyurethane tubes are pulled out of the specimen. The radial contraction of tube, when under tension, breaks the bond between the concrete and thus permitting the tubes to be removed relatively easily. One advantage of using polyurethane, compared to polyolefin, is that the mould setup is easier. However, polyolefin is easy to remove once it has been heated and the material shrunk. Both tubing materials do not require and special coatings, but removal is easier with application of mould release oil or petroleum jelly.

The polyurethane tubing has been successfully incorporated into beams 2.5m in length and into square slabs 600 mm by 600 mm. The polyurethane tubing survived the casting process and were all subsequently easily removed and are re-usable. Preliminary experiments show that the tubing placed as loops in the concrete can also be removed easily, therefore only requiring one accessible surface during casting. This would be advantageous for casting concrete foundations or other closed format structures. The details of these experiments will be presented in a forthcoming journal paper.

A 2D network was created by taking advantage of the voids left by the contact surface area between the overlapping and crossing tubes upon removal of the tubes, as illustrated by the schematic in Fig. 1c. The pathway built into the cementitious matrix between the adjacent tubes allows the healing agent to flow in multiple directions. The contact area is achieved and maximised using a weaving tube pattern shown in Fig. 1b. These voids at the contact area location are shown to be sufficiently large to allow the healing agent to flow. However, a bespoke connection designed and printed in 3D polylactic acid (PLA) material maximises the flow area between the perpendicular channels. These connections have the added advantage of securing the tubing in position during the casting. Fig. 1d shows the bespoke connection with the tubes in the mould prior to casting.



a) 1D twin b) 2D configuration c) Schematic of connection d) 2D bespoke 3D PLA connection

Fig. 1 Concrete prism mould setup for vascular network.

The healing agents used during these investigations were cyanoacrylate (CA) and sodium silicate. CA, commonly known as instant glue or ‘Superglue’, was chosen for its low viscosity and rapid polymerisation. Sodium silicate was chosen for its ability to react chemically with the cementitious matrix and for having a slower reaction rate, more suitable for site applications than the rapidly setting CA.

The concrete composition used in this investigation was designed to achieve S3 (100-150mm) slump class with a target compressive strength of 53 MPa (C35/45). Having removed the tubing the concrete specimens were left with permanent channels with no additional materials left situ, except for the specimens with bespoke connections. The chosen concrete curing regime adopted is dependent on the proposed self-healing agent. CA polymerises with water and as such, the specimens are cured at ambient conditions or dried thoroughly before the healing agent is supplied into the flow network.

Healing agents may be delivered by capillary flow alone but it has been found that the supply of agents may be improved by pressuring the healing agent fluid. Even a small additional pressure of 100mm pressure head allows the healing agent to flow more effectively along the supply channels and up into the macro-crack using the capillary rise mechanism.

The impact of supply pressure of the healing agent was also investigated for pressures up to 2 m pressure head (0.2 bar). The experimental arrangement used for these tests is shown in Fig. 2 for a three-point flexural bending test. The tests presented in the results section are on 28-day-old unreinforced beams, 255 mm by 75 mm by 75 mm in size and have two sets of channels 20 mm from the underside of the beam. The healing agent is supplied to the channels in the concrete using a supply tube, pressure is applied with air though this supply tube and the system closed before the loading test commences. The loading was controlled with a crack mouth opening displacement (CMOD) feedback loop and the pressure in the closed system was monitored. This pressurised air network connected to the specimen also has the ability to flush out the healing agent from the main channels by having one outlet open to the atmosphere. Upon flushing the healing agent remains in a thin film on the channel surface and thereby leaving the healing agent on the crack face undisturbed. This opens up the opportunity to re-supply healing agent later.

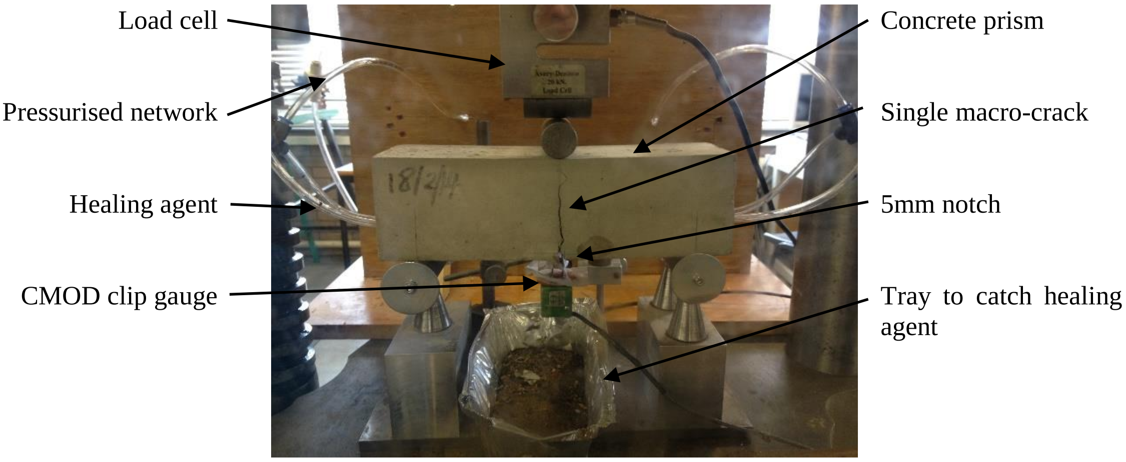


Fig. 2 Example loading setup concrete prism for pressurised 1D twin network

This paper only looks to outline the laboratory investigations carried out in developing a 2D vascular network in cementitious materials. The detailed description and impact of various parameters are subject to a forthcoming journal paper.

3 Results and discussion

A selection of experimental results is presented in this section illustrating typical findings. Fig. 3 shows a 2D connected network of channels in a prism specimen and Fig. 4 shows the fracture surface interfacing with the network.

Fig. 3 Cast beam for 2D network showing 4 mm holes on face.

Fig. 4 Fracture surface showing network interface with crack.

Fig. 5 and Fig. 6 show how the healing agent, subjected to 0.2 bar pressure, reaches the full height of the crack for both sodium silicate and CA. There is evidence of healing agent appearing on the crack at the sides of the specimen before the pressure in the system drops and a large quantity of healing agent is lost from the base of the specimen. Furthermore, the effect of pressurising the healing system (to 0.2 bar) was visualised by applying a fluorescent dye to the fracture surface after testing. Fig. 7 shows an image of one of the control beams, obtained under UV light, immediately after the dye is applied. The dye is absorbed into the whole control surface. Fig. 8 shows fluorescent dye being repelled by the healing agent. After drying, it can be seen that the healing agent did not reach the top left hand side of the crack. The full parametric study will be reported in a future journal publication.

Fig. 5 Twin 1D network showing sodium silicate on crack outer surface.

Fig. 6 2D network showing cyanoacrylate on crack surface.

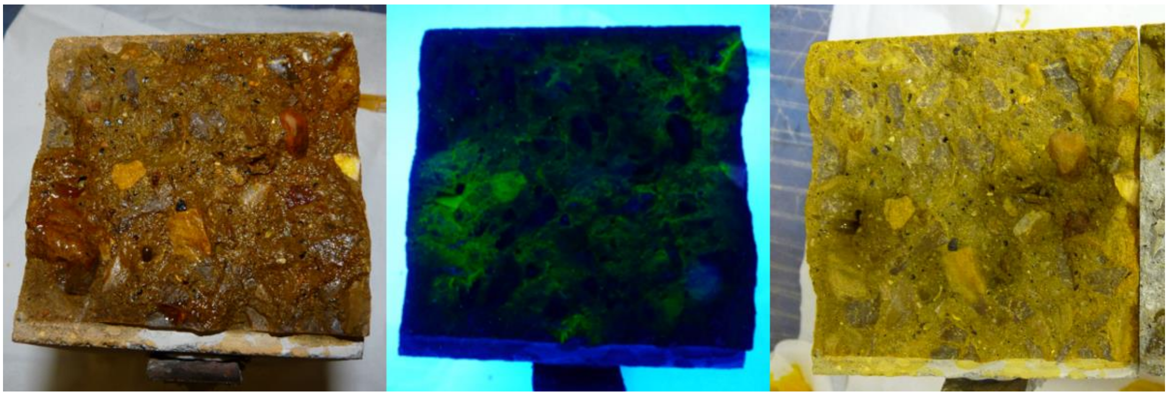


Fig. 7 Control beam fracture surface showing dye absorbed into the cementitious matrix.

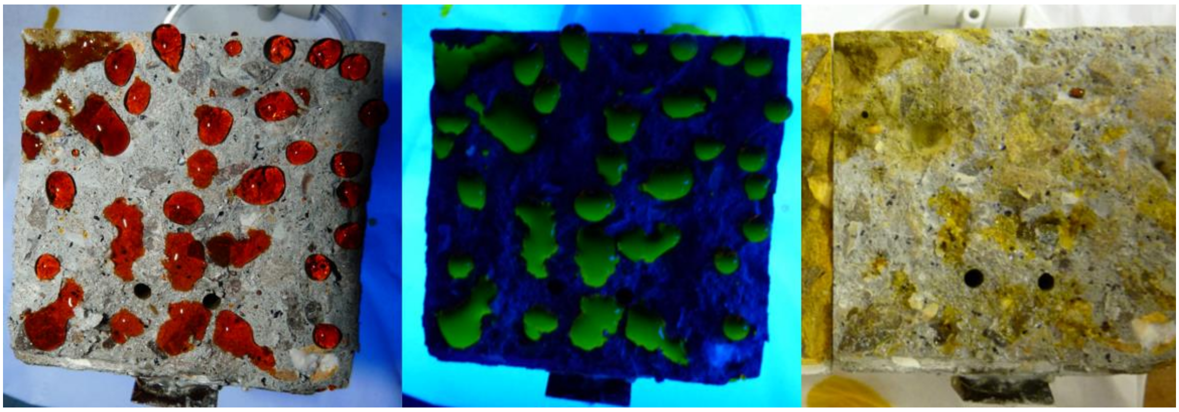


Fig. 8 Self-healing agent on surface of crack repels the dye and is not absorbed into the cementitious matrix.

Example plots of load against CMOD for beams with CA and sodium silicate healing agents are given in Fig. 9 and Fig. 10 respectively. The CA specimen in Fig. 9 is loaded to 0.3 mm CMOD and then unloaded. During this load cycle the immediate impact of the CA at 0.1 mm CMOD can be seen to increase the load carrying capability of the specimen. The pressure in the closed system also drops to zero around 0.2 mm CMOD. After waiting 5 minutes in the unloaded state, the beam was loaded again where an initial increase in strength was shown along with a later ductile response as the CMOD increases further. Unloading and allowing the CA to cure for longer leads to a higher level of strength recovery.

The sodium silicate specimen, shown in Fig 10 was also loaded until the CMOD reached 0.3 mm and then unloaded and allowed to air cure for a further 28 days. Upon reloading, there was an increase in the peak load compared to the residual strength in the specimen before unloading.

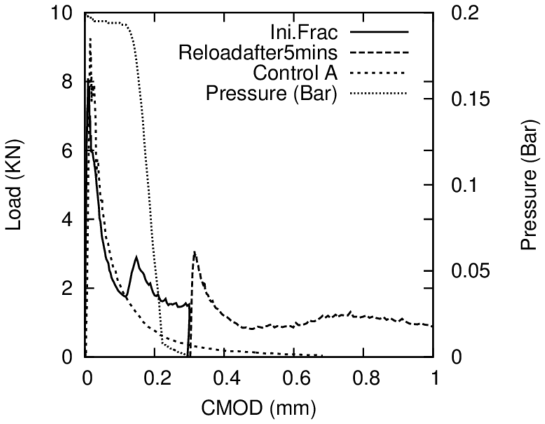


Fig. 9 CA Load CMOD and pressure response.

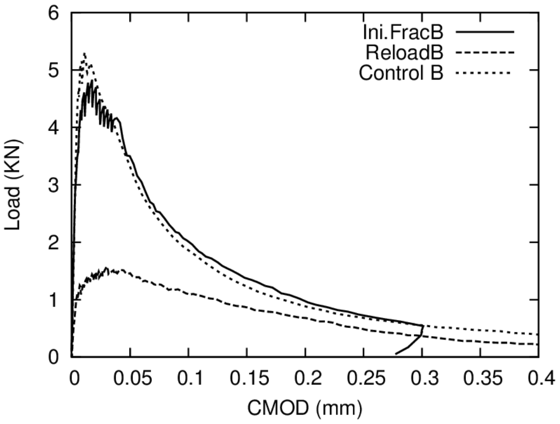


Fig. 10 Sodium silicate Load and CMOD.

4 Conclusions

The experiments presented in this paper show that a multi-use 2D network can readily be created in cementitious materials. The proposed method is scalable and robust, therefore potentially it could be used on a construction site. The network can be used with different healing agents and is re-usable, enhancing the ability to promote multi-scale healing. The results show that pressurising the network enhances the flow of healing agents such that they permeate the majority of a 0.2mm crack in a 3-point bending test. The pressurised vascular network, with externally supplied healing agent, is capable of promoting significant strength recovery.

Acknowledgements

This work has been undertaken as part of the £2M UK Research Council grant, Materials for Life (M4L), project in which Cardiff School of Engineering is working in collaboration with Cambridge and Bath Universities.

References

Boba, K., Heath, C., Bond, I.P., Trask, R.S. & Wass, D.F.(2013). Novel manufacturing method for FRP composites with a multifunctional vascular network, in: Proceedings of the 4th International Conference on Self-Healing Materials. Presented at the ICSHM 2013, Ghent, Belgium.

Concrete Society (2010), Non-structural cracks in concrete: a Concrete Society report. Concrete Society, London.

Dry, C. (1994), Matrix cracking repair and filling using active and passive modes for smart timed release of chemicals from fibers into cement matrices. Smart Mater. Struct. Vol. 3, No. 2 pp. 118-123.

Dry, C. & McMillan, W. (1996), Three-part methylmethacrylate adhesive system as an internal delivery system for smart responsive concrete. Smart Materials Structures, Vol. 5, No. 3, pp. 297-300.

Dry, C. (1999), Repair and prevention of damage due to transverse shrinkage cracks in bridge decks. pp. 253–256.

Dry, C. (2001), In-service repair of highway bridges and pavements by internal time-release repair Chemicals. NCHRP-IDEA Program Project Final Report.

Dry, C., Corsaw, M. & Bayer, E. (2003), A comparison of internal self-repair with resin injection in repair of concrete. Journal of Adhesion Science and Technology Vol. 17, No. 1 pp. 79-89.

Esser-Kahn, A.P., Thakre, P.R., Dong, H., Patrick, J.F., Vlasko-Vlasov, V.K., Sottos, N.R., Moore, J.S., White, S.R. (2011), Three-Dimensional Microvascular Fiber-Reinforced Composites. Advanced Materials Vol. 23, No. 32, pp. 3654–3658.

Hamilton, A.R., Sottos, N.R. & White, S.R. (2011), Pressurized vascular systems for self-healing materials. J. R. Soc. doi:10.1098/rsif.2011.0508

Joseph, C., Gardner, D.R., Jefferson, A.D., Lark, R.J. & Isaacs, B. (2009) Self Healing Cementitious Materials: A review of recent work, in Proceedings of the ICE: Construction Materials, Vol.164, No. 1, pp. 29-41

Joseph, C., Jefferson, A., Isaacs, B., Lark, R. & Gardner, D. (2010), Experimental investigation of adhesive-based self-healing of cementitious materials. Magazine of Concrete Research Vol. 62, No. 11, pp. 831-843.

Mihashi, H., Kaneko, Y., Nishiwaki, T. & Otsuka, K. (2000) Fundamental study on development of intelligent concrete characterized by self-healing capability for strength. Transactions of the Japan Concrete Institute. Vol. 22, pp. 441-450.

Nishiwaki, T., Mihashi, H. & Okuhara, Y. (2010) Fundamental study on self-repairing concrete using a selective healing device. Proceedings of the 5th International conference on concrete under Severe Conditions: Environment and Loading CONSEC'10, Mexico, No. 2, pp. 655-926.

Pareek, S. & A. Oohira (2011) A fundamental study on regain of flexural strength of mortars by using a self-repair network system, in 3rd International Conference on Self Healing Materials. Bath, UK. pp. 46-47.

De Rooij, M.R., Van Tittelboom, K., De Belie & N., Schlangen, E. (2013), Self-Healing Phenomena in Cement-Based Materials: State-of-the-Art Report of RILEM Technical Committee 221-SHC: Self-Healing Phenomena in Cement-Based Materials. Springer, Bagneux, France.

Sangadji, S. & E. Schlangen (2011), Porous network concrete: a new approach to make concrete structures self-healing using prefabricated porous layer, in 3rd International Conference on Self Healing Materials, Bath, UK. pp. 291-292.

Toohey, K.S., Sottos, N.R., Lewis, J.A., Moore, J.S. & White, S.R., (2007), Self-healing materials with microvascular networks. Nature Materials Vol. 6, No. 8 pp. 581–585.

Van Tittelboom, K. & De Belie, N. (2013), Self-Healing in Cementitious Materials—A Review. Materials, Vol.6, No. 6, pp. 2182–2217.