SELF-HEALING MATERIALS FOR AUTONOMOUS CABLE REPAIR

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ABSTRACT

Self-healing materials are capable, when damaged, of responding to restore the pre-damage properties of an asset. This is of particular interest for high-value electrical assets which cannot be routinely accessed for preventative maintenance or repair, such as underground or offshore cables. The incorporation of self-healing materials would effectively allow these systems to maintain themselves, resulting in enhanced resilience, lower failure rates, and longer operational lifetimes.

Here, we demonstrate self-repair systems for extruded polymeric cables containing an extruded polymer self-repair layer, and self-healing fluids for legacy fluid-filled circuits. Both self-healing candidates have been formulated for their specific applications and demonstrate excellent efficacy, with ability to move to large-scale trials planned for the near future in advance of routine deployment.

INTRODUCTION

The use of underground cables (UGCs) has become increasingly prevalent across the developed world. Although UGCs require a significantly greater capital outlay, they are highly resilient to extreme weather and benefit from reduced visual impact, meaning that they can be deployed where overhead lines (OHLs) would be inappropriate or not allowed. However, while OHLs can be accessed for inspection and maintenance, the location of UGCs means that a routine inspection is either prohibitively expensive or impossible. As a result, otherwise minor defects can develop, over several years, to the point that the integrity of the asset itself is threatened. Locating and resolving such faults is a time-consuming and expensive process, often taking up to 25x longer than a comparable fault on an OHL - with associated increases in costs and penalties[1]. As initial defects are often very small, it is unlikely that they will be detected during installation inspections. Damage that may occur in operation may vary in size and extent, and may not be detected at all.

A potential solution to this problem is to employ self-healing materials throughout the cable structure. Self-healing materials possess the capacity, when damaged, to respond to restore the original properties of the asset (see **Figure 1**). This capability is attractive for high-value assets which cannot be accessed for maintenance or repair (including underground and sub-sea cables). This allows an element of autonomous maintenance and can prevent the development of otherwise insignificant defects. The effective deployment of self-healing materials would be expected to confer a number of benefits upon the host asset, including a reduction in early failure rates, increased durability, and greater tolerance of defects. These benefits would be realised by the asset operator in the form of reduced maintenance, repair, and replacement costs.

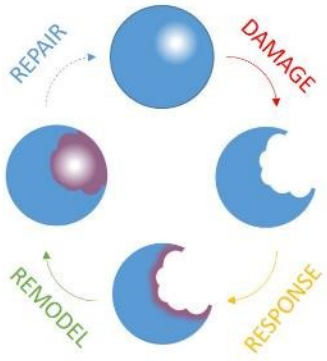

Figure 1. Schematic of self-healing material response post-damage

Although the benefits associated with self-healing materials are significant, their effective deployment is not trivial and there are many factors that require consideration. Most self-healing systems possess a specific trigger (e.g. electrical discharge, water penetration, oxygen exposure, etc.) and so it is important to select a system that would be triggered by the anticipated changes arising from a damage event. If a self-healing moiety is to be dispersed within an existing component (as opposed to being a discrete material) it should not corrupt existing properties necessary for function (e.g. mechanical strength, electrical breakdown, etc.). For these reasons, the selection of self-healing materials must be considered with regards to a specific application, rather than taking a more general view. This will be illustrated within this paper, where different cable structures have necessitated different approaches in order for self-healing to be achieved.

SELF-HEALING FLUIDS (SHFS) FLUID FILLED CABLES

Fluid filled cables (FFCs) exist in most undergrounded power networks as legacy cables. Compared to extruded polymer cables, FFCs are insulated by a layer of tightly lapped cellulosic paper impregnated with a low viscosity mineral oil. Until the 1980s, this allowed cables to operate at higher voltages than cables insulated with a layer of extruded XLPE (**Figure 2**), although developments in polymer purification have resulted in FFCs being largely supplanted by polymeric insulation. Currently, it is estimated that there are 8,500km of FFCs remaining in the UK.

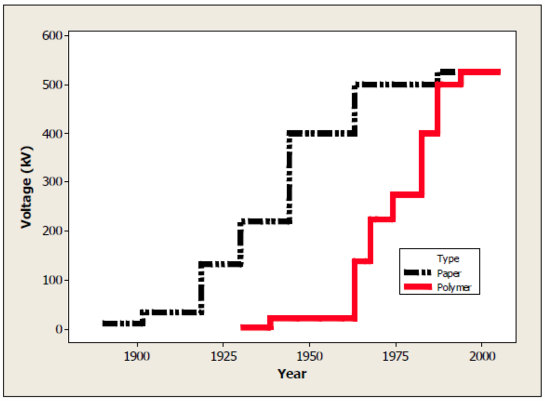

Figure 2. Improvements in AC cable voltages between cables insulated with paper and fluid (black) and extruded polymer layers (red)[2]

Within an FFC, the oil is contained by the presence of a metal outer sheath (commonly lead or aluminium). If this is breached, however, the oil will leak into the surrounding environment. This raises two problems; firstly, a significant loss of oil will rapidly lead to the degradation of the paper insulation and the failure of the asset. While the lost oil can be replaced, environmental contamination (particularly the contamination of watercourses) remains a concern; operators in the UK are obliged to report and immediately remediate leaks greater than 100L / month (40L / month in environmentally sensitive regions). Aside from the costs associated with locating and resolving the leak, operators may face fines associated with carrying out environmental remediation. If faced with a cable with several leaks (or a single severe leak) an operator may opt instead for decommissioning and replacement with a cable possessing a solid polymer insulation layer.

Concerns regarding oil leaks are becoming more significant as the cable population ages. For example, with time lead sheaths will crystallise and become increasingly brittle, increasing the chance of a breach forming due to third party action (vibration, mechanical impact) or even direct work on the cable. It is currently thought that 400,000L of oil is lost annually within the UK, with an estimated replacement cost greater than £1m. Although FFCs are being replaced, this is a slow and expensive process, and an intermediate solution is required until full replacement is achieved.

Although it might be feasible to develop a self-healing cable structure that could prevent oil loss, that approach is not suitable in this instance. Production of new FFC is limited and is normally diverted towards repair stock; as stated previously, a full replacement will normally result in the installation of a polymer-insulated FFC. Instead, Gnosys has developed a next-generation of insulation oil that is self-healing and capable of crosslinking in the presence of oxygen. Should a breach in the sheath develop, the insulation oil will react to form a solid plug, thereby preventing the flow of oil. This self-healing fluid (SHF) is intended to replace the existing oil within the cable, thereby conferring self-healing capabilities without requiring wholesale asset replacement.

The self-healing properties of the oil are demonstrated in **Figure 3** and **Figure 4**, using a bespoke experimental rig intended to mimic sheath defects. During testing, the tested SHF flows through a defined leak (0.44 mm in diameter) and then falls into a continuously weighed catchment pot. As the oil leaks, the change in mass is recorded. Over time, the SHF forms a cured mass that blocks the leak site (**Figure 3**, right) resulting in the restriction and eventual cessation of the flow of oil as seen in **Figure 4**.

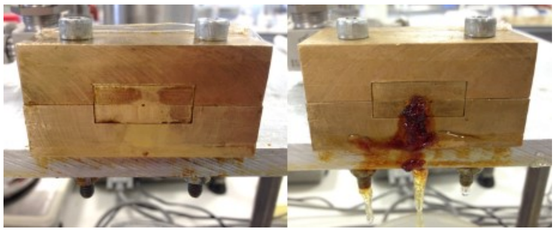

Figure 3. Demonstration of the SHF using mimic leak test rig. (Left) Before the experiment, the leak site can be clearly seen in the centre of the block. (Right) At the end of the experiment, a large mass of cured oil has built up on the surface of the block, preventing further flow.

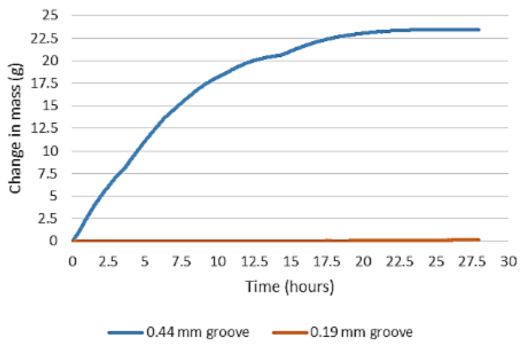

Figure 4. Recorded change in mass with time. It can be seen that for the 0.44mm defect the system initially slows after 15 hours but subsequently starts leaking again, prior to complete cessation after 22.5 hours. In contrast the 0.19 mm defect is rapidly healed.

During these tests, it was noted that the SHF possessed a secondary function. When particularly large leaks were tested, it was observed that the SHF could not seal the breach, but instead formed self-supporting stalactites that contained insulation oil. Based on this observation, it was speculated that if the SHF was unable to seal the breach itself, it would still cure in the surrounding backfill, resulting in the formation of an oil-proof perimeter that would limit the extent of environmental contamination caused by the leak.

To test this, samples of current-generation insulation oil (T3788) and SHF were allowed to flow through sharp sand (a common backfill material) and the change in flow rate measured over the course of 4 days. **Figure 5** shows that over the course of the experiment, T3788 showed only a small reduction in flow, which was attributed to subsidence. By comparison, the SHF showed a rapid and almost complete reduction in leak rate, resulting in the formation of a reservoir (**Figure 6**) as the SHF became unable to penetrate the backfill. These protective qualities were also maintained when the SHF-treated backfill was challenged with T3788; which could not penetrate the barrier.

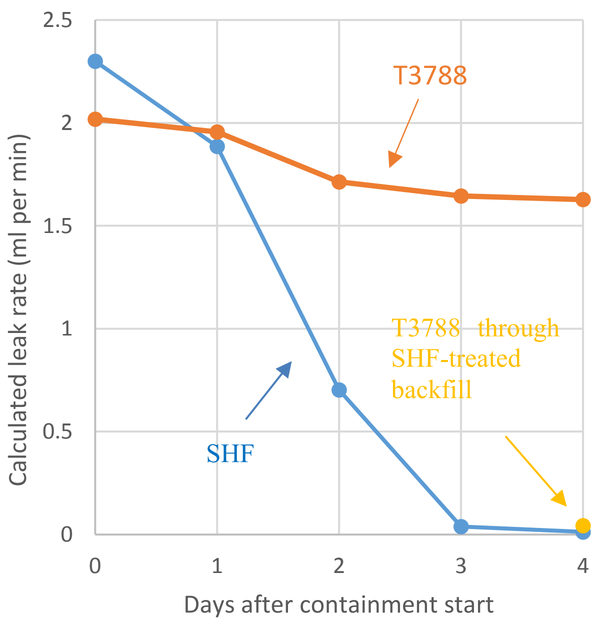

Figure 5. Change in leak rate between samples of T3788 and SHF flowing through sharp sand backfill. While the T3788 shows only a small reduction in leak rate, the leak rate of the SHF falls rapidly to almost complete cessation by day 4.

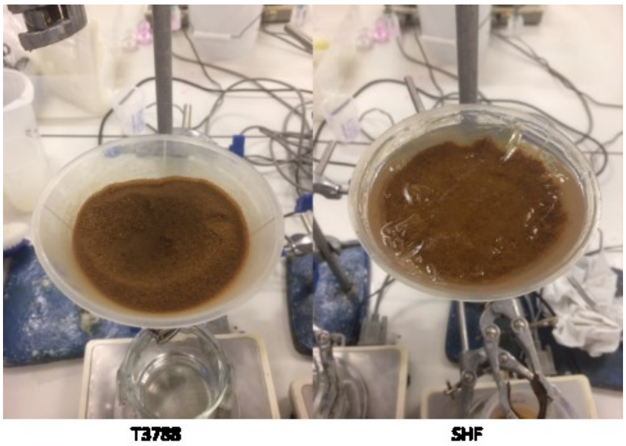

Figure 6. Comparison of backfill materials treated with T3788 and SHF at conclusion of experiment.

From these results, it can be demonstrated that Gnosys has developed self-healing fluids that have the capability to seal small breaches and contain larger leaks. As the SHF is intended to replace the insulation oil, however, it is essential that it possesses similar or superior electrical and rheological properties compared to current insulation oils. These properties depend heavily upon the purity of the fluid; as **Figure 7** shows, an unpurified SHF possesses a significantly lower breakdown voltage compared to standard insulation oils, but after purification the breakdown voltage increases to over 80 kV. This improvement is attributed to the removal of polar impurities (including water) from the blend. The removal of these impurities also results in an improvement in the rheological properties of the SHF (**Figure 8**); which exhibits a significant reduction in viscosity after purification. Although the viscosity is higher than that of pristine T3788, investigations by Gnosys have found that there is a very wide range of viscosities (between 4-13 mPa s^{-1}) found in in-service oils, which suggests that purified SHFs will be tolerated by current circuits.

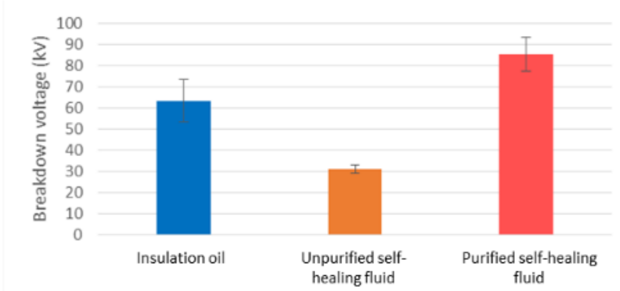

Figure 7. Breakdown voltages (kV) of insulation oil and SHFs, before and after purification

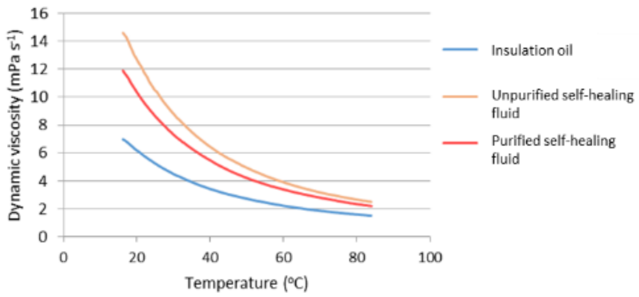

Figure 8. Dynamic viscosities of insulation oils and SHFs, before and after purification

Currently, Gnosys is developing a program of work intended to capture SHF performance within samples of ex-service cable, using a pair of bespoke, instrumented test rigs. Testing will then proceed to nominated circuits for field trials prior to full-scale deployment.

SELF-HEALING SUB-SHEATH LAYERS IN EXTRUDED POLYMERIC POWER CABLES

UGCs insulated with a layer of extruded polymer represent the vast majority of the underground power network; across Europe, it is estimated that there are approximately 4.5 million kilometres of polymer-insulated cable, growing at a rate of 4-5% per annum[3]. In some countries (such as the Netherlands) the infrastructure is fully underground.

As with FFCs, the development of sheath defects can significantly reduce the lifespan of a polymer-insulated cable. In this case, the danger is due to water (present in the backfill) passing through the defect and reaching the insulation. Here, the combination of water and high electrical fields can cause accelerated degradation of the insulation through the formation of dendritic structures known as 'water trees' (see **Figure 9**). If allowed to grow, these can eventually cross the insulation and cause its breakdown, resulting in the failure of the cable. Large water trees are also implicated in the formation of electrical trees, which can grow quickly and are a rapid route to cable failure.

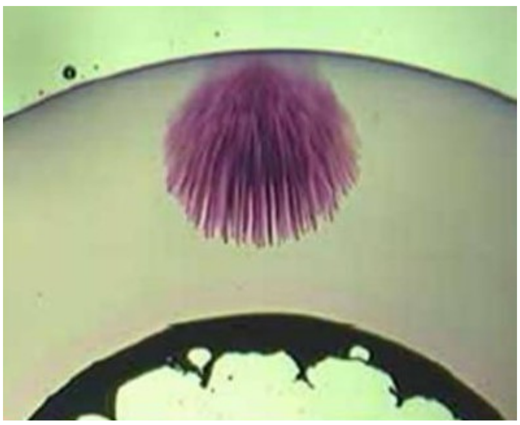

Figure 9. Example water tree, dyed to enhance visualisation[4]

Gnosys has carried out extensive investigations into the development of self-healing systems for cable protection. Here, we propose the use of a hydrophilic thermoplastic elastomers (h-TPE) deployed as a discrete layer positioned immediately under the sheath. Should the sheath be breached and water enter, the h-TPE will swell into the damaged area, closing the breach and preventing further penetration to the insulation.

Although this is conceptually similar to the 'water blocking tapes' (WBTs) commonly used by cable manufacturers, investigations by Gnosys have found that h-TPEs possess a number of advantages over WBTs. WBTs consist of a layer of water-swelling additive (commonly poly(acrylic acid)) which is positioned between two layers of woven or non-woven fabric. Although the fabric contains the additive, it does not provide any structural support, and if the WBT is challenged with a large body of water it is likely that the additive will swell to the point of dissolution, resulting in the loss of protective qualities. A similar problem is encountered if water is ingressing under high-pressures; without structural reinforcement, the additive is forced aside and the water can access critical cable elements. Finally, the high electrolyte concentration of seawater inhibits the swell response, meaning that the capacity of WBTs to prevent seawater ingress is severely reduced.

In the case of h-TPEs, the protective qualities are much improved through the synergistic action of the TPE and swelling additive. As the additive is heavily constrained within the matrix of the TPE, the system will swell to a maximum, but the support provided by the TPE prevents dissolution and maintains protection of the cable. The presence of the TPE also mitigates high-pressure ingress, and tests have demonstrated that water ingress is completely blocked at pressures up to 6.5 bar (the highest tested), equivalent to 65m of seawater. Although h-TPEs also demonstrate a reduced swell response in seawater, the hydrophobic qualities of the TPE limits water ingress, and its excellent compatibility with common sheath materials results in a watertight seal that prevents longitudinal transport along the cable length.

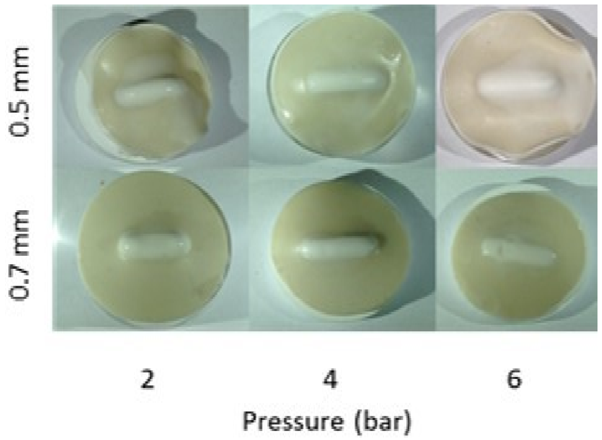

Figure 10. Samples of h-TPE after exposure to water under high pressures. The white region in the center of the disc indicates the point of water contact.

With regards to the processing of these materials, it has been found that extrudable h-TPEs possess excellent compatibility with common cable manufacturing processes, and can be extruded at speeds commensurate with cable extrusion without evidence of damage or reduction in performance (see **Figure 11**). This contrasts with WBTs, which require expensive and complicated tape-winding machinery in order to be incorporated into the cable structure, resulting in slow production rates.

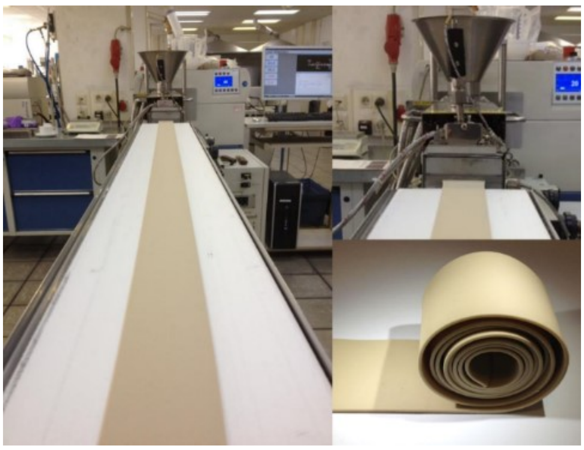

Figure 11. Extrusion of h-TPE ribbon

From these results, it can be concluded that extrudable h-TPEs have significant potential to displace WBTs within cable structures. While this may be considered a form of ‘asset self-repair’, however, it is not true materials self-repair, it is a material response resulting in self-repair. Gnosys is currently carrying out investigations into the use of ‘intrinsic’ self-healing materials, which can permanently heal if rejoined after damage (see **Figure 12**). If combined with an h-TPE system (either as a blend or as a synergistic bilayer) it may be possible to develop a self-repair layer that firstly swells in response to the presence of water, and then forms a permanent repair of both the material and the cable.

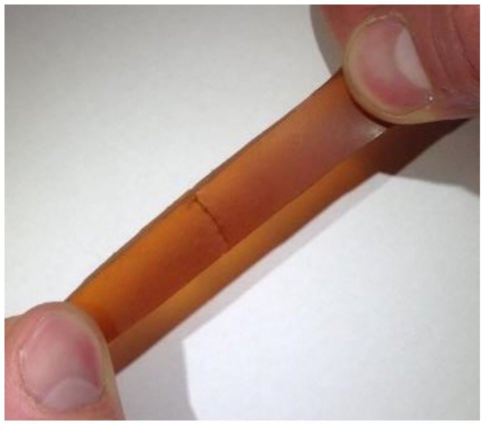

Figure 12. Sample of intrinsic self-repair material after bisection and re-joining. After 24 hours, the damaged region demonstrated excellent strength and could not be separated by physical force.

In conclusion, Gnosys is developing a range of self-healing fluids and materials to meet the requirements of love-lived assets within the power sector. Further work is being undertaken to bring these to routine deployment, while other investigations are being carried out to establish the suitability of these systems for applications in other utility sectors.

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