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POLYMER-BASED ALTERNATIVE TO STEEL MESH FOR COAL MINE STRATA REINFORCEMENT

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ABSTRACT: The University of Wollongong in collaboration with the Australian coal mining industry has shown that a viable polymer-based alternative to steel mesh in underground roadway support applications can be developed to eliminate the use and handling of steel mesh. The feasibility of developing polymeric alternatives to steel mesh in underground roadway support applications has been established, the physical and material constraints to be endured by any new polymeric skin reinforcement system have been identified by measuring the mechanical properties of steel mesh, and materials that can be spray-applied have been identified. The study has also shown that polymer mechanical properties can be optimised to produce similar mechanical properties (modulus, yield stress, elongation-at-break etc) to steel mesh. The identified materials will allow the face support cycle to be fully automated, or at least remotely operated and installed, enabling the removal of personnel from the immediate face area, thus contributing to a projected substantial improvement in underground roadway development rates.

INTRODUCTION

Steel mesh has been used in underground coal mine roadways for some years. The main role of mesh is to provide passive confinement, especially in locations where poor ground conditions prevail, preventing fragments of rock and coal from falling from the roof and ribs in the spacing between reinforcing bolts.

Installation of mesh is a manual operation, and has been identified as a slow and inherently dangerous step in the roadway advancement process. Self-drilling bolting technology, with the potential for full automation, has been widely investigated over recent years; however the meshing process remains necessarily a manual operation.

A need for an alternative to steel mesh that can be installed automatically has been identified, which will allow the roadway support process to be fully automated, and thus take advantage of self-drilling bolt technology. The University of Wollongong in collaboration with the coal mining industry has been actively engaged in the search for a suitable alternative to mesh which has the following attributes:

- provides an effective skin confinement measure equivalent or superior to that of steel mesh;
- requires minimal human intervention in its installation;
- removes personnel from the immediate face area;
- enables higher underground roadway development rates to be achieved;
- is safe to use;
- is cost effective.

Thin Spray-on Liners

Thin spray-on liners (TSLs) are polymer-based materials that are used underground, and are mostly designed to provide secondary support in addition to steel mesh. Over 20 products are available in the market at the present time, and they fall generally into one of two material types: crosslinking polyurethane- or polyurea-based systems; and cement-reinforced water-dispersible systems based on ethylene-vinyl acetate copolymer (Espley-Boudreau 1999, Potvin et al 2004). The relatively narrow range of polymeric materials that form the basis of the majority of TSLs restricts the range of properties somewhat and hence the general applicability. Also, the use of cementitious additives in some TSLs improves the structural strength but unfortunately reduces the flexibility.

Prevailing Underground Conditions

The prevailing underground conditions are different in every mine. Roadway rib support practices can range from a single rib bolt per development metre and no mesh to three or more rib bolts and complete ceiling to floor meshing, depending on the structural soundness of the rib coal and the degree of ground movement experienced. Mesh usage in the roof, however, is commonly full width and continuous with a typical "square" bolting pattern. Roadway development practices range from "cut-and-flit" to bolting and meshing directly behind the continuous miner cutting head, again depending on the stability of the strata. In some mines gas drainage is an issue, whereas others have problems with mine water at low or high pH. Any new material will have to be able to be successfully applied, and provide the requisite level of long-term support, under these widely-varying conditions.

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This paper discusses some of the important issues associated with the replacement of steel mesh with a polymer-based alternative, and some of the strategies employed to deal with those issues.

POLYMERIC SKIN CONFINEMENT PROPERTY REQUIREMENTS

The desirable material properties of a polymeric skin confinement system include:

- able to be spray-applied without slumping;
- no toxic or irritant emissions during application, initial set or the development of full strength (curing);
- rapid initial set (seconds), and develops full strength over longer term (minutes to hours);
- good adhesion to coal, rock, roof and rib bolts prior to full cure;
- not sensitive to water, rock dust or coal dust;
- not pH sensitive;
- semi-permeable to water and gases;
- high strength, yet flexible (distorts within limits without rupturing);
- able to arrest or retard flaking and spalling of roof and ribs;
- strength enhanced by reinforcing fillers;
- light coloured;
- anti-static;
- fire retardant/intumescent.

A number of polymeric alternatives have been investigated that appear to have all of the chemical and physical property attributes required. The Flow Chart shown in Figure 1 summarises the material selection process. It can be seen that the selection process has essentially four stages, and progress is controlled by "yes-no" criteria:

- cure characteristics;
- flexural properties;
- viscosity and flow characteristics (rheology);
- environmental.

Cure Characteristics

The conceptual sequence of events when driving a roadway would be to cut the roadway using a continuous mining machine, install the confinement measure (whether steel mesh or some polymeric alternative), and then drill and install the bolts. In order to achieve this in minimum time, a polymeric confinement material would need to progress from liquid to solid in a matter of a few seconds (referred to as "cure") after spray application.

Cure chemistry to a large extent governs the speed of conversion from the sprayed liquid to a solid polymer, and the type of emissions (if any). There is a range of cure chemistries that are rapid-cure (several seconds) with no small molecule emissions, or that emit only water.

Polymer crosslinking (cure) is commonly a two stage process involving gelation followed by vitrification (Chang & Chen 1987, Martin et al 2000, Cook et al 2001). Monitoring of cure can be achieved using a differential scanning calorimeter (DSC), which measures heat flow as a function of time and/or temperature. A typical DSC measurement of cure is shown in Figure 2. After a period of no heat flow (induction period) which can last from seconds to hours depending upon the promoters and accelerators used, the material forms a gel (first stage cure) and a sudden exotherm occurs. At this point the material is dimensionally stable but not structurally sound or strong, and the material could then be drilled and bolted. Over the next period of time, which could also range from seconds to hours, vitrification occurs (second stage cure - the material becomes a glass) and the material attains structural strength.

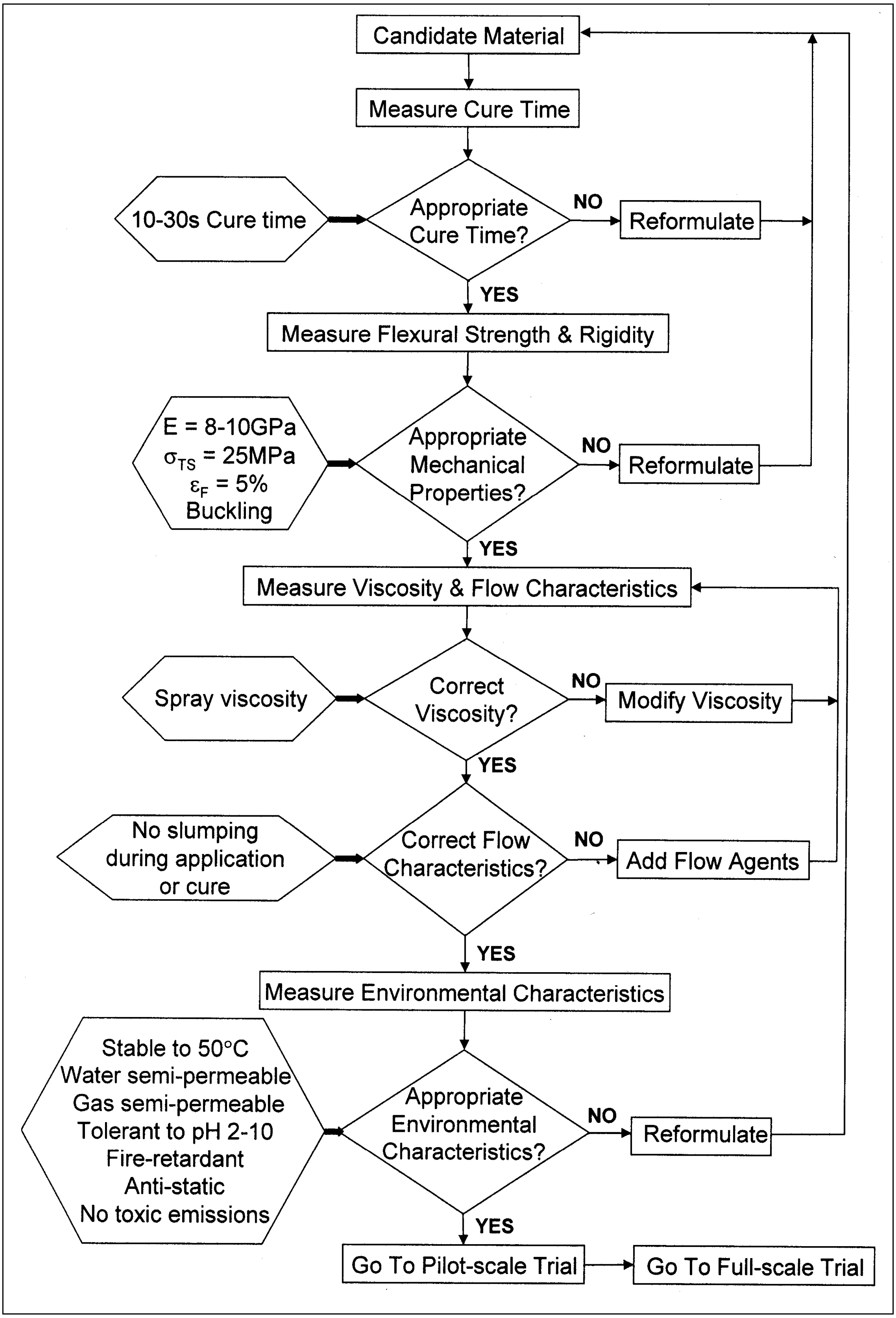

Figure 1 - Flowchart for selection of candidate materials

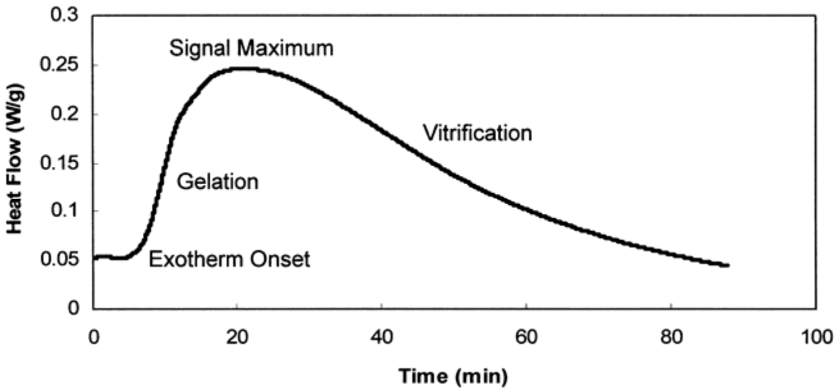

Figure 2 - Typical DSC measurement of crosslinking polymer cure

Flexural Properties

As movement occurs in underground strata, flexural loads will develop in any containment measure, so it is important to understand the flexural strength of both mesh and the polymeric replacements for mesh. Flexural strength is best measured in the laboratory by subjecting test specimens to a 3-point bend test. In this test, a rectangular beam of the test material is subjected to a bending load, and the flexural strength is calculated from the maximum load reached according to the following equation:

$$\sigma_{FS} = \frac{3FL}{2bh^2}$$

where σ_{FS} = flexural strength (MPa)
F = maximum load reached (N)
L = distance between supports (mm)
b = sample width (mm)
h = sample thickness (mm)

If the tensile modulus (E) of the material is known, it is also possible to calculate the maximum deflection (δ) that would occur before failure:

$$\delta = \frac{FL^3}{4Ebh^3}$$

The flexure behaviour of a number of reinforced polymers was measured at a constant deformation rate of 2mm/min, and the results are shown in Figure 3. Note that none of the materials exhibited catastrophic brittle failure. Instead, a gradual loss of strength was observed, due to the presence of the reinforcing filler. As shown in the Figure, some formulations were strong but too brittle, whereas others were less strong but more flexible. Hence a number of polymers have been prepared and tested that display a wide range of flexural properties. Detailed modelling of steel mesh properties will help to identify the polymer that exhibits the best properties for the application.

Rheology

It is most likely the new material will be spray applied, so an acceptable viscosity range will need to be defined and measured. In addition, the material will need to be applied without slumping, so the rheology is important. A thixotropic agent may be included in the formulation to prevent slumping, and the amount will need to be determined experimentally. Both of these can be addressed by the use of viscometry measurements.

Environmental Characteristics

Environmental issues are such things as temperature stability, pH tolerance, fire retardancy, toxicity and anti-static properties. For a crosslinked polymer, the glass transition temperature is the temperature at which the material converts from a high modulus glassy solid to a low modulus rubbery solid. In order to have stability and strength under prevailing underground conditions, the glass transition temperature of the polymer would need to be in excess of about 50°C.

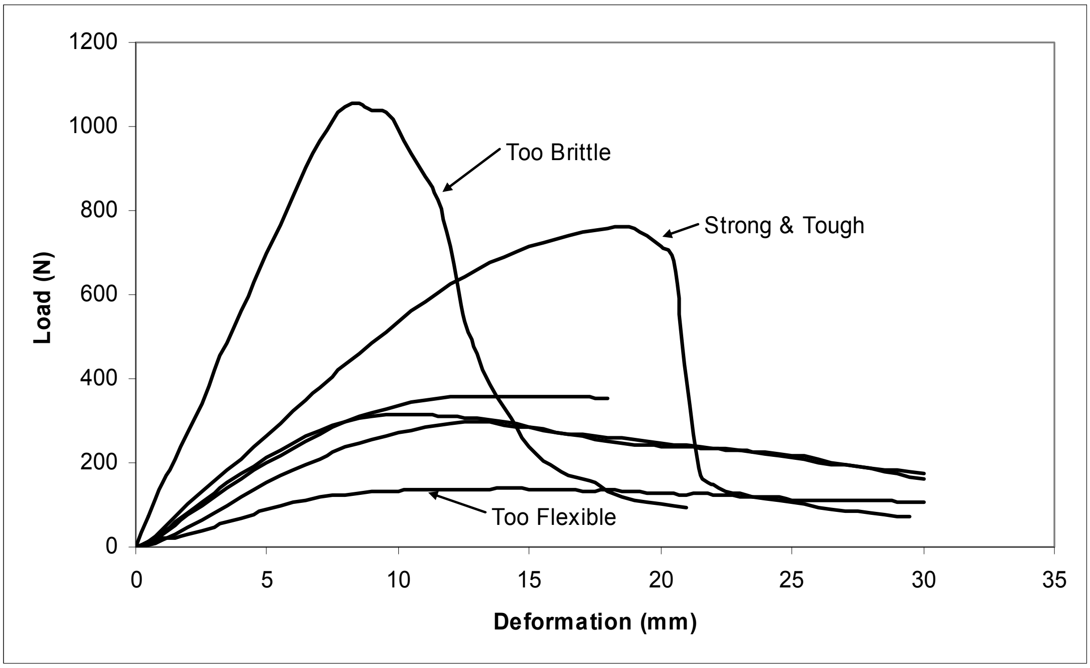

Figure 3 - Flexure Tests on Candidate Reinforced Polymers

As noted above, in some mines water is a problem. The pH of mine water can vary from 2 to 10, so the new material must be relatively unaffected by the pH of the mine water, in terms of physical properties and adhesion to wet coal.

Fire retardancy, anti-static properties and toxicity are all the subject of ASTM and Mine Safety methods.

CRITICAL ISSUES GOVERNING MATERIAL SELECTION

Results to date have shown that some reinforced crosslinking polymers can have appropriate mechanical properties as steel mesh replacements. A number of issues, however, need to be addressed before any potential material could be considered suitable for underground use. In order to identify these issues, a comprehensive product and process risk assessment has been carried out, which has identified the following critical issues:

- application quality control;
- health issues such as toxicity and irritancy during application and in the finished material;
- appropriate product mechanical properties;
- longevity;
- material must be anti-static and not propagate fire;
- no adverse effect on coal preparation plant or coal clearance systems.

Application Quality Control

As noted above, ground conditions are different in every mine. Some mines may require a continuous skin confinement measure of uniform thickness, whereas others may require a thick band in the vicinity of the bolts and thinner sections in between the bolts. There may be yet other requirements at other sites. Also, freshly-cut coal does not present a smooth surface. For these and other reasons, application quality control is seen as an important issue. Application of the polymeric mesh replacement will be automated, so the application technology will need to be able to apply the material in a manner consistent with the prevailing ground conditions.

Health Issues

The major health issue in relation to a polymeric material being used underground in large quantities is the possibility of toxic or irritant emissions during installation and/or in service. This is particularly relevant where a chemical reaction occurs to effect cure of the polymer (as in the present case). In our selection of polymer and cure chemistries, we have investigated only those systems that have no condensation product during cure, or emit only water, however the issue remains of possible volatile chemicals in confined environments prior to cure. Our investigations have identified raw materials that are very low volatility, thus would not present a toxic or irritant hazard.

Mechanical Properties

A goal of this work is to develop a polymer-based material that has equivalent or superior mechanical properties to steel mesh. In order to determine the appropriate mechanical properties of a steel mesh replacement, it is first necessary to determine the properties of steel mesh itself. This can be achieved by a number of means. Steel mesh is constructed using drawn low carbon steel wire welded in a square mesh pattern. Mesh is typically 4 % steel by volume, thus a very rough estimate of the tensile properties of mesh in the direction of the wire can be made based upon measured properties of the wire. Typical tensile properties of steel wire and mesh, and a reinforced polymer of the types described above, are shown in Table 1. It can be seen that, with the exception of failure strain, the reinforced polymers possess tensile properties similar or superior to steel mesh. Geotechnical modelling of the role of steel mesh underground will lead to a more robust and realistic system for the determination of the mechanical properties to be endured by any polymeric replacement for mesh.

Table 1 - Typical Tensile Properties of Steel Wire, Mesh and Reinforced Crosslinking Polymer

PROPERTY	Low Carbon Steel Wire	Low Carbon Steel Mesh	Crosslinking Polymer 30-50% Fibre
Young's modulus (GPa)	205-215	8	10-17
Yield Strength (MPa)	500-600	20-24	25-55
Tensile Strength (MPa)	500-600	20-24	30-70
Failure Strain (%)	4-6	4-6	1-2

A second issue in relation to mechanical properties of the mesh replacement is adhesion of the cured material to strata. The current plan is to use a material that will achieve initial cure in a few seconds (dimensional stability, but perhaps not full strength) and will then be bolted through. Some adhesion of the uncured (wet) material to the rock or coal strata would be advantageous, and adhesion of the cured material is seen as a potential additional skin reinforcement mechanism. A quantitative adhesion test has been developed which allows the measurement of adhesion strength of an applied reinforced polymer to a number of different rock types and coal under a variety of conditions (wet, dry, dusty, low pH etc).

Longevity

In longwall mining operations, gate roads are in use during the extraction of two longwalls, first as a main gate and then as a tail gate. A skin confinement measure would thus need to remain in good condition for this entire duration, which may be 2 to 3 years.

The major mechanisms by which deterioration of polymer properties can occur are degradation during processing, thermal degradation, weathering, and environmental stress cracking. Processing and thermal degradation generally occur as a result of exposure of the polymer to elevated temperatures either during synthesis, manufacture of an article from the finished polymer, or in service. In the mine environment temperatures tend to remain very stable, so thermal degradation is unlikely.

Weathering, as the name implies, is degradation as a result of exposure to weather. The most important cause of weathering is exposure of the polymer to solar ultraviolet light in the presence of atmospheric oxygen, a process known as "photo-oxidation" (Rabek 1995). Oxygen itself can have no effect on a polymer in the absence of UV light or excessive heat, hence polymer weathering is very unlikely underground.

Environmental stress cracking involves crack initiation, growth and ultimate failure by the combined action of a tensile stress and an environmental liquid or gas. As ground movement occurs constantly in mine roadways, the stress experienced by a skin confinement measure would also be constantly changing. Some polymers are very susceptible to environmental stress cracking, and the environmental liquid causing the degradation could be as otherwise-innocuous as water. Other polymers are much less susceptible to the phenomenon. The types of polymers being investigated for skin confinement are not known to be susceptible to environmental stress cracking. Accelerated testing of any potential candidate material will have to be carried out in order to ascertain that the polymer will have the required longevity in service.

Anti-static and Fire Retardancy

Polymers are typically electrical insulators, and as such can accumulate static electricity generated by friction as a result of air flow across surfaces. A build-up of static electricity underground can lead to a spark discharge, which can in turn lead to fire. Steel mesh is able to conduct static electricity safely away by way of the earthing effect of the bolts, however polymers intrinsically are not able to do this. The addition of anti-static additives may alleviate this problem. Several anti-static additives for polymer systems are available (Grob & Minder 1999), however the solution may be simply the addition of coal dust. A significant proportion of coal is graphitic carbon, which is electrically conductive. The amount of coal dust or other additive to give the conductivity required by legislation will have to be experimentally determined.

One major advantage of steel mesh over any polymeric alternative is that it is non-flammable, whereas polymers tend to be at least combustible if not spontaneously flammable. Fire retardancy can be incorporated into a polymeric formulation either by using fire-retardant monomers, which tend to be brominated materials, or by use of a fire-retardant additive. The use of brominated raw materials would increase the cost enormously, so fire-retardant additives are a better option. Such additives are of two types: fire-suppressant; and intumescent.

Fire suppressant additives typically decompose when heated to produce carbon dioxide or other non-combustible gas, which then suppresses the flame (Biswas et al 2007 & references therein). Intumescent materials carbonise and swell when burnt, removing the seat of the fire from the surface (Ma et al 2007 & references therein). Either type of additive would be suitable for the present application.

Impact on Downstream Processing

The final issue relates to the effect of the new product on coal preparation plant and coal clearance systems. The major consideration is the possibility that the polymer may become tangled in the shearer head, however the stiffness of the reinforced polymer makes this very unlikely.

CONCLUSIONS

A polymeric alternative to steel mesh for underground coal mine roadways offers numerous advantages over mesh. There are, however, also a number of issues which will need to be addressed before any polymeric material could be used in this capacity. Recent research has shown that a viable polymer-based alternative to mesh can be developed which overcomes all or most of the critical issues described.

Future work will be focussed on the further development of suitable materials, especially in relation to environmental issues such as pH sensitivity, and the control or prevention of toxic or irritant emissions during application and cure. In addition, a comprehensive geotechnical study will be undertaken into the role of steel mesh in roadway support, and this will further guide the development of a polymeric alternative.

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