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The application of polyurethane grout in roadway settlements issues

Liang Yu
Martech, Edmonton, Alberta, Canada
Rocky Wang, Roger Skirrow
Engineering Service Division, Alberta Transportation, Edmonton, Canada

ABSTRACT
Polyurethane resin has several useful and unique applications in civil engineering works. The material characteristics of different types of polyurethane resin are reviewed in this article. A discussion of the basic formulation of the resin components and associated civil engineering applications is also presented. For clarification and illustration purposes three case studies showcasing the application of polyurethane in Alberta Transportation highway projects are presented.

RÉSUMÉ
Résine de polyuréthane a plusieurs applications utiles et uniques dans les travaux de génie civil. Les caractéristiques matérielles des différents types de résine de polyuréthane sont examinées dans cet article. Une discussion sur la formulation de base des composants de la résine et des applications de génie civil associés est également présentée. Aux fins de clarification et d'illustration trois études de cas présentant l'application de polyuréthane dans les projets routiers Transports de l'Alberta sont présentés.

1 INTRODUCTION

Polyurethane was first made by Otto Bayer and his co-workers at I.G. Farben in Leverkusen, Germany in 1937. Since then, polyurethane has been used in different industrial applications and more recently in civil engineering and geotechnical applications (Avar, 2008; USACE, 1995). Over time the chemistry, materials properties and application techniques of polyurethane have been developed and improved.

Due to its light weight, insulation quality, high expansion rate, quick reaction time, and small footprint of the injection method, polyurethane has been used to: repair pipeline leaks; densify subgrades; repair foundations; make curtain walls for dam structures; install in-situ foam piles without excavation; raise sunken concrete slabs; fill void, and; repair bridge abutments.

This paper focuses on the use of polyurethane to deal with settlement issues on both concrete and asphalt roadways. In these applications the polyurethane grout is to raise sunken concrete roadway, improve geo-material performance, increase load bearing capacity, stabilize soil conditions and prevent piping and soil erosion.

2 CHEMISTRY AND APPLICATION OF POLYURETHANE

There are many different combinations and component mixes of polyurethane, however, all combinations share a similar reaction fundamentally that involves isocyanates containing two or more isocyanates groups per molecule ($R\text{-}(N{=}C{=}O)_{n \geq 2}$) and a polyol containing on average two or more hydroxy groups per molecule ($R'\text{-}(OH)_{n \geq 2}$), wherein the urethane groups — NH-(C=O)-O- link the molecular units (Figure 1).

The properties of polyurethane are greatly impacted by the types of isocyanates and polyols used in the synthesis. Long, flexible and elastic segments are contributed by the polyol polymer. High amounts of crosslinking give tough or rigid polymers. Long chains and intermediate crosslinking give polymer useful properties for making foam.

One of the most desirable and amusing attributes of polyurethanes is their ability to be turned into foam. Making foam requires the simultaneous formation of a gas and urethane polymerization. There are two sources of gas during the reaction. The first one is carbon dioxide generated by reacting isocyanate with water (Figure 2). The second source is boiling volatile liquids, in which the required heat is from exothermic polymerization causing the liquids to vaporize. This is understood how the foam is formulated.

This process provides the basic concept of polyurethane formation. The major by-product is carbon dioxide, and the reaction is irreversible. Therefore the cured product is inert and environmentally friendly. Cured polyurethane foam is either “open cell”, where entrapped bubbles have broken but the edges of the bubbles are stiff enough to retain their shape, or “closed cell”, where the entrapped bubbles remain intact. “Open cell” foams are typically used for cushion in mattresses or seats. In this paper, the foam used to mitigate roadway settlement problems is “closed cell”. Cured foam, without sand, gravel or other inclusions can range in compressive strength from 468 to 689 kPa. Due to the “closed cell” porous structure, the density of foam is greatly reduced. The density of the polyurethanes used in roadways range from 56 to 76 kg/m^3.

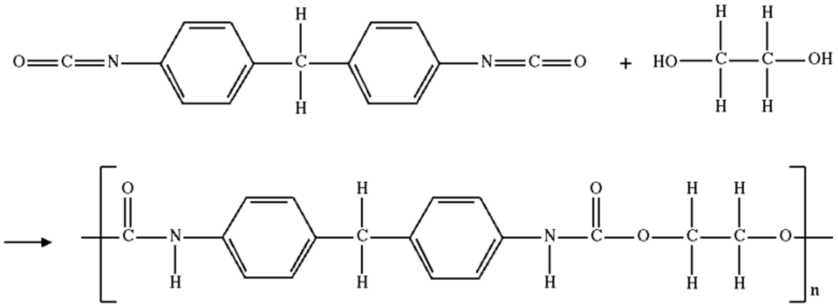


Figure 1. Polyurethane synthesis (Kaushiva, 1999)

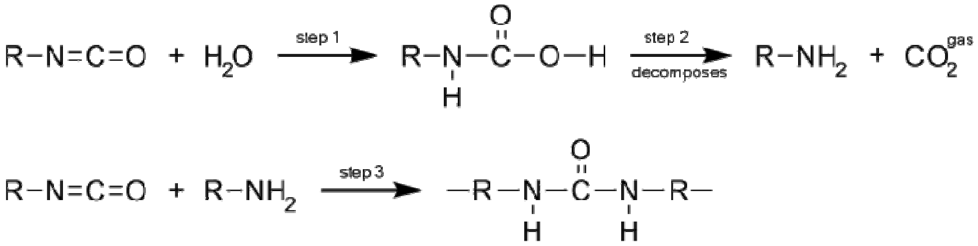


Figure 2. Carbon dioxide gas formed by reacting water and isocyanate (Kaushiva, 1999)

Viscosity is due to many factors including the size and shape of composite particles and the attractions between these particles. The longitudinal shape and the molecular size determine that polyurethane has low viscosity. The molecules in the polyurethane reaction are neutrally charged, so attractions between particles are minimal.

The reaction time to form polyurethane foam is typically between 30 seconds to 2 minutes, making it a very fast process. For practical applications, this means there is minimal time required for implementation, and issues like traffic interruption are minimized.

2.1 Hydrophilic vs. Hydrophobic

Hydrophilic expansive grouts absorb water while curing and also react upon contact with water. They are usually cured to flexible foam or gel. The typical application for hydrophilic polyurethane is to seal leaks in joints or cracks and to repair leaking water-stops. Due to the flexible and hydrophilic property, these types of form react with moisture in the crack surface to form bonds. Some hydrophilic foam grouts are certified by UL or NSF to be used with potable drinking water system, so they can be also used with potable water tank repair and dam rehabilitation. The expansion rate of hydrophilic foam is typically 5 to 7 times its original volume, so it is not ideal for the purpose of roadway lifting.

Hydrophobic grouts expel water. There are many material properties that make hydrophobic grouts ideal for use in roadway settlement mitigation projects. Hydrophobic grouts have high expansion rates (20 times and more) and low viscosity. Due to the low water content, the cured foam will not shrink over time, and is also considered as rigid foam. When mixed with sand and gravel, these types of foam perform like light-weight rock or a rigid pile. There are single-component and two-component hydrophobic foam options. The choice of which option to use depends on the application requirements and specified material properties. The single-component option is known as a “Permeation Grout”, and the two-component option is known as a “Compaction Grout”. When using single-component foam, the contractor can also control the reaction speed by using an accelerator to adjust cure time from 1 to 10 min. This will customize the foam performance to different soil conditions and application requirements.

2.2 Permeation Grouting

Permeation grout is a single component, hydrophobic polyurethane. Its reaction requires a catalyst and is activated by water or moisture. Permeation grouting saturates the soil with an extremely low viscosity resin (35-130 Centipoise), which means a higher groutability. As a reference the viscosity of olive oil is 81 Centipoise. Polyurethane manufacturers produce different versions of permeation grout to target specific applications. The end result of permeation grouting is a hard, water tight, light weight mass. These types of grouts are mainly intended for asphalt surfaced road settlement issues and deeper injection applications due to the low viscosity.

Permeation grout can be used to increase the load-bearing capacity of road structures above muskeg or other soft ground conditions. Vertical column of resin impregnated soil can be created using permeation grout. These columns are unaffected by water, and create a defined load-bearing system for the structural support of roadways. An approximately 0.3 meter diameter column can produce compression strengths of 5.2 to 8.3 MPa, and a skin friction of more than 26 kPa for clayey sands.

For roadway applications, the soil conditions below road surface are investigated through a conventional geotechnical investigation using one or more test hole. The purpose of the investigation is to determine the depth and grid pattern of the polyurethane injection application.

The implementation process involves installing a steel casing and injection tubes to the desired depth and slowly pumping the product into the ground as the rod and steel casing are both extracted. The steel casing protects the injection tubes by preventing sand or loose soil from collapsing into the drilled hole. The permeation grout application drill hole has a diameter of 10 to 25 mm; so the application footprint and associated project impacts are minimal.

Single component permeation grout can be catalyzed in different ratios to provide a rapid or slow reaction time as required by specific project needs. Some single-component polyurethane do expand upon contact with ambient soil moisture but only enough to penetrate the soils; this is a useful trait as lift of the roadway is generally not desired in foundation stabilizing projects. Polyurethane's low viscosity will penetrate sand, silt and some clays (Getzlaf, 2006).

2.3 Compaction Grouting

Compaction grouting results from injecting a two component, rapid set, highly expansive structural foam, which fills voids and compacts soil by its expansive pressure. The two component materials can react with each other without water or catalyst involved. **Table 1** shows some of the physical properties and characteristics of polyurethane.

Compaction grouting is a process by which rapidly expanding polyurethane foam (fully expanded in 30-60 seconds) is injected into the ground. The foam fills voids in the immediate area and compacts the surrounding soil using expansive pressure. The bearing capacity of the soil is increased as a result of the placement of the high strength foam. The slab can be lifted due to the hydraulic force created by the expanding foam.

This process can be utilized to lift concrete roadways, approach slab, sidewalks, driveways, warehouse, sunken tank, etc.

Once the subgrade is stabilized and consolidated a grout lift process, such as the Precision Lift process (a Prime Resins Inc. process for slab lifting by compaction polyurethane grout), can be used to lift the slab. Rapidly expanding foam is injected through small diameter holes directly beneath the slab in short bursts. By speeding up the reaction with heat and by controlling the amount of material that goes in beneath the slab, it is possible to precisely control the slab lift. This procedure requires specialized equipment and well-trained technicians.

Typically, the contractor may need to use multiple injection points to evenly distribute the lift. It may be necessary to inject holes multiple times by re-drilling the previously injected holes. It is also important to locate any buried utilities and check for obstructions before construction.

Table 1. Polyurethane Properties

Unit weight	3.5 – 7.0 pcf
Material set time	Less than an hour
Impact on existing subsoil	Minimal stressed
Size of injection hole	10 to 25 mm
Material preparation onsite	Materials stored in trailer
Clean out	None required
Shrinkage	None
Groundwater	Not affected
Equipment	Single self-contained unit houses materials, hoses and equipment
Mobility	Up to 125 m of hose with standard equipment
Waste material	Minimal waste materials. Pumps and hoses remain charged with material safely until next use.
Environmental impact	Inert after cure. No waste. Does not generate dust.
Temperature	Can be installed in both above and below zero ^{o}C conditions
Precise Control	Precision control to within 3 mm. Consistent production.
Less Intrusion	Work completed in hours/days. Dust sensitive computers and equipment can be left on site.

There are some basic limitations for polyurethane injections, related to temperature and chemical environment. Outdoor applications generally achieve the best results if done in the spring or summer. Material properties of polyurethane are less stable at very high or very low temperature. Generally speaking, polyurethane is not used under heavy service loads at temperature above approximately 105^{o}C.

Certain chemical environments with solvents are detrimental to polyurethanes, specifically the aromatic solvents such as toluene or ketones such as MEK or acetone, and esters such as ethyl acetate. Polyurethane use at locations where such chemicals are likely to be found should be thoroughly assessed and designed for.

3 CASE STUDIES

3.1 Continuous Cured Foam Column Injection of Soft Clay Foundation

Highway 56:16 is a two-lane secondary highway with a width of about 11m. A distressed area of pavement was observed about 400 m south of the intersection with Hwy 609 along the west shoulder of the road over a length of about 30 m. The shoulder and west lane of the road had experienced creep settlement requiring periodic asphalt patching such that the current asphalt thickness is about

0.5 m. Thin patches were applied about every 18 months. Settlement had also spread to the northbound lane of the highway, and the skid marks indicated that the dip had become a traffic hazard. The site was incorporated into Alberta Transportation's (TRANS) Geohazard Risk Management Program (GRMP) as site C54.

A geotechnical investigation in 2008 showed that the subgrade soil in the maximum settlement area consisted of soft to firm, medium plasticity clay. Consolidation of the soft clay and additional weight from patching asphalt were considered as two major contributing factors.

A deep polyurethane permeation grout (Prime Flex 920) injection technology was chosen to improve the strength of the subgrade and consolidate the soft clay. The advantages of this foam method were considered as follows: excavation and removal of the existing pavement structure was not required; greater depth of subgrade improvement could be achieved, and; traffic closure was not required.

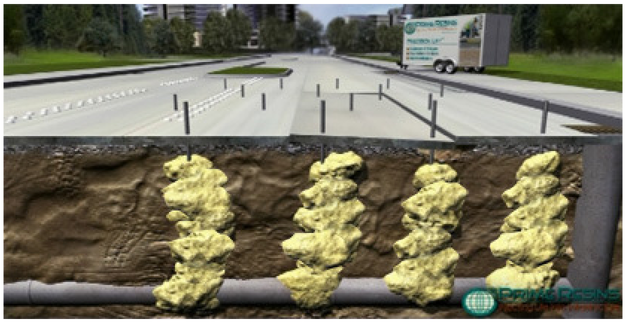
The injection holes were drilled through 1.2 m of pavement (Figure 3). Foam injection holes were spaced at about 1.2 m triangular grid intervals for a 15 m length of both highway lanes. Injection probes were inserted through the 25 mm diameter injection holes by a labourer to a depth of about 6 meter. A steel casing was used which prevented the soft clays from collapse into the drilled hole (Figure 4). The steel casing and the probes were pulled out gradually during the foam injection, so that a continuous cured foam column could be formulated. The column functions as an in-situ pile with both skin friction resistance and end-bearing resistance. Within each injection hole, the polyurethane materials usage was about 12.6 Litres per linear meter (or 1 gallon per linear foot). Based on volumes used the formulated foam columns had an average estimated diameter of 0.56 meter. In total, 130 foam columns were installed at this project.

Figure 3. Drill penetrating through 4 feet of pavement structure

The project cost was about $170k. No further settlement or pavement distress has been observed since the foam injection and repaving work in August 2011.

(a) Steel casing and probes were inserted into the ground in a 1.2 m triangular grid

(b) The finish of one foam pile injection



(c) Illustration of the cured polyurethane pile in soil stabilization.

Figure 4. Injecting high density expanding hydro-insensitive polymer into weak strata for subgrade densification at site C54

3.2 Sleeved Foam Column Injection of Muskeg Foundation

According to TRANS maintenance and operations staff, a portion of Hwy759:02, located 1.5 km north of the junction with Hwy 39, has experienced ongoing settlement for several decades. The site was identified and incorporated into TRANS's GRMP in 2002, and assigned site number NC22. The road embankment at this location crosses a deep muskeg deposits. About 50 cm of settlement has occurred at the site since 2002.

Figure 5 shows the general site conditions. A geotechnical investigation was completed in 2006 and confirmed that an embankment fill of 4m was placed over muskeg of 4 m overlying soft organic clay. The presence of muskeg can be seen on the injection drill hole (Figure 6). Based on the site conditions this location was determined to be a suitable trial site for the application of polyurethane column foam injection methodology (Smith et al. 2011). The design concept was based on the established use of stone columns under embankment (Barksdale and Bachus, 1983).

Figure 5. Settlement dip prior to foam column injection

Figure 6. Muskeg blown out of borehole during construction

Two patterns of staggered grid were selected and implemented for the site foam injection by using spacing of 1.2 m and 2.4 m on centre. The variation in column spacing was implemented in order to assess the optimal column spacing for future project. The construction process included injecting expanding polyurethane foam into fabric bag containment units installed in boreholes throughout the affected area of about 25 m by 12 m (Figure 7). The finished columns were believed to have an about 0.5m in diameter. The construction was finished in ten working days without traffic closure.

The road surface vertical profile was surveyed five times over the course of a year and negligible settlement has occurred. The method of road dip stabilization is now considered a viable mitigation option for similar settlement problem sites (Smith et al. 2011).

3.3 Concrete Roadway Surface Lifting by Compaction Grout

Anthony Henday Drive is a major ring road surrounding Edmonton, Alberta. The road surface of a portion of the southeast and southwest legs is concrete. Several localized problem sites have settled over the years. The dip in the road has created safety concerns due to the high volume of traffic and highway speed limit. Longitudinal settlements between adjacent concrete slab joints were also observed.

Figure 7. Grouting assembly with tremies, guiding conduit and three-tier sleeve bags

Different approaches were considered as remediation methods to solve the settlement issues, including cement slurry and polyurethane injection. Due to the low viscosity, fast reaction time and high expansion rate properties of the two-component hydrophobic polyurethane compaction grout it was selected as the preferred approach. This technique required the smallest construction footprint and least traffic interruption time.

Two Precision Lift polyurethane injection rigs were onsite for this project. The two-component Precision Lift 3.5# materials were pre-heated prior to arrival at the job site. Component A and B materials are mixed at a 1:1 ratio which can be achieved by adjusting the temperature of both components to match viscosities. From this perspective the temperature of the components is critical in making high-performance foam. Due to the low viscosity of polyurethane, the cured foam can travel long distances.

There were 6 holes drilled per concrete slab panel, and polyurethane compaction grout was injected, starting at the lowest point of the slab with a 5-10 second shot, with longer shot used for larger voids. Multiple shots were done at each location, with a short pause between shots not usually exceeding 5 seconds. The pause is intended to allow the foam to partially expand and fill void so that subsequent shots are restricted and the volume of foam used is managed. Once voids are filled beneath the slab the expanding foam forms a hydraulic lift and begins to raise the slab. Each layer compresses the supporting soils and produces more lift to the slab. As the slab is raised, shorter injection shots can be used with shorter intervals to fine tune the slab lift to the perfect elevation.

Multiple injection points are used to evenly distribute the lift (Figure 8). A measuring device is also used to precisely monitor the vertical increment of the slab (Figure 9). Within half an hour, a concrete slab panel can be raised to the precise level. The crew fixed 12-20 panels daily which allowed project timelines to be easily met.

Due to the high expansion rate and hydrophobic material properties, all moisture and water were expelled out of the ground (Figure 10). The 'before' and 'after' comparison is shown in Figure 11. The polyurethane injection portion was completed ahead of the designed timeline.

Figure 8 Double injections method to evenly distribute lifting force

Figure 9 Measuring device to monitor the rise of the concrete panel

Figure 10 Moisture and water were chased out by expansive polyurethane

Figure 11 'Before' and 'After' comparison (within 0.5 hour) at the same location

In addition to the above cases, in the badlands - Drumheller, say, Highway 570:01, injected expanding foam also has been used to fill sinkholes caused by internal erosion.

4 SUMMARY

Polyurethane grouting, as a mature technology, provide a unique approach for settlement issues on both asphalt and concrete roadways. Permeation grouts, due to its low viscosity, expansion rate, hydrophobic property, fast set time and developed construction method, can be used to stabilize the soil in deeper burial depth (6 meter or plus) and also install a foam pile to increase load-bearing. This method is considered as a long-term fix to eliminate frequent re-pavement and water erosion issues. It also helps save the costs for road closure and building detour. Compaction grout with superior rapid expanding property, can fix the concrete roadways settlements in hours. Since polyurethane can contain sand and gravel in the foam, the road structure will stay intact for decades when applied properly under appropriate conditions. This saves the costs for multiple mud-jacking in future years.

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