Rapid remediation using polyurethane foam/resin grout in Malaysia

Ismacahyadi Bagus Mohamed Jais PhD

Senior Lecturer, Faculty of Civil Engineering, Universiti Teknologi Mara, Shah Alam, Malaysia (ce_ismacahyadi@yahoo.com) (Orcid:0000-0002-6007-2546)

Consolidation and collapse settlements are common threats to existing highways and buildings around the world. With the emergence of various ground improvement technologies, lightweight materials are alternative solutions for filling embankment settlement, ground repair and resolving settlement issues of roadways and building structures. This alternative solution has become effective and rapid in terms of performance and time. In the polyurethane resin (PUR) injection method, the liquids, polyol and isocyanate, are injected in small drilled holes without the need for excavation. This method is fast and provides additional strength to the ground with reduction in the void ratio, hence reducing the compressibility of the soil. In fact, its lightweight and impermeable characteristics are advantageous to ground experiencing inundation and groundwater table fluctuation where it triggers the buoyancy effect. This paper presents the chemistry of PUR, the concept of PUR grouting, the properties of PUR and case studies conducted in Malaysia for rapid ground remediation.

Introduction

Peninsular Malaysia is a tropical country that experiences variable soil conditions, and this has a greater effect on construction over soft foundation soils where methods of ground improvement have been adopted to provide a stable foundation. Excessive post-construction settlements constitute an engineering challenge for structures founded on compacted fills and soft ground experiencing degradation, hence causing instability to the existing structures. For structural repair, various methods of remedial works have been proposed and implemented such as underpinning piles, grouting and pin piles. For road pavements, methods such as resurfacing and installing geotextiles are most common. However, most of these methods require major excavation and disturbance to the existing structure. The need for a rapid treatment and remediation solution for variable soil conditions was studied for the safety and economy of projects. Polyurethane (PU) foam/resin injection is a method of rapid ground repair and remediation without the process of excavation and replacement. The objectives of this method are (a) to remediate problematic foundation soil by injecting lightweight PU foam/resin at high pressure and (b) to increase the bearing resistance, hence reducing the volume change of the weakened fill layer. This method consists of injecting a hydrophobic polyol and isocyanate mix into problematic subgrade by using hydraulic power packs, producing PU foam/resin and filling the void space during the expansion of the PU foam/resin mix. With recent issues relating to pavement defects, depression and the high cost of maintenance in Malaysia, PU foam/resin injection provides an alternative to rapid ground remediation work, free from excavation, and the foam can be produced within hours compared to conventional techniques.

Polyurethane resin

Polyurethane resin (PUR) has many applications; therefore, various features of PU behaviour have been widely investigated since the 1960s (Buzzi *et al.*, 2008). PU resin/foam is a complex

and unique polymeric material with a wide range of physical and chemical properties; it comprises a chain of organic units joined by urethane links. PU resin/foam is formed from the combination of an isocyanate (–NCO) with a polyol (–OH) material (Hui *et al.*, 2013). PU resin/foam is a cellular solid consisting of an area of PU polymer separated by voids (Gibson and Ashby, 1988).

Mohamed Jais *et al.* (2015) reported that there are two types of PU foam/resin – namely, hydrophobic and hydrophilic PUs. Hydrophilic PU resin/foam is not suitable for ground repair since this grout reacts with water, absorbs it and cures to become flexible foam or gel. When it is in contact with water, hydrophilic PU expands only up to five to seven times from its original liquid volume.

Hydrophobic PU resin/foam is suitable for ground repair and remediation since it expands 6–20 times from its liquid volume. Yu *et al.* (2013) referred to hydrophobic PU as foam where it has an accelerator to control the curing time. The advantage of using this foam is that it can expel water during expansion before it stabilises the soil. PU resin/foam is a lightweight material with high insulation quality, high expansion rate and quick reaction time that also requires only small-diameter injection holes.

Polyurethane foam/resin is a mixture of two liquid resins. It can form either an elastic gel or a rigid form when reacting with water (Robinson *et al.*, 2012). This polymer is suitable as ground improvement to reduce void filling in soil, which can improve the strength of the soil itself. The formation of PU is given as follows

I. (isocyanate) + (polyol) = (polyurethane)

Isocyanate is a functional group with the formula $R-N=C=O$, which consists of nitrogen, carbon and oxygen. The oxygen and nitrogen atoms are negatively charged ions that impart the electrophilic nature of the carbon. It is known that isocyanate is a highly reactive chemical. Isocyanate reactions are divided into two groups: the reaction of isocyanate with compounds containing reactive hydrogen to give an additional product and the polymerisation of isocyanate (Chattopadhyay and Raju, 2007). Isocyanate reacts with polyol compounds to form a urethane group and with amines to form urea. Figure 1 presents the reaction of toluene diisocyanate (TDI).

Polyol ($-OH$) is a group of organic compounds that contain hydroxyl groups, including ester, ether, amide, acrylic and others. Polyester polyols are most commonly used for reaction in the production of PU. They are prepared by the reaction of glycols, which also consist of ester and hydroxylic groups. The properties of PU depend on the molecular weight of the cross-linked polyester polyols. Some polyester polyols result in rigid PU resin/foam, which has good heat and chemical resistance. High-molecular-weight polyols yield flexible PU resin/foam, while low-molecular-weight polyols produce rigid PU resin/foam (Sharmin and Zafar, 2012). Figure 2 shows the two liquid parts forming PU resin/foam.

PUR characteristics

PU resin/foam is a lightweight material with high insulation quality, high expansion rate and quick reaction time. With all of these properties, PU resin/foam is suitable for repairing pipeline leaks, repairing foundations, raising depressed concrete slabs, recompacting subgrades, repairing bridge abutments and resolving many other settlement issues. The properties of PU resin/foam derive from the types of isocyanates and polyols used in its creation; according to Yu *et al.* (2013), there are high amounts of cross-links in synthetic materials better known as rigid polymers. The ability to turn into foam is the most useful physical property of PU resin/foam; foam can uplift the settlement of slabs and roadways or cover any leakage on a pipe surface. There are two types of foam: 'open-cell' and 'closed-cell'. Open-cell foams are used for cushions in mattresses and seats; closed-cell foam is the type of foam used for reducing the settlement of soil (Yu *et al.*, 2013). Figures 3 and 4 show the microstructure of the PU resin/foam and the intrusion of PU resin/foam in laterite soil.

Concept of alternative treatment and modification using PUR grouting techniques

PU foams/resins are an extensive family of polymers that can be manufactured to achieve a wide range of physical characteristics in either expanded or non-expanded states. Expanding PU resin/

Figure 1. Toluene diisocyanate (Chattopadhyay and Raju, 2007)

Figure 2. Polyol and isocyanate compounds

Figure 3. Electron microscope view of the PU foam

Figure 4. Electron microscope view of the intrusion of PU foam into laterite soil

Table 1. Design properties of the PU foam/resin

Description	Value	Unit
Unit weight of PU foam/resin, γ	0.8–1.5	kN/m ³
Stiffness modulus, E	10 000–15 000	kN/m ²
Poisson's ratio, ν	0.3	
Compressive strength, σ	2.2–16	MPa
Permeability, k	1×10^{-12}	m/s

foam is formed from an exothermic reaction between polyol and isocyanate mixed at specific volumetric proportions. A large amount of carbon dioxide is produced during the reaction, causing volume expansion and producing a foam structure where gas bubbles (cells) are surrounded by a rigid wall. The pressure exerted during expansion and the subsequent density of the PUR depend on the extent to which the gas bubbles are able to expand before the PU foams/resins harden (Buzzi *et al.*, 2010).

Injection of PUR is an alternative method to ground modification, specifically for solving problems of excessive settlements of structures. The pressure exerted by the gas evolved during the chemical reaction forms the resin to lift up the structure. The PU foam/resin is injected at a depth of 3 m, and no excavation is required to remove the existing slab. However, if the foundation of the structure is affected, a small area of excavation is required at the injection point to locate the existing foundation before the injection process can be implemented. Table 1 presents the engineering properties of the PUR used for the purpose of design.

PU resin/foam injection

Mohamed Jais *et al.* (2016) explained that the injection of PU resin/foam was used for densification. A blowing agent was incorporated into the resin to ensure that the expansion factor

could reach up to 15 times. However, another agent (nitrogen-based catalyst) was added to improve the expansion of the resin/foam.

The curing time of the expansion resin/foam started about 15 min after the mix, and the packer was then removed. The holes were then grouted with cementitious mortar. Figure 5 shows a typical injection procedure implemented on-site, while Figure 6 shows a schematic diagram of the shallow injection procedure.

Method of slab uplifting and soil improvement using PUR injection

Mack (2010) described a unique method used for raising concrete slabs, road and even structures, called slab lifting, because that was its first area of application back in 1983. It is fast and

Figure 5. PU foam injection using two-part hydraulic power packs

Figure 6. Schematic layout of shallow PU foam injection (courtesy of Progrout Injection Sdn. Bhd., Malaysia)

economical and causes minimal inconvenience to normal activities. Experienced operators inject the PUR through small pattern-drilled holes, immediately below the slab or footing. The components are precisely machine-mixed and chemically expand immediately, exerting a mould pressure that fills voids encountered, re-establishing or confirming structural support. They cure almost immediately – the setting time is 8–15 min and curing is up to 2 h – to a strong, stable and long-lasting material. PUR is injected below existing structures to fill the voids underneath the existing slabs as shown in Figure 7. Grout injection pressure in the range of up to 1500–2000 psi ($1.03\text{--}1.38 \times 10^4$ kPa) allows lifting of the existing floor to fractional tolerance. The spread of the material is controlled, while the rate of uplift is a gentle and precise operation. The uplifting movement is carefully monitored by laser and computer measurement. The results are immediate and permanent with shelving and machinery in place, resulting in huge savings in both time and cost (Mack, 2010).

PU friction root system for geotechnical reinforcement

PU friction roots work efficiently as a combination of geotechnical reinforcement and compaction grouting elements, aided by skin friction/cohesion and base resistance. All materials and equipment arrive on-site in one purpose-designed self-contained vehicle, with a team of at least four to five men. The installation equipment is portable, and one man can safely carry several 32 mm dia. steel rods at a time. Element lengths are currently available from 1 to 5 m.

This method strengthens the shallow foundation underneath, where the soil bearing will be increased. In addition, this system provides a buoyancy effect to the existing structure. Moreover, the PU friction root system will provide additional geotechnical support to the problematic foundation structure. This will reduce

Figure 7. Propagation of resin and uplifting process: (a) injection within cracked zone, propagates, reaches the surfaces and lifts the structure; (b) injection below the crack depth, fractures the soil, creates a body and lifts the cracked soil and structure (Buzzi *et al.*, 2010)

Figure 8. Schematic layout of the PU friction root system

Table 2. Range of pressures for variable injection procedures (psi, pounds per square inch)

Description	Pressure: psi	Pressure: kPa
Void/cavity filling	500–800	3450–5515
Soil strengthening and compaction	800–1200	5515–8275
Hydrofracturing and friction resistance	1200–1500	8 275–10 345
Compensation and uplifting	1500–2000	10 345–13 790

settlement by mitigating the excess pore water pressure underneath the PUR. The PU friction root system will act as a pile to support the existing overburden pressure and provide a buoyancy effect to the existing foundation structure. Figure 8 shows the schematic diagram of the PU friction root system. Table 2 presents the variation in injection pressures used for various ground repair and modification procedures.

Ground treatment and remediation works

The five different locations included in this paper are actual problems where the research was conducted and the outcomes from the remediation solutions have shown significant improvement to the problematic foundation soil. In situ and laboratory tests were conducted to determine the initial and remediated conditions, before and after PUR injection. The soil samples were taken from the sites and tested for verification of the natural soil before treatment, and then the modified soil samples after PUR was injected were taken back to the laboratory to be tested. The cases are described referring to their practical applications previously described in the section headed 'Concept of alternative treatment and modification using PUR grouting techniques'.

Route FT31, Jalan Banting Semenyih, Selangor Darul Ehsan, both eastbound and westbound

Massive depression was observed on this project for a stretch of about 600 m due to water ponding and saturation, causing settlement of the bituminous pavement. The project involved remedial works to be performed to rehabilitate the settlement of

the expressway by injecting PUR into the ground, increasing the strength of the surrounding soil and filling the voids that were present due to scouring.

Kota Damansara toll plaza, both northbound and southbound

The existing concrete pavement experienced massive depression due to loss of subgrade underneath the pavement. It is difficult to conduct rehabilitation works that include excavation, removing and replacing the subgrade with strengthened soil since the work involved could cause disruption to the services provided. Therefore, PUR injection was executed to uplift the depressed concrete pavement, hence increasing the bearing resistance of the weakened subgrade. This concrete pavement uplift monitoring was performed for the proposed rehabilitation works of the concrete pavement at Kota Damansara toll plaza at the exit towards the expressway.

Petronas (Chemicals) MTBE, Gebeng, Kuantan, Pahang

The chemical plant at Petronas (Chemicals) MTBE, Gebeng, Kuantan, experienced massive depression, where 39 of their concrete sleepers supporting three gas pipes were experiencing massive settlement due to inundation collapse of the fill. The solution was to inject lightweight PUR that had sufficient strength and additional buoyancy effect, which could assist the sleepers. Therefore, three injection points per sleeper were proposed, acting as artificial roots to support the existing structure, enhancing the engineering properties of the soil and providing buoyancy to the ground with less overburden effect. The work was carried out in less than 2 months, and settlement monitoring was conducted within a period of 1 year. This case was presented in detail by Mohamed Jais *et al.* (2015).

km 88-78, both northbound and southbound, North–South Expressway, Ayer Hitam, Johor

A recent case history of approach settlement was also recorded at the North–South Expressway, Ayer Hitam, Johor Bahru, Malaysia. At km 87-88 on the expressway, the transition zone experienced massive depression between the fill and the slab embankments, causing riding discomfort to the expressway users. The solution adopted was a compensation grouting method, increasing the bearing resistance and recompacting the existing soil with PUR. With the injection of lightweight PUR into the problematic foundation soil, there is no additional overburden pressure and primary consolidation of the foundation soil was minimised.

km 48-7 eastbound, Kuala Lumpur–Karak Expressway, Karak, Pahang

The heavy vehicle lane experienced massive depression for a stretch of around 200 m. The Kuala Lumpur–Karak Highway was originally built in the 1970s by the government of Malaysia as an alternative for the winding, narrow Federal Route, which runs from Gombak in Kuala Lumpur to Bentong, Pahang. The highway included a 900 m tunnel at Genting Sempah, which became Malaysia's first highway tunnel ever constructed. The highway was officially opened to traffic in 1977. The project involved remedial works to be performed to rehabilitate the settlement of the expressway. By injecting PUR into the ground, the strength of the surrounding soil has increased and the voids that were present due to scouring have been filled.

Results of the remediation

The results included the initial condition of the soil for four sites – namely, the Route FT31, Jalan Banting Semenyih, Petronas MTBE, km 88-78 Ayer Hitam and km 48-7 Kuala Lumpur–Karak Expressway sites. In situ tests and soil sampling were conducted for both conditions – which were before treatment and after treatment of the four sites, explained previously. The laboratory test results obtained were for before and after the grouting procedures were executed. The modified properties obtained are strength, stiffness, compression characteristics and cone penetration resistance. Uplift monitoring was carried out only at the concrete approach of the Kota Damansara toll plaza to assess the ability of the PUR injection to uplift the concrete pavement.

Initial physical soil properties

Table 3 presents the physical properties of the soil at four locations described in the previous section. For the Route FT31, Jalan Banting Semenyih, Petronas MTBE and km 88-78 Ayer Hitam sites, the soils were described as very silty gravelly sand, whereas for the km 48-7 Karak site, the soil was described as well-graded, very gravelly sand. It is interesting to note that, for the Petronas MTBE site, there is significant clay content, which can cause further depression due to the absorption properties of the clay.

Initial and modified strength characteristics

Figures 9–12 show the results of the unconfined compressive strength (U_{CS}) test conducted on the natural soil samples and the modified samples after remediation taken from the sites specified in

Table 3. Initial soil physical properties for four different test sites

Soil property	Route FT31, Jalan Banting Semenyih	Petronas MTBE	Ayer Hitam km 88-78	Karak km 48-7
Gravel content: %	21-58	19-86	24-86	42-80
Sand content: %	58-19	40-69	40-25	51-20
Silt content: %	13-70	26-88	29-99	5-76
Clay content: %	6-54	12-58	4-90	—
Specific gravity	2-68	2-60	2-51	2-65
In situ moisture content: %	15-43	18-92	38-42	26-20
Liquid limit: %	31-0	44-0	31-0	—
Plastic limit: %	24-0	34-0	24-0	—
Plasticity index: %	7	10	7	—

Figure 9. U_{CS} of natural samples and samples after remediation obtained from the Route FT31, Jalan Banting Semenyih site. BH, borehole; BMS, Banting modified soil; BNS, Banting natural soil

Figure 10. U_{CS} of natural samples and samples after remediation obtained from the Petronas MTBE site. MS, modified soil; MTBE, site name; NS, natural soil; UCT, unconfined compression test

the previous section. During sample extraction, the soil is fully saturated since the water table is just below the crusher run. The natural soil specimens are designated as NS, and the specimens extracted after the remediation process are designated as MS.

The unconfined compressive stress of the soil specimens after remediation has shown an increase of up to two and even three times the stresses that they can sustain. The soil behaviour was slightly modified from an elasto-plastic behaviour to elastic brittle failure. The compressive stress of the natural soil was within a loose state. However, when PU resin/foam was injected into the ground, the compressive stresses increased to within dense to very dense

states for the Route FT31 site, the medium state for the Petronas MTBE and km 88·87 Ayer Hitam sites and the dense state for the km 48·7 Karak site. Tables 4 and 5 present the natural and remediated soil strength properties obtained from the test for four sites. The increase in strength by almost 300% shows that the PU resin/foam provides additional strength after injection where the compensation method recompacts the surrounding soil, filling void space and inducing hydrofracturing to restructure the soil particles. No chemical reaction was recorded since the PU resin/foam does not react with the soil but reacts only between its two chemical compounds.

Figure 11. U_{CS} of natural samples and samples after remediation obtained from the Ayer Hitam km 88-78 site. AHNS, Ayer Hitam natural soil; AHTS, Ayer Hitam treated soil; BH, borehole

Figure 12. U_{CS} of natural samples and samples after remediation obtained from the Karak km 48.7 site. KARAK, site name; MS, modified soil; NS, natural soil

Table 4. U_{CS} data for initial and modified soils for the Route FT31, Jalan Banting Semenyih and Petronas MTBE sites

Site location	Sample	Unconfined compressive stress: kPa	Undrained stiffness, E_u : kPa
Route FT31, Jalan Banting Semenyih	NS01	56.8	1000
	NS02	280.2	13 333
	NS03	257.5	20 000
	MS01	616.9	10 000
	MS02	728.2	25 000
	MS03	510.0	40 000
Petronas MTBE	NS01	58.4	666
	NS02	91.0	3000
	NS03	62.1	1333
	MS01	131.5	4000
	MS02	126.0	1200
	MS03	145.0	7000

Table 5. U_{CS} data for initial and modified soils for Ayer Hitam and Karak sites

Site location	Sample	Unconfined compressive stress: kPa	Undrained stiffness, E_u : kPa
Ayer Hitam km 88.78	NS2.1	59.1	2500
	NS2.2	83.7	5000
	NS2.3	90.1	4000
	MS2.1	225.0	8000
	MS2.1	206.1	7000
	MS2.1	190.4	6667
Karak km 48.7	NS01	90.2	2500
	NS02	102.3	2000
	NS03	114.8	2000
	MS01	114.4	2500
	MS02	375.4	30 000
	MS03	303.6	25 000

Natural soils' and modified soils' compressibility characteristics

Figures 13–15 illustrate the consolidation curve obtained from the oedometer test to determine the compressibility characteristics of the natural and remediated soils taken from the Route FT31, Jalan Banting Semenyih, Ayer Hitam km 88.78 and Karak km 48.7 sites. The soils have high void ratios, and since the void spaces during consolidation were filled with water, as water was expelled from the soil samples, massive volume change of the soil therefore occurred. Hence, settlement values were high as seen in most loose and soft soils, with significant fines present.

The initial void ratio, e_0 , was reduced, and the obtained preconsolidation pressure showed a slight increase as the PU resin/foam was injected into the soil. This confirms that the void ratios of the soils are significantly reduced after the remediation process. This was due to the fact that the voids between the particles were cemented with PU resin/foam, creating an additional bond and reducing the voids in the soils. As a result, the remediated soil underneath the bituminous pavement experienced lower compressibility characteristics and reduction in the initial void ratio by almost 80%.

In situ strength

The cone penetrometer test was conducted at the Petronas MTBE site next to the borehole to determine the in situ strength of the soil before and after the remediation procedure. The length of the cone penetrometer rod was 800 mm; therefore, in the natural condition, the cone penetrometer would be able to penetrate down to 800 mm. Point 1 represents the cone resistance for the

Figure 13. Consolidation curve for natural and remediated soil samples obtained from the Route FT31, Jalan Banting Semenyih site. C_c , compression index; C_s , swelling index; p_c , preconsolidation pressure

Figure 14. Consolidation curve for natural and remediated soil samples obtained from the Ayer Hitam km 88.78 site. c_c , compression index; c_s , swelling index; p_c , preconsolidation pressure

borehole in the natural condition, whereas point 2 represents the cone resistance for the borehole modified with PU resin/foam. Figure 16 shows the results for the test where, at point 1, the cone penetrometer could be easily pushed into the borehole. However, once the soil had been injected with PU resin/foam, the cone penetrometer had difficulties in penetrating into the modified soil.

A Mackintosh probe test was also conducted after sample extraction for the Mackintosh probe location proposed to determine the in situ strength of the soil after modification using PU resin/foam at the Karak km 48.7 site. Figure 17 presents the Mackintosh probing results with respect to depth. From the plots shown, it is seen that the number of blow counts per 300 mm penetration was more than 300 after PU foam/resin injection. These plots show an

increase in the strength of the subgrade before 600 mm, whereas before injection, the Mackintosh probe could easily penetrate (less than 100 number of blows) to a maximum depth of 9 m below ground level. This proves that shallow injection of PU resin/foam could restabilise and restrengthen the subgrade layer that had experienced massive depression in the past.

The plate loading test was conducted for both northbound and southbound carriageways both before and after remediation at the Ayer Hitam km 88.78 test site. This test was to determine the bearing pressure that the soil experienced in its initial state and after remediation had taken place. The tests on both northbound and southbound carriageways were designated as PLNS, indicating plate loading on natural ground conditions, whereas PLTS indicates plate loading on treated ground conditions. The bearing pressure increases for northbound and southbound carriageways as shown in Figure 18. For the 40 mm criterion for coarse fill material, the bearing pressures increased to more than twice the criterion set by the Public Works Department of Malaysia of 150 kPa.

Figure 15. Consolidation curve for natural remediated soil samples obtained from Karak km 48.7 site. c_c , compression index; c_s , swelling index; p_c , preconsolidation pressure

Uplifting capabilities and reinstatement of concrete slab

Figure 19 presents the axial displacement against time during the injection and uplifting process of the depressed concrete pavement conducted at the Kota Damansara toll plaza, Selangor Malaysia. The displacements are divided into several stages, namely

- stage 1 – injection of PU foam at point 1 (furthest from the toll plaza)
- stage 2 – demobilisation and mobilisation of the injector and generator to point 2
- stage 3 – injection of PU foam at point 2 (inset of point 1)
- stage 4 – demobilisation and mobilisation of the injector and generator to point 3

Figure 16. Cone penetration at Petronas MTBE site: 9a) P1SL04; (b) P2SL07; (c) P3SL14; (d) P4SL17

- stage 5 – injection of PU foam at point 3 (inset of point 1)
- stage 6 – demobilisation of the injector and generator.

In stage 1, during injection of the PUR, the concrete pavement located nearest to the point of injection uplifted. Therefore, the point where the instrument was located depressed by about 1.2 mm. About 16 min later, the concrete pavement started to uplift by about 6.4 mm. During stage 2, the value slightly reduced to 5.5 mm, where the PU foam experienced expansion and relaxation.

At stage 3, the PUR was injected for about 8 min and the expansion caused the concrete to be uplifted drastically to 30 mm. During stage 4, the PU foam was allowed to expand and

experienced relaxation but the section where settlement occurred drastically was due to the movement of heavy vehicles on the concrete pavement, causing the pavement to be depressed abruptly at about 26 mm.

In stage 5, the injection resumed and the concrete pavement uplifted to its desired level at about 46.8 mm. Initially, the depression of the pavement before the injection was recorded at about 45 mm. During the injection process, heavy vehicles entered the lane but the injection did not stop and the traffic was allowed to flow during the injection process. This is an advantage whereby the remediation work can be continued, although minimum lane closure was allowed. Moreover, the procedure was quick and about 2–3 h after injection the lane could be opened to traffic.

Figure 17. Mackintosh probe results before and after remediation using PUR at the Karak km 48.7 site

Figure 18. Displacement against bearing pressure for the northbound and southbound carriageways of the Ayer Hitam km 88.78 expressway before and after remediation

Conclusion

From the in situ and laboratory tests and uplifting procedure conducted for the five sites, the following can be concluded.

- The strength and stiffness of the fill increased through rehabilitation. This procedure ensured that volume change of the modified soil could be reduced; hence, the

Figure 19. Axial displacement against time of the concrete slab uplifting work at Kota Damansara toll plaza, Malaysia

bearing resistance of the foundation layer increased significantly.

- The compressibility characteristics also increased, and the void ratio reduced significantly. This shows that the PU resin/foam filled the parts of the voids consisting of air and water, thereby reducing the compressibility of the problematic subgrade.
- The uplifting process managed to raise the depressed concrete pavement to the desired level and showed that the expansion of PU resin/foam underneath the pavement can be controlled by monitoring the injection process.
- This shows that PU resin/foam injected at a higher pressure can uplift the concrete pavement to its original level.

REFERENCES

- Buzzi O, Fityus S, Sasaki Y and Sloan S (2008) Structure and properties of expanding polyurethane foam in the context of foundation remediation in expansive soil. *Mechanics of Materials* **40**: 1012–1021, <http://dx.doi.org/10.1016/j.mechmat.2008.07.002>.
- Buzzi O, Fityus S and Sloan S (2010) Use of expanding polyurethane resin to remediate expansive soil foundation. *Canadian Geotechnical Journal* **47**(6): 623–634, <http://dx.doi.org/10.1139/T09-132>.
- Chattopadhyay DK and Raju KVSNA (2007) Structural engineering of polyurethane coatings for high performance applications. *Progress in Polymer Science* **32**: 352–418, <https://doi.org/10.1016/j.progpolymsci.2006.05.003>.

-
- Gibson LL and Ashby MF (1988) *Cellular Solids: Structure & Properties*. Pergamon Press, Oxford, UK.
- Hui W, Qing SW, Jia JH, Zhan LM and Jinhua S (2013) Study on the pyrolytic behaviors and kinetics of rigid polyurethane foams. *Procedia Engineering* 52: 377–385, <https://doi.org/10.1016/j.proeng.2013.02.156>.
- Mack P (2010) *Uretek Ground Engineering*. Mainmark Corporation Pty Ltd, Sydney, Australia.
- Mohamed Jais IB, Md. Ali MA and Muhamad H (2015) Alternative ground improvement solution with polyurethane foam/resin. *Proceedings of the 3rd International Civil and Infrastructure Engineering Conference, Kuala Lumpur, Malaysia*, pp. 425–440.
- Mohamed Jais IB, Md. Ali MA and Muhamad H (2016) Polyurethane foam/resin for immediate solution to ground repair and modification. *Proceedings of the 19th Southeast Asian Geotechnical Conference and 2nd AGSSEA Conference, Kuala Lumpur, Malaysia*, pp. 517–522.
- Robinson HD, Matheson GM and Gómez JE (2012) Mechanical properties of polyurethane grout for permanent ground support applications. In *Grouting and Deep Mixing 2012* (Johnsen LF, Bruce DA and Byle MJ (eds)). American Society of Civil Engineers, Reston, VA, USA, pp. 1758–1766.
- Sharmin E and Zafar F (2012) *Polyurethane: an Introduction*. InTech, Rijeka, Croatia.
- Yu L, Wang R and Skirrow R (2013) The application on polyurethane grout in roadway settlement issues. *Proceedings of Geo Montreal 2013, Montreal, QC, Canada*.

How can you contribute?

To discuss this paper, please submit up to 500 words to the editor at journals@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial board, it will be published as a discussion in a future issue of the journal.