

A review of polyurethane as a ground improvement method

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Article history

Received 10 July 2018

Revised 2 May 2019

Accepted 3 July 2019

Published Online 2 February 2020

Abstract

Ground improvement based on lightweight materials is commonly applied as a method to overcome the problem related to excessive and differential settlement. The application of polyurethane (PU) as a ground improvement work currently increases in demand due to its well performance in many ground improvement projects. The properties and strength of different types of PU available in the market, together with the safety issues and precautions are highlighted in this paper. Due to its lightweight properties, buoyancy behavior of the lightweight foam often causes uplift which jeopardize the stability of the existing structure. Since it is applied in the ground, awareness on PU degradation needs to be emphasized. The suitability and applications of PU as one of alternative method for ground improvement works are also highlighted in this paper.

Keywords: Polyurethane, lightweight, buoyancy, ground improvement

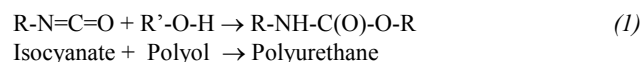
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INTRODUCTION

Excessive soil settlement has caused many instabilities of soil foundation for structure construction. To ensure the stability of structure constructed on soft soil, ground improvement is very crucial to be executed. However, inadequate ground improvement during pre-construction works commonly lead to post-construction failure of the soil foundation. Rapid remedial work is required to mitigate the failed foundation thus prevent further deterioration of the soil foundation. Amongst the available conventional ground improvement methods in the market, the emphasize is on the lightweight material in order to minimize additional load impose to the poor soil foundation. The remedial work under consideration should not cause major disruption to the existing structure. Therefore, ground improvement using polyurethane (PU) seems to be the most efficient method as a remedial work. Thus, this study is carried out in order to review the properties, strength, applications, and suitability of PU as a ground improvement method.

Chemical properties and composition of PU

Production and investigation of PU was initiated by Dr. Otto Bayer in 1937 (Howard, 2012). PU is a class of polymer which exhibits a wide range of mechanical properties (Hepburn, 1992). It is a mix of polyol (-OH) and isocyanate (-NCO) which react at two major reactions occurred during polymerization of PU (Bayer, 1947; Buzzi *et al.*, 2008; Badri, 2012). Isocyanate that reacts with water will disubstituted with urea and generates carbon dioxide. This process is known as blowing reaction because the carbon dioxide is acting as an auxiliary-blowing agent. Reaction also occurs between the polyfunctional alcohol (polyol) and the isocyanate ratio. It generates a urethane linkage in a reaction referred to as the gelation reaction. The isocyanate reacts slowly with alcohols, water, and the unstable amino products without the presence of catalyst. The reaction between polyol and isocyanate is as follows (Badri, 2012):



Isocyanate + Polyol \rightarrow Polyurethane

There are two types of polyol which are polyester and polyether polyols. Polyester polyols are generally consisting of adipic acid, phthalic anhydride, dimer acid (dimerized linoleic acid), monomeric glycol, and triol. Polyester polyols have low acid number (normally 1–4 mg KOH/g) and low moisture content (less than 0.1 %). These properties are not easily achieved unless a high-technology processing method is applied. Polyester polyols are usually supplied at higher price compared to polyether polyols. Polyether polyols on the other hand are commercially produced from catalytic reaction of alkylene oxide i.e. propylene oxide or ethylene oxide to di- or polyfunctional alcohol (Badri, 2012).

Diisocyanates are a family of chemical building blocks used to make a wide range of PU products. The most widely used aromatic diisocyanates are toluene diisocyanate (TDI) and methylene diphenyl diisocyanate (MDI). Less widely used, but still important, are the aliphatic diisocyanates, including hexamethylene diisocyanate (HDI), hydrogenated MDI (H12MDI), and isophorone diisocyanate (IPDI). Exposure to uncured diisocyanates may cause certain health effects, however, consumer exposures to uncured isocyanates are expected to be of very low magnitude and frequency. Consumer products containing uncured isocyanates (such as certain adhesives and sealants) are accompanied by product safety information like warning labels that include the characteristics of the chemicals, their approximate cure time, and how consumers can properly protect themselves while handling the product. However, fully reacted PU polymer is chemically inert (Dernehl, 1966). Because of the flammability of the material, it has to be treated with flame retardants, almost all of which are considered harmful (United States Environmental Protection Agency, 2014). Due to the severe toxicity of isocyanate, some researches have been undertaken to minimize the use of isocyanates to synthesize PUs. Non-isocyanate-based PUs (NIPUs) have recently been developed

from sustainable resources as a new class of PU polymers to mitigate health and environmental concerns (Zhang *et al.*, 2016; Delebecq *et al.*, 2013).

Strength and rigidity/flexibility of PU

Polyether foam is useful in the production of rigid foam whereas polyester polyol produces a more flexible foam (Badri, 2012; Singh *et al.*, 2006). Rigidity of the PU also contributes by the composition of isocyanate and polyol whereby a low equivalent of polyol results in a high rigidity of PU (Badri, 2012; Lat *et al.*, 2015). Hence, more isocyanate is required for the production of rigid PU foam. This ratio contributes to high compressive strength, modulus, thermal stability, and dimensional stability of PUs (Badri, 2012). First developed in 1937, this versatile polymer is soft and processable when heated, hard when cooled, and capable of being reprocessed multiple times without losing its structural integrity. Used either as a malleable engineering plastic or as a replacement for hard rubber, Murata *et al.* (1998) discuss the hydrolysis resistance of PUs and show the importance of the diol chemistry on molecular weight stability in water.

Investigations on the long-term durability of PU in marine environments have been done by many researchers. For instance, a study has been done on materials for deep sea applications in 1969 including some data on the behavior of common polymers (Chin, 2004). Various mechanisms contribute to the durability of polymer adhesives in the presence of water such as plasticization, swelling, hydrolysis, and debonding of fillers (Jacob, 2006). A series of resin specimens were tested in the thickness (rise) direction by Valentino *et al.* (2014). The stress-strain responses were established to determine the peak stress, Young's Modulus, and fracture energy densities whereby the increase in the density results in the increase in the failure stress and Young's Modulus whilst the yield strain was reduced. These results are consistent with the finding by Saha *et al.* (2005) which indicated that the peak stresses are strongly dependent on the density of PU. In particular, an exponential relationship between the peak stress and resin density as well as between Young's Modulus and resin density were found. Experimental tests were performed on two different types of resin, and the results revealed that the higher the confinement stress is during the expansion phase, the greater the hardened resin density.

Compressive stress-strain curve of PU resin for two different quasistatic strain rates which are 0.01 s^{-1} and 0.001 s^{-1} was investigated by Dung *et al.* (2014). The non-linear behavior showed that the initial trend of the stress-strain curve was the same, however the specimens showed considerably higher strength and failure strain at higher strain rate. The compressive strength and failure strain at 0.001 s^{-1} strain rate were measured to be $9.3 \pm 1.5\text{ MPa}$ and $58 \pm 2.0\%$, respectively whereas the strength and failure strain at 0.01 s^{-1} strain rate were found to be $15.2 \pm 3.6\text{ MPa}$ and $68 \pm 1.8\%$, respectively. The compressive strength increased by 63.4% and the failure strain increased by 17.2% as the strain rate was increased. Compressive strength of urethane foam degraded with test temperature while the strength dropped by 40% from 31 psi at room temperature to 19 psi at 90 °C. Confined compression tests conducted on 3.1 pcf density foam failed the compressibility requirement (<10% deformation at 75 psi) for overburden loads. Higher density foams (4–7 pcf) showed improved response in confined compression tests. However, (6.6 pcf) performed best in both directions, i.e., parallel and perpendicular to the foam rise (Singh *et al.*, 2006).

Fiber and nano reinforcement of resins to enhance mechanical properties is a common practice in impact-related material applications, e.g. sports equipment design (Jacob, 2006) and the aerospace industry (Hazell, 2008). Reinforcement of PU replacement resin (PRR) with carbon nano-tubes unfortunately does not significantly improve tensile strength (Chin, 2004). Addition of inorganic polyhedral oligomeric silsesquioxane (POSS), nano-fillers control the degree of cross-linking within the PRR and key thermo-mechanical properties such as elasticity and coefficient of thermal expansion (Strachota *et al.*, 2007).

Degradation of PU

Peter (2007) has carried out a study on accelerated aging of PUs for marine applications. PU has been sunk at sea in the Brest Estuary for up to five years and measurement on tensile strength to determine

mechanical properties has been done after aging. The accelerated test results and FTIR analysis indicated more than 100 years is recorded for 50% property loss at sea temperature based on a linear Arrhenius extrapolation estimation. The results from sea aging after five years of immersion indicated that PU retain 100% of their initial tensile properties. Rutkowska *et al.* (2002) examined the degradation of polyester and polyether-based PUs in sea water for periods up to 12 months. The result indicated that polyether PU gained higher strength retention compared to polyester PU. A recent review of elastomers used in the offshore industry described different modes of deterioration, including mechanical degradation, chemical changes, and cracking due to UV and ozone attack (Campion *et al.*, 2005). A study on degradation of the isocyanate segment of PU indicated that degradation is almost impossible, however, the production of ammonia indicates that it might occur in certain cases (Howard, 2012). Several reports have appeared in the literature on the susceptibility of PU to fungal attack (Howard, 2012; Singh, 2006; Huntsman; Kaplan and Darby, 1968 and Kaplan *et al.*, 1968). These studies revealed that polyester PU is more susceptible to fungal and microbial attack than polyether PU while polyether PU is moderately resistant to fungal and microbial. In applications where a polyether PU is in regular contact with soil in either hot or humid environments, this material is able to resist microbial attack. Thus, polyether PU is often being used in cable industry. Flexible polyester PU can be vulnerable to damage from fungi and bacteria. The enzymes present in microorganisms can split ester bonds causing the PU to discolor and crack thereby affecting load bearing capabilities (Huntsman). Hydrolysis resistance of polyester PU is at risk when exposed to high temperature levels and in humid environments.

Boubendir (1993) isolated enzymes with esterase and urethane hydrolase activities from the fungi *Chaetomium globosum* and *Aspergillus terreus*. The organisms grow with induction of the enzymes by adding the polyester PU to the growth media. Activity of the enzymes was determined by assays based on ethyl carbamate (urethane) as artificial substrate. Cosgrove *et al.* (2007) reported on the involvement of soil fungal communities in the biodegradation of polyester polyurethane. In another study, four species of fungi, *Curvularia senegalensis*, *Fusarium solani*, *Aureobasidium pullulans*, and *Cladosporium* sp. were isolated based on their ability to utilize a colloidal polyester PU as the sole carbon and energy source (Crabbe *et al.* 1994). Wales and Sagar (1988) proposed a mechanism for the degradation of polyester PU by extracellular esterases. In a large-scale test of bacterial activity against PU, Kay *et al.* (1991) investigated the ability of 16 bacterial isolates to degrade polyester PU. Seven of the isolates tested degraded PU when the media were supplemented with yeast extract. In a further study, Kay *et al.* (1993) tested the chemical and physical changes in degraded polyester PU. Polyurethanes taken from *Corynebacterium* sp. cultures had significant reductions in both tensile strength and elongation after three days of incubation. Infra-red spectrophotometer analysis revealed the ester segment of the polymer to be the main site of attack. The investigators noted that supplementing the media with glucose inhibited esterase production. Blake and Howard (1998) reported bacterial degradation of a polyester PU by a species of *Bacillus*. The pattern of degradation involved the binding of cells to the polymer with subsequent floc formation and the degradation of substrate.

Polyether PU is highly resistant to hydrolysis that can be used in underwater applications as well as humid and damp situations. Increasing temperatures would normally cause hydrolytic degradation, however, polyether PU indicates good hydrolysis resistance at a high temperature (Huntsman). This makes polyether PU a good solution for applications including ABS cables located on the anterior of automobiles, which come into constant contact with dirt and water. Huang *et al.* (1981) derived polyester PU from polycaprolactonediol in an effort to produce biodegradable PU to be used in the medical field. Several different PUs containing polyester subunits of various lengths were subjected to degradation by the enzyme axion and two species of fungi. Labrow *et al.* (1996) treated polyester PU and polyether PU with human neutrophil elastase and porcine pancreatic elastase. The polyester PU was readily degraded by porcine pancreatic elastase at a rate ten times higher than that by human neutrophil elastase. The rate

of polyester PU degradation by porcine pancreatic elastase was also ten times higher than its activity against the polyether PU. Human neutrophil elastase had no significant activity against the polyether PU. PU with long repeating units and hydrophilic groups would less likely to pack into high crystalline regions as normal PU and it is more accessible to biodegradation (Huang and Roby, 1986). The increase in the chain length of the polyesters also increase the biodegradability of the polyester PU (Huang *et al.*, 1981).

In the long-term testing (1000 h) of foam with 6.6 pcf density under a fixed compressive stress of 75 psi (equivalent to 90-ft soil depth), the maximum deformation resulted in no significant degradation of the foam (Singh *et al.*, 2006). PU is a durable material as it has high tensile strength and melting points (Bayer, 1947). It is an excellent material to replace plastics as it is highly resistant to degradation by water, oils, and solvents (Saunders and Frisch, 1964). PU coating exhibits excellent adhesion to many substances, abrasion resistance, electrical properties, and weather resistance for industrial purposes (Saunders and Frisch, 1964; Urbanski *et al.*, 1977; Fried, 1995).

Lightweight materials and buoyancy behavior

Due to its lightweight property, the excessive settlement problem can be overcome by PU remedial measures. Expanded polystyrene (EPS) geofoam is one of the lightweight materials for ground improvement. The thickness of the geofoam is an important consideration in improving footing behavior on marine clay, compared with density of geofoam (Daigavane and Jain, 2015). Major concern for lightweight materials as a ground improvement application is the buoyancy of the materials (Stephen, 2016). There were a few failure cases of embankment founded on lightweight geofoam reported by Frydelund and Aaboer (2002a) due to buoyancy. Unpredicted rainfall and the raise of flood level in Oslo, Norway in 1987 caused the first EPS fill built in 1972 floated off due to the initial design prediction made in 1972 was 0.85 m lower than the flood level occurred in 1987. The other incident occurred in Thailand where the unexpected water level washed away the road filled with EPS. A study by Stephen (2016) revealed that geofoam was potentially vulnerable to uplift movement during periods of flooding due to inadequate weight of the earth fill above the geofoam. The low amount of compacted earth fill provided low resistance against uplift due to buoyancy. There were indications of block movement and uplift, such as discoloration between block layers on excavation and removal. Buoyancy turned out to be the primary controlling factor in determining the most cost-effective redesign alternative and corresponding factor of safety against uplift (Riad *et al.*, 2004).

The importance of density on the buoyancy of PU foam has been investigated by Witkiewicz and Zielinski (2006). The compression test results indicated that the foam of 16 kg/m³ density is not able to resist the mechanical force. Low density of the foam caused high water absorption, high buoyancy and great discontinuities (cavities) at the border between portions of the foam and low compressive strength which indicates a significant number of open pores. On the other hand, higher density of PU foam (62 kg/m³) caused low water absorption and low buoyancy indicated a major presence of close pores. Costly and inconvenient repairs may be required during construction or design life of any geotechnical structure with high ground water table.

Buoyancy is an upward force exerted by a fluid that acts on an immersed object. Over two millennia ago, Archimedes of Syracuse (Heath, 1897) developed the Archimedes' Principle, which states, "any object, wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object." A buried tank can fail due to the buoyancy force when the groundwater exerts more pressure upward on the underside of the base slab than can be counteracted downward by the weight of the tank. The failure that commonly encountered for buried tanks are due to the groundwater generated buoyancy force causing structural failure of the base slab and complete tank flotation (Bruder, 2013). A study by Stuedlein and Negusse (2013) is on the application of lightweight materials using EPS geofoam on bridge supported on piles where the approach experienced significant settlement while requiring constant grade maintenance. Replacement of fill with EPS geofoam blocks successfully eliminate further settlement. Buskiewicz and Culp

(2014) considered the foam as inexpensive even in the twentieth century and the high pay is due to fast work done and efficient construction material that offers significant schedule advantages to new building or expanding existing infrastructure especially in locations with poor soil conditions and high seismicity.

Challenge to cast lightweight treated soil below water table is the unit weight control to avoid buoyancy and the effect of mechanical behavior due to considerable water pressures. Unit weight of the treated soil is normally between 11 kN/m² to 12 kN/m² in order to prevent from buoy up in coastal areas (Tsuchida and Tang, 2007). In order to manage the uplift forces developed as geofoam is submerged, adequate weight of fill over the foam to hold it down during periods of high water levels is vital. The use of Helical Soil Anchors to resist the uplift forces and restrain the EPS geofoam during periods of high water levels is an effective way to manage uplift force (John, 1993). Study by Timothy *et al.* (2012) found that the EPS geofoam buoy up due to its closed-cell structure and light weight. Adequate surcharge, i.e., soil or pavement cover, or an alternate means of passive restraint must be provided against uplift. Alternately, the material can be installed above the water table or the water table can be lowered using suitable drains or other dewatering systems. Drainage (generally a sand or gravel layer) can be provided between the EPS geofoam fill and the natural soils to reduce potential uplift forces. Providing adequate drainage of groundwater or surficial waters below EPS geofoam will prevent water from infiltration and reduces the development of uplift forces. The way to manage uplift force due to buoyancy by Timothy *et al.* (2012) is in a good agreement with John (1999).

A variety of techniques have been reported to reduce the embankment deformation and prevent potential stability failure. These methods include improving the fill properties, using lightweight fill, over excavation and replacement, pile supported, and geosynthetic reinforced (Han and Gabr, 2002; Ariyaratne *et al.*, 2013). The use of waste materials as a lightweight fill such as foamglass, sawdust and bark residue, foamed concrete, lightweight clay aggregate, and shredded tires have been discussed by Frydelund and Aaboer (2002b). The materials have successfully reduced the settlement and expedite the construction works on soft subsoil. The benefits of geosynthetic reinforced embankment have been reported in several works in the references (Hufenus *et al.*, 2006; Frankowska, 2007). These benefits have yielded to remarkable improvement in road life and reduction in maintenance cost (Palmeira and Antunes, 2010). Another solution for addressing the above concerns with obvious advantages is employing lightweight fills, such as expanded polystyrene (EPS) geofoam. The EPS geofoam, characterized by lightweight and high strength/stiffness to weight ratio (Hazarika, 2006) is an excellent material for embankment construction and has been successfully used between the approach embankment and the bridge abutment aiming at preventing over large differential settlement.

PU as a ground improvement method

Research on PU as a soil improvement has been undertaken by many researchers. Buzzi *et al.* (2008) has carried out a study on structure and properties of expanding PU in the context of foundation remedial works and found that compressive strength is reduced by structural heterogeneity and hydraulic conductivity is increased but only to a typical value of clay soil. In 2010, Buzzi *et al.* (2010) furthered their study on the long-term swelling potential of composite resin-clay on Maryland clay. From their study, it is found that propagation of resin is unpredictable and long-term soil rehydration cannot be prevented but at most can be delayed. It does not enhance swelling potential. The results obtained from micropile made of PU investigated by Valentino *et al.* (2013) is useful for engineers to design PU resin in order to improve the substructure performance of shallow foundations, railway or motorway embankments, and airstrips. Soga *et al.* (2004) carried out a study on grout injection in the lab on clay specimen prepared at different over consolidation ratio ranging 1–10 on E-Kaolin soil using two different methods namely fracture grouting by injecting epoxy resin and compaction grouting. From their study, they found that better grout efficiency was obtained in compaction grouting compared to fracture grouting.

Nawamooz (2016) has carried out a study on resin injection in clay with high plasticity and found that results from pressure meter test and cone penetration test before and after injection of PU showed significant increase in pressure limit and soil resistance for all the depth studied close to injection point. Non-simultaneous injections created large stress concentration around injection point leading to larger soil consolidation. In 2015, Lat et al. (2015) evaluated PU injection pile and slab in comparison with lightweight concrete for ground improvement using PLAXIS. The results showed that the PU successfully reduced future settlement significantly as the material is lightweight and able to fill the void between the soil particles.

An alternative to petroleum-based PU, a bio-based PU is used as a ground improvement (Lat et al., 2017). Compressive strength test on PU Palm kernel oil-based polyol showed comparable strength with petroleum-based PU. Optimum ratio of the polyol to isocyanate is 0.75:1 to obtain rigid PU which is suitable for ground improvement method. Jais (2017) compiled the case studies of rapid remediation using PU resin/grout in Malaysia. The overall review showed that the use of PU as a rapid remediation work was successful for all ground improvement projects in Malaysia. Ghani (2017) has carried out a study on the use of PU for road flood damage control. This study was conducted based on two types of soil that are usually used as soil embankment in road construction. California Bearing Ratio (CBR) test was conducted on various categories of soaking days and repeated submerged conditions to determine the strength of subgrade soil with and without PU layer. It can be concluded that PU layer can be used to increase or maintain the strength of subgrade soil from the inundation effect. Fakhar and Asmaniza (2016) has undertaken the case study on road maintenance experience using PU foam injection system. It is learned that the strong expansion of injection causes significant compression and compacting of the surrounding soil and subsequently improve ground properties and uplift sunken structure.

CONCLUSIONS

The use of PU foam as a ground improvement method has several advantages over conventional methods. The undegradable and cost-effective polyether PU is more suitable for ground improvement works to produce rigid foam compared to polyester PU. Since PU is a closed cell foam, it does not absorb water which is very helpful to prevent water from seeping through the underlying soil that could soften and reduce the shear strength of soil. Furthermore, PU foam is a lightweight material that could minimize additional load contribution to the underlying soil and therefore minimizing further settlement. The uplift behavior of the foam can be controlled by providing adequate overburden on the PU foam, anchorage, or proper drainage system to overcome the rise of ground water table.

REFERENCES

Ariyaratne, P., Liyanapathirana, D. S., Leo, C. J. 2013. Comparison of different two-dimensional idealizations for a geosynthetic-reinforced pile-supported embankment. *Int. J. Geomech.* 13: 754-768.

Badri, K. 2012. Biobased polyurethane from palm kernel oil-based polyol [internet]. *InTechOpen*. Available from <https://www.intechopen.com/>

Bayer, O. 1947. Polyurethanes. *Mod. Plast.* 24: 149-152.

Boubendir, A. 1993. Purification and biochemical evaluation of polyurethane degrading enzymes of fungal origin. *Diss. Abstr. Int.* 53: 4632.

Bruder, M. 2013. *Beware of buried tank buoyancy*. In Environmental Science & Engineering Magazine. Aurora, Canada: Environmental Science and Engineering Publication, pp. 56-58.

Buksowicz, M., Culpán, S. 2014. Use of EPS as a lightweight fill material on the port mann highway improvement project. *2014 Conference of the Transportation Association of Canada Montreal, Quebec*.

Buzzi, O., Fityus, S., Sasaki, Y., Sloan, S. 2008. Structure and properties of expanding polyurethane foam in the context of foundation remediation in expansive soil. *Mech. Mater.* 40: 1012-1021.

Buzzi, O., Fityus, S., Sasaki, Y., Sloan, S. 2010. Use of expanding polyurethane resin to remediate expansive soil foundation. *Can. Geotech. J.* 47: 623-634.

Campion, R. P., Thomson, B., Harris, J. A. 2005. Elastomers for fluid containment in offshore oil and gas production: Guidelines and review, *HSE Research Report* 2005: 320.

Chin, S. J. 2004. *Investigation of nanotechnology enhanced polyurethane replacement resin (PRR) as a transparent armour material*. MSc Thesis, Cranfield University, Shrivenham Campus.

Cosgrove, L., McGeechan, P. L., Robson, G. D., Handley, P. S. 2007. Fungal communities associated with degradation of polyester polyurethane in soil. *Appl. Environ. Microbiol.* 73: 5817-5824

Crabbe, J. R., Campbell, J. R., Thompson, L., Walz, S. L., Schultz, W. W. 1994. Biodegradation of a colloidal ester-based polyurethane by soil fungi. *Int. Biodeter. Biodegrad.* 33:103-113.

Daigavane, P. B., Jain, K. 2015. Improved foundation system on marine clay using geofaam. *Inter. J. Mod. Trends Engin. Res. (IJMTER)* 2: 151-156.

Delebecq, E., Pascault, J. P., Boutevin, B., Ganachaud, F. 2013. On the versatility of urethane/urea bonds: Reversibility, blocked isocyanate, and non-isocyanate polyurethane. *Chem. Rev.* 113(1): 80-118.

Dernehl, C. U. 1996. Health hazards associated with polyurethane foams. *J. Occupat. Medic.* 8: 59-62.

Dung, D. L., Vasanth, C. S., Oliver, M. S., Nikhil, G. 2014. High strain rate compressive behavior of polyurethane resin and polyurethane/Al₂O₃ hollow sphere syntactic foams. *J. Compos.* Vol. 2014.

Fakhar, A. M. M., Asmaniza, A. 2016. Road maintenance experience using polyurethane (PU) foam injection system and geocrete soil stabilization as ground rehabilitation. *IOP Confer. Ser. Mater. Sc. Eng.* 136: 12004.

Fattah, M. Y., Al-Saidi, A. A., Jaber, M. M. 2015. Improvement of bearing capacity of footing on soft clay grouted with lime-silica fume mix. *Geomech. Eng.* 8: 113-132.

Frankowska, K. K. 2007. Influence of geosynthetic reinforcement on the load-settlement characteristics of two-layer subgrade. *Geotext. Geomembr.* 25: 366-376.

Fried, J. R. 1995. *Polymer science and technology*. Englewood Cliffs: Prentice Hall PTR.

Frydelund, T. E., Aaboer, R. 2002a. Lightweight filling materials for road construction. *EPS Geofoam 3rd International Conference*, Salt Lake City.

Frydelund, T. E., Aaboer, R. 2002b. Use of waste materials as for lightweight fills. *International Workshop on Lightweight Geomaterials*, Tokyo.

Ghani, A. N. A., Radzi, S. M., Ismail, M. S. N., Hamid, A. H. A. A. 2017. Study on the use of polyurethane for road flood damage control. *Int. J. GEOMATE*. 12: 82-87.

Han, J., Gabr, M. A. 2002. Numerical analysis of geosynthetic-reinforced and pile-supported earth platforms over soft soil. *J. Geotech. Geoenviron. Eng.* 128: 44-53.

Hasan, M., Marto, A., Hyodo, M., Makhtar, A. M. 2011. The strength of soft clay reinforced with singular and group bottom ash columns. *Electron. J. Geotech. Eng.* 16 N: 1215-1227.

Hazarika, H. 2006. Stress-strain modeling of EPS geofoam for large-strain applications. *Geotext. Geomembr.* 24: 79-90.

Hazell, P. J., Stennett C and Cooper G. 2008. The shock and release behavior of an aerospacegrade cured aromatic amine epoxy resin. *Polym. Comp.* 29(10): 1106-1110.

Heath, T. L. 1897. *The works of Archimedes*, Edited in Modern Notation with Introductory Chapters. Cambridge, UK: Cambridge University Press.

Hepburn, C. 1992. Polyurethane elastomers. Dordrecht: Springer Netherlands.

Howard, G. T. 2012. *Polyurethane Biodegradation*. In Environmental Science and Engineering. Berlin: Springer-Verlag Berlin Heidelberg.

Hufenus, R., Rueegger, R., Banjac, R. 2006. Full-scale field tests on geosynthetic reinforced unpaved roads on soft subgrade. *Geotext. Geomembr.* 24: 21-37.

Huang, S. J., Macri, C., Roby, M., Benedict, C., Cameron, J. A. 1981. *Biodegradation of polyurethanes derived from polycaprolactonediol*. In: Edwards K. N. (ed.). Urethane chemistry and applications. Washington, DC: American Chemical Society, pp. 471-487.

Huang, S. J., and Roby, M. S. 1986. Biodegradable polymers poly(amideurethanes). *J. Bioact. Compat. Polym.* 1:61-71.

Huntsman, A. *Guide to Thermoplastic Polyurethanes (TPU)*[Internet]. [Cited on 1/1/2017]. Available on <http://www.huntsman.com>

Jacob, A. 2006. The popularity of carbon fibre. *Reinforc. Plast.* 50(3): 22-24.

Jais, I. B. M. 2017. Rapid remediation using polyurethane foam/resin grout in Malaysia. *Geotech. Res.* 4: 107-117.

Jais, I. B. M., Ali, M. A. M., and Muhamad, H. 2016. Alternative ground improvement solution with polyurethane foam/resin. In: Yusoff, M., Hamid, N., Arshad, M., Arshad, A., Ridzuan, A., and Awang, H. (eds). InCIEC 2015. Singapore: Springer

Jais, I. B. M., Lat, D. C., and Endut, T. N. D. T. 2019. Compressibility of peat soil improved with polyurethane. *Malaysian J. Civ. Engin.* 31: 35-41.

John, S. H. 1999. *Lessons learned from failures involving geofaam in roads and embankments* (Manhattan College Research Report No. CE/GE-99-1). GeoTech Systems Corp: Bronx, New York, U.S.A.

Kaplan, A. M., and Darby, R. T. 1968. Fungal susceptibility of polyurethanes. *Appl. Microbiol.* 16: 900-905.

- Kaplan, A. M., Darby, R. T., Greenberger, M., and Rodgers, M. R. 1968. Microbial deterioration of polyurethane systems. *Dev. Ind. Microbiol.* 82: 362–71.
- Kay, M. J., Morton, L. H. G., and Prince, E. L. 1991. Bacterial degradation of polyester polyurethane. *Int. Biodeter. Bull.* 27: 205–22.
- Kay, M. J., McCabe, R. W., and Morton, L. H. G. 1993. Chemical and physical changes occurring in polyester polyurethane during biodegradation. *Int. Biodeter. Biodegrad.* 31: 209–225.
- Labrow, R. S., Erfle, D. J., and Santerre, J. P. 1996. Elastase-induced hydrolysis of synthetic solid substrates: Poly(ester-urea-urethane) and poly(ether-urea-urethane). *Biomater.* 17: 2381–2388.
- Lat, D. C., Jais, I. B. M., Mohamed, K. T., and Razali, R. 2015. Performance comparison between polyurethane injection pile and slab system against lightweight concrete as a ground improvement using finite element analysis. *J. Appl. Sci. Res.* 11: 11-16.
- Lat, D. C., Jais, I. B. M., Mohammed, K., Baharom, B., Samat, N., and Zainuddin, A. N. 2016. Evaluation of strength characteristics for palm kernel oil-based Polyurethane (PKO-P) as a ground improvement method. *Mal. J. Fund. Appl. Sci.* 12: 126-129.
- Marto, A., and Tan, C. S. 2016. Properties of coal bottom ash from power plants in Malaysia and its suitability as geotechnical engineering material. *Jurnal Teknologi* 78: 1–10.
- Murata, S., Nakajima, T., Tsuzaki, N., Yasuda, M., and Kato, T. 1998. Synthesis and hydrolysis of polyurethane derived from 2,4-diethyl-1,5-pentanediol. *Polym. Degrad. Stab.* 61: 527-534.
- Nowamooz, H. 2016. Resin injection in clays with high plasticity. *Comptes rendus – Mecanique* 344: 797-806.
- Palmeira, E. M., and Antunes, L. G. S. 2010. Large scale tests on geosynthetic reinforced unpaved roads subjected to surface maintenance. *Geotext. Geomembr.* 28: 547-558.
- Peter, D., and Guy, E. 2007. Accelerated ageing of polyurethanes for marine applications. *Polym. Degrad. Stab.* 92: 1455-1464.
- Riad, H. L., Ricci, A. L., Osborn, P. W., D'Angelo, D. A., and Horvath, J. S. 2004. Design of lightweight fills for road embankments on Boston's central artery/tunnel project. In *International Conference on Case Histories in Geotechnical Engineering*, New York; 13-17 April 2004.
- Rutkowska, M., Krasowska, K., Heimowska, A., Steinka, I., and Janik, H. 2002. Degradation of polyurethanes in sea water. *Polym. Degrad. Stab.* 76: 233-239.
- Saha, M. C., Mahfuz, H., Chakravarty, U. K., Uddin, M., Kabir, M. E., and Jeelani, S. 2005. Effect of density, microstructure, and strain rate on compression behavior of polymeric foams. *Mater. Sci. Eng. A* 406: 328–336.
- Saunders, J. H., and Frisch, K. C. 1964. *Polyurethanes: Chemistry and technology* (Part II: Technology). New York: Interscience Publishers.
- Singh, D., Chen, N., Martin, C. L., Routbort, J. L., Pagilla, Demirtas, M. U., Reddy, K., Gangathulasi, J., Del Cul, G. D., Simmons, C. M., and Icenhour, A. S. 2006. *Study on degradation of a commercial rigid polyurethane foam used for filling of process gas equipment (PGE) and pipes and corrosion behavior of pipes at K-25/K-27*. Oak Ridge: Argonne National laboratory, Nuclear Engineering Division, U. S. Department of Energy.
- Soemiro, R., Leong, E. C., and Rahardjo, H. 2000. Soil improvement by surcharge and vacuum preloadings. *Geotechnique* 50: 601–605.
- Soga, K., Au, S. K. A., Jafari, M. R., and Bolton, M. D. 2004. Laboratory investigation of multiple grout injections into clay. *Geotechnique* 54: 81-90.
- Stephen, S. 2016. *Pressure reduction on wide culverts with EPS geofoam backfill*. Master Dissertations, Syracuse University, Syracuse, New York.
- Strachota, A., Whelan, P., Kříž, J., Brus, J., Urbanová, M., Šlouf, M., and Matějka, L. 2007. Formation of nanostructured epoxy networks containing polyhedral oligometric silsesquioxane (POSS) blocks. *Polymer* 48: 3041-3058.
- Stuedlein, A. W., and Nagessey, D. 2013. Use of EPS geofoam for support of a bridge. In: Stuedlein, A. W., Christopher, B. R. (eds.). *Sound geotechnical research to practice: Honoring Robert D. Holtz*. *Geotech. Spec. Pub.* 230: 344-345.
- Timothy, D. S., Steven, F. B., and David, A. 2012. *Expanded polystyrene (EPS) geofoam applications & technical data* [Internet]. Retrieved from <https://my.civil.utah.edu/~bartlett/Geofoam/EPS%20Geofoam%20Applications%20&%20Technical%20Data.pdf>
- Tsuchida, T., and Tang, Y. X. 2007. Mechanical properties of lightweight treated soil cured in water pressure. *Soils Found.* 47: 731-48.
- United States Environmental Protection Agency. June 2014. *Flame retardants used in flexible polyurethane foam*. Available from: https://www.epa.gov/sites/production/files/2015-08/documents/ffr_final.pdf
- Urbanski, J., Czerwinski, W., Janicka, K., Majewska, F., and Zowall, H. 1977. *Handbook of analysis of synthetic polymers and plastics*. Chichester: Ellis Horwood Limited.
- Valentino, R., Romeo, E., and Misra, A. 2013. Mechanical aspects of micropiles made of reinforced polyurethane resins. *Geotech. Geolog. Eng.* 31: 463–478.
- Valentino, R., Romeo, E., and Stevanoni, D. 2014. An experimental study on the mechanical behaviour of two polyurethane resins used for geotechnical applications. *Mech. Mater.* 71: 101–113.
- Wales, D. S., and Sagar, B. R. 1988. Mechanistic aspects of polyurethane biodeterioration. In: Houghton, D. R., Smith, R. N., Eggins, H. O. W. (eds.) *Biodeterioration* (7th ed.) (pp. 351-358). London: Elsevier Applied Science.
- Witkiewicz, W., and Zieliński, A. 2006. Properties of the polyurethane (PU) light foams. *Adv. Mater. Sc.* 6: 35-51.
- Zhang, K., Nelson, A. M., Talley, S. J., Chen, M., Margareta, E., Hudson, A. G., Moore, R. B., and Long, T. E. 2016. Non-isocyanate poly (amide-hydroxyurethane)s from sustainable resources. *Green Chem.* 18: 4667–4681.