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Introduction

Upon review of *Q6+1 Asset Management Programme, B6210.02 Pavement Safety and Resilience,* Geobear understand that the main Asset Management Objectives in relation to Charlie Taxiway and Delta Taxiway are:

- *"Harm no-one that builds, maintains, operates or uses our assets*
- *Meet licensing and legislative requirements*
- *Over the long term, reduce the total expenditure by optimising cost, risk and performance*
- *Enable the flying schedule to be fully completed every day*
- *To understand and manage asset related risks so that we continuously improve operational resilience*
- *Understand, define and improve the performance that our customers' (passengers and airlines) want from our assets – no surprises*
- *Deliver the masterplan as efficiently as possible and provide capacity just ahead of planned demand*
- *We will meet our environmental and sustainability targets*
- *Ensure our assets are adaptable and can efficiently meet our customers' future needs"*

With the major benefits of addressing the conditions of the aforementioned taxiways stated as:

- "No SQR events related to airfield pavement condition
- Overall improvement in surface condition and reduced risk of impacting the airfield operation
- Increased life between maintenance interventions will be achieved which will reduce future OPEX increases in undertaking reactive emergency repairs."

By exploiting the use of Geopolymer injection, Geobear can assist in delivering the above objectives. Due to the efficiency associated with the onsite implementation of Geopolymer injection works, airfield pavement assets can be managed with minimal disruption.

Geobear are the original founder of Uretek solutions, utilising a variety of Geopolymer injection systems to offer solutions to Ground Engineering and Infrastructure asset management issues.

Working with a worldwide leading chemical manufacturer, Geobear has developed a portfolio of over 30 materials for use in various settings depending on the project scope, soil properties and other relevant factors. Each Geopolymer material possesses different characteristics, making them advantageous in different scenarios. These characteristics include:

- Cream Time - The time taken for a Geopolymer to begin to change state from a liquid to a solid
- Gel Time - The time taken for a Geopolymer to adhere to a surface, signifying the beginning of the expansive phase
- Tack Free Time - The time taken for a Geopolymer to cease adhering to a surface, thus signifying the end of the expansive phase
- Free Rise Density - The density of a Geopolymer when injected without containment (the level of containment will directly impact the density of the Geopolymer, thus the free rise density is the lowest possible density)
- Viscosity - The resistance of a Geopolymer to flow

Through the installation of different Geopolymers, Geobear undertake a variety of project types, these can be categorised as:

- Relevelling - The installation of a highly expansive Geopolymer directly beneath slabs/structures. The overlying asset is lifted via the expansive force of the installed material
- Stabilisation - Geopolymer is installed beneath rocking/pumping slabs to re-establish full contact between the underside of the slab and the underlying soils, thus providing stability.
- Ground Improvement - The selected Geopolymer is injected to the required depth, improving the treated soils via compaction/consolidation as a result of the expansion of the Geopolymer
- Permeability Reduction - Given the hydro insensitive nature of Geopolymers, injection into granular soils can reduce permeability (due to the properties of the material and the compaction of the soil treated)
- Void Filling - Bulk void filling via the installation of Geopolymers (which can be selected to suit varying needs such as Compressive Strength)

Environmental Impact Of Geopolymers

The manufacturers of our Geopolymers have carried out multiple studies on a variety of characteristics of the materials, and subsequently produced technical bulletins to display their findings. One of these bulletins is titled "*Environmental impact of the Uretek Resins on soil and groundwater*". This paper discusses the effects of Geopolymers once injected, along with the testing carried out by the material manufacturer regarding this matter. The summary of this paper states:

"*The Uretek material components are injected into soil and could therefore influence the environmental and ecological condition of the soil and surrounding groundwater. Based on several environmental impact studies of Uretek Resin to soil and groundwater, it was concluded that the Uretek Resins have no or little impact.*"

In order to further validate the contents of the aforementioned technical bulletin, Geobear engaged ESI Consulting Ltd to carry out appropriate testing and produce a technical note titled "*Environmental Impact Assessment for use of expandable polymer*", which focuses on *"leachability testing to determine the leachable concentrations of hazardous substances and non-hazardous pollutants..."* within the Geopolymer samples tested. The Environmental Impact Assessment of the technical note states:

"The source of potential contamination is the expandable foam polymer. This is injected in the ground down a borehole as two parts: a resin and a hardener. The two parts combine in the borehole as a liquid which moves under pressure into the ground. The mix is adjusted to control viscosity and curing time, but curing times will be within minutes. Therefore, the material in solid form has been assessed.

Once solid, the foam comprises a solid structure surrounding pore spaces which are filled with carbon dioxide. Thus the permeability of the foam is expected to be low and groundwater will preferentially flow around it. Nonetheless, leachability testing has been undertaken on crushed samples, which gives a much larger surface area exposed to leaching. Thus these test results would be equally applicable should groundwater be able to flow through the material.

Any contaminants that leach out of the materials would be diluted in the receiving groundwater. Given the leached concentrations presented in Section 3 it is considered that, following dilution, there would be no discernible presence of hazardous substances or non-hazardous pollutants. Thus it is considered that the leachability test results demonstrate that the discharge would be of a "quantity and concentration so small as to obviate any present or future danger of deterioration in the quality of the receiving groundwater". Thus the activity is not a 'groundwater activity' as it meets the criteria of clause (b) of EPR (2016) Schedule 22.3.3.

The *Background to legislation* section of the document states that the Environment Agency may determine that a discharge, or an activity that might lead to a discharge, is not a groundwater activity if the input of the pollutant (EPR, 2016 Schedule 22.3.3).... " b) *is or would be of a quantity and concentration so small as to obviate any present or future danger of deterioration in the quality of the receiving groundwater".*

Carbon Footprint associated with Geopolymer injection

From an environmental perspective the main impacts of alternative methods to Geopolymer injection are noise pollution, vibration, dust and traffic movement. Some of the main causes of noise, vibration and dust are often cited as:

- Materials stored on site
- Spoil removal
- Use of large plant

Geobear's operation negates the above items causing issues by being a byproduct of the on-site activities. Due to Geobear working out of self contained injection units (either in the form of a van, a truck or a containerised unit), typically all materials are stored on board, thus removing the need to store any materials outside of the truck. Geobear's injection works uses predetermined amounts of material, and is installed through 12/14mm diameter holes (which can be drilled via dustless drilling if required), thus associated spoil is minimal. Besides Geobear's injection unit (and injection hose/gun), the only plant needed to complete most common projects in an airport setting are hand drills (and associated rig), monitoring equipment and post works testing equipment, thus no large plant is required.

Given that the only traffic associated with Geobear's on site operation is the injection unit (which will be parked on site), minimal traffic movement arises due to Geobear's presence on site.

In order to develop knowledge relating to the sustainability of Geopolymer injection, Geobear commissioned KLH Sustainability to undertake a review of Geopolymer injection vs conventional cement based grouting (with the input of an independent specialist with knowledge of both systems). The review/comparison was carried out on the required operation for the two systems to be utilised to carry out the same scope of works. The document considered:

- *"Carbon footprint (building life cycle stage A1 through to A5, as qualified by BS EN 15978:20111 , have been included as once installed the stabilisation requires no further intervention, and at the end of life will remain in the ground)*
- *Total number of HGV movements and the associated socio-economic costs*
- *Water footprint*
- *Total waste generation (on-site and off-site)*
- *Other Life-cycle impacts*
- *Environmental impacts associated with leaching and potential contaminated ground issues*
- *Installation programme*
- *Health and safety impacts associated with manufacture and use"*

The study notes that for the scope of works considered, the Geobear operation would result in 10.4 tonnes CO2e, whereas the conventional grouting solution would produce 19.5 tonnes CO2e (see Figure 1) , with the main contributing factor being cited as the grouting efficiency of the use of Geopolymers (i.e. far less Geopolymer would be required to undertake the works than cement based grout).

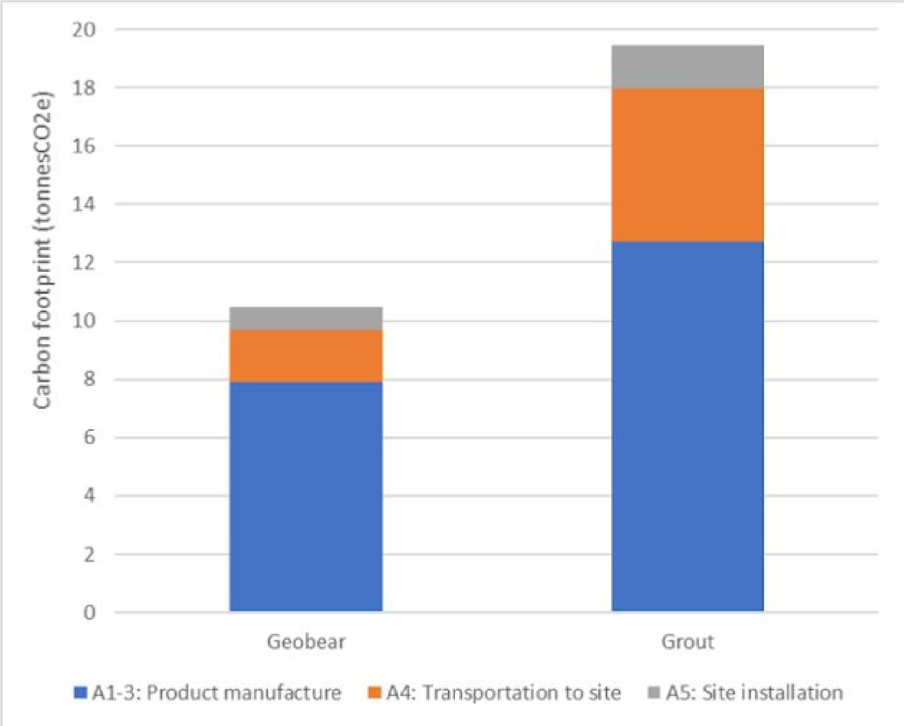


Figure 1: Carbon footprint by life-cycle stage

Fig 1 - Screenshot from KLH Sustainability Report

The discussion of the study states:

The Geobear ground stabilisation system offers improved sustainability credentials over traditional grout stabilisation in a number of areas. The scale of the individual benefits and disbenefits will vary depending on the exact requirements of any one project and its location.

The environmental impact assessment is qualitative only at this stage, however the scale of the operations significantly differ to achieve the same outcome and consequently the environmental impacts are typically less for the Geobear process compared to the conventional grouting. The Geobear pollution risk is considered significantly lower during the application compared to the traditional grout.

However, due to the relative magnitude of the differences (with the exception of photochemical oxidation) it is likely that the aspects against which Geobear demonstrates a positive impact will be consistent, regardless of project (assuming Geobear offers a 40 to 50 fold reduction in the quantity of materials required, compared to a grout solution). These aspects include:

- *carbon footprint*
- *water footprint*
- *total HGV movements*
- *socio-economic cost of deliveries within the UK*
- *total non-hazardous waste generated*
- *acidification potential*
- *installation programme*
- *site environmental impacts: noise, dust and water pollution potential"*

Design of Geopolymer injection

Depending upon the Geobear solution implemented on site, along with the project specific performance specification, there can be varying degrees of interaction between soils and the installed Geopolymer (e.g. when installed in a Ground Improvement scheme, there is far more interaction than when installed with the purpose of solely re-levelling/lifting a slab).

The classification of the soil being treated has a significant impact upon the way in which the improvement of the soil is achieved as a consequence of injecting a Geopolymer. In coarse grained soils, the improvement is gained mostly due to the ability of the injected Geopolymer to permeate pores within the soil, with a small contribution made by the compaction caused by the expansion of the Geopolymer (via kinetic energy transfer). Manasero et al (2016) states:

"*… the hydraulic conductivity is sufficiently high to allow the resin to penetrate the pores, with the consequent formation of a bulb of grouted soil, which expands until it reaches a state of equilibrium with the confining stresses generated by the surrounding soil.*"

In fine grained soils, the improvement is gained mainly as a result of the expansion of the Geopolymer, with a small contribution made by the ability of the material to penetrate the soil. Manasero et al (2016) states:

"*… and its expansion determines the formation of fractures, whose direction depends above all on the homogeneity and isotropy of the soil and on the initial stress state. The resin propagates into the fractures, thus determining variations in the soil density state and significant displacements of the surrounding soil.*"

When undertaking the design of Geopolymer injection projects, Geobear will generally consider three main areas:

- The project performance specification (i.e. the aim of the works)
- The required materials/labour to undertake the works successfully
- The requirements of any design codes or criteria specified in the project specification

Auxiliary items considered include
- The site in general
- Ground conditions
- Scope of works
- Codes and standards applied
- Risk
- Design calculations as appropriate

Because soils are naturally variable, the relative contributions of the improving mechanisms vary and can be difficult to predict. The approach to the design of Geopolymer injection works is generally an observational one in accordance with BS EN 1997 Part 1 clause 2.7. Execution is generally in accordance with the provisions of BS EN 12715.

Based on BS EN 1997:1: Eurocode 7, the following requirements shall be met before injections are started:

- *Acceptable limits of behaviour shall be established;*

- *the range of possible behaviour shall be assessed, and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits;*
- *a plan of monitoring shall be devised, which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage, and with sufficiently short intervals to allow contingency actions to be undertaken successfully;*
- *the response time of the instruments and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system;*
- *a plan of contingency actions shall be devised, which may be adopted if the monitoring reveals behaviour outside acceptable limits.*

Considering the above, Geobear will select the most appropriate Geopolymer to be installed and most suitable installation method, in order to fulfil the aim of the works. Throughout execution of the works, a monitoring programme is implemented to assess the impact of the Geopolymer injections. Geobear will pre-determine the actions to be adopted for the different monitoring results which may occur. Depending upon the solution Geobear deploy on site, Geobear will select the most suitable monitoring regime (including the potential use of Real Time Level Monitoring, Level Surveys, Probe Testing, GPR Surveys, Camera Surveys, etc).

Expansion Of Geopolymers

Throughout the Geobear network, multiple laboratory tests have been commissioned with the aim of determining physical and mechanical properties of Geopolymers.

One such test was carried out with the aim of assessing the relationship between expansive force and density. This test was carried out using a specially constructed device that enabled Geopolymer to be injected inside a rigid metal cylinder fitted with a piston. Immediately after injection, the Geopolymer started to expand in a vertical direction (due to the rigidity of the container, this was the path of least resistance).

Upon expansion, the Geopolymer drove the piston upwards, which after a stroke of a few centimetres, was blocked by a transversal contrast fitted with a manometer. The expansive force was then determined by measuring the pressure that the transversal contrast supplied in order to prevent the piston from moving upwards.

The experiment results have yielded the following relationship:

$$Lift\ Pressure = e^{\left(x\left(W - Wfr\right)\right)} - 1$$

Where: W = Specific Weight (kN/m^3)
Wfr = Free Rise Weight (kN/m^3)
x = Variable dependant upon Geopolymer type

Geobear have since undertaken research and development trials, involving the use of Geopolymers to lift a train carriage to test the above formula, alongside other formulae (produced by Manassero M, Boffa G, Dominijianni A & Puma S), led by Prof Colin Eddie, which established how expected lifting pressure and expansion ratios can be determined (in some cases, the expansion of Geopolymers, and subsequent impact on surrounding soils/assets can be modelling via Finite Element Analysis, allowing for visual aid to be provided alongside Geopolymer injection design documentation).

Durability

The manufacturers of our Geopolymers have carried out in house studies on the longevity of Geobear Geopolymers. With a technical bulletin released post study titled "*Longevity of Uretek Resins*". The summary of this paper states:

"*Based on experience of polyurethanes in general, in combination with accelerated ageing tests regarding mechanical stresses, heat, moisture, temperature cycling, radiation exposure and also chemical, mechanical and biological degradation, it was concluded that polyurethane foam integrity is maintained for a very long time under geological conditions.*

All of this would consequently lead to the conclusion that the longevity of the Uretek Resins will be at least 120 years."

Another technical bulletin produced by the manufacturers is titled "*Chemical resistance of Uretek Resins*" which summarised research which related to the measuring of chemical resistance of Geopolymers by immersing the material for 28 days in numerous chemicals. The volume change after the immersion period was determined according to DIN 53428 and ISO 2869.

The testing concluded the resistance of the Geopolymers to multiple chemicals, most notably, showing a resistance rating of *excellent* against Aviation Fuel (excellent resistance equates to a volume change of 0-3% volume change).

Upon completion of previous phases of Geopolymer injection work at Heathrow Airport (under the name Uretek), Dyer & Butler produced a document titled "*Heathrow Concrete Stabilising Works - Grout Injection Proposal Following Trials*".

The document states that the reason for the injection works was to "*raise the level of bays to eliminate trip hazards, reduce the damage to baggage trolleys and prevent concrete bays from rocking in the medium term"*. With the long term aim being "*to extend the life of Heathrow Airport's assets by tackling the core of the issue; the voids under the concrete bays*".

The works referred to in the document took place at what is described as "*various failure prone locations, including:*

- *Stand 546 (limestone concrete) - this stand was of particular interest as there were a number of dropped bays in one of the newest areas of the airport; Terminal 5*
- *Block 100 (flint concrete) - due to a number of rocking bays Dyer & Butler decided that trialling this method on some of the older parts of the airport would enable them to visualise the effect of stabilising sound bays over various parts of the airport"*

Upon successful undertaking of the works, it was concluded that:

"*Dyer & Butler found that using this method across Heathrow Airport will eliminate the need to break out a perfectly sound concrete bay, excavate the sub base materials and then replace it with another PQ/fast pave bay. The results from the trials were very successful and show great promise with major cost effective solutions.*"

Case Studies

London City Airport

Geobear undertook Ground Improvement works across 118 slabs on the runway and taxiway at London City Airport. The requirement for Geobear's works was due to the presence of incompetent soils underlying numerous concrete slabs (typically between 15-20m^2 - see Figure 4) with GPR surveys showing loose soil or voiding to a depth of approximately 0.75m - 1m. As a result of the introduction of traffic loading coupled with the voiding, signs of distress had appeared on the runway surface. The airport wanted to ensure maximum life cycle for the upcoming overlay and hence chose to increase the bearing capacity by injecting geopolymer before the overlay would take place.

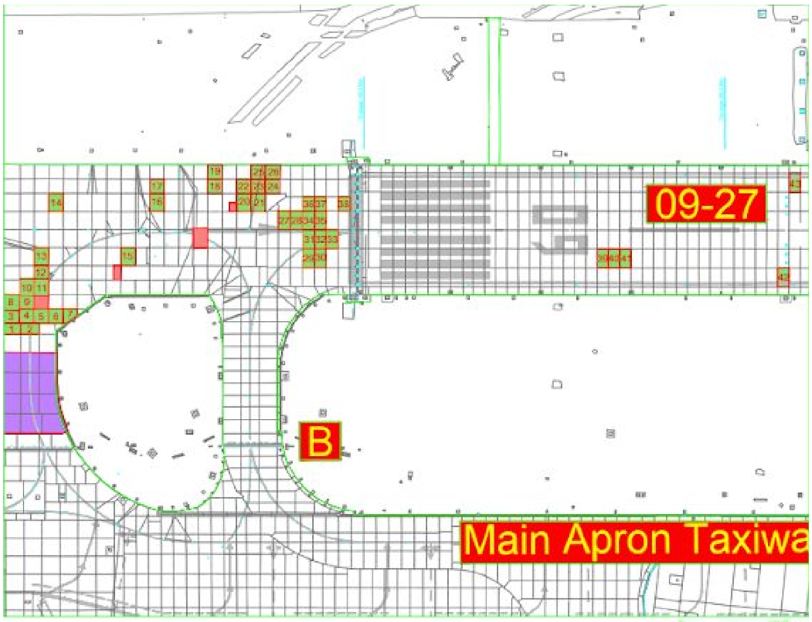


Fig 4 - Sample of Geobear Treatment Area (Denoted in Green)

Throughout the injection works, the area relevant to each injection was monitored using laser levelling equipment with sensors placed at relevant locations. During the works, each injection was prolonged until movement was registered on the nearest sensor (< 0.5mm). This movement displayed when a degree of compaction and densification of the previously compromised soils has been achieved. This also showed that the treated slab has been sufficiently reinforced as an upward force will be acting upon the underside of the slab, causing the movement.

In order to carry out the works successfully and taking into consideration the potential for the presence of water and to also ensure a high level of control throughout the Geopolymer injection works, Geobear specified a Geopolymer with a relatively short liquid phase, and a medium amount of expansive force for the works. This liquid phase will mean that the injected liquid Geopolymer would not migrate away from the region of slab targeted by the treatment, before being able to expand (change state) and consequently improve soils beneath the slab being treated.

The injection works were completed successfully, with the site handed over to the main contractor to complete subsequent works involving widening the taxiway and resurfacing the runway.

London Heathrow Airport

Geobear have undertaken multiple phases of work on London Heathrow Airport, consisting of remediating soils beneath Taxiway slabs, and stabilising/lifting a slot drain.

The reason for Geobear's works to treat beneath Taxiway slabs was that the Pavement Quality (PQ) concrete pavements forming Taxiway Charlie were exhibiting signs of failure in the form of sunken bays, mud pumping and cracked slabs. Geobear treated twelve 7m x 7m slabs on Charlie Taxiway, with two of the slabs lifted as well as stabilised (see Figures 5 & 6).

Monitoring via laser levelling equipment was carried out throughout the works, with each injection prolonged until movement was registered on the nearest sensor (< 0.5mm). When installing Geopolymer beneath the slabs to be lifted, injections were prolonged until the desired amount of lift/heave was achieved.

Fig 5- Slab before treatment

Fig 6- Slab after treatment

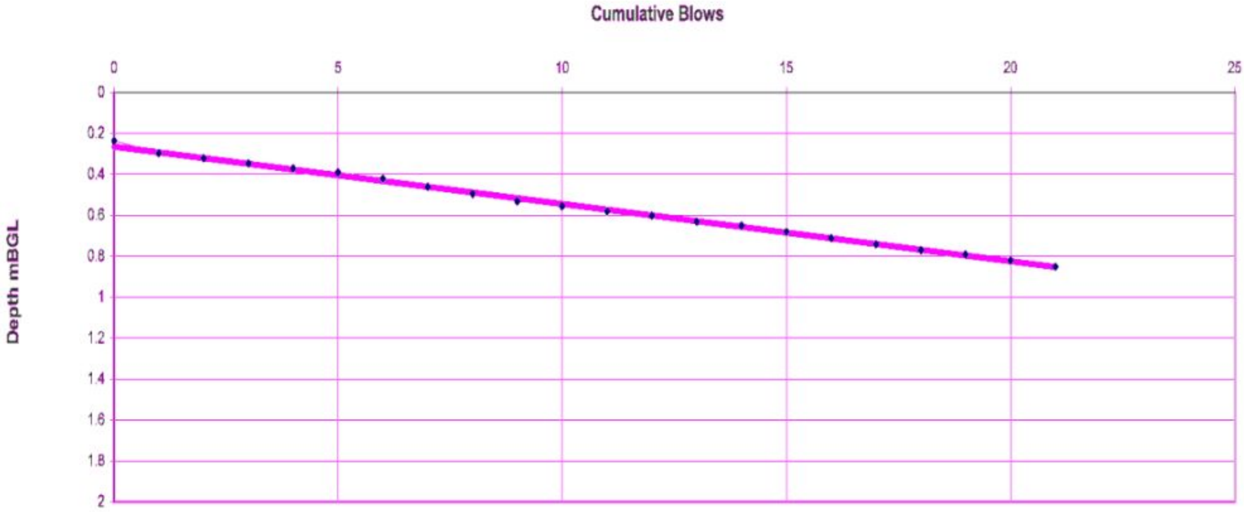
Similar works have been carried out by Geobear over multiple phases resulting in the stabilising/lifting of a slot drain, which was causing issues with plane movements across the drain. The latest phase of works involved the treatment of 100m of airside slot drain, with the greatest lift required being circa 25mm.

The result of the injection works was that normal operations could continue without delay.

Southend Airport

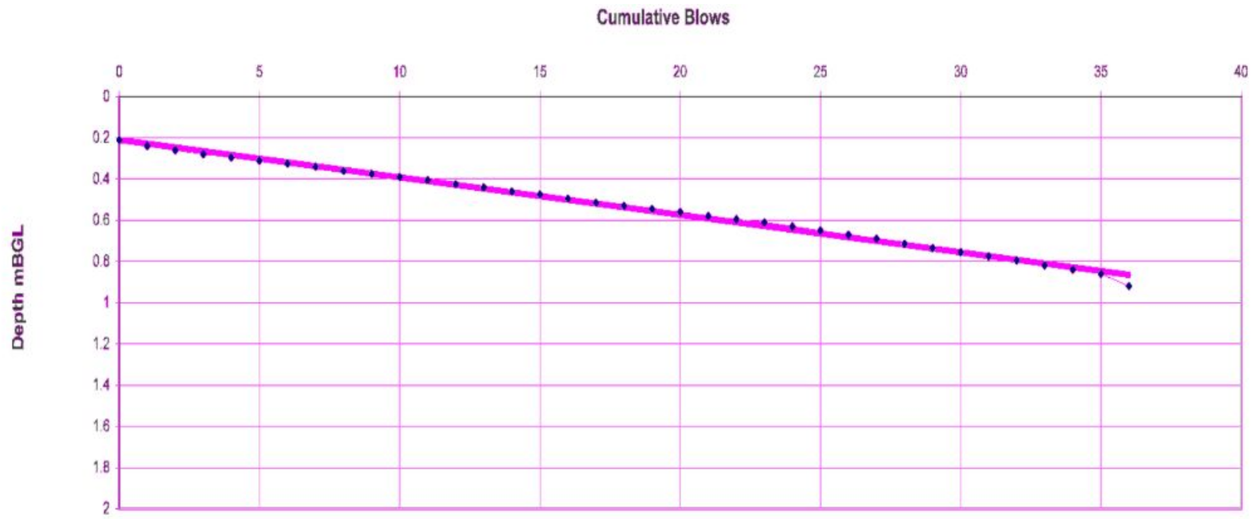
Geobear undertook Ground Improvement works across an area of runway at Southend Airport, with the aim of improving soils beneath runway slabs to display a California Bearing Ratio (CBR) value of 12%. Pre works testing showed that treatment was required to maximum depth of 1.2m below slab level. The Geopolymer works comprised of 27nr 14mm injection points, installed at 0.6m & 1.2m below the wearing course tarmac runway level.

Throughout the injection works, the area relevant to each injection was monitored using laser levelling equipment with sensors placed at relevant locations. During the works, each injection was prolonged until movement was registered on the nearest sensor (< 0.5mm). This movement displayed when a degree of compaction and densification of the previously compromised soils has been achieved. Figure 2 & Figure 3 (below) provide an example of pre and post treatment TRL probing, carried out within the treatment area, showing the improvement achieved via the installation of a high density Geopolymer.



Top (mBGL)	Base (mBGL)	CBR (%)	Stiffness Modulus (Mpa)	Foundation Class
0.24	0.85	9	71	Class 1

Fig 2 - TRL Probing Results Before Ground Improvement via Geopolymer Injection



Top (mBGL)	Base (mBGL)	CBR (%)	Stiffness Modulus (Mpa)	Foundation Class
0.21	0.92	14	96	Class 1

Fig 3 - TRL Probing Results After Ground Improvement via Geopolymer Injection

The results of the Geopolymer injection works undertaken by Geobear were that a 24m^2 target area was successfully remediated within six hours, and allowed for the formulation of a proposal to treat a larger area on site.

Other applications on airports:

- Leveling of sunken asphalt shoulders
- Stabilisation of soil prior to tear out and replacement of concrete panels
- Void Filling
- Sealing water leaks
- Below ground contamination containment

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