Field Evaluation of a New Road Sub-Base Concept Including Bauxite Residue and Other Industrial By-Products

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Abstract

The refining of alumina produces significant amount of residue (BR, Bauxite Residue) which is similarly produced by other ferrous and non-ferrous metals industrial sectors. Alumina refining, iron and steel production can establish innovative industrial symbiosis models for the construction sector to valorise large volumes of residues and by-products. In the present study, results from a European pilot plant to produce and evaluate the performance of a new road sub-base concept using bauxite residue, coal fly ash and ground granulated blast furnace slag. The paper includes details and results of the project, the experimental work undertaken to determine the mechanical and environmental performance and the results achieved from the quality control and monitoring plan established. Mechanical results were compared with the Spanish and Irish regulations for hydraulically bound materials for roads. The results show that the key performance parameters have been achieved and that the new material developed is suitable for road sub-base construction. The proposed solution appears robust from a safety and environment point of view and the project showed no major construction process difficulties. In summary, the field evaluation has demonstrated the added value of using waste and by-products as alternative construction materials delivering a mechanical performance like soil cement pavement layer and a suitable circular economy strategy to reduce the environmental impact of alumina production and BR management.

Keywords: Bauxite residue, Road construction, Mechanical strength, Fly ash, GGBFS.

1. Introduction

Recycling of inorganic industrial waste and surplus materials have a decisive role in the development of the circular economy globally. This is because the solid waste stream represents billions of tons of material resources and a range of different types of materials (e.g. combustion ashes, slags and residue from metallurgic manufacturing, tailings from mining). The more secondary material resources we manage to keep in the circular economy, the more we can reduce the amount of natural resources used as primary resource resulting in less extractive waste stored at industrial sites.

Bauxite residue (BR) from alumina production is an alkaline by-product from the processing of bauxite through the well-known Bayer process. The alumina is extracted using sodium hydroxide under high temperature and pressure, where the so-called BR (insoluble part) is removed from the sodium aluminate solution. Typical range of residue to alumina production ratio is 0.75 to 2 tonnes of residue per tonne of alumina produced. Based on updated figures of the International Aluminium Institute [1], an estimate of almost 170 million tonnes of BR was generated in 2021. If we include BR storage in approximately 50 closed legacy sites, the total volume of BR may be around 3 billion tonnes of residue [2]. Hence, increasing the re-use of BR will contribute significantly to circular economy.

Ground granulated blast furnace slag (GGBFS) is a by-product from the iron and steel making industrial sector that has been dried and ground into fine powder. In Europe, almost 18 million tonnes of GGBFS is used in the cement and concrete industries. This is the most common use for GGBFS. It acts as a direct replacement for cement, and has many advantages including extending the life cycle of concrete, making concrete more durable, and reducing the carbon and energy footprint of concrete production. Blended cements (GGBFS and ordinary Portland cement) have a superior resistance to sulphates and an increased chloride binding capacity.

Pulverised coal fly ash (PFA) is a waste produced from the combustion of coal in the generation of electricity at power plants. It is most commonly used as a high-performance substitute for Portland cement or as clinker for Portland cement production. Cements blended with PFA have become common. Building material applications range from grouts and masonry products to cellular concrete and roofing tiles. Many concrete pavements contain PFA. Geotechnical applications include soil stabilization, road base, structural fill, embankments and mine reclamation.

Secondary materials for road construction offer wide range of possibilities for waste and by-products re-use. Materials required for road construction vary in particle sizes (surfacing, base course, sub-base, subgrades, embankments) and the civil engineering sector is huge in every country and there are always construction projects ongoing. Hence, the pilot road project makes it ideally to apply different types of alternative materials like recycled excavated soil, recycled aggregates, recycled glass [3, 4].

Several studies have been published on the use of BR with coal fly ash and calcium hydroxide to stabilise soil subgrade [5]. Mukiza et al [6] concluded in their review that BR was suitable as soil subgrade stabiliser for light traffic roads.

The use as road sub-base material needs addition of activators to boost up the geopolymer reactions. The effect of different activators (10 % addition) on BR have been ranked in the sequence of decreasing strength, calcium hydroxide, GGBFS, cement kiln dust and coal fly ash [6]. Not surprisingly, a strong correlation was established with the CaO content. Another study [7] using BR, coal fly ash and lime confirmed that this combination shows good geotechnical results, and that BR can be used as a geotechnical material with the appropriate method of stabilisation.

Leaching measured at single pH have been frequently reported including BR with flue gas desulfurization fly ash and cement [6], BR with rice husk ash [8], BR and fly ash in sulphuric acid and deionised water [9], BR and sintered BR [10]. However, only a few studies exist regarding equilibrium based leaching characterisation that cover the full pH range [11, 12]. Hence, a full pH dependent characterisation was conducted in RemovAL project [13]. Regarding full scale demonstration, only a few studies have been reported with road pilots with large use of BR in road pavement achieving high level of performance [14].

In the RemovAL research project funded by the European Union (www.RemovAL-project.com), large-scale use of geopolymer based BR as road sub-base (150 mm layer) was demonstrated. Firstly, laboratory studies were carried out to evaluate both the mechanical and environmental performance [13, 15], demonstrating that the use of BR combined with PFA, GGBFS and calcium hydroxide (hydrated lime) is suitable for roads construction and potentially a very good opportunity for the valorisation of BR. This study shows the results of the RemovAL sub-base layer pilot, a full-scale demonstration project using BR, PFA, GGBFS and hydrated lime, for the construction of a 150 mm sub-base pavement layer of a secondary road within the Bauxite Residue Deposit Area (BRDA) located at the Aughinish Alumina (Aughinish) refinery in Ireland.

The main results of the leaching and mechanical characteristics both in laboratory and at field site are also presented in this study.

2. Materials and Methods

2.1 Description of the Materials and Samples

The materials used for the RemovAL pilot road were BR, PFA, GGBFS and hydrated lime. BR fines (particles of 5-6 µm) and BR coarse sand (particles of 350 µm) was provided by Aughinish. The BR coarse sand is removed and washed at Aughinish before the residue washing circuit. Class F pulverised coal fly ash (CaO < 10 %) was supplied by Moneypoint ESB power station (Clare, Ireland) who also received approval from the Irish Environment Protection Agency (EPA) to supply PFA. The moisture content in the PFA was 5–7 %. The GGBFS used was purchased in 1-tonne sealed bags from an Irish Cement facility in East of Ireland. The commercially available hydrated lime ($Ca(OH)_2$) was procured from Clogrennane (Carlow, Ireland). The various materials were covered with liners in a dedicated location inside the BRDA boundaries to protect the material while developing the best recipe on site.

The BR (fine and sand) materials were mixed with PFA, GGBFS and hydrated lime and applied as a sub-base layer in the pilot road. The mixture design selected for the works included up to 82 % of BR and defined amount of binder constituents. Table 8/11: "Minimum Binder or Binder Constituent Additions for Hydraulically Bound Materials" of the UK Series 800 road pavements specification for unbound, cement and other hydraulically bound mixtures [16] was used for guidance. As a batching by mass mix-in-plant method was used for the works, the minimum addition of hydrated lime and GGBFS specified in Table 8/11 is 1.5 % and 3 % respectively by mass (dry basis). In the RemovAL pilot, the final mixture design defined at laboratory scale in previous investigations [15] included 1.5 % of hydrated lime and 4.5 % of GGBFS.

As capping layer to prepare the existing sub-base prior the application of the RemovAL sub-base layer and as wearing or surface course (Figure 1) a granular rockfill material type C was used.

Drilled cores of the RemovAL sub-base layer were taken at different sections after hardening and before applying the waterproofing coat. The total chemical concentrations were determined from the cores.

2.2 Mechanical and Physical Characterisation

Field density and moisture content were evaluated using a Nuclear Density Gauge (NDG). The results were assessed using as reference the Optimum Moisture Content (OMC) and Maximum Wet Density (MWD) determined in previous laboratory tests according to EN 13286-4 (Unbound and hydraulically bound mixtures - Part 4: Test methods for laboratory reference density and water content - Vibrating hammer), where the MWD and OMC accepted ranges established for the works were 1.55–1.64 mg/m^3 and 22 ± 2 % respectively.

The mechanical characterisation carried out was based on the requirements established by EN 14227-5:2014 (Hydraulically bound mixtures - Specifications - Part 5: Hydraulic road binder bound granular mixtures) and Transport Infrastructure Ireland (TII) Publications for Road Pavements-Unbound and Hydraulically Bound Mixtures (CC-SPW-00800) for:

- Sampling and mixture composition (BS 1377:Part 2:2022), Cl.9.2 (Methods of test for soils for civil engineering purposes - Classification tests and determination of geotechnical properties Part 2 - Particle Size Distribution).
- Compaction tests: field density and moisture content (BS 1377 Part 9:2022), Cl.2.5 (Methods of test for soils for civil engineering purposes - In-situ tests - nuclear density testing).

- Unbound and hydraulically bound mixtures - Part 41: Test method for the determination of the compressive strength of hydraulically bound mixtures.
- Strength after immersion according to the protocol established in CC-SPW-00800: comparison of the average strength of:
    - 3 wet specimens initially cured in a sealed condition for 14 days at test temperature (20 °C); and then removed from their moulds and immersed in aerated water for 14 days at the same test temperature.
    - 3 dry specimens cured in sealed condition for 28 days at the same test temperature.

Results were compared with the Spanish and Irish Specifications for soilworks [17, 18]. The Irish Specifications was chosen as the trial section was built in Ireland using the BR from Aughinish, and with the Spanish regulations to evaluate potential replication strategies using BR from other similar refineries (like alumina refinery located in Spain).

2.3 Field Site Construction Description and Measurements

Aughinish undertook the role of demonstrator lead in the project in developing a process using equipment available in Ireland to prepare, mix, transport, apply the RemovAL pilot road sub-base and construct a sampling system to monitor leaching performance.

The RemovAL pilot road design shown in Figure 1 consist of a 150 mm capping layer deposited on top of the existing granular base of the road, then the RemovAL sub-base (150 mm) layer is laid on top of this capping layer (limestone layer) and finally a granular surface course layer of 200 mm provides the finishing layer of the road.

The road was constructed for light traffic with the existing BRDA using a total of 500 tonnes of BR, GGBFS, PFA and hydrated lime.

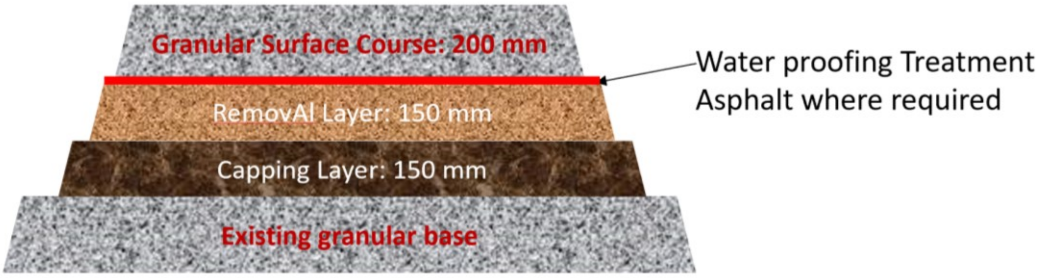

Figure 1. Road layer design.

The RemovAL pilot road design (Figure 2) includes a specific leachate sampling system to allow leachate monitoring. The leachate from the road is directed into the BRDA perimeter channel where it gets sent to the water treatment plant.

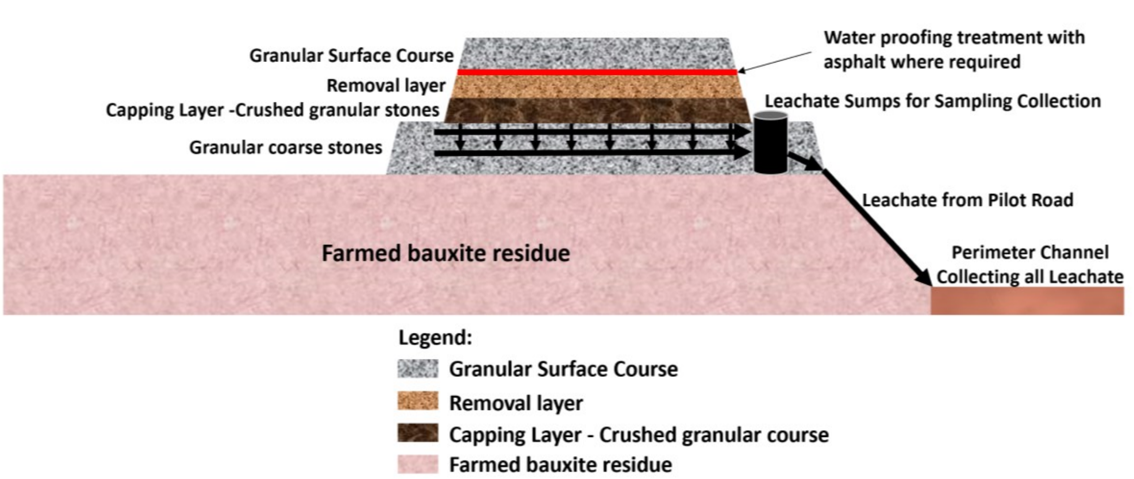

Figure 2. Road design with integration of the sampling system.

As mentioned in previous section, the PFA was collected from a PFA stockpile located in Moneypoint ESB power station a few kilometres away from Aughinish. The GGBFS and hydrated lime were delivered in bags from Irish cement (GGBFS) and Clogrennane (hydrated lime) who already supplies quick lime to the refinery. All the materials were covered with liners to avoid getting wet before being used.

The construction process was similar to existing soil stabilisation works. The main difference was on the manufacturing process, where a non-conventional small batching plant (by mass) was used but the mixing performance and workability of the final material was as per requirement and the material mixture was homogeneous.

Prior to producing the RemovAL layer, some preparation works as shown in Figure 3 had to be completed to ensure good foundation and capping laying were in place with drainage into sampling Sumps at four locations. Geosynthetic clay liners were fitted (10 meters in front of each Sump) below the capping layer to trap the leachate to drain it towards the sampling Sump.

Figure 3. Capping layer and drainage system.

As part of the recipe, the BR (coarse and fine fraction) had to be mixed on the BRDA using a large rotovator. The binder materials (GGBFS, PFA and hydrated lime) were pre-mixed using a concrete bucket mixer before finally mixing it with the BR into the larger mixer. This resulted in approximately 1100 m^2 of road and parking area shown in Figure 4 (date of the picture November 2021).

Figure 4. RemovAL sub-base construction and aerial view of finish RemovAL pilot road.

Core samples were taken on Day 1, Day 14 and Day 28 from the RemovAL sub-base layer for compressive strength, moisture content, density and compaction measurements. The sampling was carried out by BHP certified laboratory based in Limerick, Ireland (BHP). Additionally, leachate samples (Sump shown in Figure 5) were taken by Aughinish employee over a period of 2 years and these samples were analysed by SINTEF in Norway to determine leaching performance. Results for both mechanical properties and leaching performance are discussed in Section 3.

Figure 5. Leachate sampling system using Sumps.

2.4 Chemical Analyses

Determination of Al, As, Ca, Cd, Cu, Cr, Cr(VI), Fe, K, Mg, Mn, Na, Ni, P, Pb, Si, Ti and Zn in the crushed sample materials was carried out using sector field inductive coupled plasma mass spectrometry (ICP-SFMS) according to SS-EN ISO 17294-2:2016 and US EPA Method 200.8:1994. Determination of Hg was carried out using atomic fluorescence spectrometry (AFS) according to SS-EN ISO 17852:2008.

The following methods were used for the leachates collected from Sump 1-4 at the pilot road. Ca, K, Mg, Na, S, Si were determined using inductively coupled atomic emission spectrometry (ICP-AES) according to SS-EN ISO 11885:2009 and US EPA Method 200.7:1994, whereas Al, As, Cd, Cu, Cr, Fe, Ni, Mn, Pb and Zn were determined with ICP-SFMS according to SS-EN ISO 17294-2:2016 and US EPA Method 200.8:1994. Determination of Hg was carried out using AFS according to SS-EN ISO 17852:2008 and Cr(VI) by ion chromatography with spectrophotometric detection according to CSN EN 16192, EPA 7199, SM 3500-C. The elemental analyses were carried out by ALS Laboratory Group Norway.

For loss on ignition (LOI) determination, dry sample was accurately weighed and dried at 105 °C before being heated for 75 minutes at 1000 °C. The cooled sample was weighed accurately to calculate the LOI. These analyses were conducted by ALS Laboratory Group Norway.

3. Results and Discussion

3.1 Mechanical Characterisation

3.1.1 Particle Size Distribution

The particle size distribution was evaluated after sampling different batches during the construction works. Results showed homogeneous grading curves (nine tests undertaken: three batches assessed x three samples evaluated), results were similar to what was expected for a hydraulically bound material HBM type B considering the grading envelop included in the Irish specification CC-SPW-00800.

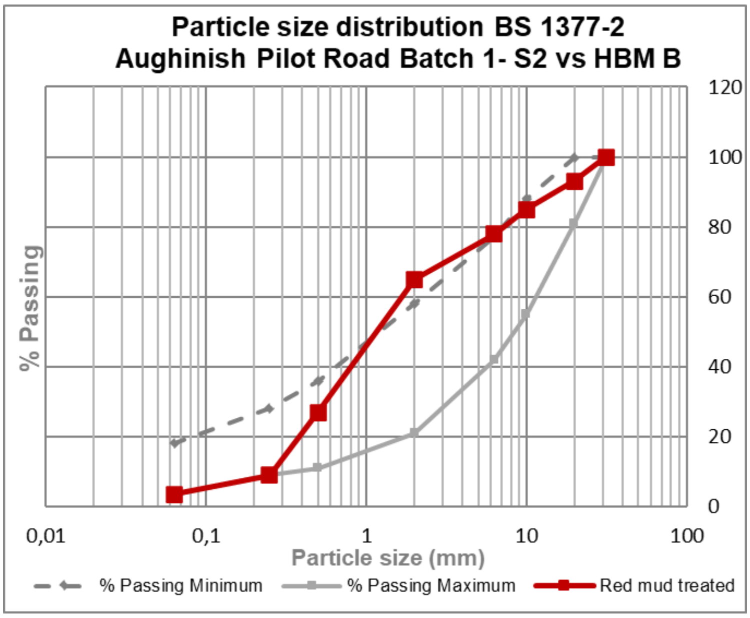

Figure 6. Grading curve of one of the batches.

As described by the Figure 6, the curve of the material assessed, does not completely fit the grading envelop for HBM type B but it is very close. The final mixture design selected for the works included mostly sand and fines fractions as the target in the RemovAL project was to maximise the use of BR and secondary raw materials (PFA and GGBFS), so this minor deviation is not of significance and was included as part of our investigation. It should be noted that regular grading curves envelop is defined for mixtures using cement as binder which was used as a guidance to facilitate comparison with the traditional materials (material in this study is not strictly subjects to these specifications).

3.1.2 Compaction Related Tests

To facilitate mixing, compaction and avoid stickiness difficulties during compaction operations, it was decided to work with a moisture content lower than the OMC established at laboratory scale, as it was verified at laboratory scale, that strength and compaction at lower moisture content (15–18 %) were still acceptable.

Results of the in-situ measurements are shown in

Table 1 and all compaction tests were successful in achieving the HBM Compaction Requirements even though the moisture content was slightly lower than the OMC.

Table 1. Compaction tests - nuclear density testing (NDG) BS 1377: Part 9. Depth 50 mm.

Parameter	**Test Method**	**Moisture content (%)**	**Dry Density (mg/m3)**	**Group result* (%)**	**TII CC-SPW-00800 (%)**	**ORDEN FOM/2523/2014**
Relative Compaction	Nuclear Density Gauge	15.6–19.2	1.81–2.06	100 %	Group Average ≥ 95 %MWD	Group Average ≥ 98 %MWD

* To set up the result ranges nine tests were included from three different working days.

3.1.3 Compressive Strength

To verify the mechanical performance of the mixtures produced, samples from different batches were taken to produce cubic specimens (150 × 150 × 150 mm) that were tested at different ages (after curing period of 7, 14 and 28 days), following EN 13286 Part 41. Results are shown in Figure 7.

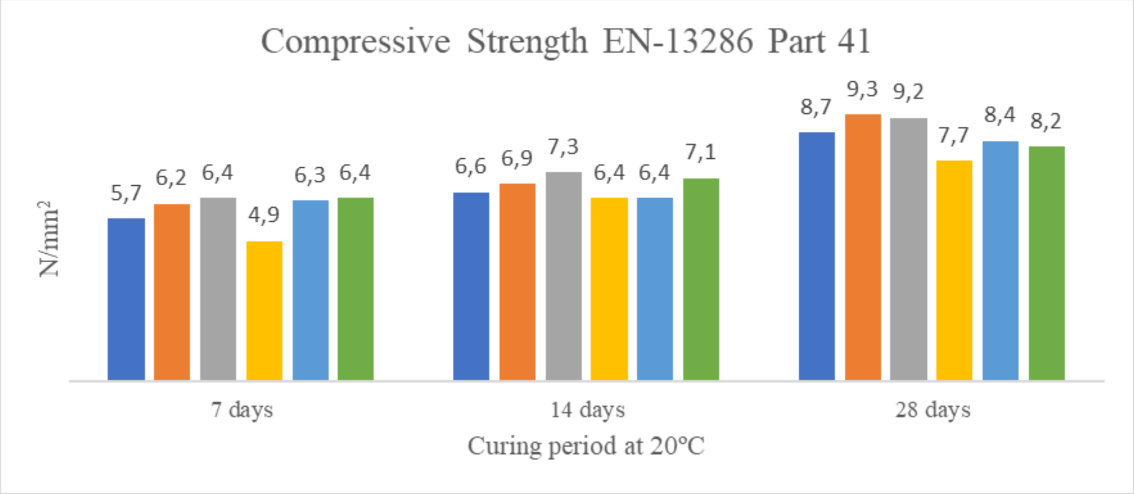

Figure 7. Strength at 7, 14 and 28 days.

The IAPDM (Irish Analytic Pavement Design Method) performance required for HBM in the TII specification for works is C8/10 (group average > 10 MPa (N/mm^2) for cubic specimens) and > 6.7 MPa for single locations. In the case of the Spanish regulation (ORDEN FOM/2523/2014), it is established that strength after curing for 7 days should be in the range of 2.5–4.5 MPa. Consequently, results are above the recommended threshold strength after 7 days in the case of the Spanish specifications, accomplish the specification for single locations but are slightly below the recommended performance average included in the Irish specification for HBM.

It should be noted that in both specifications, the binder considered was cement, and not a combination of GGBFS, hydrated lime and PFA to promote geo-polymerisation. Hence, as mentioned for the grading curve, the material evaluated is not strictly subject to these specifications, but they were considered for guidance and to facilitate comparison. However, for further replication, it would be recommended to modify the particle size distribution of the mixture, reducing the amount of fines and introducing a granular material (e.g. gravel or a recycled material or waste aggregates suitable for roadworks like crushed concrete in line with the RemovAL aim of fostering circular economy). This could be an easy way to increase the skeleton of the mixture and accomplish the requirements set for the particle size distribution and strength.

As part of the investigation undertaken, compressive strength was monitored to evaluate the mechanical performance evolution as the chemical and physical reactions to gain strength are not the same in the material developed versus what is occurring when using cement as binder. Cores were drilled out after 90 and 180 days and results showed that compressive strength could be considered as stabilised, which is quite positive (Strength after 90 days: 8.55 MPa and after 180 days: 8.31 MPa).

3.1.4 Strength after Immersion

The monitoring of the mechanical performance continued and after 365 days, a group of six cores was drilled out to evaluate the performance of the pilot section under demanding conditions and the strength after immersion test described in CC-SPW-00800 was undertaken. Results meet the strength after immersion requirement of 80 % ($\mathbf{I_{Ri/R} = I_{0.8}}$). showing a $\mathbf{I_{Ri/R}}$ of 94 % ($I_{0.94}$), which confirms the good valorisation potential of the technology developed.

3.2 Total Element Concentrations in the Drilled Core Samples

The heavy metal concentrations in the drilled cores are shown in Table 2 and compared with Norwegian regulatory limits. The NWR 14 is a newly developed Norwegian criteria for concrete and masonry waste that is categorised as construction and demolition waste (e.g. from demolition of road infrastructure). Concrete and masonry waste complying with these criteria, can be used without restriction above ground water level. Furthermore, the Norwegian Environmental Pollution Agency (NEPA) is the strictest soil quality criteria (class 1) and reflect the background values of soil.

Table 2. Total concentrations (mg/kg) of the heavy metals in the drilled core samples.

Parameter	CS 1/2[a]	CS 2[a]	CS 3/4-A[a]	NWR 14[b]	NEPA[c]
As	39	42	39	15	8
Cd	0.11	0.10	0.14	1.5	1.5
Cr	321	239	223	100 (tot)	50
Cr^{6+}	1.2	1.2	1.9	8	2
Cu	44	45	45	100	100
Hg	0.09	0.09	<0.01	1	1
Ni	23	22	20	75	60
Pb	44	45	40	60	60
Zn	77	68	72	200	200

[a] [19].

[b] Norwegian Waste Regulations. Chapter 14a. Concrete and masonry waste can be used without restriction above ground water level.

[c] Norwegian Environmental Pollution Agency soil quality criteria (Class 1).

In general, the results showed that the element concentrations are normal, except for Arsenic (As) and Chromium (Cr). The findings are also in agreement with earlier results obtained for coarse and fine BR materials in RemovAL project. It can be emphasised that most of the Cr was on the trivalent form (Cr^{3+}) since only a small fraction was determined on the hexavalent form (Cr^{6+}). The former Cr species has low solubility at the field pH of interests and is therefore less mobile than water soluble Cr^{6+} species. Hence, the actual leaching at field site is therefore important to monitor over a longer time period to assess any elevated leaching behaviour.

3.3 Leaching Performance from Pilot Road

3.3.1 Development of pH

Based on the materials used in the pilot sub-base, the drainage pH will be in the alkaline region. The pH determined during a monitoring period of 2 years is shown in Figure 8. It can be seen that the pH at the 4 collection Sumps is stabilising. It seems that Sump 1 and 2 have stabilised at pH 8 and Sump 3 and 4 at a pH around 10. This was not expected, and after inspection of the lining system, the lining system got damaged during construction impacting Sump 3 and Sump 4. Hence, the results from Sump 1 and Sump 2 will be discussed in the following paragraphs.

3.3.2 Leaching of As and Cr

The elements As and Cr may appear on their anionic (AsO_4^{3-} and CrO_4^{2-}) in basic solutions under oxidizing conditions. These species appear in cement-based leaching systems (Mulugeta et al 2010) [20]. These oxyanionic species form covalent bonding between the metal and oxygen. Hence, elements that are close to oxygen in electronegativity tend to form oxyanions (Engelsen et al 2010) [21]. The field leaching of As and Cr are shown in Figure 8 during the monitoring period.

The results are compared with EU Drinking Water Directive (DWD) limits, which very often are used as limits for ground water quality. In addition, annual average environmental quality standards (AA-EQS) in the EU Water Framework Directive (WFD) are also included in the figure. The purpose for establishing the environmental quality standards (EQS) limits shown in Figure 8, has been to protect the most water sensitive species.

It can be seen that the As and Cr leaching were both well below the drinking water directive limits. Furthermore, it was found that the leachable content of Cr, was mostly on the hexavalent form (Cr^{6+}), as shown in Figure 8. The leaching of Cr and Cr^{6+} were around the level of EQS and PNEC (Predicted No Effect Concentration) for Sump 1 and well below these levels for Sump 2. This is also in agreement with the total concentrations in Table 2, which showed that relatively low contents of Cr^{6+} were found in the drilled core samples.

The results for leaching of As, was beyond the EQS. However, it is emphasized that a direct comparison is made without considering the dilutions due to the water transport in an aquifer. Upon use in a road construction project, a site-specific risk assessment is required, which includes the contaminant transport to the recipient (e.g. freshwater lake), i.e. the location point where the EQS limits should be complied with. Hence, the obtained concentrations are considered to be low for As in the monitoring period.

3.3.3 Leaching of Heavy Metal Cations

The leaching of the heavy metals that normally form cations are shown in Figures 9 and 10, and the same comparison with DWD and EQS limits was conducted for these elements as for the oxyanions. It was found that the leaching was mostly below the EQS limits for all elements during the monitoring period. This is also in agreement with the expected speciation and solubility of the elements at the obtained field pH. It can be expected that at mildly basic conditions (pH 8–10), the solubility is at minimum for the metal cations in the form of hydroxides or as metal carbonates. Furthermore, sorption to iron and aluminum oxide surfaces seems to control the leaching in this pH region for the elements in Figures 9 and 10 [21]. It is noted that the release mechanisms of mercury (Hg) are somehow not entirely clear. It is believed that it is in the cationic form (Hg^{2+}) and gets incorporated into cement minerals due to the relatively high solubility of $Hg(OH)_2$.

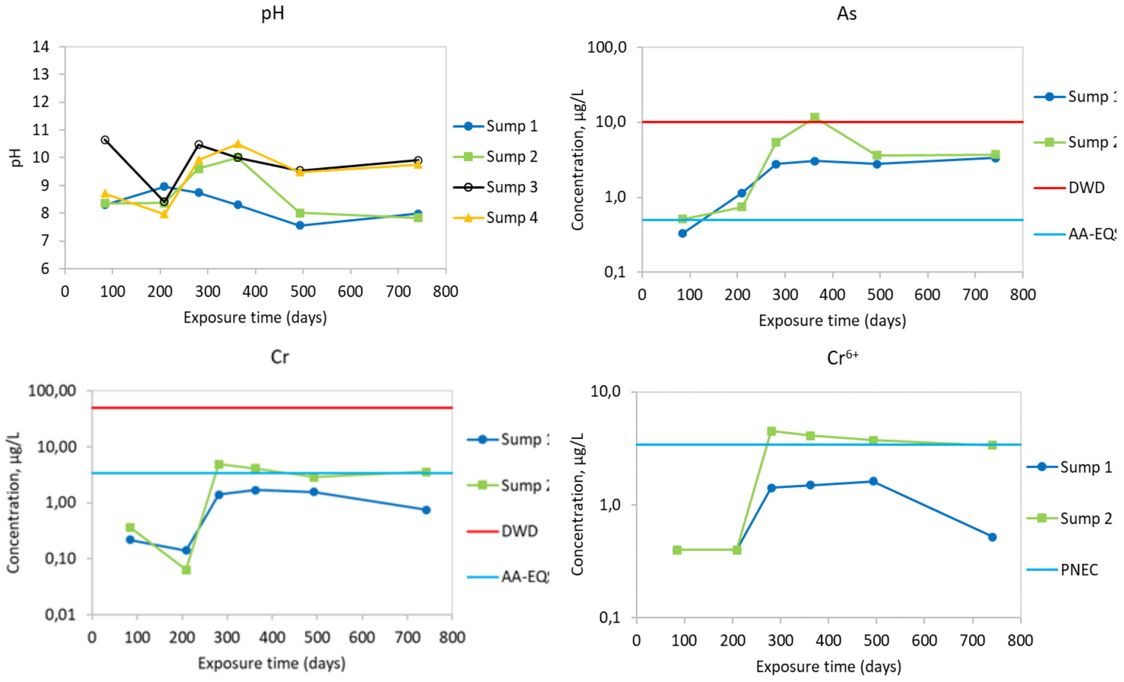

Figure 8. Concentration of pH, As, Cr (total) and hexavalent chromium (Cr^{6+}) in the leachate samples collected from the drainage Sumps (Sump 1 and Sump 2).

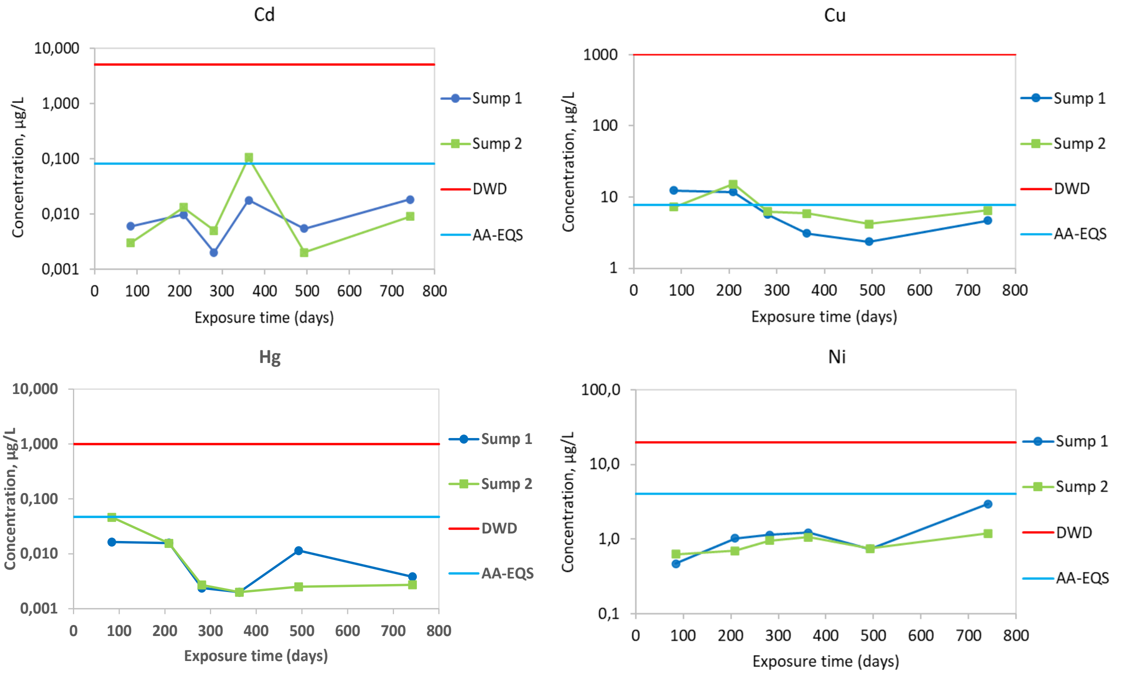

Figure 9. Concentration of Cd, Cu, Hg and Ni in the leachate samples collected from the drainage Sumps (Sump 1 and Sump 2).

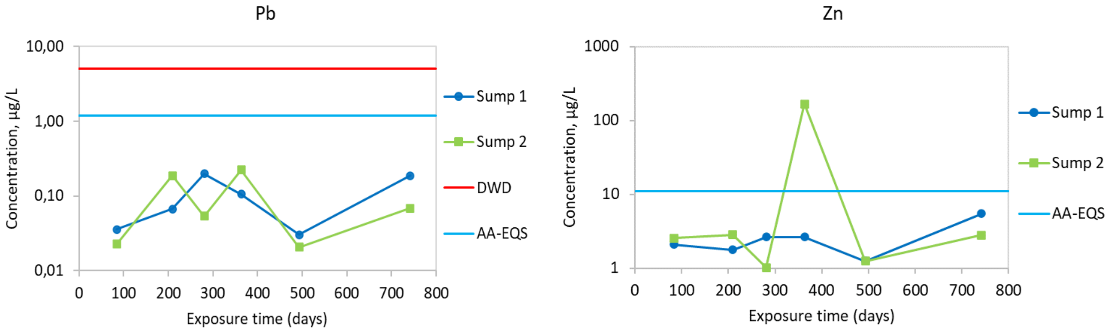

Figure 10. Concentration of Pb and Zn in the leachate samples collected from the drainage Sumps (Sump 1 and Sump 2).

4. Future Works

Aughinish in partnership with research institutes and other industrial facilities is planning to continue the work on road sub-base application. More opportunities exist on the technical side to improve the recipe from both mechanical and leaching performance and this should be pursued at Aughinish in coming years.

It is important to note that the business model is specific to every alumina refinery and it is still unclear to Aughinish today how this technology could be deployed in Ireland and in Europe due to the significant regulation and societal barriers for secondary raw material reuse. However, there is increased momentum in Ireland and Europe in making circular economy more possible for industrial by-products and waste.

5. Conclusions

The study results confirmed that the mechanical performance was similar to regular hydraulic bounded material. Further investigations are required to complement the actual specifications and facilitate the deployment of alternative materials that can be suitable for roads construction like the evaluated in this study.

The total concentrations of the heavy metals in the drilled core samples were increased for As and Cr, as expected due to concentration effect of extracting the alumina from the bauxite (~ 45 % content in bauxite). Most of the Cr was in the trivalent form (Cr^{3+}), which is far less soluble than the hexavalent form (Cr^{6+}). Low leaching during the monitoring period of two years was determined for both oxyanion (Cr and As) and cation (As, Cd, Cr, Cu, Hg, Ni, Pb and Zn) species. Further continuous monitoring will provide valuable information about the chemical stability and the following leaching levels.

As lessons learnt from this field evaluation and next steps proposed for further developments, it could be mentioned that the application of a waterproofing coat or treatment for the entire sub-base layer would be recommended and that the modification of the particle size distribution of the mixture (e.g. introducing a small amount of gravel or crushed concrete), could improve the mechanical and leaching performance.

Finally, considering the amount of BR and secondary raw materials included in the mixture design and the volumes of materials used for roads construction, it can be concluded that the upscale and replication of the new sub-base concept evaluated, could significantly contribute to circular economy and the deployment of interesting industrial symbiosis models.

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