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Our Ref: **A190707**

Your Ref: **A190707/VER**

Date: 12th November 2020

RE: A190707 Hornsey Gas Works, London Stabilisation Technology Verification

Dear Jack,

We are pleased to provide geochemical validation datasets and associated interpretations relating to 11 No. 8 fraction verification semi-dynamic tank tests, in addition to geotechnical verification datasets including; CBR Swell and UCS testing undertaken during the recent stabilisation works at Hornsey Gas Works, London.

Project Background

The suitability of stabilisation technology for the re-use of contaminated materials as hydraulically bound engineered fill was demonstrated in CE Geochem Report A190707 and associated Addendum Reports. Subject to geotechnical requirements, stabilised materials may be suitable for subsequent site development works such as foundations / sub-base to car parking and hardstanding areas, piling mats or associated development platforms at the Hornsey Gas Works site. Stabilisation works of contaminated materials were subsequently completed in September 2020 in accordance with the revised controlled waters Detailed Quantitative Risk Assessment (DQRA) and Remediation Method Statement (RMS) produced by Atkins. This report has been produced as part of the verification strategy in order to validate the geotechnical and geochemical performance of stabilised materials.

From laboratory bench scale stabilisation trials, mix designs containing 5% CEMI were demonstrated to be satisfactory for deployment at the subject site for materials containing ammoniacal nitrogen up to 1250 mg/kg (CE Geochem Report: A190707 Hornsey Gas Works Addendum Report - Revised LAC) with mix designs incorporating 5% CEMI + 10% GGBS suitable for soils exceeding these values. However, no defined upper treatability window was established during this study. CE Geochem understand that 5% CEMI was designated to be used on site at the time of emplacement for most remedial works, with additional 10% GGBS used for 2 No batches as highlighted in Table 1 below.

The stabilised mass is understood to have been incorporated into earthworks activities centred around the infilling of 2 No. gas holder structures, separately identified within this verification report as illustrated in Figure 1. Validation samples Val-001 – Val-006 represent Area 1 verification specimens, whilst Val-007 – Val-011 represent Area 2. Modelling has been undertaken on each verification sample separately as these represent separate stabilised soil masses placed during filling.

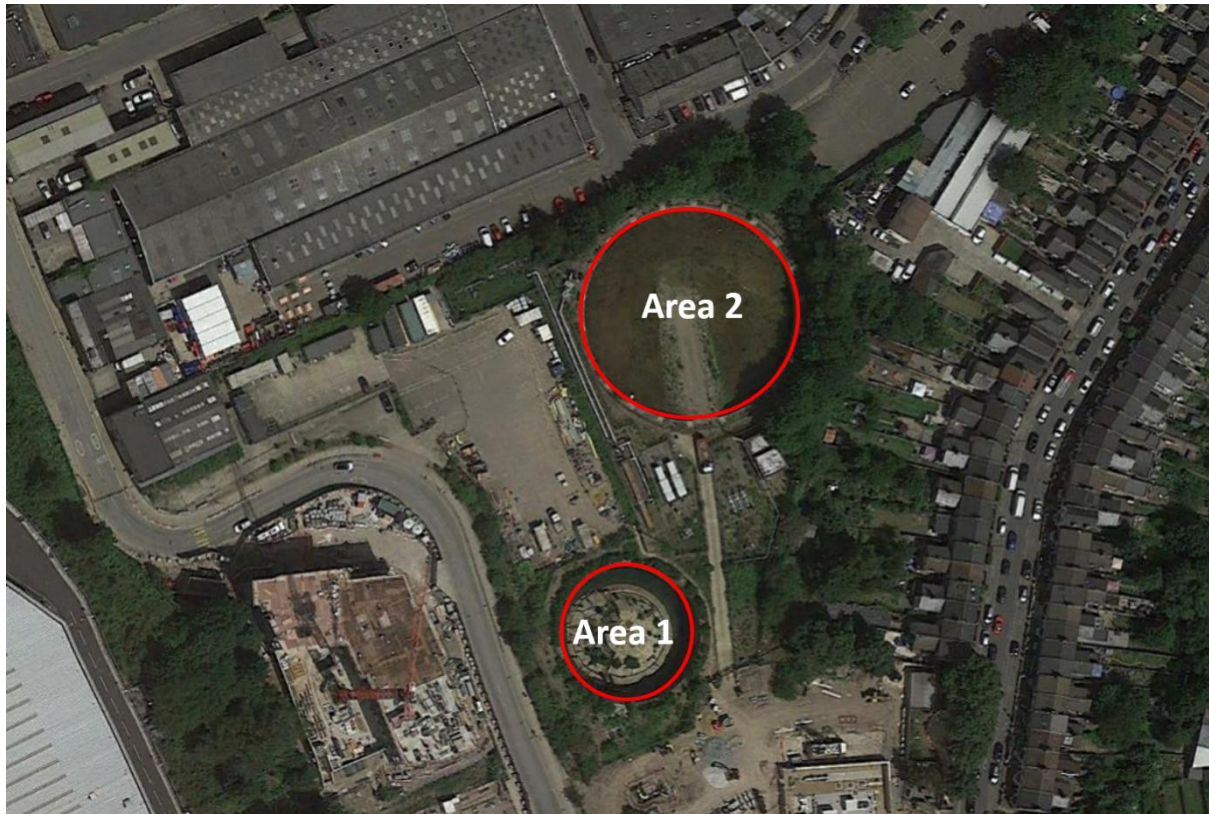


Figure 1. Verification areas as defined by internal walls of pre-existing gas holder structures.

Verification Testing for Geochemical Performance

CE Geochem has undertaken 8 fraction semi-dynamic tank testing on nominal 100 mm cylindrical monolithic specimens (1:1 axial to diametric ratio) manufactured from the as mixed stabilised matrix produced on site. Monoliths were prepared on site by compaction to refusal from homogenised 5 kg sub samples collected from as mixed materials. Details for verification monoliths are presented in Table 1. All verification specimens were cured for a minimum of 14 days prior to commencement of leaching assessments.

Verification semi-dynamic tank tests were conducted using the same sampling intervals as described in the aforementioned report, for a regulatory approved reduced analytical suite focusing on ammoniacal nitrogen and sulphate only. In regard to tank testing procedures, verification leaching methodologies remained consistent with pre-construction phase bench scale stabilisation trials, so allow a direct comparison of remedial compliance against previously determined leaching trajectories.

Sample ID	Sampled Date	Material*	Binder addition	Mass (g)	Diameter (mm)	Height (mm)
Val-001	26/06/2020	Granular	5% CEM I	1624.57	103.93	100.58
Val-002	04/08/2020	Granular	5% CEM I	1775.18	104.41	104.36
Val-003	07/08/2020	Clay	5% CEM I	1649.50	102.90	101.77
Val-004	07/08/2020	Clay	5% CEM I	1623.98	103.72	101.69
Val-005	01/09/2020	Granular	5% CEM I & 10% GGBS	1456.61	103.38	97.41
Val-006	01/09/2020	Granular	5% CEM I	1621.89	102.89	101.57
Val-007	10/09/2020	Granular	5% CEM I	1636.00	103.68	101.29
Val-008	10/09/2020	Clay	5% CEM I	1691.50	104.27	103.52
Val-009	10/09/2020	Clay	5% CEM I	1635.50	104.06	101.43
Val-010	10/09/2020	Clay	5% CEM I & 10% GGBS	1705.00	103.71	107.58
Val-011	10/09/2020	Granular	5% CEM I	1665.50	103.54	99.45

Table 1. Verification specimens. *Material as described on site by client

Source Term Characterisation

Source term characterisation samples were obtained from each of the homogenised bulk samples taken at each verification sampling location. Sub-samples were formed by compositing 5 No. increment samples randomly selected from 5 kg homogenised soil used for the manufacture verification monoliths. Summary source term analysis is presented in Table 2 below. All verification samples demonstrated similar textural and contaminant composition to those investigated during the bench scale trials with ammonium concentrations comparable to TP517, TP517 2.2m and TP514. Sulphate concentrations for validation samples was reported higher than during bench scale trials for all samples (with the exception of Val-005 and Val-007).

Asbestos was reported for Val-002 and Val-003 with identification as Amosite within both samples reported at 0.085 wt. % and 0.026 wt.% respectively

Certificates of Analysis for source characterisation samples are presented in Appendix A.

Determinand	Units	LOD	Sample ID										
			Val 001 ST	Val 002 ST	Val 003 ST	Val 004 ST	Val 005 ST	Val 006 ST	Val 007 ST	Val 008 ST	Val 009 ST	Val 010 ST	Val 011 ST
ACM Type		N/A	-	Free Fibres, Insulation	Fibres/Clumps	-	-	-	-	-	-	-	-
Asbestos Identification	%	0.001	N.A.D	Amosite	Amosite	N.A.D	N.A.D	N.A.D	N.A.D	N.A.D	N.A.D	N.A.D	N.A.D
ACM Detection Stage		N/A	-	Screen Visible by Eye	Stereo Microscopy	-	-	-	-	-	-	-	-
Asbestos by Gravimetry	%	0.001	-	0.085	0.026	-	-	-	-	-	-	-	-
Total Asbestos	%	0.001	-	0.085	0.026	-	-	-	-	-	-	-	-
Moisture	%	0.02	13	8.2	20	14	14	14	12	17	13	13	10
Chloride (Water Soluble)	g/l	0.01	0.92	0.44	0.16	1.0	1.4	0.3	0.13	0.28	0.69	0.60	0.15
Sulphate (2:1 Water Soluble) as SO ₄	g/l	0.01	4.6	2.4	2.4	6.60	0.01	2.10	0.01	2.6	4.0	3.2	4.0
Calcium	mg/kg	100	75000	43000	34000	65000	74000	32000	45000	73000	54000	57000	63000
Sodium	mg/kg	10	610	350	430	590	800	470	420	530	520	680	520
Ammonium (Extractable)	mg/kg	0.5	15	120	63	37	0.5	43	26	14	38	22	47

Table 2. Summary of source term concentrations for verification monoliths. Data presented to 2 significant figures. (N.A.D – No Asbestos Detected)

Semi-dynamic Verification Tank Tests

Analytical datasets from verification semi-dynamic tank tests are enclosed in Appendix A. The geochemical performance of stabilised materials has been assessed using the site-specific Technology Verification Model (TVM) described below. The leaching trajectory of verification specimens is assessed as minimum, maximum and average diffusivity coefficients and compared with the predicted mass flux and interfacial pore water concentrations modelled using the experimentally derived effective diffusion coefficients (D_e) from design phase laboratory stabilisation trials. Corresponding source term contaminant mass is based on concentrations as presented in Table 2.

Verification semi-dynamic tank test leachates were analysed for the following reduced suite of compounds as advised by Keltbray Remediation. All compounds were reported above analytical LOD in at least one or more of the 8 No. leaching fractions.

- Chloride*
- Sulphate
- Sodium*
- Ammonium
- Calcium*

*Not considered a contaminant of concern, used only to assess matrix stability.

Technology Verification Model

The TVM used to assess the leaching potential from stabilised materials over time is enclosed as an interactive Excel™ model in Appendix B.

The TVM model prepared for the subject site has been developed on the same technical basis as the pore water diffusion model presented in CE Geochem Report A190707 section 7. The model does not account for attenuation processes (dispersion, degradation or retardation) that are likely to occur during transport within the vadose zone. Specifically, the model calculates the average porewater concentration of contaminants adjacent to the monolith surface (interfacial zone). In addition, the model makes the conservative assumption that the entire geometric surface area will behave as an active diffusive flux boundary.

Briefly, the TVM is based on comparing predicted maximum, minimum and average mass flux derived from the effective diffusion coefficient (D_e) determined from verification leaching assessments for 2 No. verification areas as discussed above. Diffusive flux modelling is based on the numerical framework presented in USEPA 1315, which is consistent with EA NEN 7375, whereby contaminant release is expressed as mass released per unit area with respect to a defined time interval. This approach provides mass flux rate estimates in mg/m^2 from the following equation;

$$U_{diff} = 2\rho AC_o \bullet \sqrt{\frac{D_e t}{\pi}}$$

In the above equation C_o is the source term concentration of the contaminant (mg/kg), D_e is the minimum, maximum or average effective diffusion coefficient (m^2/s), t is the duration of the leaching event (s), A is the surface area of the monolith (m^2), ρ is the density of the monolith (kg/m^3).

The above equation allows direct parameterisation for site specific applications taking into consideration a scale correction factor to correct for the difference between leachant volume

: monolith surface area conditions used in laboratory leaching assessments and contact infiltration volume : monolith surface areas at the subject site.

The mass transfer model is based on deriving absolute mass leaching rates (mg/m^2) using verification *De* discussed above. These are subsequently dimensionalised to the site-specific geometric surface area of the stabilised monolith. We have based simulations on a rectilinear stabilised source area with dimensions for each specific verification sample provided by Keltbray following emplacement on site.

The absolute mass flux, in terms of total contaminant mass leached per unit time, is then diluted by the interfacial pore water exchange volume, in order to calculate a pore water leachate concentration, ignoring any solubility control.

The pore water flushing rates are derived for the interfacial exchange volume (zone next to the monolith where diffusive flux will influence pore water concentrations). The interfacial exchange pore volume has been calculated from the monolith surface area (m^2) x the interfacial zone thickness (m) x porosity. Infiltration rates are used to define a time step for one pore water flushing event, allowing discretisation of the model in time. The interfacial zone thickness has been assumed to be 0.1m in accordance with sensitivity analysis undertaken as part of the bench scale trials modelling assessment.

Consistent with the original CDM, the Dilution Attenuation Factor (DAF) has been set to unity ($\text{DAF}=1$) for direct comparison with Leachate Acceptance Criteria (LAC) generated by Atkins.

Parameter	Value	Unit	Source
Infiltration Rate	0.7	m/yr.	Atkins Appendix B1
Effective Infiltration Rate	0.7	m/yr.	Atkins Appendix B1
Effective Diffusion Coefficients	Contaminant Specific	m^2/sec	Derived from this study
Monolith Dimensions	Verification Sample Specific	m	Provided by Keltbray Remediation Ltd
Monolith Surface Area	Verification Sample Specific	m^2	Computed from dimensions
Porosity	0.33		Assumed
Density	1.900	Mg/m^3	Average Bulk density from UCS
Interfacial Exchange Zone	0.1	m	Assumed
Source Concentrations	Contaminant Specific	mg/kg	Derived from test work samples used in this study

Table 3. Hydrogeological model parameters used to define the TVM.

TVM Interpretation

The TVM is configured to allow direct comparison of mass leaching trajectories and estimated time averaged ground water concentrations below the source area. We provide here a summary of modelling outputs for the main potential CoCs determined above the limits of analytical detection for verification areas 1 and 2, with each verification sample modelled independently to represent an individual stabilised mass.

Previous modelling studies presented in sections 6 and 7 of CE Geochem Report A190707 and subsequent addendum reports, demonstrated that site soils, stabilised using 5% CEMI or 5% CEMI + 10%GGBS, are unlikely to present a risk to controlled waters.

Determinand	Area 1 Verification Specimens - De parameters					
	Val 001 ST	Val 002 ST	Val 003 ST	Val 004 ST	Val 005 ST	Val 006 ST
SO ₄	3.43E-14	8.46E-12	1.34E-12	1.39E-13	2.79E-08	1.07E-12
NH ₄	3.16E-10	3.61E-14	8.33E-13	2.09E-14	6.50E-11	6.98E-15

Determinand	Area 2 Verification Specimens - De parameters				
	Val 007 ST	Val 008 ST	Val 009 ST	Val 010 ST	Val 011 ST
SO ₄	1.36E-08	1.19E-15	5.10E-15	5.04E-15	9.01E-13
NH ₄	2.59E-14	6.81E-14	1.83E-14	2.81E-14	6.99E-15

Table 4. Table of derived De parameters for each verification specimen for Areas 1 and 2.

Table 4, presented above, shows the De parameters derived from verification leaching assessments (Appendix B). TVM modelling assesses each verification sample independently against derived source characterisation datasets and the provided monolithic dimensions.

Satisfactory average pore water concentrations are predicted for ammonium when modelled against Atkins leachate acceptance criteria (LAC) as demonstrated in Figure 3 for validation specimens Val-002 – Val-011. Minor exceedances are predicted for Val-001. However, these exceedances are predicted to show compliance with the LAC following 0.02 years (8 Days) following installation with no long term threat to controlled waters.

Many of the verification leaching datasets demonstrate deletional mass transfer behaviour for ammoniacal nitrogen. For example, closer inspection of the linearisation plot for the ammoniacal nitrogen release from Val-001, shown in Figure 2 (representing the maximum ammonium line in the TVM), indicates an initial high mass transfer rate for ammoniacal nitrogen through fractions 1-4 followed by the characteristic plateau that accompanies a depletion based leaching mechanism. The mass transfer reported for the final 2 fractions is below the limits of analytical detection.

Under a precautionary approach, De parameters are calculated from the steepest gradient of the linearization plot (F1-5) and therefore assume maximum flux rates. In the case of Val-001 and other specimens showing similar leaching trajectories, this approach leads to very conservative estimates of mass flux for this compound. In general the release of ammoniacal nitrogen will be short-lived due to source term depletion. Long term risk to controlled waters are deemed highly unlikely under this scenario.

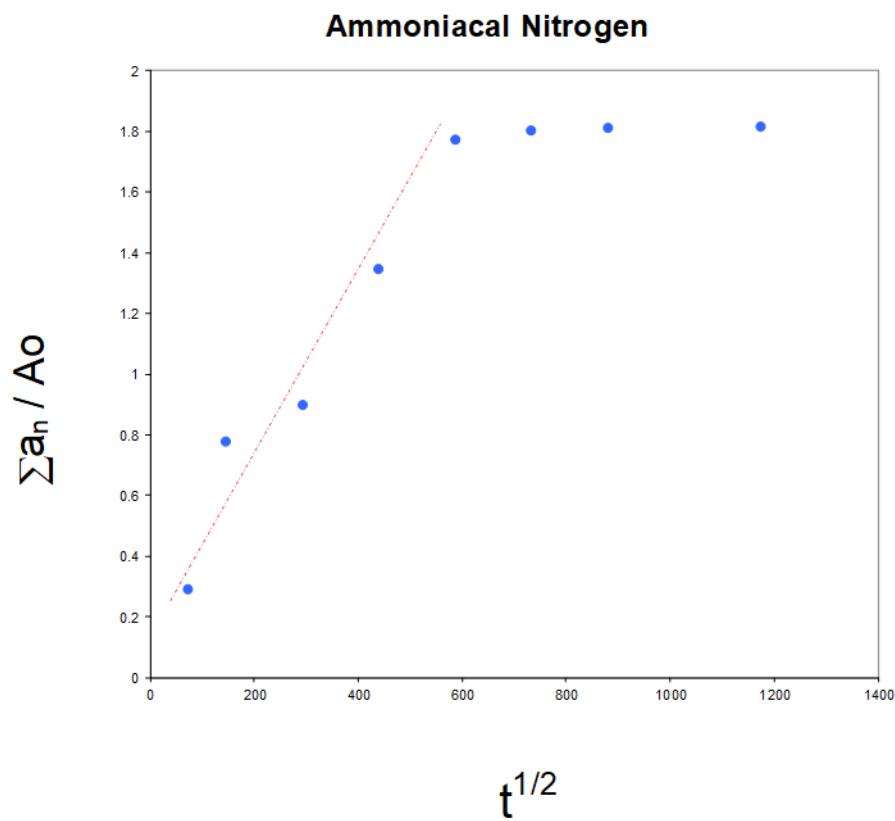
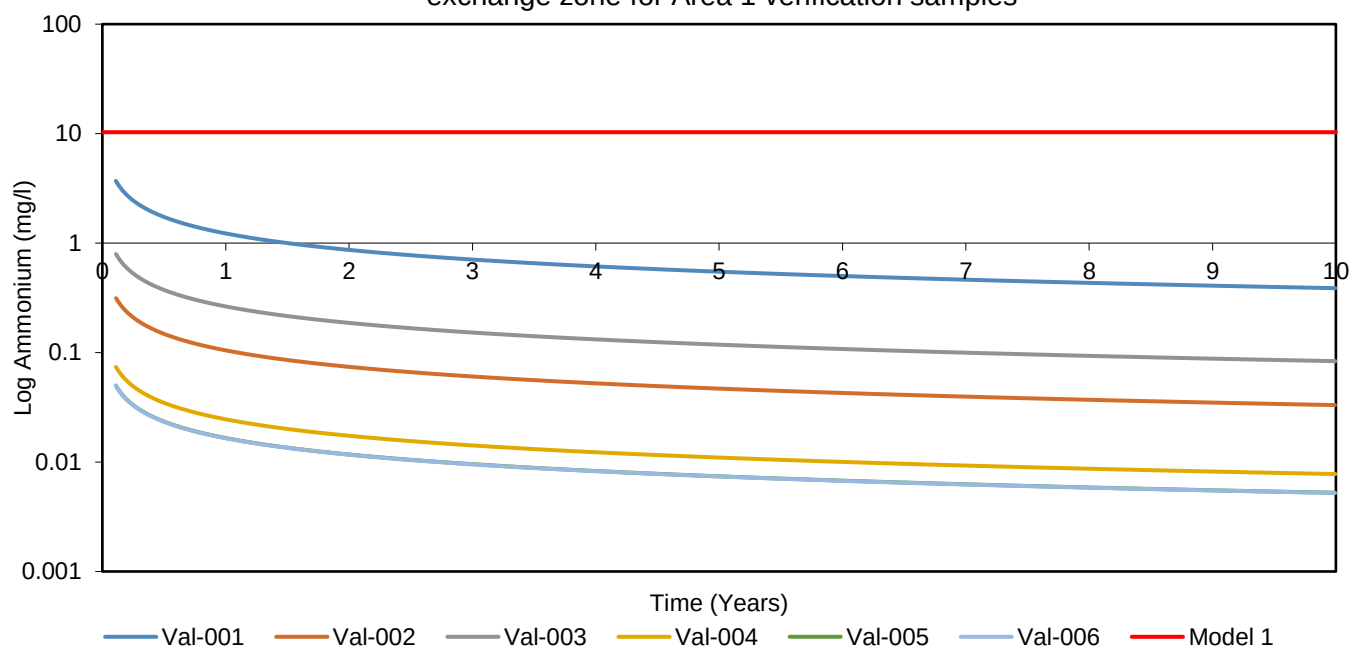


Figure 2. Linearization Plot for ammoniacal nitrogen flux from Val-001 demonstrating a depletion-based leaching mechanism.

Predicted Pore water Concentrations of Ammonium (mg/l) within the interfacial exchange zone for Area 1 verification samples



Predicted Pore water Concentrations of Ammonium (mg/l) within the interfacial exchange zone for Area 2 verification samples

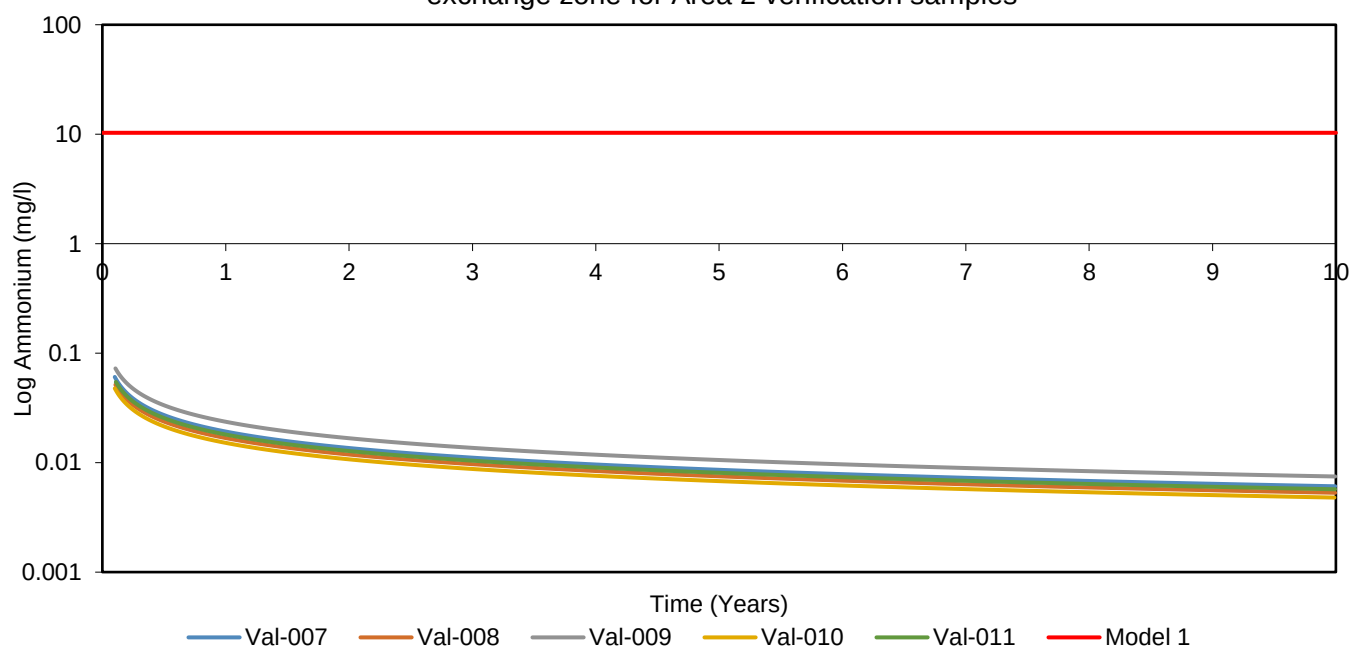


Figure 3. Predicted pore water concentrations of ammonium for each verification specimen split into Area 1 (top) and Area 2 (bottom).

De parameters used to predict pore water concentrations for sulphate show compliance against LAC as presented in Figure 4 below for all verification samples investigated. No exceedances are predicted for either validation area.

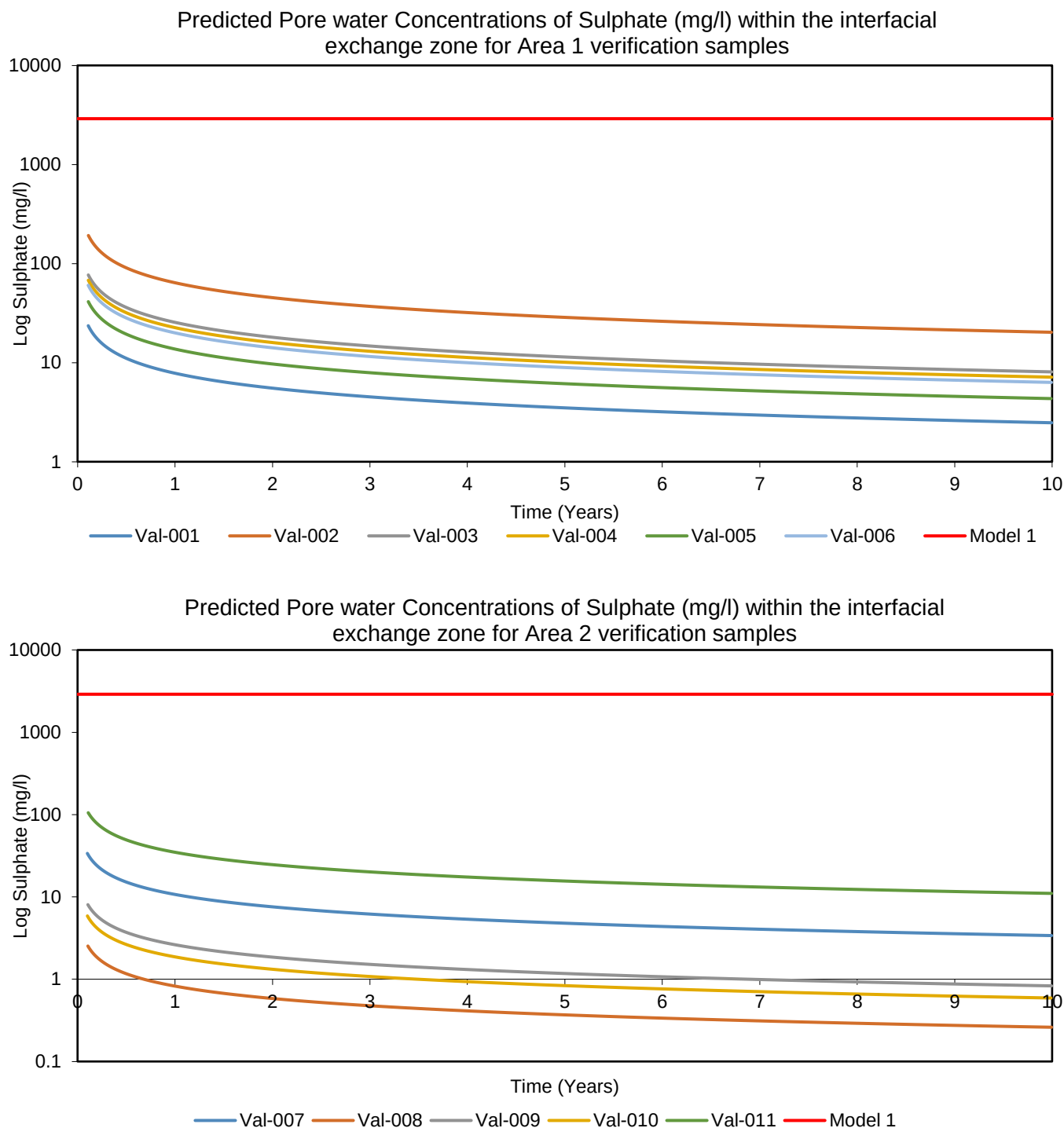


Figure 4. Predicted pore water concentrations of sulphate for each verification specimen split into Area 1 (top) and Area 2 (bottom).

CE Geochem conclude that, based on the use of De parameters generated from verification specimens, stabilisation works conducted at the subject site have achieved the key remedial objectives for the main contaminants of concern for both stabilised source areas.

Geotechnical Validation

CBR Swell analysis was conducted in general accordance with BS 1377-4 / BS EN 13286 - Part 47 on 150mm x 120mm monoliths produced from as-mixed stabilised soils. CBR swell results confirm that materials are not susceptible to swelling with no significant volumetric expansion observed. CBR analysis undertaken following a 28-day immersion period generated CBR values ranging from 20 – 172%, typically exceeding a CBR value of 64% with only Val-003 and Val-004 reporting lower CBR values of 20% and 42% respectively.

Terminal CBR for Val-003 is reported as 20% CBR. CE Geochem attribute this result to the elevated moisture content for this sample (reported as 20% on ST analysis). Elevated MC for this sample is attributed to the clayey nature of materials and dust suppression operations conducted on site (mist cannons and jet washes) to ensure air quality standards were maintained.

Sample ID	Material*	CBR Index (%)	Vertical Swell (mm)	Volumetric Swell (%)
Val-001	Granular	100	0.02	0.013
Val-002	Granular	172	0.69	0.454
Val-003	Clay	20	0.88	0.579
Val-004	Clay	42	0.29	0.191
Val-005	Granular	117	0.06	0.039
Val-006	Granular	64	0.11	0.072
Val-007	Granular	140	0.06	0.039
Val-008	Clay	94	0.05	0.033
Val-009	Clay	110	0.05	0.033
Val-010	Clay	100	0.01	0.007
Val-011	Granular	140	0.33	0.217

Table 5. CBR Swell Analysis for 2 No. Verification samples. *Material as described on site by client.

BRE-SD1 analysis was completed on each of the verification samples (with the exception of Val-001) to identify potential risk of sulphate attack. All verification samples showed elevated TPS levels, significantly exceeding the HA 74/07 threshold of 0.25%. Therefore, materials present on site would be classified as potentially producing very aggressive ground conditions. However, it should be noted that no evidence of adverse binder phase reactions such as Delayed Ettringite Formation (DEF) or Thaumasite Sulphate Attack (TSA) were identified for any verification CBR Swell tests.

	BRE-SD1 Assessment - Verification Specimens										
	VAL-001	VAL-002	VAL-003	VAL-004	VAL-005	VAL-006	VAL-007	VAL-008	VAL-009	VAL-010	VAL-011
TPS (%)	-	12.90	12.30	12.30	12.00	3.60	4.50	1.95	4.80	2.91	6.90
WSS (mg/l)	-	2000	1700	1700	9300	1900	1500	2600	3500	2500	1500
ASS (%)	-	7.30	5.80	5.80	5.50	2.90	1.90	0.62	1.10	0.56	2.20
OS (%)	-	5.60	6.50	6.50	6.50	0.70	2.60	1.33	3.70	2.35	4.70

Table 6. BRE-SD1 for verification samples. TPS = Total Potential Sulphate; WSS = Water Soluble Sulphate (2:1 as SO₄); ASS = Acid Soluble Sulphate; OS = Oxidisable Sulphates.

UCS determinations were undertaken for each of the 11 No. verification specimens manufactured as 100mm monoliths at axial : diametric ratio = 1, cured at 95%+ RH for curing

times (t) = 7, 14, and 28 Days. UCS determinations were generally found to plateau for all of the verification specimens investigated at 7 days with the exception of Val-003 and Val-005.

Val-003 showed a sharp increase in strength following the 14-day analysis with an 800% increase from 0.25 MPa to 2 MPa. CE Geochem would suggest that the terminal 28-day UCS testing result is anomalous, with VAL-003 also previously reporting the lowest terminal CBR index.

Val-005 showed an inconsistent set of results over the 3 curing periods. Although this specimen included GGBS and thus latent strength gain would be expected, the disparity between the UCS determinations for the time points is significant and therefore we would suggest that these verification samples should be excluded from any geotechnical assessments.

All geotechnical control and validation testing certificates are presented in Appendix C.

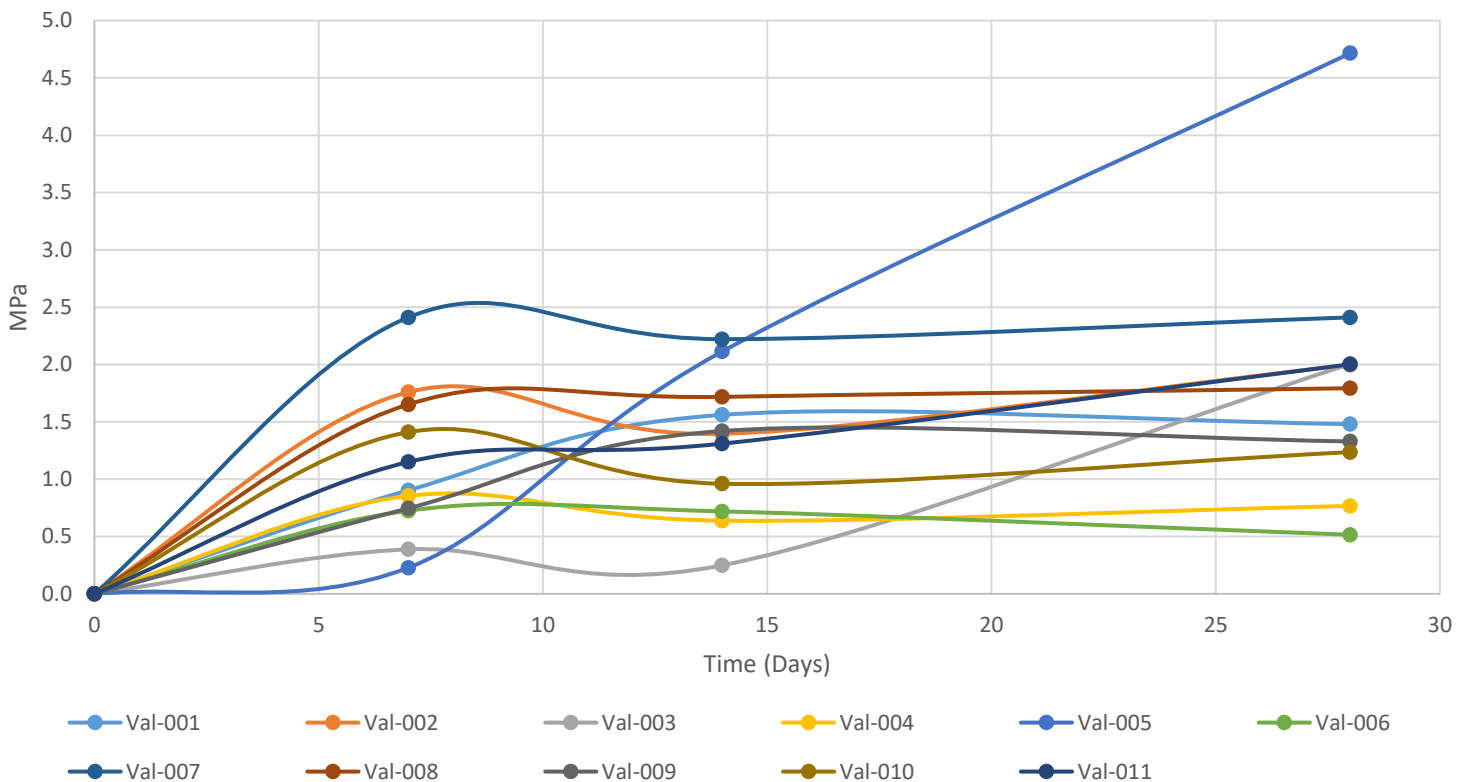


Figure 5: UCS Strength Gain Curves for 5 No. validation sample areas

Conclusions

CE Geochem provide the enclosed TVM for the purpose of assessing site specific environmental compliance against regulatory approved groundwater remedial target values, which may include additional attenuation processes not covered within this TVM.

In closing, we also wish to draw your attention to the experimental conditions under which the verification leaching trajectories were derived. All tank testing datasets relate to monolithic specimens under constant immersion that are subjected to sequential replenishment with de-ionised water. This latter condition ensures the maximum diffusion gradient is re-established during each tank exchange. In the opinion of CE Geochem, this leads to conservative estimates of mass flux rates. In addition, the TVM presented here assumes all geometric surfaces of the stabilised source area are fully exposed and constantly saturated, a condition that is unlikely to be satisfied by materials placed at the subject site.

We trust that this report will be satisfactory for the purpose of evaluating the remedial performance of stabilisation works. Should you have any queries however, or wish to discuss any of the data or interpretations presented within this report further, please do not hesitate to contact the undersigned.

Yours Sincerely



Dr Jamie Cutting
Environmental Geochemist

For and on behalf of **CE Geochem Ltd.**

Enc.	Appendix A	Certificates of Analysis
	Appendix B	TVM model
	Appendix C	Geotechnical Validation

Report Limitations

CE Geochem Ltd ("CE Geochem") has prepared this document for the sole use of Keltbray Remediation Ltd ("Client") in accordance with the Terms of Reference under which the original services were offered [P190707]. No other warranty, expressed or implied, is made as to the professional advice included in this document or any other services provided by CE Geochem. This document is confidential and may not be disclosed by the Client nor relied upon by any other party without the prior and express written agreement of CE Geochem.

The interpretations and recommendations contained in this Proposal are based upon information generated from samples provided by others. For all intents and purposes, samples are assumed to be representative. CE Geochem have tested samples as instructed, without influence or prejudice on samples selection except where acknowledged.

The methodology adopted and the sources of information used by CE Geochem in providing its services are outlined in the original Proposal [P190707]. The description of work packages described in this Report are based on the information available during the offer period. The scope of the original Proposal and offered services are accordingly factually limited by the availability of factual data and clarifications provided by the client to CE Geochem during the Proposal process.

Where assessments of works or costs identified in this Report are made, such assessments are based upon the information available at the time and where appropriate are subject to further investigations or information which may become available during the performance of scheduled tasks.

CE Geochem disclaim any undertaking or obligation to advise any person of any change in any matter affecting this test work, which may come or be brought to CE Geochem attention after the date of submission of the Final Report.

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Unless otherwise stated in this Report, the assessments made assume that the sites and facilities will continue to be used for their current purpose without significant changes.

Where field sampling has been conducted, CE Geochem have assumed that samples are suitable to meet the stated objectives of the services. The inherent variability of real samples may affect the results of any laboratory test works detailed herein, in such a manner that cannot be resolved using the proposed methodologies. Such variability is beyond the control of CE Geochem and no warranties or assurances are offered or implied, as to appropriateness of results or the applicability of laboratory data to site conditions.

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