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PORE SOLUTION/AGGREGATE ENHANCEMENT OF ALKALIES IN HARDENED CONCRETE

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Aggregate/pore solution interaction has been investigated using selective dissolution of concrete and aggregates by HNO_3 and EDTA. It was found that basalt is both heavily leached by HNO_3 and also interacts with pore solution to significantly increase the alkalies available to enhance AAR. The investigation also showed that leaching of alkalies from concrete during curing and weathering can be significant. The results explain why severe AAR has occurred in some concretes made with low-alkali cement.

INTRODUCTION

The extent to which the alkaline pore solution of hardened concrete interacts with aggregates to enhance the concentration of alkalies derived from the cement has remained an unresolved question. For instance, severe cases of AAR have occurred in New Zealand where there is good evidence to show that low-alkali cement was used in the concrete. These cases raise the question as to whether the aggregates reacted at low alkali levels, contrary to laboratory testing, or whether alkali was supplied to the pore solution of the concrete from sources other than the cement. At the heart of the question is the problem of measuring alkali levels in old concretes because the alkalies Na and K are mobile and especially subject to localised concentration and leaching. Unless these effects can be disentangled and the sources of alkali in a concrete identified, the problem will not be resolved.

The leaching effects of the outer portions of concrete due to weathering are clearly apparent when concretes undergoing AAR are examined in thin-section (1). Where weathering has occurred AAR is invariably absent from the outer 50 - 75 mm of the concrete. On the other hand, around reacting aggregates increased concentrations of alkalies have been measured by electron microprobe analyses (2). Diamond and other workers (3) have carried out numerous analyses of pore solution extracted from concrete and showed the ranges of alkalies, Ca and SO_4 that occur as concrete hardens. The interpretation of the results of these pore solution analyses remains in question (4). Van Aardt and co workers (5) exposed a range of aggregates to saturated $Ca(OH)_2$ solution and showed that clays and feldspars released alkalies. However, their samples were finely ground before reaction with the $Ca(OH)_2$ solution.

Recently, Goguel and St John (6) when investigating the chemical identification of cements in hardened concrete found that alkaline leaching provided some evidence that pore solution/basalt interaction was enhancing the alkalies in the hardened cement paste. This paper describes the ongoing work on old concretes to further define this pore solution/aggregate interaction.

SAMPLES

The two cements used to prepare the experimental mortars and pastes were a low-alkali cement from the Cape Foulwind plant, F9/87, and high-alkali cement from the Tarakohe plant, T-HA date unknown. The compositions of these cements, corrected for loss on ignition, are as follows.

	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	SO_3	Na_2O	K_2O	Mn_2O_3	P_2O_5	I.R.	F.L.
F9/87	20.14	5.84	3.37	0.29	64.34	1.83	2.70	0.78	0.67	0.06	0.13	0.12	1.51
T-HA	21.60	4.29	2.20	0.26	67.53	0.84	2.37	0.22	0.34	0.34	0.13	0.07	1.03

The basalt aggregates used were from Lunn Avenue and East Tamaki, two commercial quarries in the Auckland area.

The mortar and concrete samples investigated are as follows:-

1) Experimental mortars and pastes. (a) 50/50 mixture of basalt crusher dust and quartz sand with F9/87. (b) 50/50 mixture of basalt crusher dust and quartz sand with T-HA. (c) Cement paste with F9/87. (d) Cement paste with T-HA.

2) Pahurehure Inlet bridge, precast box beams from deck, constructed 1964. Cement content 400kg/m^3, W/C = 0.5 approx.

3) Whenuapai Airfield pavement constructed 1963/64. Cement content 330 kg/m^3, W/C = 0.5 approx. (a) Area in which the concrete contains Auckland basalt as coarse aggregate and crusher dust together with Waikato River sand (2T). (b) Area in which the concrete contains Auckland basalt as coarse aggregate and crusher dust together with a marine sand consisting primarily of quartz and feldspars together with minor mafics and shell (1T).

4) 200 x 100 mm, 28 day old test cylinder cured in water, (215A). Cement content 250 kg/m^3.

5) Concrete wall constructed 1983, (6/4). Cement content 350 kg/m^3, W/C = 0.6 approx.

6) 300 x 150 mm compression test cylinder, over 12 months old. Retrieved from discarded test cylinders stored outside.

METHODS

<u>Sample Preparation.</u> The sands used in the experimental mortars were basalt crusher dust of a similar grading to that supplied commercially in the Auckland area and Leighton Buzzard standard graded quartz sand. 12 g of cement were mixed with 60.8 g of sand at a water/cement ratio of 0.6. The dry mortar ingredients were placed in a plastic bag, blended by kneading, the water added and further kneaded until the mortar was well mixed. The bags were heat sealed and stored in the fog room for 56 days at 100% RH and 21 °C. The pastes were mixed similarly at W/C = 0.35.

Aggregate samples for leaching were prepared as follows. 25 mm cores (surface area 0.002 m^2) were diamond drilled from large pieces with ends cut accurately by a diamond saw and two crushed fractions, 0.5 - 1 mm (coarse grains) and 0.063 - 0.125 mm (fine grains) were prepared.

Core samples, 100 mm in diameter, obtained by drilling the structures were thoroughly dried at 105 °C. A 250 g portion taken from the bottom of each core was broken with a steel hammer in a heavy plastic bag and the 0.5 -1 mm fraction collected by sieving. Larger fragments rich in cement were selected from the remaining fragments and further crushed in a percussion mortar to produce sufficient of the 0.5 - 1.0 mm fraction. The aim of the preparation method was to produce particles of the concrete which were rich in cement. This procedure was repeated to produce the 0.063 - 0.125 mm fraction. In addition some 25 mm cores with a surface area of 0.002 m^2 were drilled from the larger core samples. The small cores and crushed fractions of the rocks and concretes were analysed using the method below. In the case of the crushed rock samples 0.25 g samples were leached while in the case of the crushed grains of concrete the sample size was 0.5 g. The 0.25 g rock sample was chosen on the basis that it represented the amount of aggregate present in the experimental mortars.

Leaching. The cores and the crushed fractions were shaken in a 50 ml polypropylene centrifuge tube for 1 hour, in 35 g of leaching solution of either 1M HNO_3 or 0.2M NH_4EDTA at pH 7-8 or NH_4-EDTA-triethanolamine at pH 10 or Li-EDTA-triethanolamine at pH 12.7. The solution was separated by centrifuging for 10 minutes at 3000 rpm and the clear liquid decanted and analysed without dilution. Seven elements were determined on the leachates of the experimental mortars and pastes, rocks and concrete samples. Sequential analyses were performed to determine Al, and SiO_2 by AA, Na, K, Rb and Ca by AE and Sr by ICP-AE. All elements were determined directly on the final solutions using standards that contained identical matrices of Ca, Si, Al and Na as well as matched anion concentrations.

RESULTS

The results of leaching Lunn Avenue basalt at pH 0 and pH 7-8 are given in Table 1. These are compared to analyses of experimental mortar samples 1a and 1b and pastes 1c and 1d in Tables 2 & 3. Results of alkaline leaching of samples from concrete structures and test cylinders are listed in Table 4. Data from cement analyses made during the period of construction of these structures and the contribution of basalt and rhyolite to the leaching solutions have been included in Table 4 to allow the extent of the pore solution/aggregate reaction to be estimated. Finally, the effects of leaching some common New Zealand aggregates under a range of conditions are tabulated in Table 5. Comparison of acid leaching of basalt without added Ca (results not given) showed that exchange of Na for Ca is comparatively minor.

TABLE 1 - Concentrations in solution (mg/kg) from leaching 0.25g fractions of Lunn Avenue basalt crusher dust <0.6mm, in 35 ml of either 0.2M NH_4-EDTA or 1 M HNO_3

pH	Time of leach (mins.)	Na	K	Rb	Ca	Sr	Al	SiO_2
7-8	60	0.34	0.77	0.0019	1480	0.032	0.13	1
0	60	113	31.9	0.109	1580	0.218	128	431

DISCUSSION

In contrast to concretes, experimental mortars represent a closed system as they were mixed and cured in sealed plastic bags. When they are leached with EDTA at pH 7-8 for 60 minutes the results given in the last two rows of Table 2 are obtained. When these are compared with the sum of the results of leaching pastes made from the same cements and separate leaching of the basalt aggregate as shown in Table 1 it is seen that in the 56 days of curing there has been a discernable contribution of Na made to the pore solution from the basalt aggregate.

TABLE 2 - Concentrations (mg/kg) from EDTA leaching (pH = 7-8, leaching time = 60 minutes) of Mortars 1a and 1b compared with contributions from cements and leaching of the aggregates.

Concentrations from EDTA leaching of pastes 1c (cement F) and 1d (cement T).					
Cement	Na	K	Rb	Ca	Sr
F	3.76	6.02	0.026	1076	0.821
T	12.3	11.3	0.044	1000	1.76
Sum of concentrations from pastes 1c and 1d and separate EDTA leaching of basalt aggregate (see table 1)					
F	4.1	6.8	0.028		0.853
T	12.6	12.1	0.046		1.79
Concentrations from EDTA leaching of Mortars 1a (cement F) and 1b (cement T) containing quartz and basalt aggregate.					
F	6.5	6.8	0.026	998	0.82
T	14.3	11.7	0.044	958	1.55

Although the leaching time of 60 minutes is not long enough to dissolve all the hardened cement paste, Na exceeds the expected levels derived from the cement pastes and any contribution from leaching the basalt aggregate. Calcium is a measure of the degree of dissolution achieved and the level of K is as expected. Al and SiO_2 are only partially dissolved from the mortar at pH 7-8. This shows that some migration of material from the basalt to the pore solution and the hardened cement paste of the mortars has occurred within the 56 days of curing.

Tables 1 and 5 show that significant amounts of alkali, mainly as Na, are released from basalt when leached with 1 M HNO_3 and this will prevent meaningful determination of alkalies in an acid leach of concrete containing basalt. However, Na, Al and Si tend to reflect their levels found in the basalt and should provide useful information on the availability of these elements for aggregate/pore solution reaction. The results of leaching experimental mortars 1a and 1b with 1 M HNO_3 minus the concentrations due to leaching the cement pastes at pH 7-8 are given in Table 3. When these results are compared with the acid leaching of the basalt in Table 1 it seen that unlike the EDTA leaches of the basalt all the constituent values obtained are low. While the reasons for this are still under investigation, if the values are scaled to K it is found that Al and SiO_2 are similar but Na is low. That is, dissolution with 1 M HNO_3, unlike alkaline EDTA, has apparently failed to detect any aggregate/pore solution interaction. This conclusion appears to be valid as similar results have been found when leaching concretes from structures.

TABLE 3 - Contribution from aggregate estimated from concentrations (mg/kg) from leaching Mortars 1a and 1b with 1 M HNO_3 for 60 minutes minus the contributions from the cements.

Mortar	Na	K	Rb	Ca	Sr	Al	SiO_2
1b	82	33.9	0.100	1150	1.00	167	890
1a	93	40.1	0.141	1050	1.85	183	830
The concentrations from leaching the Mortars minus the concentrations from the cements.							
1b - F	78	27.9	0.074	75	0.18	111	407
1a - T	81	28.8	0.097	50	0.05	113	370

The reason for this apparent failure lies in the less discriminating nature of attack by 1 M HNO_3. While alkaline EDTA essentially attacks only the hardened cement paste, 1M HNO_3 dissolves phases from both basalt and cement paste. The portion of the basalt most likely to be attacked by both acid and alkaline pore solution is its glassy matrix. It is rapidly dissolved in HNO_3 but only very slowly in alkaline EDTA solution. However, aggregate/pore solution interaction in old concretes has had sufficient time to mobilise aggregate constituents so that they rapidly dissolve in slightly alkaline EDTA solution. Acid leaching is far too aggressive to reflect these changes but may provide an excellent indicator of the potential for a non calcareous aggregate to interact with pore solution. Acid leaching of the New Zealand acid/intermediate rock types, including the Waikato river sands, indicates they should not make significant contributions to the pore solution of a concrete as shown in Table 5. This is a significant finding and has considerable potential for the determination of aggregate/pore solution interaction in hardened concrete. It provides a method for investigating whether aggregates have contributed alkali to the pore solution in a concrete to enhance alkali-aggregate reaction.

Investigation of the concrete structures was complicated because they contain both basalt aggregate and other sands such as marine derived quartz rich materials or alluvial sand from the Waikato River consisting of a mixture of predominantly rhyolite and intermediate volcanic rock types. It is further complicated by the use of geologically similar basalts from a range of quarries which show some variation in the amount of acid leaching they undergo. Variation in the leachability of aggregates as well as the chemical composition of cements can cause problems in interpretation of results especially if the chemistry of these materials is not known.

The results for acid leaching show that in all the old concretes, Na is depleted relative to Al. There are a number of possible reasons for this depletion of alkalies relative to Al. The most obvious cause is leaching due to weathering. The younger test specimens generally show little leaching as would be expected for 28 day old concretes even though as will be shown later water curing can remove considerable alkali. In spite of deep sampling from the older concretes it is difficult to guarantee that some leaching has not occurred. In the case of samples 3a and 3b from the Whenuapai, the pavement is only 200 mm thick and is isolated from the ground by a mastic coated tidy slab. It is probable that some leaching and diffusion of alkalies has occurred throughout the depth of the slab. Leaching of alkalies can occur during sampling. The small cylinders, sampled to provide a defined surface area were wet cored and washed to remove surface dust just prior to acid leaching. These showed greater alkali depletion than the crushed fractions of concrete. This type of effect must apply to all wet sampling methods.

The contribution of Al and SiO_2 together with Na and K is the most striking effect of long term aggregate/pore solution interaction as shown by leaching with EDTA solution at pH 12.7. This effect is illustrated in Table 4 where the concentrations of the selected major constituents extracted under alkaline conditions are now presented as percentages of their oxides. In all cases, observed Al_2O_3 + SiO_2 exceed the combined contributions from the cement and the aggregate. While some increases may be close to experimental error, other increases are substantial which indicates considerable variation in the interaction of the basalts with the pore solutions.

The concentration of Na_2O in the samples from the three structures investigated has been increased by 50 - 300% due to basalt/pore solution interaction. It could be argued that these increases are due to release of Na_2O from the rhyolite in the sand by alkali-aggregate reaction but in the case of sample 3b this is not possible as no acid/intermediate volcanic aggregates are present in this portion of the pavement and AAR is absent. The Whenuapai pavement was built as two separate contracts and while both portions contain basalt, (not necessarily from the same quarry), and the same brand of cement, the sands are different as indicated in Table 4. The increases for K_2O are less and vary from an increase of 0 - 100%. These lower figures are consistent with the acid leaching of the basalts where the amount of K leached is only 15-30% of Na indicating that much smaller amounts of K are available for aggregate/pore solution interaction.

The results for the tests cylinders are of considerable interest. Sample 4 (215A) appears to contain an anomalously low concentration of K_2O even though the alumina and silica levels are consistent. It is known that cement P was produced with K_2O averaging 0.5% during the period of construction. However, this 28 day old test sample was cured in water and leaching of the alkalies will occur. It is simplistic to assume that there has been no leaching of Na_2O. Na leaching appears to be offset by the compensating effect of Na mobilisation from the basalt. These two competing effects lead to the coincidence of the Na_2O results with the comparison cement. The effect of alkali leaching is obvious for K because only relatively small concentrations can be mobilised from the basalt.

TABLE 4 - Concentrations (%) of selected major constituents leached from concrete under conditions specified compared with expected values from some cements and aggregates.

Structure or sample	Cem	Aggregate	Sample	Fraction leached (mm)	pH of EDTA leach	Na_2O	K_2O	Al_2O_3	SiO_2
East Tamaki basalt		Basalt		.063-.125	12.7	0.04	0.02	0.07	0.28
" " "		Basalt		.063-.125	7-8	0.02	0.02		
Lunn Av basalt		Basalt	-----	.063-.125	7-8	0.05	0.09	0.02	0.1
Rhyolite		Volc		.063-.125	12.7	0.02	0.02	0.04	0.19
" " "		Volc		.063-.125	7-8	0.01	0.02	-	-
Pahurehure Bridge	F	Bas/volc	2	0.5 - 1	12.7	0.88	0.61	5.36	23.7
" " "	F	Bas/volc	2	.063-.125	12.7	0.94	0.66	5.71	24.3
" " "	F	Bas/volc	2	0.5 - 1	7-8	0.90	0.70		
Comparison cements	F-/64	-------	2	---------	-----	0.30 0.34	0.53 0.58	4.7 5.0	21.6 22.4
Whenuapai 1T	P	Bas/qtz	3b	0.5 - 1	10	1.20	0.77		
" " "	P	Bas/qtz	3b	0.5 - 1	12.7	0.97	0.51	6.47	28.4
Whenuapai 2T	P	Bas/volc	3a	0.5 - 1	10	0.72	0.77		
" " "	P	Bas/volc	3a	.063-.125	12.7	0.45	0.40	8.80	34.3
Comparison cements	P 63-64	--------	3	-------	-----	0.12 0.23	0.22 0.29	3.8 4.5	23.4 24.4
Sample 6/4	P	Bas/volc	5	.063-.125	12.7	0.69	0.42	8.29	33.7
Comparison cements	P 83-84	--------	5	--------	-----	0.15 0.26	0.40 0.52	3.88 3.88	22.5 23.1
Test cyl. 215A	P	Bas/volc	4	0.5 - 1	10	0.20	0.28		
" " "	P	Bas/volc	4	0.5 - 1	12.7	0.21	0.24	4.63	24.1
Comparison cement	P 10/88	--------	4	---------	-----	0.20	0.50	4.00	23.3
Test cyl.	B	Phonolite	6	0.5 - 1	10	0.044	0.025		
" " "	B	Phonolite	6	.063-.125	12.7	0.029	0.016	5.73	22.4
Comparison cements	B-/88	--------	6	--------	-----	0.17 0.21	0.38 0.46	4.67 5.12	20.9 22.1

The effects of leaching are clearly present in sample 6. This unused compression test cylinder has been exposed to the weather for over a year. The dramatic reduction in alkalies is due to weathering and indicates the extent of leaching that may occur. In this case, the 300 x 150 mm dimensions were insufficient to prevent leaching of alkalies from much of the sample although the depth of carbonation did not exceed 5-10 mm.

The results given in Table 4 explain why a portion of the Whenuapai pavement has undergone serious alkali-aggregate reaction though the cement only contributed 1 kg/m^3 of alkali to the concrete. Basalt/pore solution interaction effectively contributed sufficient alkali to ensure reaction with the reactive volcanic sands present. Large amounts of alkali have also been contributed by the basalt in the unreacted portion of the pavement. However, in this portion the sand is unreactive irrespective of the alkali level in the concrete.

The question must be raised as to why condition surveys in the Auckland area have only identified a small percentage of structures which are undergoing alkali-aggregate reaction when the combination of basalt coarse aggregate, basalt crusher dust and reactive volcanic sand from the Waikato river has been extensively used as concrete aggregate. Undoubtedly leaching effects due to weathering have played an important role as the structures are well washed by rain throughout the year. Then there is the possibility that some Auckland basalts, not yet investigated, may be less interactive with pore solution. However, most structures in the Auckland area undergoing alkali-aggregate reaction contain cement contents in the range of 300-400 kg/m^3 and this suggests that a high pH in the pore solution may be a prerequisite for significant basalt/pore solution interaction. These are matters that require investigation.

CONCLUSIONS

1. Leaching of concretes with EDTA at pH 12.7 allows estimation of Na, K, Ca, Al and SiO_2 and shows that where basalt is present, Na_2O and K_2O are contributed from the basalt by basalt/pore solution interaction. Other important contributions are found for SiO_2 and to a lesser extent Al_2O_3.

2. While the basalt/pore solution interaction was apparent from leaching with alkaline EDTA, leaching with 1 M HNO_3 did not show this effect. Because 1 M HNO_3 attacks both the glassy matrix of the basalt and the hardened cement paste it cannot be used to measure basalt/pore solution interaction. The extent of aggregate leaching by 1 M HNO_3 may be a good indicator of the potential leachability of the aggregate by pore solution.

3. Leaching of alkalies by weathering is significant and indicates that unless concrete is sampled from depths not subject to weathering, the true extent of the alkalies present in the concrete cannot be estimated. This applies even where aggregate/pore solution interaction is essentially absent. Both Al_2O_3 and SiO_2 appear to be unaffected by weathering.

4. The results provide an explanation as to why some concrete structures containing low-alkali cement have undergone alkali-aggregate reaction with sands containing reactive rhyolite and andesite. Basalt/pore water interaction has effectively increased the alkalies, especially Na_2O, so that in effect alkali concentrations in the pore solution can exceed the levels obtained from a high-alkali cement.

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TABLE 5 - Contributions (mg/kg leachate) of leaching 0.25g of rock with 35g of solution.

	Core	0.5-1	<0.125	Core	0.5-1	<0.125	Core	0.5-1	<0.125	Core	0.5-1	<0.125	Core	0.5-1	<0.125	Core	0.5-1	<0.125	Core	0.5-1	<0.125
Rhyolite Total		176			238			1.0			38			0.36			475			5570*	
2 pH 0	0.67	0.38	1.23	1.78	0.86	1.64	0.0082	0.0074	0.0013	1.6	2.3	3.0	0.015	0.016	0.019	2.55	1.80	3.79	2.9	2.3	8.0
pH 7-8	0.82	0.20	0.75	3.45	0.63	1.18	0.0190	0.0050	0.0090	1.66	2.11	2.55	0.018	0.016	0.019	0.60	0.10	0.20	2.2	<1	<1
pH 10	-	0.18	0.68	-	0.72	1.38	-	-	-	-	1.90	2.38	-	0.015	0.020	-	0.17	0.89	-	<1	1
pH 12.7	-	0.21	0.80	-	0.45	1.33	-	-	-	-	2.10	2.38	-	0.014	0.019	-	0.26	1.50	-	3.0	13.6
Andesite Total		201			125			0.36			417			5.2			708			4000*	
pH 0	0.87	0.32	1.51	0.53	0.20	0.58	0.0020	0.0014	0.0038	42	18	78	0.068	0.032	0.140	5.09	2.57	10.00	7.8	4.0	19.0
pH 7-8	0.66	0.10	0.48	0.91	0.14	0.34	0.0030	0.0010	0.0040	1.03	0.53	2.00	0.011	0.008	0.015	0.29	0.10	0.54	<1	<1	5
pH 10	-	0.06	0.30	-	0.15	0.40	-	-	-	-	0.40	1.25	-	0.007	0.014	-	0.08	0.68	-	<1	5
pH 12.7	-	0.11	0.68	-	0.17	0.61	-	-	-	-	0.40	1.15	-	0.008	0.024	-	0.22	0.91	-	1.7	10
Basalt Total		211			90			0.16			490			4.8			514			3140*	
pH 0	126	106	104	22.4	17.5	16.3	0.0510	0.0450	0.0450	43	45	47	0.170	0.160	0.200	154	135	139	383	486	503
pH 7-8	7.90	0.21	0.68	4.00	0.24	0.44	0.0110	0.0010	0.0030	3.97	0.76	3.15	0.044	0.007	0.019	2.08	0.10	0.33	11	<1	2
pH 10	-	0.20	0.44	-	0.20	0.45	-	-	-	-	0.46	1.85	-	0.006	0.015	-	0.02	0.25	-	<1	3
pH 12.7	-	0.29	1.18	-	0.25	0.70	-	-	-	-	0.37	1.44	-	0.006	0.024	-	0.33	1.44	-	1.7	10
Greywck3 Total		135			126			0.63			42			1.5			441			5070*	
pH 0	0.38	0.23	1.45	0.86	0.87	5.83	0.0078	0.0066	0.0360	9.1	5.9	11.6	0.042	0.031	0.094	3.70	2.03	10.9	3.3	1.9	22.8
pH 7-8	0.80	0.13	0.61	1.47	0.37	1.78	0.0130	0.0050	0.0130	3.23	1.05	2.34	0.045	0.017	0.053	1.17	0.15	0.61	<1	<1	<1
pH 10	-	0.09	0.47	-	0.37	2.10	-	-	-	-	0.54	1.86	-	0.013	0.073		0.17	1.30	-	<1	2
pH 12.7	-	0.11	0.56	-	0.34	2.51	-	-	-	-	0.47	1.78	-	0.011	0.061		0.36	2.80	-	2.5	14
Greywck4 Total		179			142			0.63			49			1.7			447			5070*	
pH 0	0.28	0.20	0.93	0.28	0.59	3.43	0.0020	0.0037	0.0200	12.0	5.9	11.0	0.030	0.028	0.044	1.82	2.72	6.86	1.2	1.9	10.4
pH 7-8	0.45	0.11	0.60	0.48	0.21	0.96	0.0020	0.0010	0.0050	3.82	1.70	2.41	0.046	0.021	0.029	0.24	0.10	0.23	<1	<1	2
pH 10	-	0.06	0.50	-	0.20	1.01	-	-	-	-	1.26	2.06	-	0.012	0.032		0.20	1.25	-	<1	2
pH 12.7	-	0.17	0.91	-	0.15	1.42	-	-	-	-	1.11	2.06	-	0.011	0.032		0.05	1.43	-	1.1	11

* Typical value for rock type

Total refers to analysis of rock divided by dilution factor of 140 to give equivalence to results of leaching with solutions.