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WRc

Improved Materials Testing

Leaching Tests on Ready-Mixed Concrete

Report to the Department of the Environment, Transport and the Regions



IMPROVED MATERIALS TESTING

LEACHING TESTS ON READY-MIXED CONCRETE

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Authors: M W Norris, S Blake and K Moore

Contract Manager: I M Wilson

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Any enquiries relating to this report should be referred to the Contract Manager at the following address:

WRc plc, Henley Road, Medmenham, Marlow, Buckinghamshire SL7 2HD.
Telephone: 01491 571 531

IMPROVED MATERIALS TESTING LEACHING TESTS ON READY MIXED CONCRETE

EXECUTIVE SUMMARY

The objective of this study was to establish 'benchmark' levels for the leaching of metals listed in BS 6920 from generic ready-mixed concretes and assess these against current maximum admissible concentrations (MAC).

The aqueous leaching of metals was performed using the methods in BS 6920, 'Suitability of non-metallic products for use in contact with water intended for human consumption with regard to their effect on the quality of the water'. The metals content of the selected ready-mixed concretes was also determined to establish if there was a correlation between the aqueous leaching and the total metal content. Two sample preparation procedures were used for the analysis of solid samples, to give results for acid extractable and total metals.

Quarry Products Association (QPA) arranged for the preparation and curing of concrete test cubes using six different ready-mixed concrete mix compositions each with two types of aggregate, gravel and granite. The concrete test cubes were cured for a period of 28 days. Standard curing conditions were used for 14 of the test cubes, ie total immersion in water, cured at a temperature of 20 °C. In addition two test cubes were air cured at a temperature of 20 °C for comparison.

The type of cement and additions used for the test specimens is given below;

Cement	Additions
Portland (UK)	none
Portland (Imported)	none
Portland (UK)	Pulverised fuel ash
Portland (UK)	Ground granulated blastfurnace slag
Portland (UK)	Microsilica
Sulfate-resisting Portland cement	none

In addition one test sample was prepared using Portland cement manufactured at a works using Cemfuel as a supplementary fuel.

Results for the aqueous leachates showed only four of the thirteen listed metals to be present above the limit of detection of the methods used. Aluminium was detected in all the leachate samples, barium, chromium and iron were detected in some of the aqueous leachate samples. Of these metals only aluminium was detected leaching above the MAC of 200 µg l⁻¹ for drinking water in the majority of the aqueous leachate samples.

The highest concentration in the aqueous leachates appeared to occur with test specimens prepared using gravel as aggregate. Greater leaching of aluminium and iron was observed in test specimens prepared containing ground granulated blastfurnace slag regardless of the other constituents.

Results for the analysis of total metals in the solid samples showed that the ready-mixed cement mixtures did not contain silver, cadmium, mercury or selenium. Of the metals

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found, aluminium and iron were found in the greatest concentration, followed by barium and manganese.

When digested in concentrated acid the metals arsenic, chromium, manganese, nickel and lead were readily extracted from the solid test specimens. However none of these metals were detected in the aqueous leachates, except chromium which was found at low concentrations. Aluminium, barium and iron were also readily extracted by the acid digestion process at the high concentrations of acid used.

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1. INTRODUCTION

Ready-mixed concrete has traditionally been used in contact with water for public supply under the provision of Regulation 25 (1) (c) of the Water Supply (Water Quality) Regulations 1989. The Drinking Water Inspectorate (DWI) has recently issued notice that exemption of traditional materials, such as cementitious materials, from approval is to be removed. Consequently water undertakers will be required to use only products which are approved under Regulation 25 (1) (a) in application to water supply pipes, service reservoirs and water towers.

A protocol is required for 'benchmarking/generic' type-testing of ready-mixed concretes to enable an approval of generic types of ready-mixed concrete to be given. To determine if the use of traditional ready-mixed concretes based on a range of Portland Cement types could present a health hazard with respect to the leaching of metals, a study was commissioned to determine the aqueous leachability and the total concentration of selected metals.

In order to establish a data-base the DWI requested WRC to undertake a survey of leaching of metals from ready-mixed concrete as a part of the DWI contract Improved Methods for Materials Testing (70/2/72).

Quarry Products Association (QPA) arranged for the preparation and curing (standard and non-standard) of moulded test specimens. These were prepared from a range of "water-retaining quality" concretes, which included many of the cement types and two of the aggregate types, currently supplied to the water industry. The metals chosen for study were those listed in BS 6920.

Triplicate test cubes were prepared using six different ready-mixed concrete mix compositions each with two types of aggregate, gravel and granite. The concrete test cubes were cured totally immersed in water at a temperature of 20 °C for a period of 28 days. In addition two test cubes were air cured at a temperature of 20 °C for comparison.

2. OBJECTIVES

The objectives of this project were to:

- a) to identify aqueous leaching of metals from ready-mixed concrete using the method of test in BS 6920.
- b) to determine if there is any correlation between the aqueous leaching of metals and the total metal content of ready-mixed concrete.

3. METHODOLOGY

3.1 Test Specimens

The test specimens of ready-mixed concrete mixtures were prepared and cured at the quality control laboratories of ARC Southern - Premix (granite aggregates) and Tarmac Topmix (gravel aggregates).

The test specimens (100 mm cubes) are typically used, by industry, for the determination of compressive strength. The test specimens were prepared using six different ready-mixed concrete mix compositions each with two types of aggregate, gravel and granite.

The test specimens were prepared using Portland cement, manufactured in either the UK or imported from Europe. The additions used were pulverised fuel ash, ground granulated blastfurnace slag or microsilica. Test specimens were also prepared using sulfate resisting Portland cement using both aggregates types, but without any additions.

At the request of QPA an additional test sample using UK Portland cement, manufactured at a cement works using Cemfuel as a supplementary fuel source, with no additions and gravel as aggregate, was also included in the test.

The test specimens were cured in water (deionised water for granite aggregate and tap water for gravel aggregate) for a period of 28 days at 20 ± 2 °C (standard cure conditions for physical testing). In addition two test specimens, prepared from each of the aggregates and UK Portland cement, were air cured.

In total 16 mix compositions (triplicate test specimens) of ready-mixed concrete were submitted to WRc for testing. The test specimens were sealed in plastic bags to retain moisture. The ready-mixed concrete samples identified for testing, the aggregate used and the curing conditions are listed in Table 3.1.

Table 3.1 Composition and curing conditions of Test Specimens

Cement Type	Source	Code	Aggregate	Curing conditions (28 days at 20 °C)	QPA Mix No	WRc Ref
Portland	[REDACTED] (UK)	PC/UK/GL/TW ✓	Gravel	Tap water	1a	046C
Portland	[REDACTED] (UK)	PC/UK/GL/AC ✓	Gravel	Air	1b	047C
Portland	[REDACTED] (UK)	PC/UK/GL/DI ✓	Gravel	DI water	1c	048C
Portland	[REDACTED] (UK)	PC/UK/GE/AC ✓	Granite	Air	2a	022C
Portland	[REDACTED] (UK)	PC/UK/GE/DI ✓	Granite	DI water	2b	023C
Portland	[REDACTED] (Imported)	PC/IM/GL/DI ✓	Gravel	Tap water	3	051C
Portland	[REDACTED] (Imported)	PC/IM/GE/DI ✓	Granite	DI water	4	025C
Sulfate-resisting Portland	[REDACTED]	SRPC/GL/TW ✓	Gravel	Tap water	5	053C
Portland /Pulverised fuel ash,	[REDACTED] (UK)	PC/PFA/GL/TW ✓	Gravel	Tap water	6	049C
Portland /Ground granulated blastfurnace slag	[REDACTED] (UK)	PC/GGBS/GL/TW ✓	Gravel	Tap water	7	050C
Portland /Microsilica	[REDACTED] (UK)	PC/MS/GL/TW ✓	Gravel	Tap water	8	054C
Sulfate-resisting Portland	[REDACTED]	SRPC/GE/DI ✓	Granite	DI water	9	024C
Portland /Pulverised fuel ash,	[REDACTED] (UK)	PC/PFA/GE/DI ✓	Granite	DI water	10	026C
Portland /Ground granulated blastfurnace slag	[REDACTED] (UK)	PC/GGBS/GE/DI ✓	Granite	DI water	11	027C
Portland /Microsilica	[REDACTED] (UK)	PC/MS/GE/DI ✓	Granite	DI water	12	028C
Portland	[REDACTED] *	PC/GL/TW ✓	Gravel	Tap water	13	052C

*Cement prepared at a works using Cemfuel as a supplementary fuel source

3.2 Preparation of aqueous leachates

The method used to prepare the aqueous leachates was according to the method in BS 6920

The test cubes were 100 mm square, total surface area 60,000 mm². To ensure that the required surface to volume ratio of 0.15 cm² ml⁻¹ was achieved the volume of test water was increased to 4 litres.

Duplicate test cubes of each concrete mix were pre-conditioned in Medmenham tap water, aggressivity index 12.1 (aggressivity index = pH + log (total alkalinity x calcium hardness)), for 24-hour periods until the pH of the water was less than 9 on two consecutive occasions.

The pre-conditioning water for the test cubes prepared using granite as aggregate and cured in deionised water initially had a pH greater than 9 after the first 24 hours. However the pH was less than 9 for the second and third 24 hour period. The test cubes prepared using gravel as aggregate and cured in tap water initially had a pH less than or near to 9 after the initial 24 hour period.

The test cubes were then transferred to clean containers (5 litre borosilicate beakers) and leached in test water (4 litres, deionised water) according to BS 6920.

The test specimens were leached for 24 hours after which time the leachate was discarded. The test specimens were then leached for a further six sequential periods, five 24-hour and one 72-hour period and concluding with a 24-hour period. Samples of the final leachates were taken for the determination of metals.

3.3 Preparation of solid samples

The third test cube of each concrete mix was analysed for the total content of the same metals as above. Two methods of sample analysis were used, to give information on the total and acid extractable metal concentrations in the concretes.

The damp test cube, as received, was weighed and the weight recorded. The test cube was pulverised and milled to <50 µm and the powdered material dried at 105 °C.

3.4 Analysis

The final aqueous extracts and the dried pulverised material were analysed using the analytical methods given in Table 3.2. The choice of analytical method was made in relation to the required limit of detection (normally 1/10 of the maximum admissible concentration (MAC)) and as appropriate to the determinand to be analysed. WRc has NAMAS accreditation (Lab No 1550) for the analytical techniques in Table 3.2.

Table 3.2 List of specified metals as given in BS 6920 Part 1 (Specification) and Methods of Analysis for the Metals Determined.

Metal	MAC ($\mu\text{g l}^{-1}$)	Solid samples		Aqueous leachates
		Total metals	Acid extractable metals	
Aluminium (Al)	200	A, E	D, E	E
Antimony (Sb)	10	B, F	D, F	F
Arsenic (As)	50	B, F	D, F	F
Barium (Ba)	1000	A, E	D, E	E
Cadmium (Cd)	5	A, E	D, H	G
Chromium (Cr)	50	A, E	D, G	G
Iron (Fe)	200	A, E	D, E	E
Lead (Pb)	50	A, E	D, H	G
Manganese (Mn)	50	A, E	D, E	E
Mercury (Hg)	1	C, I	D, I	I
Nickel (Ni)	50	A, E	D, H	G
Selenium (Se)	10	B, F	D, F	F
Silver (Ag)	10	A, E	D, E	G

MAC - Maximum admissible concentration

A: Digestion with hydrofluoric/perchloric acid

B: Acid digestion/dry ashing with magnesium nitrate

C: Acid digestion with vanadium pentoxide

D: Aqua-Regia digestion

E: Inductively coupled plasma atomic emission spectrometry

F: Hydride generation atomic absorption spectrometry

G: Graphite furnace atomic absorption spectrometry

H: Flame atomic absorption spectrometry

I: Cold vapour atomic absorption spectrometry

4. RESULTS

The tables of results are given below. Results in bold italics are those metals whose concentration exceeds the MAC.

The duplicate results for the concentration of metals in aqueous leachates prepared from granite aggregate test cubes and gravel aggregate test cubes are given in Tables 4.1 and 4.2 respectively.

The concentration of acid extractable metals in pulverised samples are given in Table 4.3.

The concentration of total metals in pulverised samples are given in Table 4.4

No metals of interest were found in the procedural blank aqueous leachate samples. (There were no procedural blanks for the extract of the solid samples).

The following codes are used in the Tables;

Code	Definition
AC	Air cured
DI	Deionised water cured
GE	Granite
GGBS	Ground granulated blastfurnace slag
GL	Gravel
IM	Imported
MS	Microsilica
PC	Portland cement
PFA	Pulverised fuel ash
SRPC	Sulfate-resisting Portland cement
TW	Tap water cured

Table 4.1 Concentration of metals in aqueous leachates prepared from duplicate Granite Aggregate test cubes ($\mu\text{g l}^{-1}$)

Test Sample	Ag	Al	As	Ba	Cd	Cr	Fe	Hg	Mn	Ni	Pb	Sb	Se
PC [redacted] /GE/AC	<0.20	60	<0.5	13	<0.10	<0.50	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] /GE/AC	<0.20	120	<0.5	13	<0.10	<0.50	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] /GE/DI	<0.20	100	<0.5	8	<0.10	<0.50	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] /GE/DI	<0.20	120	<0.5	8	<0.10	0.60	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] /GE/DI	<0.20	160	<0.5	5	<0.10	1.15	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] /GE/DI	<0.20	220	<0.5	5	<0.10	1.87	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
- SRPC/GE/DI	<0.20	90	<0.5	4	<0.10	<0.50	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
SRPC/GE/DI	<0.20	170	<0.5	4	<0.10	<0.50	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC/PFA/GE/DI	<0.20	170	<0.5	72	<0.10	<0.50	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC/PFA/GE/DI	<0.20	230	<0.5	67	<0.10	<0.50	5	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC/GGBS/GE/DI	<0.20	310	<0.5	9	<0.10	1.80	6	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC/GGBS/GE/DI	<0.20	470	<0.5	9	<0.10	0.53	7	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC/MS/GE/DI	<0.20	70	<0.5	4	<0.10	0.88	7	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC/MS/GE/DI	<0.20	90	<0.5	3	<0.10	0.81	12	<0.1	<2	<1.0	<2.0	<1.0	<0.5
MAC	10	200	50	1000	5	50	200	1	50	50	50	10	10

Table 4.2 Concentration of metals in aqueous leachates prepared from duplicate Gravel Aggregate test cubes ($\mu\text{g l}^{-1}$)

Test Sample	Ag	Al	As	Ba	Cd	Cr	Fe	Hg	Mn	Ni	Pb	Sb	Se
PC [redacted] GL/TW	<0.20	300	<0.5	5	<0.10	6.29	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] GL/TW	<0.20	290	<0.5	4	<0.10	<0.50	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] GL/AC	<0.20	290	<0.5	<2	<0.10	2.32	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] GL/AC	<0.20	350	<0.5	<2	<0.10	1.78	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] GL/DI	0.27	60	<0.5	<2	<0.10	<0.50	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] GL/DI	<0.20	<40	<0.5	<2	<0.10	<0.50	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] GL/TW	<0.20	250	<0.5	8	<0.10	0.58	24	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] GL/TW	<0.20	290	<0.5	12	<0.10	0.78	18	<0.1	<2	<1.0	<2.0	<1.0	<0.5
SRPC/GL/TW	<0.20	200	<0.5	15	<0.10	<0.50	7	<0.1	<2	<1.0	<2.0	<1.0	<0.5
SRPC/GL/TW	<0.20	200	<0.5	17	<0.10	<0.50	15	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC/PFA/GL/TW	<0.20	360	<0.5	<2	<0.10	2.22	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC/PFA/GL/TW	<0.20	380	<0.5	<2	<0.10	0.67	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC/GGBS/GL/TW	<0.20	410	<0.5	10	<0.10	<0.50	15	<0.1	4	<1.0	<2.0	<1.0	<0.5
PC/GGBS/GL/TW	<0.20	280	<0.5	8	<0.10	<0.50	6	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC/MS/GL/TW	<0.20	160	<0.5	5	<0.10	<0.50	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC/MS/GL/TW	<0.20	140	<0.5	3	<0.10	<0.50	<4	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] GL/TW	<0.20	260	<0.5	12	<0.10	<0.50	13	<0.1	<2	<1.0	<2.0	<1.0	<0.5
PC [redacted] GL/TW	<0.20	260	<0.5	11	<0.10	<0.50	12	<0.1	<2	<1.0	<2.0	<1.0	<0.5
MAC	10	200	50	1000	5	50	200	1	50	50	50	10	10

Table 4.3 Concentration of metals extracted by acid digestion from pulverised samples (mg kg⁻¹ dried material)

Test Sample	Ag	Al	As	Ba	Cd	Cr	Fe	Hg	Mn	Ni	Pb	Sb	Se
PC [redacted] /GL/TW	<10	7100	3.80	124	<0.2	19.2	6825	<0.1	129	6.74	3.98	0.81	<0.25
PC [redacted] /GL/AC	<10	6445	2.40	135	<0.2	22.0	6295	<0.1	140	7.05	3.74	0.74	<0.25
PC [redacted] /GL/DI	<10	6760	2.79	153	<0.2	22.7	6485	<0.1	150	6.69	3.96	0.88	<0.25
PC [redacted] /GE/AC	<10	7585	3.33	65.0	<0.2	19.5	8415	<0.1	188	8.54	5.74	<0.25	<0.25
PC [redacted] /GE/DI	<10	8040	3.72	52.0	<0.2	23.5	9730	<0.1	201	10.1	109	<0.25	<0.25
PC [redacted] /GL/TW	<10	6150	4.27	117	<0.2	66.5	7480	<0.1	118	30.1	5.22	0.87	<0.25
PC [redacted] /GE/DI	<10	7555	9.20	44.0	<0.2	57.3	9770	<0.1	170	30.8	15.9	0.73	<0.25
SRPC/GL/TW	<10	6675	3.77	170	<0.2	21.3	9385	<0.1	264	9.83	45.2	1.16	<0.25
PC/PFA/GL/TW	<10	7515	7.33	162	<0.2	24.8	7490	<0.1	122	9.04	9.44	1.41	<0.25
PC/GGBS/GL/TW	<10	8315	2.69	226	<0.2	20.2	6405	<0.1	285	5.58	3.47	0.92	<0.25
PC/MS/GL/TW	<10	5915	3.42	154	<0.2	20.5	6290	<0.1	145	6.86	6.73	1.8	<0.25
SRPC/GE/DI	<10	7910	3.24	67.0	<0.2	16.0	11505	<0.1	240	10.4	13.1	0.44	<0.25
PC/PFA/GE/DI	<10	9500	9.01	228	<0.2	18.3	11075	<0.1	220	11.2	9.99	0.53	<0.25
PC/GGBS/GE/DI	<10	10100	3.55	80.0	<0.2	20.4	9650	<0.1	297	10.2	6.22	<0.25	<0.25
PC/MS/GE/DI	<10	7995	4.04	67.0	<0.2	19.3	9610	<0.1	189	10.2	12.5	0.31	<0.25
PC [redacted] /GL/TW	<10	7540	4.75	167	<0.2	20.2	7490	<0.1	107	7.70	9.25	1.02	<0.25

Table 4.4 Concentration of total metals in pulverised samples (mg kg⁻¹ dried material)

Test Sample	Ag	Al	As	Ba	Cd	Cr	Fe	Hg	Mn	Ni	Pb	Sb	Se
PC [redacted] /GL/TW	<0.5	10350	3.26	229	<0.2	20.0	4556	<0.1	91.0	8.34	6.40	1.61	<1.0
PC [redacted] /GL/AC	<0.5	12885	3.41	277	<0.2	28.0	5931	<0.1	128	9.20	5.86	2.29	<1.0
PC [redacted] /GL/DI	<0.5	11946	3.50	261	<0.2	25.6	5344	<0.1	120	9.26	6.25	2.03	<1.0
PC [redacted] /GE/AC	<0.5	48009	3.26	548	<0.2	23.6	8993	<0.1	200	11.9	18.9	0.271	<1.0
PC [redacted] /GE/DI	<0.5	35807	3.53	412	<0.2	19.4	7013	<0.1	154	12.2	121	0.244	<1.0
PC [redacted] /GL/TW	<0.5	13464	5.04	261	<0.2	75.8	7087	<0.1	106	36.8	7.72	1.72	<1.0
PC [redacted] /GE/DI	<0.5	34341	9.29	405	<0.2	48.4	7022	<0.1	133	35.8	28.0	0.948	<1.0
SRPC/GL/TW	<0.5	13399	4.03	317	<0.2	27.2	8157	<0.1	226	12.8	51.2	1.60	<1.0
PC/PFA/GL/TW	<0.5	16742	7.88	342	<0.2	31.8	7193	<0.1	114	13.7	14.2	2.56	<1.0
PC/GGBS/GL/TW	<0.5	14544	3.24	387	<0.2	28.6	5587	<0.1	248	8.45	6.86	1.81	<1.0
PC/MS/GL/TW	<0.5	13426	3.98	321	<0.2	22.3	6201	<0.1	134	8.95	9.91	4.38	<1.0
SRPC/GE/DI	<0.5	46014	3.08	535	<0.2	18.4	10347	<0.1	224	13.1	26.0	0.587	<1.0
PC/PFA/GE/DI	<0.5	48265	3.45	716	<0.2	25.2	10190	<0.1	203	15.2	24.7	0.758	<1.0
PC/GGBS/GE/DI	<0.5	38732	3.90	430	<0.2	24.0	7242	<0.1	232	12.9	18.5	0.241	<1.0
PC/MS/GE/DI	<0.5	42789	4.73	529	<0.2	21.8	8637	<0.1	177	12.9	24.1	0.435	<1.0
PC [redacted] /GL/TW	<0.5	13304	5.06	320	<0.2	22.0	5992	<0.1	88.8	9.25	11.6	1.55	<1.0

5. DISCUSSION

5.1 Aqueous leachates

Only four of the thirteen metals measured were detected at concentrations above the limit of detection. Aluminium was detected in all the leachates and in some of the leachates above the MAC ($200 \mu\text{g l}^{-1}$). Barium was detected in 13 of the 16 concrete mixtures tested, however the concentration of barium never exceeded 10% of the MAC ($1000 \mu\text{g l}^{-1}$). Iron was detected in 7 of the 16 concrete mixtures tested, however only one of the duplicate test specimens (PC ~~UK~~/GL/TW) gave a result greater than 10% of the MAC ($200 \mu\text{g l}^{-1}$). Chromium was detected in 8 of the 16 concrete mixtures tested, only one of the duplicate test specimens (PC ~~UK~~/GL/TW) gave a result greater than 10% of the MAC ($50 \mu\text{g l}^{-1}$). There was however a large discrepancy for chromium concentration between the duplicate samples, this may be due to non-homogeneity in the solid samples.

The highest concentration in the aqueous leachates appeared to occur with test specimens prepared using gravel as aggregate (eg PC/UK/GL/TW aluminium = $295 \pm 5 \mu\text{g l}^{-1}$ compared with PC/UK/GE/DI aluminium = $110 \pm 10 \mu\text{g l}^{-1}$). Greater leaching of aluminium was also observed in the test specimens containing ground granulated blastfurnace slag, regardless of the aggregate used (PC/GGBS/GE/DI aluminium = $390 \pm 80 \mu\text{g l}^{-1}$, PC/GGBS/GL/DI aluminium = $345 \pm 65 \mu\text{g l}^{-1}$) compared with the other test specimens.

The curing conditions (deionised or tap water) did not appear to significantly affect the concentration of metals detected in the aqueous leachates. The leaching patterns from the air-cured samples were similar to those of the corresponding samples cured either in deionised or tap water.

Also there was no significant difference in the results for the test sample prepared using Portland cement manufactured at a works using Cemfuel as a supplementary fuel or the test sample prepared using Portland cement manufactured using conventional fuel.

Mean concentrations of aluminium, barium, chromium, and iron in aqueous leachates prepared from duplicate test cubes are given in Table 5.1.

5.2 Metals in solid samples

Results for the analysis of total metals in the solid samples showed that the ready-mixed concretes did not contain silver, cadmium, mercury or selenium. Of the metals found, aluminium and iron were found in the greatest concentration, followed by barium and manganese.

Some metals, namely arsenic, chromium, manganese, nickel and lead, were readily extracted from the solid samples when digested in concentrated acid. However none of these metals were detected in the aqueous leachates, except chromium which was found at low concentrations. Aluminium, barium and iron were also readily extracted in concentrated acid.

The type of the aggregate did not appear to affect the total concentration of metals found in the solid samples.

Table 5.1 Mean concentrations of aluminium, barium, chromium and iron in the aqueous leachates prepared from duplicate test cubes ($\mu\text{g l}^{-1}$)

Test Sample	Al	Ba	Cr	Fe
PC/GGBS/GE/DI	390 ±80	9	1.2 ±0.6	6.5 ±0.5
PC/PFA/GL/TW	370 ±10	<2	1.4 ±0.8	<4
PC/GGBS/GL/TW	345 ±65	9 ±1	<0.50	11 ±5
PC ^{JK} /GL/AC	320 ±30	<2	2.1 ±0.3	<4
PC ^{JK} /GL/TW	295 ±5	5	6.29	<4
PC ^{IM} /GL/TW	270 ±20	10 ±2	0.7 ±0.1	21 ±3
PC /GL/TW	260	12	<0.50	13
PC/PFA/GE/DI	200 ±30	70	<0.50	4.5 ±0.5
SRPC/GL/TW	200	16 ±1	<0.50	11 ±4
PC ^{IM} /GE/DI	190 ±30	5	1.5 ±0.4	<4
PC/MS/GL/TW	150 ±10	4 ±1	<0.50	<4
PC/SRPC/GE/DI	130 ±40	4	<0.50	<4
PC ^{JK} /GE/DI	110 ±10	8	0.6 ±0.1	<4
PC ^{JK} /GE/AC	90 ±30	13	<0.50	<4
PC/MS/GE/DI	80 ±10	4	0.9	10 ±3
PC ^{JK} /GL/DI	50 ±10	<2	<0.50	<4
MAC	200	1000	50	200

6. CONCLUSIONS

Results for the aqueous leachates showed only four of the thirteen listed metals to be present above the limit of detection of the methods used. Aluminium was detected in all the leachate samples, barium, chromium and iron were detected in some of the aqueous leachate samples. Of these metals only aluminium was detected leaching above the MAC of $200 \mu\text{g l}^{-1}$ for drinking water in the majority of the aqueous leachate samples. The concentration of the other metals was mostly below 10% of the MAC.

The highest concentration of aluminium in the aqueous leachates appeared to occur with test specimens prepared using gravel as aggregate. There was also more aqueous leaching of aluminium and iron in test specimens prepared containing ground granulated blastfurnace slag, regardless of the other constituents. This may be due to the type of addition or the ratio of the addition to cement and aggregate.

The curing conditions (deionised water, tap water or air cured) did not significantly affect the concentration of metals detected in the aqueous leachates.

There was no significant difference in the results for the test sample prepared using Portland cement manufactured at a works using Cemfuel as a supplementary fuel or the test samples prepared using Portland cements manufactured using conventional fuel.

Results for the analysis of total metals in the solid samples showed that the ready-mixed concretes did not contain silver, cadmium, mercury or selenium. Of the metals found, aluminium and iron were found in the greatest concentration, followed by barium and manganese. Some metals, namely arsenic, chromium, manganese, nickel and lead, were readily extracted from the solid samples when digested under concentrated acid conditions. However none of these metals were detected in the aqueous leachates, except chromium which was found at low concentrations. Aluminium, barium and iron were also readily acid extracted at the high concentrations used.

A meeting with representatives of QPA and the DWI was arranged at WRc Medmenham to discuss the results of this study. At the meeting DWI stated that the concentration of the specified metals found in the aqueous leachates was not of concern and that actual testing of 'admixture-free' concretes was unlikely to be required to obtain an authorisation for use for water supply pipes, service reservoirs and water towers after 1st April 2000. The methods used for this study could be used to 'benchmark' ready-mixed concretes.

7. REFERENCES

BS 6920 Suitability of non-metallic products for use in contact with water intended for human consumption with regard to their effect on the quality of water;

BS 6920 1996 Part 1 Specification

BS 6920 1996 Part 2 Methods of test, Section 2.1 Samples for test

BS 6920 1996 Part 2 Methods of test, Section 2.6 The extraction of metals