An Assessment of Iron and Steel Slag for treatment of Stormwater Pollution.

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(iron & steel) slag
association

An Assessment of Iron and Steel Slag for treatment of Stormwater Pollution.

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Summary

Project and Client

The Australasian (iron & steel) Slag Association Inc (ASA) engaged Landcare Research to study the performance of slag in removing stormwater contaminants.

Impervious surfaces are a major contributor to urban stormwater impacts. Stormwater has been identified as a major contributor to water quality degradation as it can have significant concentrations of harmful pollutants that can adversely affect the receiving aquatic environment. Materials that can remove harmful pollutants and can be incorporated into stormwater treatment devices offer part of the urban stormwater solution. Previous research into the use of iron and steel furnace slag aggregates as a water filtration medium has demonstrated high adsorptive capacity for various metals and phosphorus and the removal of fine particulates in the source solution. This project tests filter material designed to remove contaminants while maintaining hydraulic performance and provide data on the potential environmental effects and effectiveness of different iron and steel slags produced in New Zealand and Australia for remediation of stormwater pollution.

Objectives

- Assess the environmental impact of different iron and steel slags (ISS) by reviewing and analysing existing data on ISS background levels of contaminants to identify any potential impact of iron and steel slags and associated leachate on the environment.

- Test different types of slag stormwater treatment filter media under laboratory conditions to assess their ability to retain phosphorus, nitrogen and the M17 list of “metals” (Table 1).

- Assess the potential usefulness of iron and steel slag products as a treatment media in storm water treatment devices and identifying where this treatment can be used

Methods

Assessment of environmental impact of iron and steel slag was carried out by a desktop search of scientific literature and the internet. The resulting data were collated and potential environmental contaminants from iron and steel slag were identified.

Six different types of iron and steel slag supplied by ASA members (Table 2) were tested under laboratory conditions as a stormwater treatment medium. The ability of the slag to remove contaminants was trialled by irrigating filter media columns with artificial stormwater containing the phosphorus, nitrogen, and the list of M17 “metals” and measuring the concentration in the resulting leachate. Concentrations of the constituents of the artificial stormwater were similar to those found along arterial roads by previous studies in Australia and New Zealand.

The usefulness of iron and steel slag products as a treatment media in storm water treatment devices was assessed taking into account the results of the laboratory study and published literature on the use of slag materials in other types of treatment system.

Results

Iron and steel slag containing “free lime” components have been used in many industrialised countries for many years in civil engineering, as a lime surrogate and a fertiliser. Although slag has elevated total concentrations of trace metals compared to non-contaminated soil, very little is likely to leach into the environment.

The laboratory study tested removal or release of contaminants and the hydraulic conductivity of stormwater. The pH of the leachate is important as this affects the mobility and bioavailability of many contaminants. Some metals, such as aluminium, are more toxic at both low and high pH so, to avoid these toxic affects, it is preferable that the pH in the leachate remains between 5 and 9. Leachate from 3 of the slags tested (MS1, EAF1 and BF1) were within this pH range. The hydraulic conductivity for all 6 slags tested was greater than could be supplied ($K_{sat} > 100\,000$ mm h^{-1}) and they have the potential to pass large volumes of stormwater. All the slags tested reduced the concentrations of the main elemental contaminants of concern in stormwater (arsenic cadmium, chromium, copper, lead, nickel, zinc, phosphorus and nitrogen). However, very little nitrogen was removed. Some, but not all the slags tested also reduced the concentrations of aluminium, boron, barium, manganese and molybdenum in the artificial stormwater while other slags tested released them. Sulphate was released by all the slags tested. With the one exception of the initial 4 samples of BF2 for barium, the concentration of contaminants in the leachate was below the upper limits in drinking water imposed by Food Standards Australia New Zealand for all samples. Dilution in the receiving environment will reduce the concentrations further. Antimony, beryllium, mercury, selenium, and tin are normally in road runoff only at extremely low concentrations and these contaminants were not detected in any of the slag leachates.

Conclusions

Literature review suggests that despite elevated total concentrations of trace metals in all the slag compared to uncontaminated soil, very little is likely to leach into the environment and there is minimal environmental or health hazard.

All the six slags tested have potential as stormwater filter media as they reduced the concentrations of arsenic cadmium, copper, lead, nickel, zinc, phosphorus and nitrogen in the artificial stormwater. Some, but not all the slags also reduced the concentrations of aluminium, chromium, manganese and molybdenum. Only 3 slags reduced the concentrations of boron and the other 3 released boron. All but one slag released concentrations of barium. However, with the one exception of the initial 4 samples of BF2 for barium, the concentration of contaminants in the leachate was below the upper limits in drinking water imposed by Food Standards Australia New Zealand for all samples.

The best slag for neutralising the acidity in stormwater are BF1 and MS1 (limited to runoff pH > 4). The MS1 steadily declined in pH value (from 8 to 6) indicating less buffering capacity than the other slags and so should only be used to treat runoff with pH >4 (i.e. not acid industrial runoff). EAF1 is the best slag for use where the receiving waters are already alkaline. Slags with leachate of pH >9 could be used where the receiving waters are already alkaline, such as in areas of limestone. However, site-specific ecological risk assessment may be needed for slag use in and around small water bodies with limited dilution volume due to high pH adversely affecting aquatic plant growth. The slags with leachate above pH 10 are also probably suited to treating highly acidic stormwater such as found in acid mine drainage (Ziemkiewicz 1998).

The hydraulic conductivity for all 6 slags was greater than could be supplied (K_{sat} > 100 000 mm h^{-1}) and no practical hydraulic restrictions are expected from the slag filters until and unless they become clogged.

No antimony, beryllium, mercury, selenium, and tin were detected in the leachates indicating little environmental impact from the release of antimony, beryllium, mercury, selenium, and tin by any of the slags tested. The release of aluminium, boron, manganese, molybdenum, in the leachate by some of the slags, and sulphate by all the slags was below the upper limits in drinking water imposed by Food Standards Australia New Zealand for all samples. Dilution in the receiving environment will reduce the concentrations further and there is unlikely to be any negative environmental affect from the use of these slag materials as stormwater filter media. There is a potential environmental effect from leachate from the BF2 that barium will accumulate in the bodies of fish and other aquatic species but only if high concentrations continue. However, as already stated, dilution in the receiving environment will reduce the concentration further, and there is unlikely to be significant environmental impact from this release.

Literature research also indicates slag may be suitable for treatment of landfill leachate, domestic, industrial and agricultural wastewater, and acid mine drainage, as well as treatment of stormwater.

Recommendations Specific To This Project

1 On the basis of the results obtained from this laboratory trial, it is recommend that the most promising media of the 6 slags tested, be field trialled in a stormwater filter to confirm promising initial laboratory results. The filter media tested here should be employed not in isolation but as part of a treatment train to ensure maximum efficiency and longevity in the urban stormwater treatment system.

2 The slag should be further tested in a controlled field study to assess long-term removal efficiencies as this experiment was designed only to test the short-term removal efficiency.

3 The necessary maintenance regime should be determined by a field study measuring clogging potential of the media.

4 The suitability of the 6 slags tested in our study for landfill leachate treatment and industrial and agricultural wastewater treatment drainage should be determined in pilot-scale field studies, as iron and steel slags already have a track record of successful use, particularly in domestic wastewater treatment.

5 The suitability of the 3 very alkaline slags tested in our study for treating acid mine drainage should be further tested in a laboratory study.

6 The feasibility of using slag to reclaim aluminium in residues from aluminium smelting should be investigated by initiating discussions with those in that industry.

General Recommendations

1 Laboratory studies provide an approximation of field conditions, and further testing should be done in a controlled field study because:

   a. depending on the type of construction, slag may retain or provide a suitable surface to degrade other contaminant not tested here, e.g., oils often found in car parks (Bond et al. 1999). The removal of hydrocarbons should be studied.

   b. clogging of medium may occur due to the retention of sediment. The hydrodynamic performance under sediment loading should be investigated.

   c. the complex interaction between environmental, physical and chemical factors is only accurately testable in a controlled field situation.

2 Cost/benefit should be identified by economic and lifecycle analysis of:

   a. stormwater treatment systems.

   b. wastewater treatment systems.

   c. acid mine drainage treatment systems.

3 Locations should be identified that are suitable for the installation of slag based:

   a. stormwater treatment systems. The general features of such suitable locations are large paved areas, heavy vehicular traffic, and site that use or store contaminants (Pitt 2002).

   b. wastewater treatment systems.

   c. acid mine drainage treatment systems.

1. Introduction

Roading surfaces are typically impervious. These surfaces promote rainfall runoff commonly known as stormwater. Urban stormwater can degrade habitat and carry contaminants (Pitt 2002). Stormwater generated from road runoff contains contaminants that are either dissolved in stormwater or bound to particulates (Robien et al. 1997). Although roading infrastructure may represent only 10 to 20% of an urban catchment, road runoff can contribute between 35 to 75% of total heavy metals, 16 to 25% of total hydrocarbons, and 50% of total suspended solids input budgets to a receiving water body (Ellis et al. 1987). Many of these contaminants are potentially toxic and can have detrimental effects on the receiving environment (Ellis & Revitt 1991). Contaminants accumulate in sediments, plants and filter feeding organisms, causing health issues and habitat degradation (ARC 2003). In particular, 80% of all metals in particulate form remain potentially bioavailable and a source for further pollution (Colandini et al. 1995; Mikkelsen et al. 1996).

Road runoff should be treated. A common approach is filtration. Filtration systems can detain runoff, reducing peak flows compared with conventional piped stormwater drainage systems (Pitt 2002). Contaminants are retained and sometimes degraded in a filter medium by processes such as adsorption, precipitation, filtration, and microbial degradation (Pratt 1995). Different substrates may be combined to enhance or better target treatment (Pandey et al. 2003). Slag produced from iron and steel making may have potential as a filter medium for road runoff.

The aim of this research was to:

- Assess the environmental impact of different iron and steel slag by analysing existing data on ISS background levels of contaminants to identify any potential impact of iron and steel slag and associated leachate on the environment.
- Test different types of slag stormwater treatment filter media under laboratory conditions to assess the filters' ability to retain phosphorus, nitrogen and the M17 list of "metals" (Table 1).
- Assess the potential usefulness of iron and steel slag products as treatment media in storm water treatment devices, and identify where this treatment can be used.

Table 1: The M17 "metals"

Metals (M17)	Symbol
- aluminium	Al
- antimony	Sb
- arsenic	As
- boron	B
- barium	Ba
- beryllium	Be
- cadmium	Cd
- chromium (total)	Cr
- copper	Cu
- lead	Pb
- manganese	Mn
- mercury	Hg
- molybdenum	Mo
- nickel	Ni
- selenium	Se
- tin	Sn
- zinc	Zn

A number of New Zealand and overseas laboratory studies have tested removal rates of filter media (Pandey & Taylor 2004a, b; Clark et al. 1999; Tenney et al. 1995). These studies provide data for comparison with the results of our study. Regional guidelines estimate long-term removal rates from infiltration devices, such as paver/filter media systems, to be 85–90% for metals, 60–70% for total P, and 55–60% for total N (ARC 2003). These removal rates are also helpful to provide context to our results.

2. Methods

2.1 Assessment Of Existing Data

A desktop search of scientific literature and the internet was carried out and potential environmental contaminants from iron and steel slag were identified.

2.2 Laboratory Experimental Design

The experiment was carried out under laboratory conditions. The 6 slag materials were chosen and supplied by the ASA (Table 2).

Table 2: Origin and Type

Medium	short code
SteelServ melter slag	MS1
SteelServ electric arc furnace slag	EAF1
Whyalla blast furnace slag	BF1
Whyalla basic oxygen steel slag	BO1
Port Kembla blast furnace slag	BF2
Port Kembla basic oxygen steel slag	BO2

XRF analysis of the slag samples was carried out at NZ Steel Glenbrook using industry standard procedures.

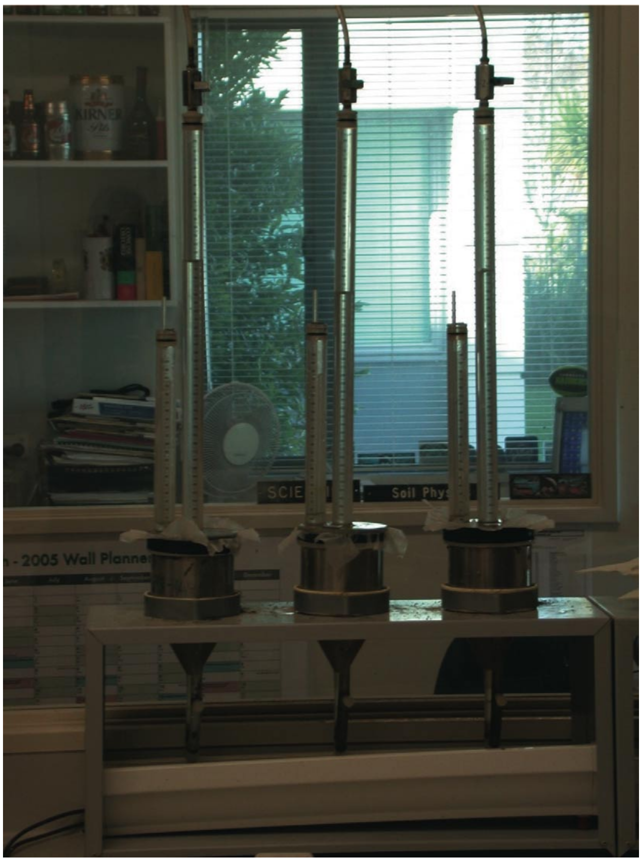


Figure 1: Measuring hydraulic conductivity of filter media using disk permeameters

Figure 2: The filter media packed in to cores

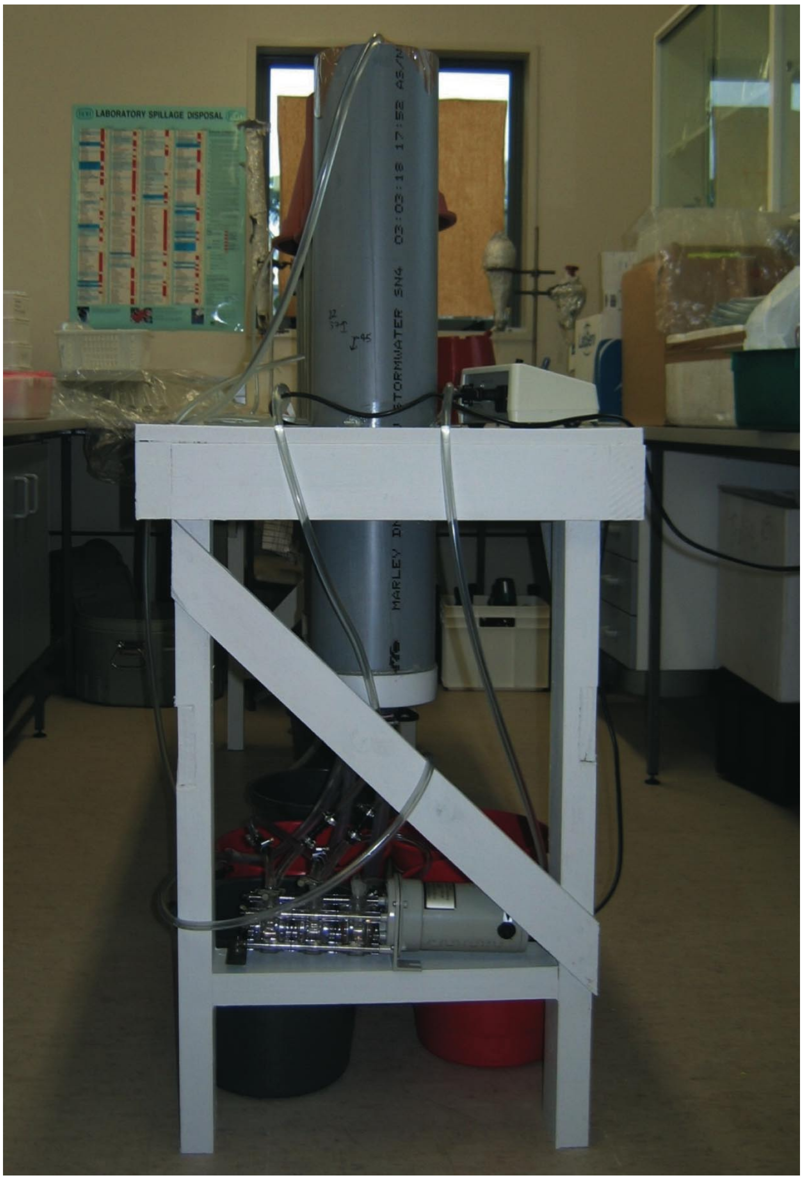


Figure 3: Applying artificial stormwater to filter media columns

Saturated hydraulic conductivity of the filter media was measured on repacked 10-cm cores using the constant head method (Klute & Dirksen 1986). A head of 0 mm was set for the disk permeameters (Figures 1–2) to allow direct reading of K_{sat}. Five litres of each filter media was weighed and then packed into 150-mm diameter columns made of high density polyethylene (Figure 3). The filter media were tested for their contaminant retention capacity by applying six applications of artificial stormwater using a peristaltic pump to control flow rate. Artificial stormwater was used instead of natural stormwater to facilitate consistency between applications (Table 3). The alternative, stored stormwater, is not stable, with solid and dissolved fractions of contaminants changing over time (Burton & Pitt 2001). The metals Cu and Zn are common contaminants of concern in urban stormwater, present in the dissolved form (Shaver et al. 2005). Similarly, the nutrients P and N are considered ‘typical’ problem contaminants in urban stormwater. The other contaminants in the M17 suit were requested by the ASA. The concentrations we tested were similar to those reported along arterial roads in Australia (Kumar et al. 2002) and New Zealand (Taylor & Pandey 2005) or, for those contaminants lacking local measurements, The International Stormwater BMP Database (2005). No particulates were added to the artificial stormwater.

Table 3: Contaminant target and actual concentrations and detection limits

Contaminant	***Target concentration g m^{-3}**	**Measured concentration g m^{-3}**	**Detection Limit Required g m^{-3}**	**Actual Detection Limit g m^{-3}**
- aluminium	0.420	0.441±0.003	5	0.003
- antimony	0.0007	<0.0002	5	0.0002
- arsenic	0.013	0.013±0.001	5	0.001
- barium	0.017	0.029±0.001	5	0.0001
- beryllium	0.00001	<0.0001	5	0.0001
- boron	0.010	0.239±0.002	5	0.005
- cadmium	0.004	0.005±0.000	5	0.00005
- chromium (total)	0.008	0.009±0.000	10	0.0005
- copper	0.084	0.093±0.001	5	0.0005
- lead	0.070	0.067±0.001	5	0.0001
- manganese	0.084	0.061±0.000	5	0.0005
- mercury	0.0000001	<0.00008	5	0.00008
- molybdenum	0.0017	0.5±0.000	0.1	0.0002
- nickel	0.008	0.009±0.000	5	0.0005
- selenium	0.00001	<0.001	5	0.001
- tin	0.00002	<0.0005	0.5	0.0005
- zinc	0.350	0.360±0.002	5	0.001
- nitrogen	9	9.21±0.103	ns	0.026
- phosphorus	0.2	0.22±0.009	ns	0.008
- sulphate	0.6	0.61±0.093	ns	0.02

ns = not specified
* from Kumar et al. 2002; Taylor & Pandey 2005; The International Stormwater BMP Database 2005.

The pump was set to apply the equivalent of a 27-mm rainfall event over 1 hour, which is the equivalent of a 2-year return event, assuming a 10:1 catchment to filter ratio (ARC Environmental data online, *http://maps.arc.govt.nz/website/maps/map_hydrotel.htm,* accessed 8/6/2005). A total of six applications were applied. For each application, the columns were left to drain completely (a minimum of 6 hours) and the leachate collected and analysed immediately for pH using a Radiometer PHM62 pH meter. Homogenisation of samples was ensured by stirring the leachate before the samples were taken. Samples were then frozen until analysis for N, P and M17 “metals”. Water quality analysis followed standard methods for analysis of water and waste water (American Public Health Association 1998) unless otherwise stated. Total N and P were measured after persulphate oxidation by ion chromatography. Mercury was measured following permanganate/persulphate digestion and analysed by FIMS (US EPA 245.2). The other M17 “metals” were analysed by ICP–MS after filtration through nitric washed 0.45 μm membrane filter.

2.3 Assessment Of Iron And Steel Slag Products As A Treatment Media

A desktop search of scientific literature and the internet was carried out and resulting data collated. Based on this data and our own experience, the 6 slags were ranked as to their effectiveness and potential uses identified.

3. Results And Discussion

3.1 The Environmental Impact Of Different Iron And Steel Slags

Iron and steel slags have been used in many industrialised countries for many years in civil engineering, as a lime surrogate and as a fertiliser (Motz & Geiseler 2001; Rex 2002).

Results from Germany suggest, except for pH, the leaching of contaminants is insufficient to cause significant environmental impact (Motz & Geiseler 2001); however, chromium was in higher quantities than the other trace metals. Results from test roads built using steel slag more than 25 years before continue to show good engineering properties to the present. Steel slag has also been used as a phosphatic fertiliser since 1880. Rex (2002) reported investigations of long-term field trials with up to 50 years annual application of iron and steel slag, which showed crop yields were consistently higher compared with those fertilised with non-slag materials.

Studies in North America indicate steel and iron slags contain trace metals at concentrations higher than those found in most soils, although these metals do not leach to any appreciable degree. Proctor et al. (2000) analysed 73 slags from 58 mills throughout the United States and Canada. Blast furnace iron slag contained beryllium, chromium, manganese, molybdenum, and selenium at concentrations above background soil concentrations. Blast furnace steel slag contained antimony, cadmium, chromium, manganese, molybdenum, selenium, silver, thallium tin and vanadium above background soil concentrations. Electric arc furnace slag contained antimony, cadmium, chromium, copper, manganese, molybdenum, nickel, selenium, silver, tin vanadium and zinc above background soil concentrations. Although these concentrations are elevated relative to soil, the metals and metalloids were tightly bound to the slag matrix and are not readily leached. Leaching potential testing of these 73 slags showed very low concentrations of metals in the leachate and that the aqueous extraction of these metals was extremely low, and none of the slag tested exceeded the US EPA standards for determining whether a substance should be characterised as hazardous. A further assessment of human health and ecological risks (Proctor et al. 2002) found no significant hazards to human health.

However, site-specific ecological risk assessment may be needed for slag application in and around small water bodies with limited dilution volume due to high pH adversely affecting aquatic plant growth (Shilton et al. 2005; Koryak et al. 2002). Addition of basic slag to soil has also been shown to increase soil pH to the extent that plant growth is affected (O'Connor et al 2005; McDowell 2004). Depending on existing soil pH and the type of plant being grown, this affect could be beneficial or detrimental.

In Australia, blast furnace slag has been shown as a suitable medium for immobilising low concentrations of toxic elements (Solomon 1994). Blast furnace slag doped with 1% of arsenic, antimony, cadmium, chromium and zinc showed the capacity of the slag to hold these toxic elements depended on the basicity of the slag. Leaching of toxic elements was a function of surface area and the phases present, both of which were affected by the mode of cooling.

A general thinking throughout the papers reported above, is that although slag has elevated total concentrations of trace metals, very little is likely to leach into the environment and there is minimal environmental or health hazard.

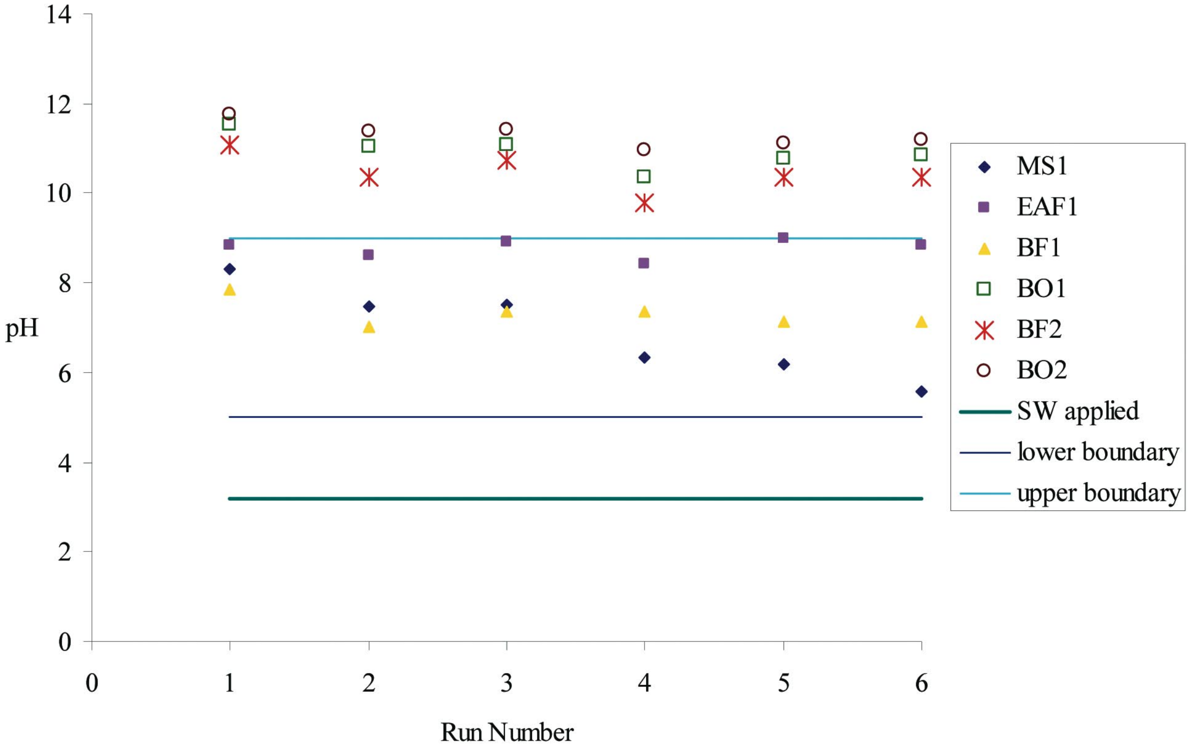
3.2 Removal Of Contaminants From Stormwater By Filter Media

In this section we consider the removal of contaminants from the stormwater by the filter media. Each contaminant is discussed in turn.

pH

It is preferable that the pH in the leachate remains close to neutral, between pH 5 and 9, as some metals, such as aluminium, are more toxic at both low and high pH. The six slag filter media reduced the acidity so the pH in the leachate was more than that applied as stormwater (Figure 4). Three of the slag tested (MS1, EAF1 and BF1) met the Australian and New Zealand guidelines for fresh and marine water quality (ANZECC & ARMCANZ 2000) of between pH 5.0 and 9.0. However, these are guidelines for pristine waters, not limits for contaminated water. Neither the Food Standards Australia New Zealand, nor the USEPA has set limits for the pH of drinking water. The importance of acidity is that it affects the availability and toxicity of many trace metals in water. The pH of the slag material had a clear impact on many of the metal concentrations measured in this study, with slag with pH close to neutral being differentiated from those which were alkaline At higher pH values, many metals will precipitate out of solution as metal hydroxides or other salts, reducing toxicity. However, high pH values can impact on aquatic biota.

Figure 4: pH of stormwater before and after leaching through slag samples.



All the slags except MS1 showed fairly consistent pH in the leachate during the experiment. The MS1 steadily declined in pH value (from 8 to 6) indicating less buffering capacity than the other slag and so should only be used to treat runoff with pH >4 (i.e. non-acid industrial runoff). Slags with leachate of pH >9 could be used where the receiving waters are already alkaline, such as in areas of limestone. However, site-specific ecological risk assessment may be needed for slag use in and around small water bodies with limited dilution volume due to high pH adversely affecting aquatic plant growth (Shilton et al. 2005; Koryak et al. 2002). Slag with leachate above pH 10 are also probably suited to treating highly acidic stormwater such as found in acid mine drainage (Ziemkiewicz 1998). The best slag for neutralising the acidity in road runoff are BF1 and MS1 (limited to runoff pH > 4). EAF1 is the best slag for use where the receiving waters are already alkaline.

Hydraulic Conductivity

High hydraulic conductivity is preferable as it allows treatment of greater volumes of water. The hydraulic conductivity for all 6 slags was greater than could be supplied (K_{sat} > 100 000 mm h^{-1}), and these slags have the potential to pass large volumes of stormwater. Hydraulic conductivity is greater than that typical of unconsolidated gravel (11250 mm h^{-1}, Shaw 1993). Therefore, no practical hydraulic restrictions are expected from the slags until and unless they become clogged.

Aluminium

Five of the slag tested (MS1, EAF1, BF1, BF2, BO2) retained aluminium, so the concentration of aluminium in the leachate was less than applied as stormwater, while BO1 released more aluminium to the leachate than was applied (Figure 5, Table 4). Aluminium is one of the most widely used metals and also one of the most frequently found compounds in the earth's crust and is considered harmless unless in very high concentrations. Similar to pH, neither Food Standards Australia New Zealand, nor the USEPA, has set an upper limit for aluminium in bottled water for drinking, even though levels up to 18 g m^{-3} have been measured (FSANZ press release 1 November 2004). As the levels of aluminium released by the BO1 are below this value, and dilution in the receiving environment will reduce the concentration further, there is unlikely to be significant environmental impact from this release.

Figure 5: Aluminium content of stormwater before and after leaching through slag samples.

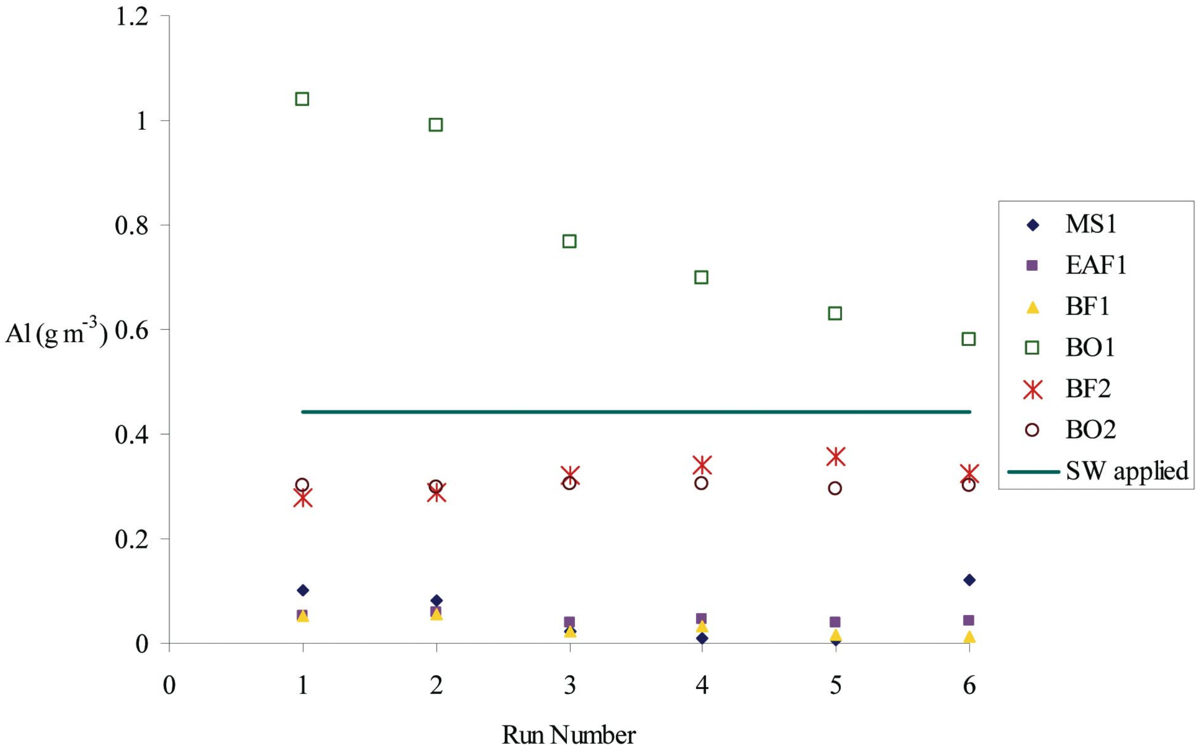


Table 4: Aluminium applied in stormwater and leached through slag samples.

	MS1	EAF1	BF1	BO1	BF2	BO2
Al (g) applied	0.12	0.12	0.12	0.12	0.12	0.12
Al (g) in leachate	0.02	0.01	0.01	0.22	0.09	0.09
% retention	87	89	93	-78	28	32

Antimony

Antimony is normally only present at extremely low concentrations in road runoff (below the detection limit). No antimony was detected in any of the slag leachates, indicating no significant environmental impact from the release of antimony by any of the slag tested.

Arsenic

Arsenic is commonly considered an undesirable and potentially toxic metalloid (ARC 2003, Shaver et al. 2005). The six slag filter media retained arsenic so the concentration of arsenic in the leachate was less than applied as stormwater (Figure 6, Table 5).

Figure 6: Arsenic content of stormwater before and after leaching through slag samples.

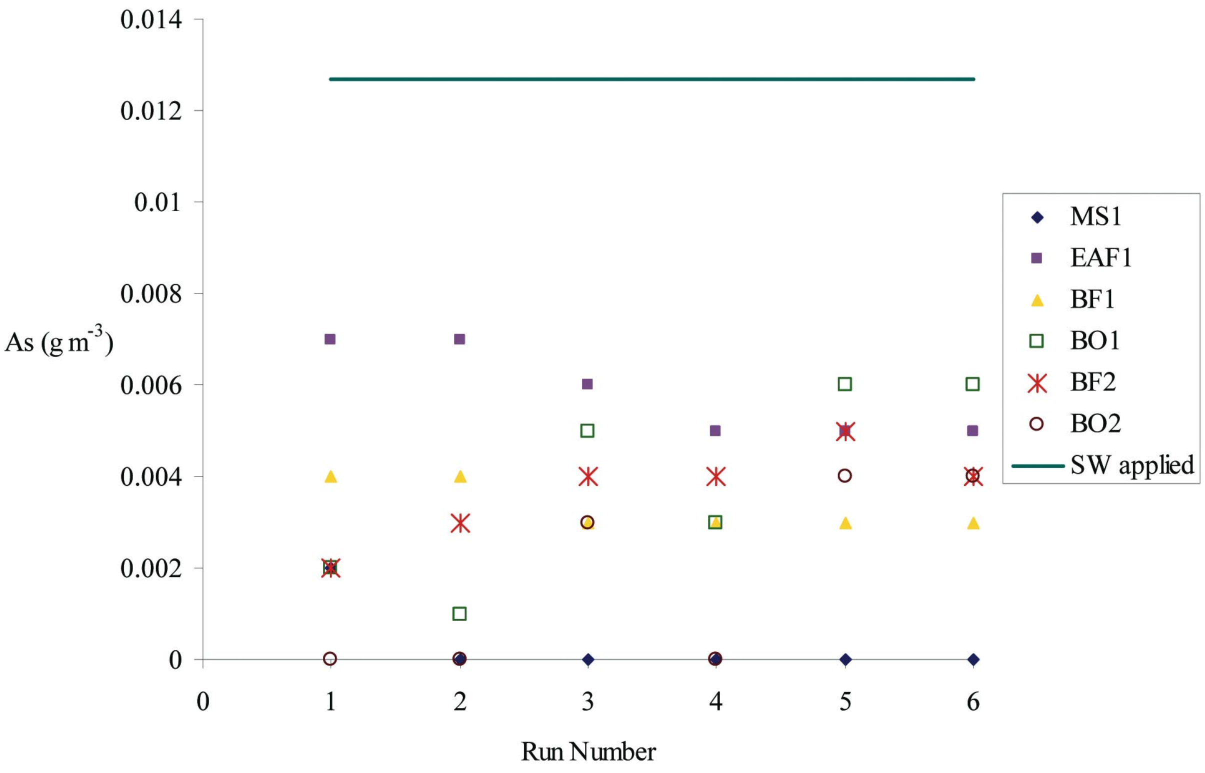


Table 5: Arsenic applied in stormwater and leached through slag samples.

	MS1	EAF1	BF1	BO1	BF2	BO2
As (g) applied	0.0036	0.0036	0.0036	0.0036	0.0036	0.0036
As (g) in leachate	0.0001	0.0017	0.0010	0.0011	0.0011	0.0005
% retention	97	54	74	70	71	86

Barium

All the slag materials, except BO1 released barium between 2 to 5 times of what was applied. BO1 could retain only 12% barium (Figure7, Table 6). However, the concentration of barium in the leachate was below the upper limit of 1.0 g m^{-3} for barium in drinking water imposed by Food Standards Australia New Zealand for all samples for 4 slags. Only the 4 initial samples for the BF2 exceeded the drinking water standard and concentrations rapidly decreased. As this is a short-term study, the long-term effect of barium from BF2 remains unknown. There is only a potential environmental effect from leachate from BF2 that barium will accumulate in the bodies of fish and other aquatic species if high concentrations continue. Dilution in the receiving environment will reduce the concentration further, and there is unlikely to be significant environmental impact from this release.

Figure 7: Barium concentration of stormwater before and after leaching through slag samples.

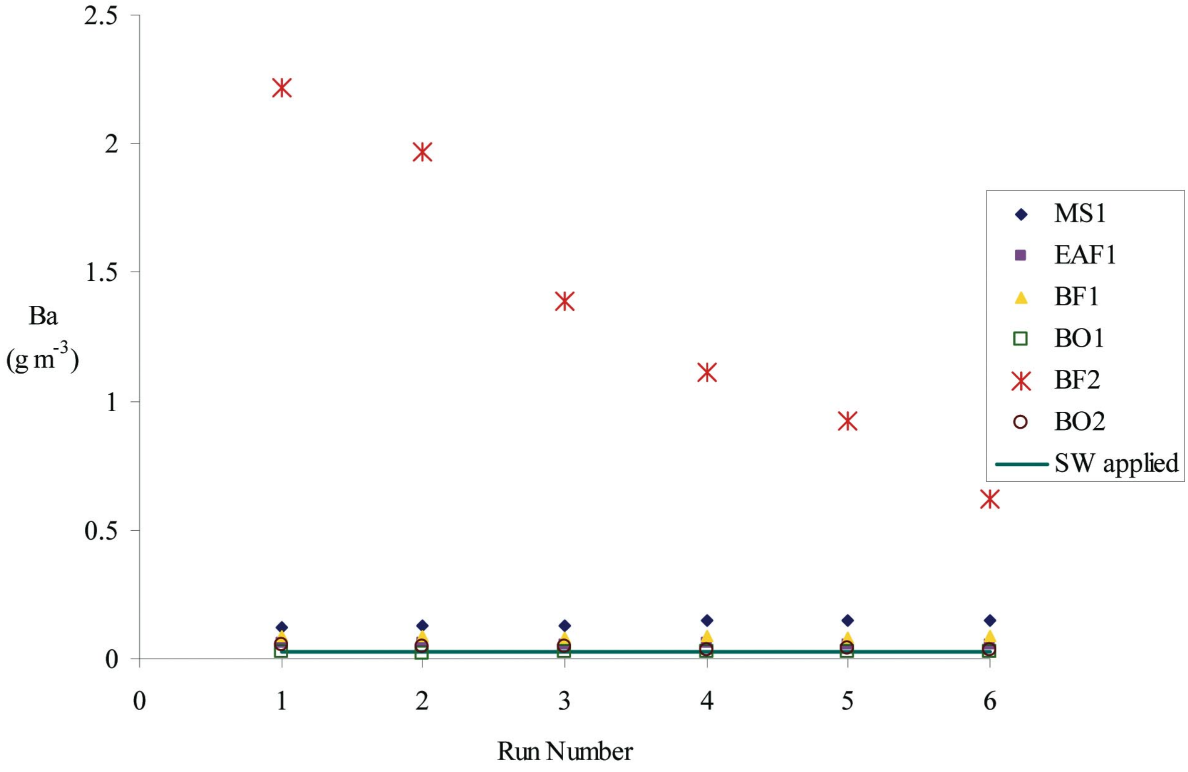


Table 6: Barium applied in stormwater and leached through slag samples.

	MS1	EAF1	BF1	BO1	BF2	BO2
Ba (g) applied	0.008	0.008	0.008	0.008	0.008	0.008
Ba (g) in leachate	0.040	0.017	0.024	0.007	0.393	0.012
% retention	-371	-97	-187	12	-4581	-45

Beryllium

Beryllium is normally only present at extremely low concentrations in road runoff (below the detection limit). No beryllium was detected in any of the slag leachates, indicating no significant environmental impact from the release of beryllium by any of the slags tested.

Boron

The 3 most alkaline slags (BO1, BF2, BO2) retained between 6 and 23% of applied boron, while the other 3 slag released boron in the leachate (Figure 8, Table 7). However, the concentration of boron in the leachate was below the upper limit of 5.2 g m^{-3} for boron in drinking water imposed by Food Standards Australia New Zealand for all samples. The release of boron in the first run of MS1 was very close to this limit, but concentrations decreased in subsequent runs. Dilution in the receiving environment will reduce the concentration further and there is unlikely to be significant environmental impact from this release.

Figure 8: Boron content of stormwater before and after leaching through slag samples.

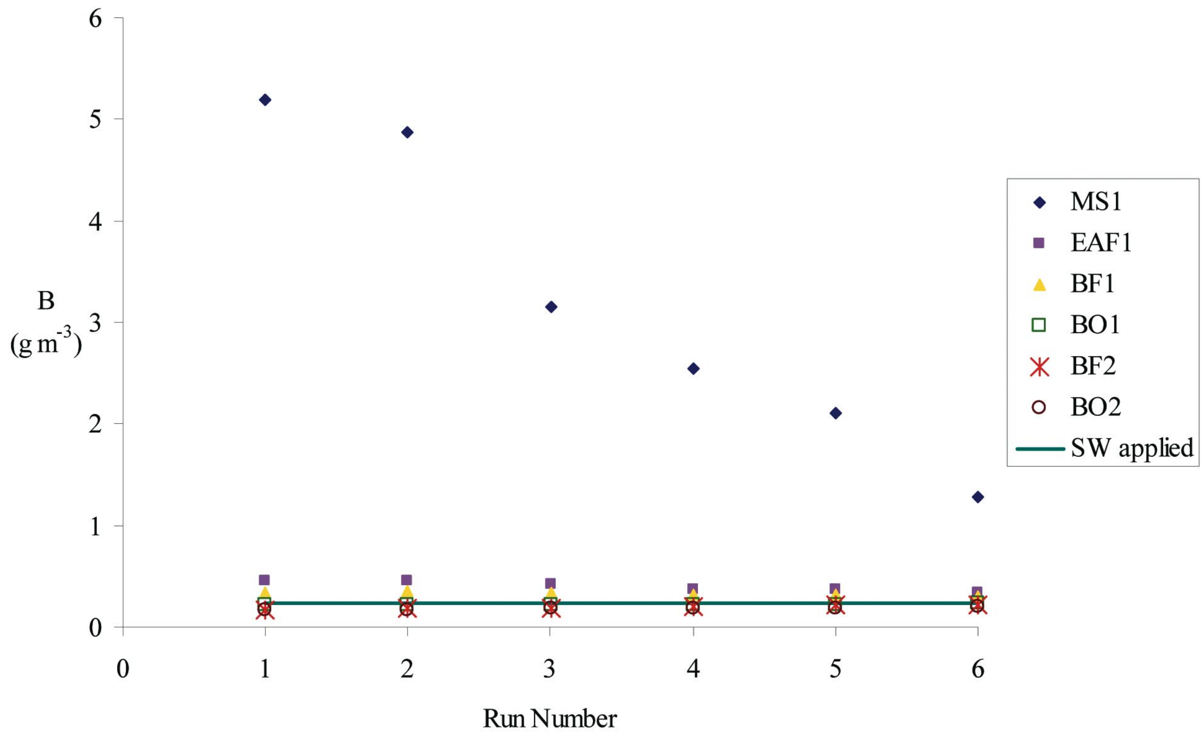


Table 7: Boron applied in stormwater and leached through slag samples.

	MS1	**EAF1**	**BF1**	**BO1**	**BF2**	**BO2**
B (g) applied	0.068	0.068	0.068	0.068	0.068	0.068
B (g) in leachate	0.915	0.115	0.094	0.064	0.056	0.053
% retention	-1233	-67	-37	6	18	23

Cadmium

Cadmium is commonly considered an undesirable and potentially toxic metal (ARC 2003, Shaver et al. 2005). The six slag filter media retained cadmium, so the concentration of cadmium in the leachate was less than applied as stormwater (Figure 9, Table 8). Two slags, MS1 and BF1, showed a steady decline in retention over the 6 runs. This behaviour is explained by these two slags having near neutral pH, while the other slags have higher pH values. Cadmium is less soluble at higher pH values (Alloway 1995).

Figure 9: Cadmium content of stormwater before and after leaching through slag samples.

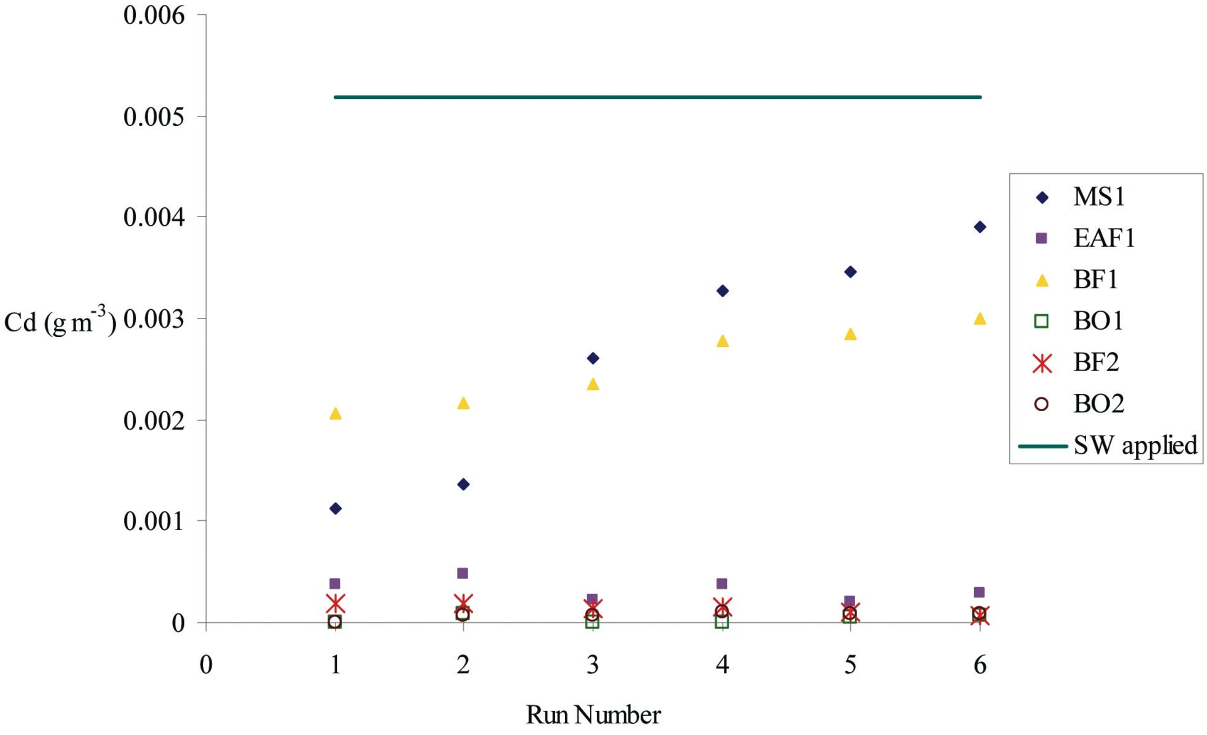


Table 8: Cadmium applied in stormwater and leached through slag samples.

	MS1	EAF1	BF1	BO1	BF2	BO2
Cd (g) applied	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Cd (g) in leachate	0.0008	0.0001	0.0007	0.0000	0.0000	0.0000
% retention	49	94	51	99	97	99

Chromium

Chromium is commonly considered an undesirable and potentially toxic metal (ARC2003, Shaver et al. 2005). One of the slags tested (MS1) retained >95% chromium, four (BF1, BO1, BF2, BO2) retained only up to 50% chromium, while EAF1 released more chromium to the leachate than was applied (Figure10, Table 9). However, the concentration of chromium in the leachate was below the upper limit of 0.05 g m^{-3} in drinking water imposed by Food Standards Australia New Zealand for all samples. Dilution in the receiving environment will reduce the concentration further and there is unlikely to be significant environmental impact from this release.

Figure 10: Chromium content of stormwater before and after leaching through slag samples.

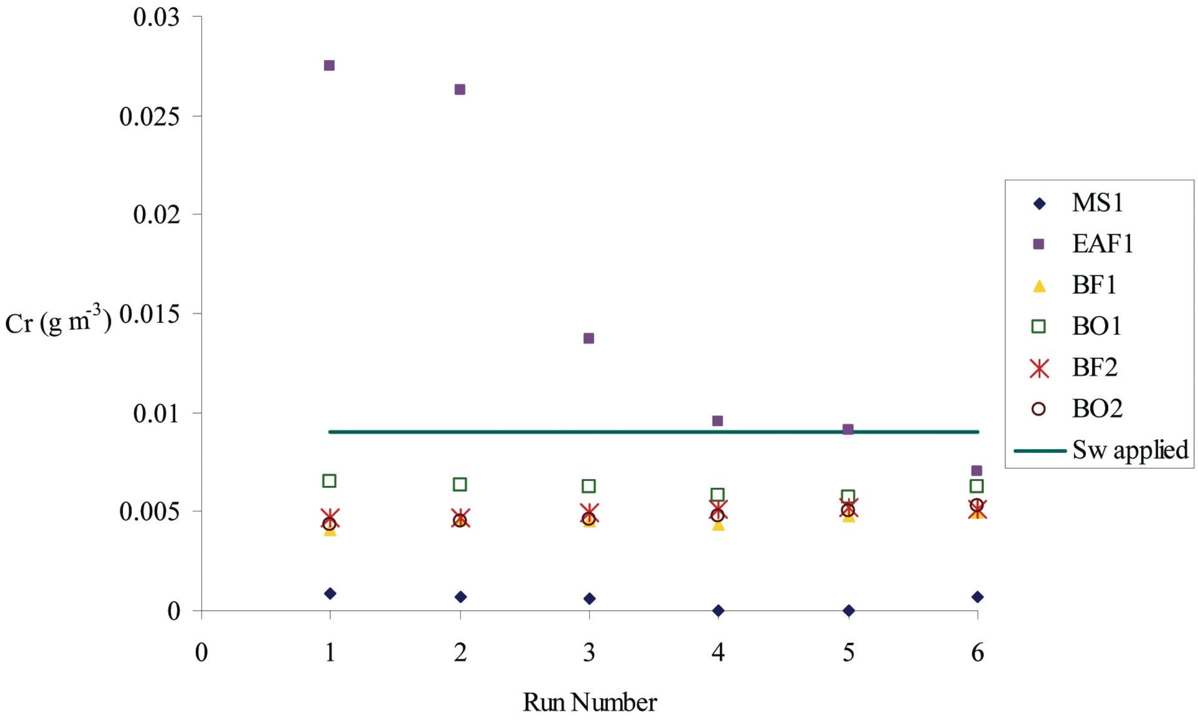


Table 9: Chromium applied in stormwater and leached through slag samples.

	MS1	EAF1	BF1	BO1	BF2	BO2
Cr (g) applied	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026
Cr (g) in leachate	0.0001	0.0045	0.0013	0.0018	0.0014	0.0014
% retention	95	-72	50	32	45	47

Copper

While copper is an essential element for plants and animals, excessive amounts are toxic and copper is commonly considered undesirable in stormwater (ARC 2003, Shaver et al. 2005). The six slag filter media retained copper, so the concentration of copper in the leachate was less than applied as stormwater (Figure 11, Table10). All six slags showed high retention (84 to 96%) of copper, one of the most prominent contaminant of concern in road runoff.

Figure 11: Copper content of stormwater before and after leaching through slag samples.

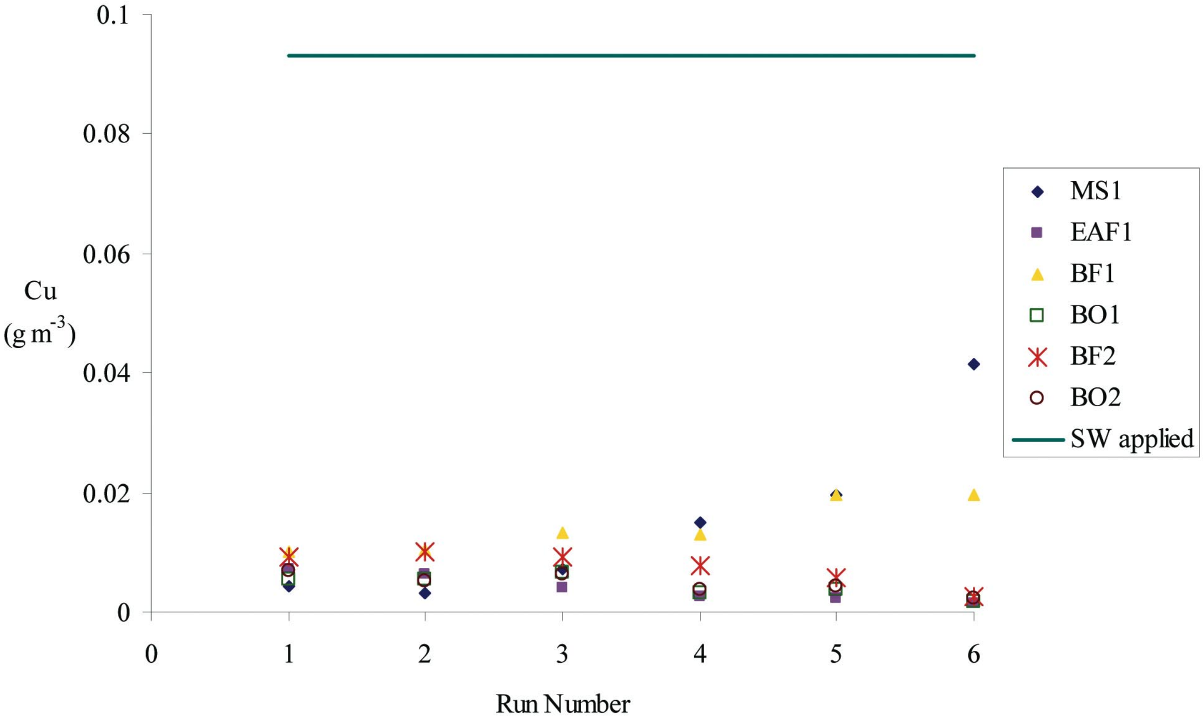


Table 10: Copper applied in stormwater and leached through slag samples.

	MS1	**EAF1**	**BF1**	**BO1**	**BF2**	**BO2**
Cu (g) applied	0.0267	0.0267	0.0267	0.0267	0.0267	0.0267
Cu (g) in leachate	0.0043	0.0011	0.0041	0.0013	0.0021	0.0014
% retention	84	96	85	95	92	95

Lead

Lead is commonly considered an undesirable and potentially toxic metal (ARC 2003). All six slag filter media retained between 83 and 100% lead, which is historically one of the most prominent contaminants of concern in road runoff, so the concentration of lead in the leachate was less than applied as stormwater (Figure 12, Table 11).

Figure 12: Lead content of stormwater before and after leaching through slag samples.

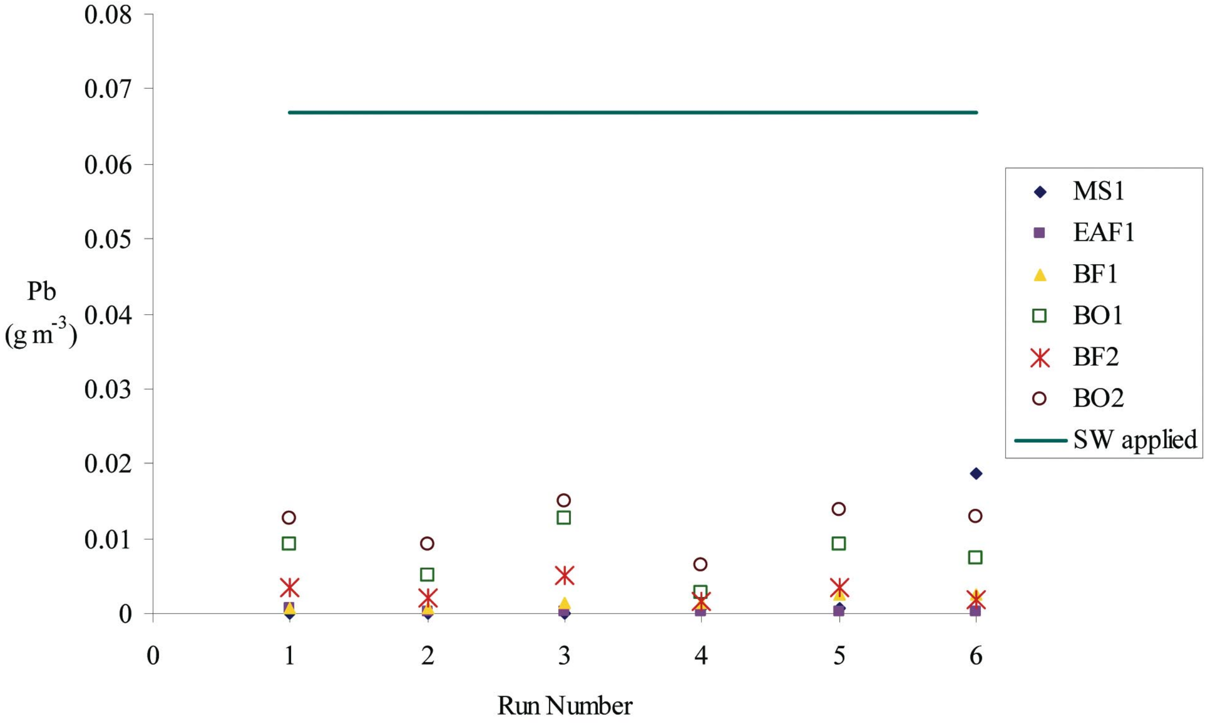


Table 11: Lead applied in stormwater and leached through slag samples.

	MS1	EAF1	BF1	BO1	BF2	BO2
Pb (g) applied	0.0192	0.0192	0.0192	0.0192	0.0192	0.0192
Pb (g) in leachate	0.0010	0.0001	0.0004	0.0022	0.0008	0.0034
% retention	95	100	98	88	96	83

Manganese

Four slag with alkaline pH (EAF1, BO1, BF2, BO2) retained manganese, so the concentration of manganese in the leachate was less than applied as stormwater, while MS1 and BF1 slag released more manganese to the leachate than was applied (Figure 13, Table 12). However, the concentration of manganese in the leachate was below the upper limit of 2.0 g m^{-3} for manganese in drinking water imposed by Food Standards Australia New Zealand for all samples. The concentration of manganese in the leachate from MS1 is close to this limit and increases with time, possibly peaking at run 5. Dilution in the receiving environment will reduce the concentration further and there is unlikely to be significant environmental impact from this release as long as concentrations do not continue to rise.

Figure 13: Manganese content of stormwater before and after leaching through slag samples.

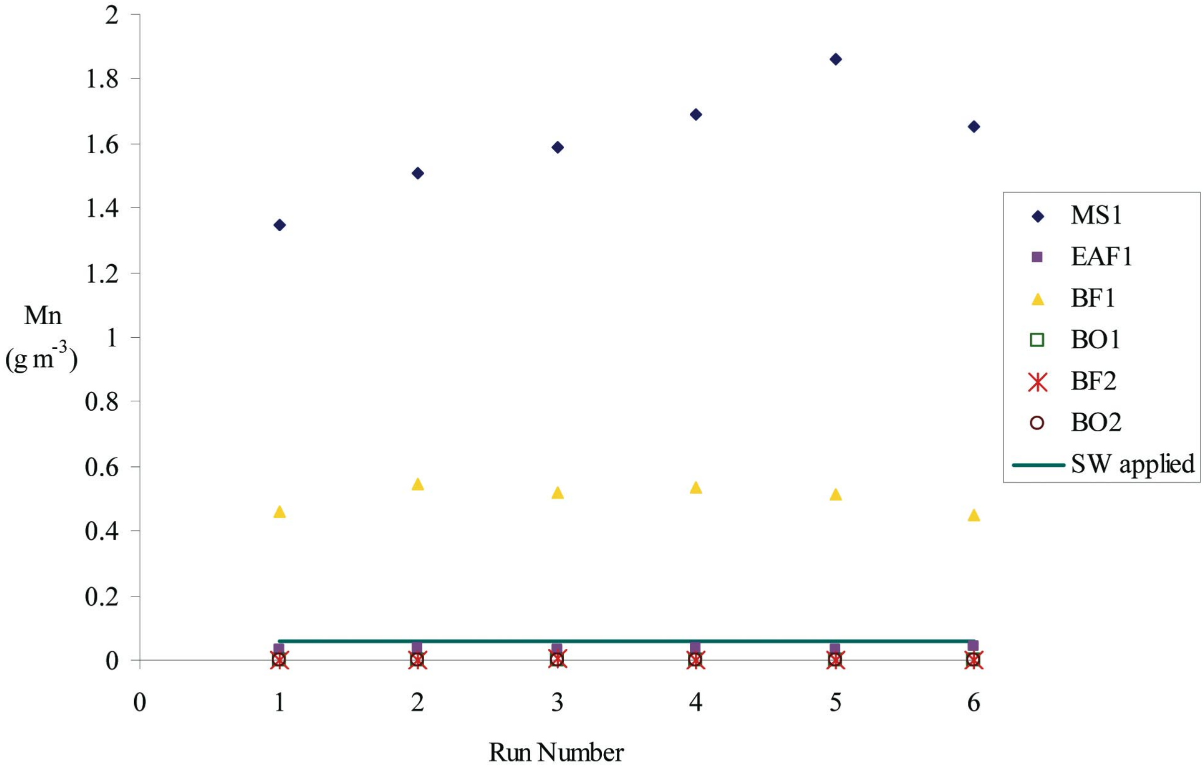


Table 12: Manganese applied in stormwater and leached through slag samples.

	MS1	EAF1	BF1	BO1	BF2	BO2
Mn (g) applied	0.017	0.017	0.017	0.017	0.017	0.017
Mn (g) in leachate	0.461	0.010	0.144	0.000	0.001	0.000
% retention	-2548	41	-728	99	97	98

Mercury

Mercury is normally only present at extremely low concentrations in road runoff (below the detection limit). No mercury was detected in any of the slag leachate indicating no significant environmental impact from the release of mercury by any of the slag tested.

Molybdenum

As only the MS1 retained about 31% molybdenum, the concentration of molybdenum in the leachate was less than applied as stormwater, while the other five slags released more molybdenum to the leachate than was applied (Figure 14, Table 13). No upper limit for molybdenum in drinking water was found for Food Standards Australia New Zealand, the US Environmental Protection Agency or a guideline value in the Australian and New Zealand guidelines for fresh and marine water quality (ANZECC & ARMCANZ 2000). However, the maximum permitted level in drinking water in California (Title 22 California Code of Regulations (CCR) Sections 64431–64444) is 0.05 g m^{-3}. The concentration of molybdenum in the leachate was below the maximum permitted level for all samples. Dilution in the receiving environment will reduce the concentration further and there is unlikely to be significant environmental impact from this release.

Figure 14: Molybdenum content of stormwater before and after leaching through slag samples.

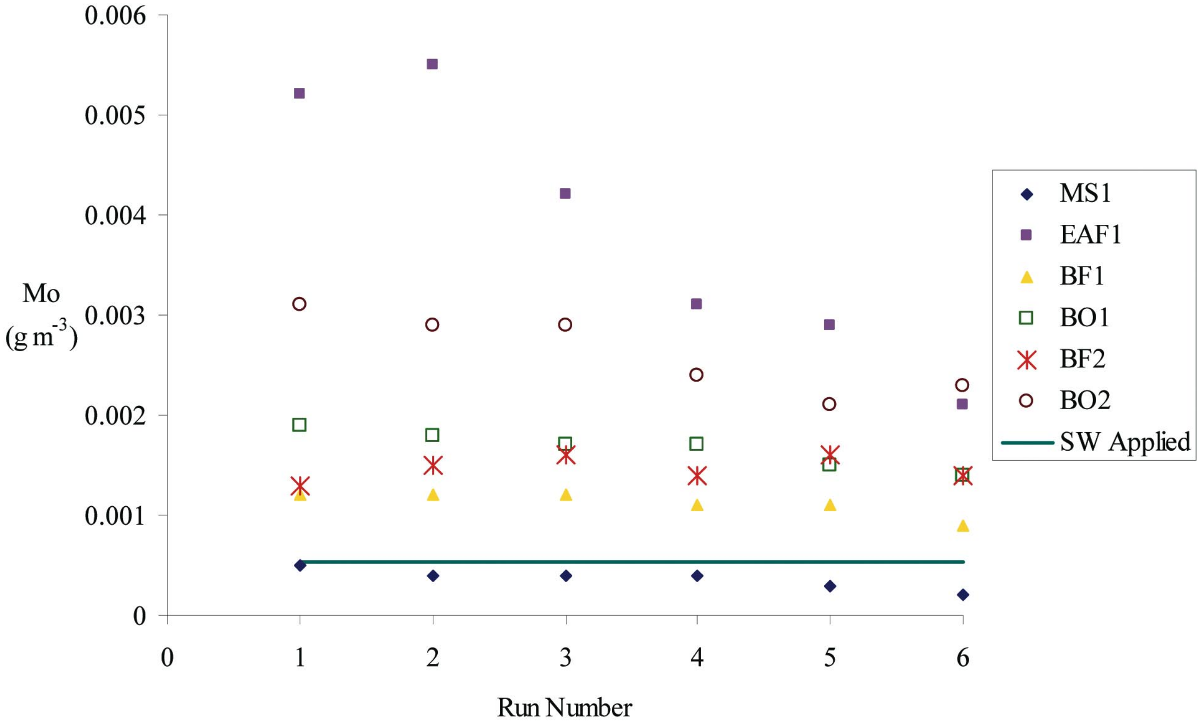


Table 13: Molybdenum applied in stormwater and leached through slag samples.

	MS1	EAF1	BF1	BO1	BF2	BO2
Mo (g) applied	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015
Mo (g) in leachate	0.00010	0.00110	0.00032	0.00048	0.00042	0.00075
% retention	31	-619	-109	-213	-175	-391

Nickel

Nickel is commonly considered an undesirable and potentially toxic metal (ARC 2003, Shaver et al. 2005). All six slag filter media retained nickel, so the concentration of nickel in the leachate was less than applied as stormwater (Figure 15, Table 14). There was a steady decrease in nickel retention over the first four runs for MS1 and BF1. Retention in subsequent runs did not decrease and nickel concentrations stayed at the same level. This behaviour is likely due to these two slags having near neutral pH while the other slags have higher pH values. Slag BO1, BF2 and BO2 have alkaline pH and removed nearly all nickel as it is less soluble at higher pH values (McGrath 1995).

Figure 15: Nickel content of stormwater before and after leaching through slag samples.

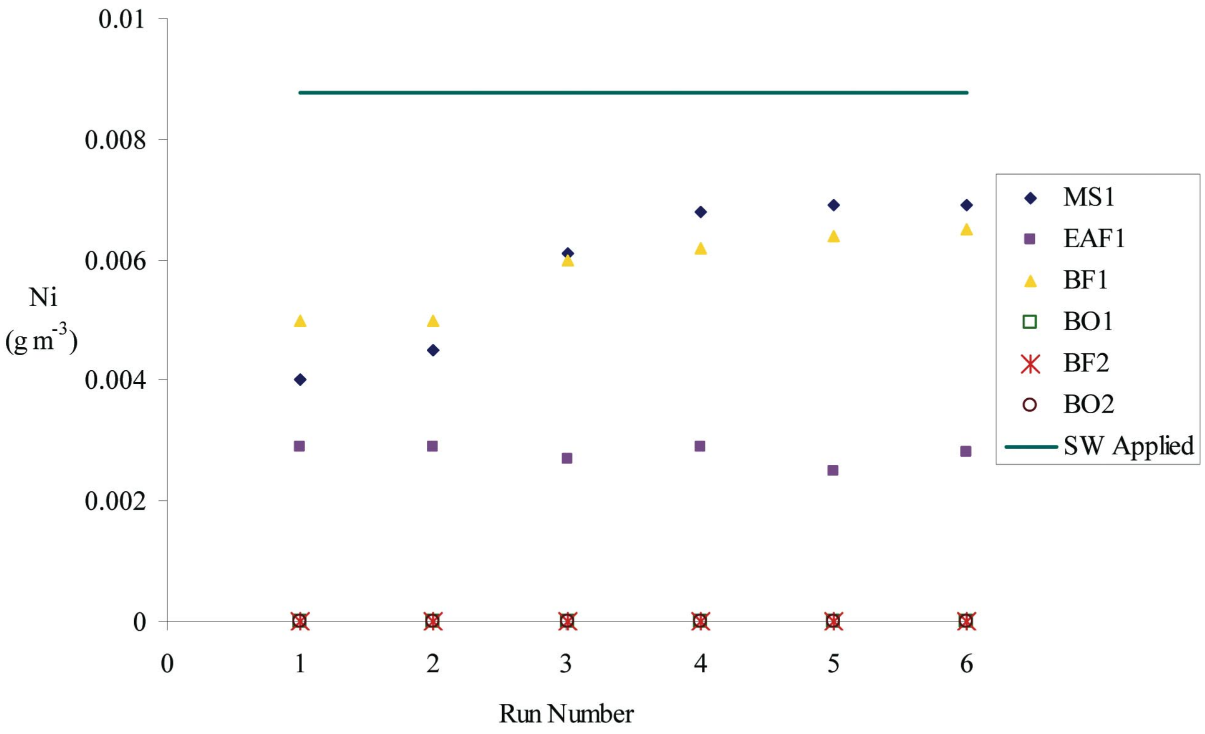


Table 14: Nickel applied in stormwater and leached through slag samples.

	MS1	EAF1	BF1	BO1	BF2	BO2
Ni (g) applied	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025
Ni (g) in leachate	0.0017	0.0008	0.0017	0.0000	0.0000	0.0000
% retention	33	68	33	100	100	100

Selenium

Selenium is present in road runoff only at very low concentrations, below the detection limit. Three samples of the BF1 and four samples of the BF2 exceeded the detection limit indicating release of selenium (Figure 16, Table 15). The concentration of selenium in the leachate was below the upper limit of 0.01 g m^{-3} for selenium in drinking water imposed by Food Standards Australia New Zealand for all samples. Dilution in the receiving environment will reduce the concentration further and there is unlikely to be significant environmental impact from this release.

Figure 16: Selenium content of stormwater before and after leaching through slag samples.

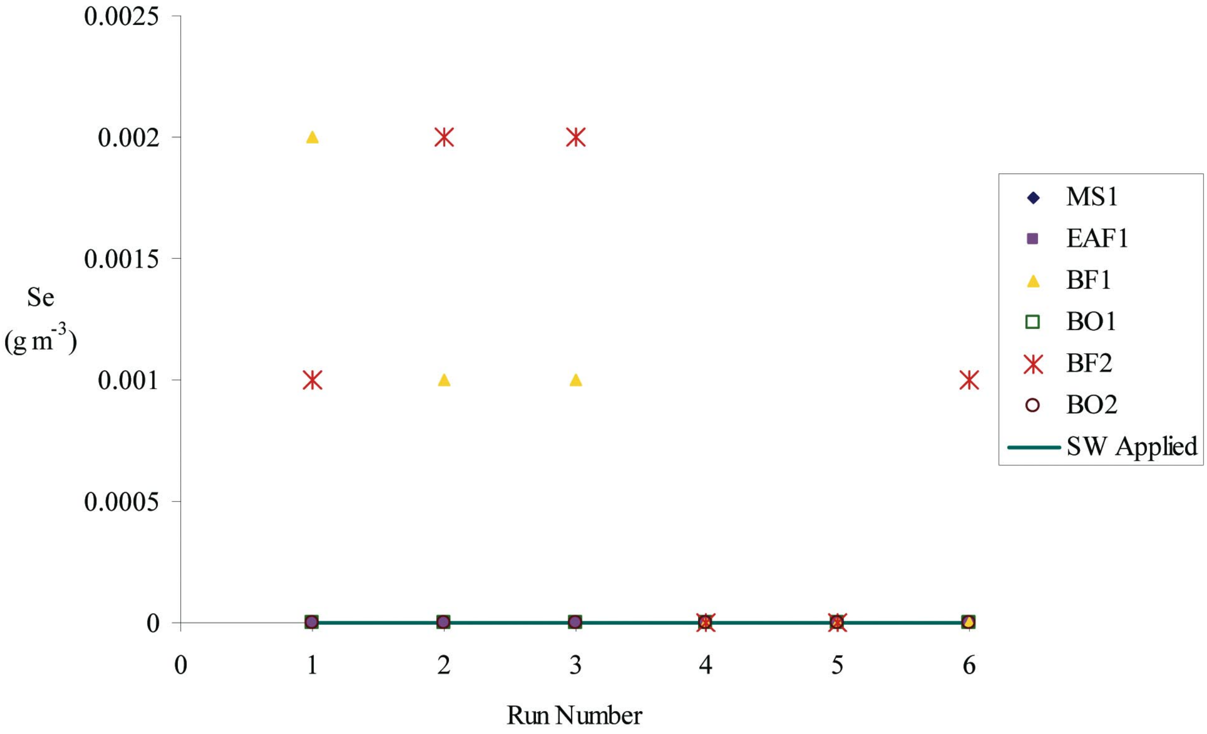


Table 15: Selenium applied in stormwater and leached through slag samples.

	MS1	EAF1	BF1	BO1	BF2	BO2
Se (g) applied	0.000003	0.000003	0.000003	0.000003	0.000003	0.000003
Se (g) in leachate	0.000000	0.000000	0.000191	0.000000	0.000287	0.000000

Tin

Tin is normally only present at extremely low concentrations in road runoff (below the detection limit). No tin was detected in any of the slag leachate, indicating no significant environmental impact from the release of tin by any of the slags tested.

Zinc

While zinc is an essential element for animals and higher plants it is toxic to other biota and is commonly considered the most prominent contaminant of concern in road runoff (ARC 2003, Shaver et al. 2005). As the six slag filter media retained zinc, the concentration of zinc in the leachate was less than applied as stormwater (Figure 17, Table 16). Two slags, MS1 and BF1, showed a steady decline in retention over the 6 runs. These two slags have near neutral pH, while the other slags have higher pH values. Slag BO1, BF2 and BO2 have alkaline pH and removed nearly all Zinc as it is more strongly adsorbed at high pH values (Kiekens 1995). Slag EAF1, with a pH of less than 9, also removed nearly all zinc.

Figure 17: Zinc content of stormwater before and after leaching through slag samples.

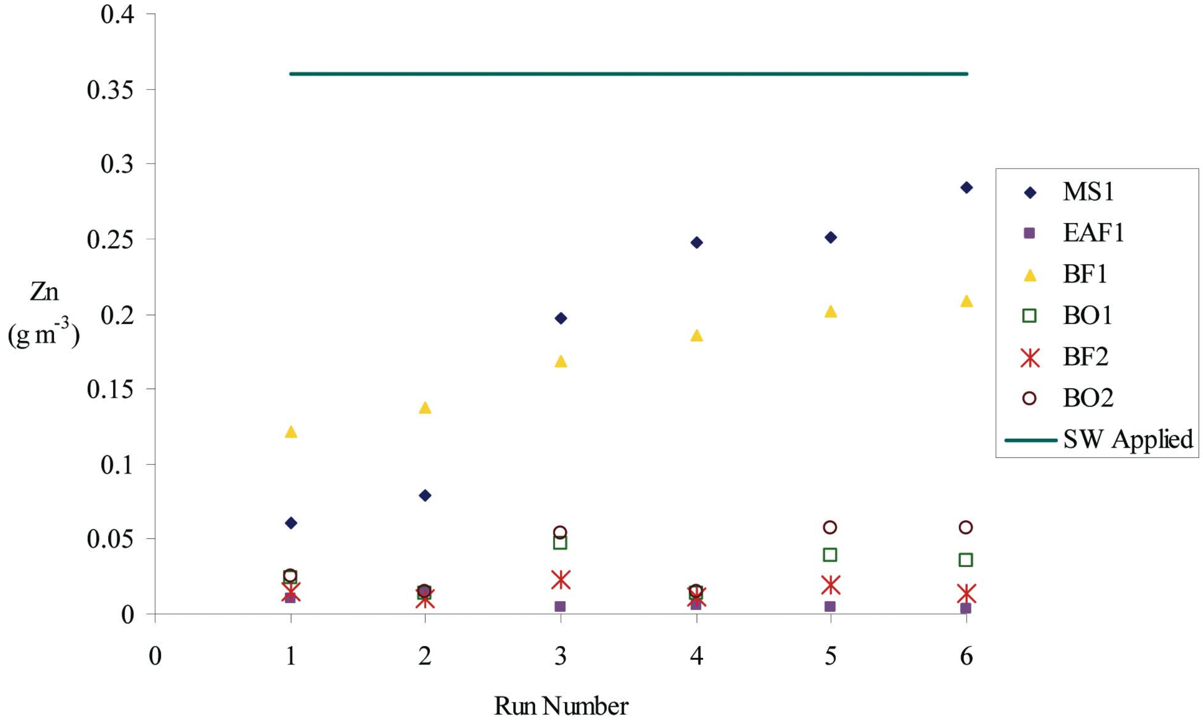


Table 16: Zinc applied in stormwater and leached through slag samples.

	MS1	EAF1	BF1	BO1	BF2	BO2
Zn (g) applied	0.103	0.103	0.103	0.103	0.103	0.103
Zn (g) in leachate	0.054	0.002	0.049	0.008	0.004	0.011
% retention	48	98	53	92	96	90

Nitrogen

Excessive levels of nutrients such as nitrogen are undesirable in stormwater as they stimulate plant and algal growth (ARC 2003, Shaver et al. 2005). Nitrogen exists as nitrate in oxygenated water and is not easily adsorbed (Shaver 2005). The concentration of nitrogen in the stormwater was not consistently reduced by any of the filter media tested and there was no release of nitrogen from any of the slags (Figure 18, Table 17). The slag tested did not retain nitrogen from the stormwater.

Figure 18: Nitrogen content of stormwater before and after leaching through slag samples.

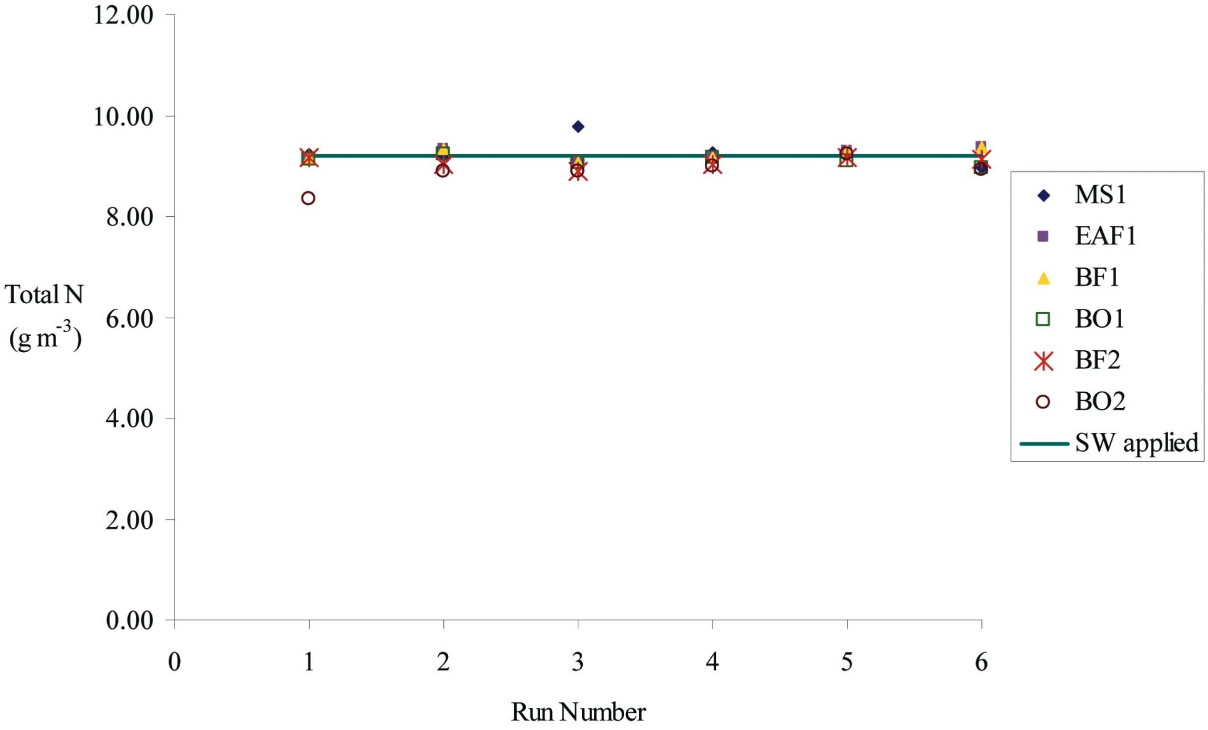


Table 17: Nitrogen applied in stormwater and leached through slag samples

	MS1	EAF1	BF1	BO1	BF2	BO2
N (g) applied	2.64	2.64	2.64	2.64	2.64	2.64
N (g) in leachate	2.22	2.65	2.61	2.54	2.60	2.55
% retention	16	0	1	4	2	4

Phosphorus

Excessive levels of nutrients such as nitrogen are undesirable in stormwater as they stimulate plant and algal growth (ARC 2003, Shaver et al. 2005). The six slag filter media retained from 30 to 84% phosphorus, so the concentration of phosphorus in the leachate was less than applied as stormwater (Figure 19, Table 18).

Figure 19: Phosphorus content of stormwater before and after leaching through slag samples.

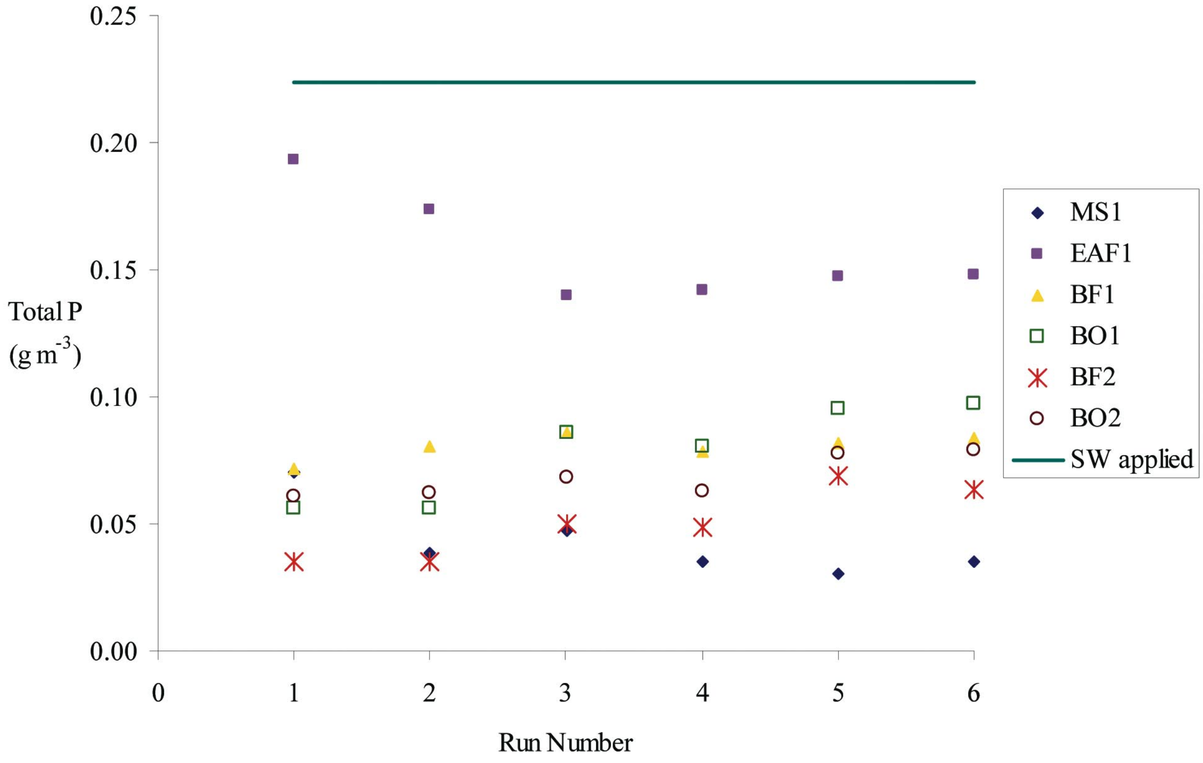


Table 18: Phosphorus applied in stormwater and leached through slag samples

	MS1	EAF1	BF1	BO1	BF2	BO2
P (g) applied	0.064	0.064	0.064	0.064	0.064	0.064
P (g) in leachate	0.010	0.045	0.023	0.022	0.014	0.020
% retention	84	30	64	65	78	69

Sulphate

As the six slag filter media released sulphate, the concentration of sulphate in the leachate was more than applied as stormwater (Figure 20, Table 19). The BF1 released much larger concentrations of sulphate than the other five slag, particularly in the initial leachate. Explaining this behaviour would require further investigations. Concentrations of sulphate decreased markedly over the six stormwater applications but were still higher than any measurements of the other slags. Food Standards Australia New Zealand has not set limits for sulphate in drinking water. However, the concentration of sulphate in the leachate was below the Australian and New Zealand guidelines for fresh and marine water quality (ANZECC & ARMCANZ 2000) of 400 g m^{-3}. These Guidelines are designed for pristine waters, not for modified water-way systems to which stormwater is discharged, so achieving this limit indicates there would be no significant negative environmental impact from this release, and as sulphur is an essential plant nutrient it might even be beneficial. Aquatic organisms use sulphur, and reduced concentrations have a detrimental effect on algal growth. When sulphate is less than 0.5 g m^{-3}, algal growth will not occur. Problems caused by sulphates are most often related to their ability to form sulphuric acid, which changes the pH. Sulphate ions also are involved in complexing and precipitation reactions, which affect the solubility of metals and other substances.

Figure 20: Sulphate content of stormwater before and after leaching through slag samples.

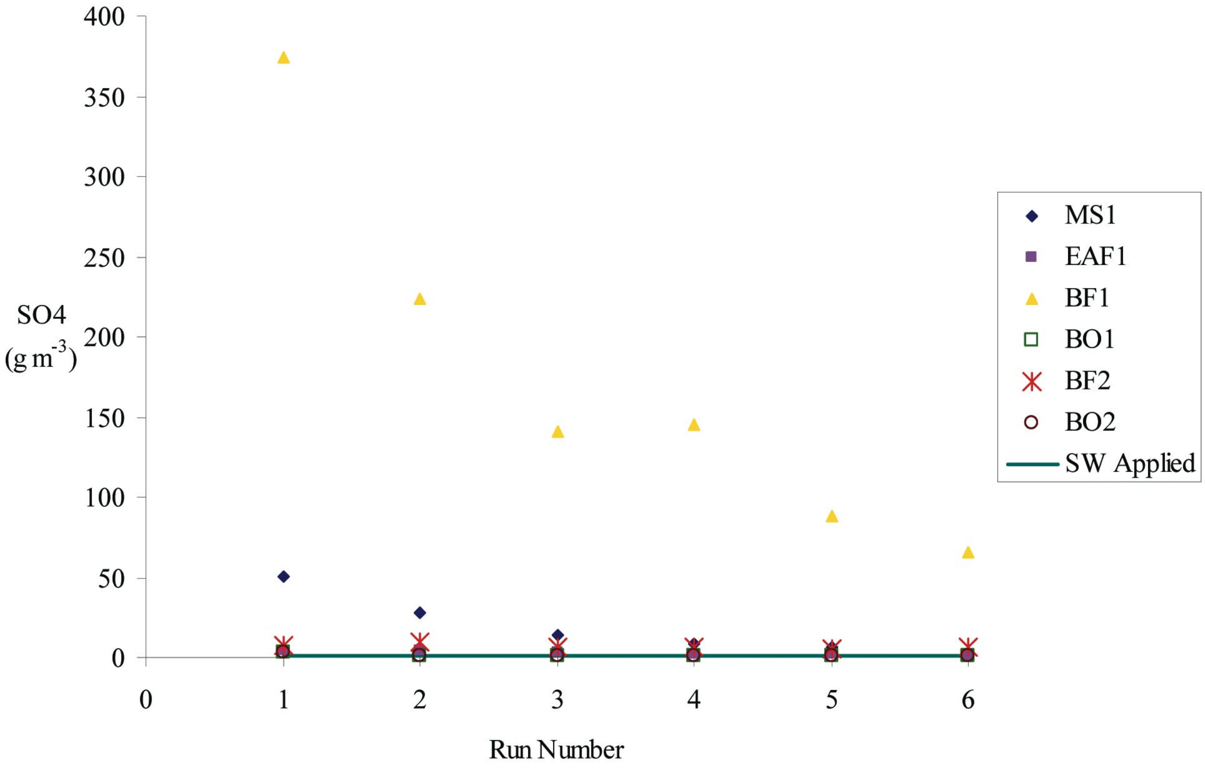


Table 19: Sulphate applied in stormwater and leached through slag samples

	MS1	EAF1	BF1	BO1	BF2	BO2
SO$_4$ (g) applied	0.175	0.175	0.175	0.175	0.175	0.175
SO$_4$ (g) in leachate	4.007	0.830	49.621	0.429	2.046	0.336
% retention	-2194	-375	-28310	-146	-1072	-93

Slag composition

Total element analysis of the slags before and after leaching with 6 stormwater applications is presented in Table 20. The results show changes up to 10 % between the slag without leaching and the slag after leaching. However, the changes appear caused by inherent variability within the slags, not due to changes due to retention or release of contaminants. Both the amount of silicon, virtually insoluble in water, and titanium, insoluble in water and only attacked by acids if they are heated (MERCK Index 1989), have changed when they should remain constant or increase slightly (as other elements are solubilised and washed out of the slag matrix). Silicon has increased or decreased by up to 7% although no silica has been added in the stormwater, while titanium has also increased or decreased by up to 6%. Again, there was no titanium in the stormwater. This variability precludes being able to perform mass balance calculations as the amounts of contaminants added are too small to be accurately measured, i.e. only 2.64 g of nitrogen were added in the 6 applications of stormwater to 6 kg of BF1 or 0.044%. The trace metals additions are even lower.

3.3 Assessment Of Slag As A Treatment Media For Stormwater

Treatment efficiencies can be used as an indication of performance and are useful when comparing different stormwater treatment filters (USEPA 2002). Treatment efficiency data are included in the Auckland Regional Council stormwater guidelines (ARC 2003). There are a number of different methods used to determine treatment efficiency. We used the following widely adopted method (USEPA 2002):

$$1-\left(\frac{\text{average output concentration}}{\text{average input concentration}}\right) \times 100$$

Treatment efficiency data for six slag samples leached with artificial stormwater are presented in Table 21. These data are compared with removal rates provided in regional guidelines, which estimate long-term removal rates from infiltration devices, such as paver/filter media systems, to be 85–90% for metals, 60–70 % for total phosphorus, and 55–60% for total nitrogen (ARC 2003). All six slags tested met the estimated removal rate targets for some but not all metals. The phosphorus removal rate target was met by five slags but none of the slags met the nitrogen removal rate target. MS1 met the removal rates for aluminium, arsenic, chromium, lead and phosphorus, while the removal rate for copper, at 84 % retention, was just below target. EAF1 met the removal rates for aluminium, cadmium, copper, lead and zinc. BF1 met the removal rates for aluminium, copper, lead, zinc and phosphorus. BO1 met the removal rates for cadmium, copper, lead, zinc and phosphorus. BF2 met the removal rates for cadmium, copper, lead, nickel, zinc and phosphorus. PK SFS met the removal rates for arsenic, cadmium, copper, nickel, zinc and phosphorus, while the removal rate for lead, at 83%, was only a little below the target.

The removal rates of cadmium, nickel and zinc declined over the 6 runs for MS1 and BF1, the two near neutral slags tested, reducing their effectiveness for treating stormwater containing these contaminants.

Table 20: Total element analysis of slag samples before and after 6 stormwater applications

Sample No.	Stormwater application	Fe	CaO	SiO$_2$	TiO$_2$	Al$_2$O$_3$	MgO	P	V$_2$O$_3$	MnO	S	Na$_2$O	K$_2$O	Zn	Cr	Cu	Tot %
MS1	Before	3.05	15.74	13.34	34.44	18.95	13.43	0.00	0.25	1.26	0.13	0.35	0.13	0.01	0.00	-0.01	102.370
	After	3.16	16.13	13.18	33.82	19.32	13.48	0.01	0.26	1.19	0.14	0.31	0.12	-0.01	0.01	-0.02	102.284
Change		0.11	0.39	-0.16	-0.62	0.37	0.05	0.01	0.01	-0.07	0.01	-0.04	-0.01	-0.02	0.01	-0.01	
EAF1	Before	27.35	23.08	9.80	6.54	8.04	9.36	0.18	0.45	4.57	0.09	0.07	0.00	-0.01	0.90	0.00	102.195
	After	30.99	25.71	9.43	1.17	6.11	8.23	0.22	0.47	5.24	0.07	0.01	0.00	0.01	1.01	0.00	101.991
Change		3.64	2.63	-0.37	-5.37	-1.93	-1.13	0.04	0.02	0.67	-0.02	-0.06	0.00	0.02	0.11	0.00	
BF1	Before	15.32	30.44	20.32	2.60	11.46	8.99	0.15	0.16	4.70	0.28	0.21	0.19	0.00	0.29	-0.01	101.670
	After	5.76	38.66	26.98	0.67	14.57	9.34	0.15	0.05	1.33	0.42	0.24	0.25	-0.02	0.01	-0.02	100.884
Change		-9.56	8.22	6.66	-1.93	3.11	0.35	0.00	-0.11	-3.37	0.14	0.03	0.06	-0.02	-0.28	-0.01	
BO1	Before	13.64	41.41	17.47	0.76	5.76	8.88	0.44	0.14	6.41	0.07	0.02	0.01	-0.01	0.10	-0.01	100.943
	After	16.62	42.85	16.12	0.79	2.95	9.78	0.54	0.16	3.74	0.07	0.03	0.01	-0.01	0.08	-0.01	100.867
Change		2.98	1.44	-1.35	0.03	-2.81	0.90	0.10	0.02	-2.67	0.00	0.01	0.00	0.00	-0.02	0.00	
BF2	Before	1.29	41.30	34.59	0.90	14.07	6.73	0.00	0.03	0.39	0.52	0.26	0.31	-0.02	0.00	-0.02	100.905
	After	1.38	41.24	34.71	0.83	13.97	6.74	0.00	0.03	0.40	0.44	0.25	0.28	-0.02	0.00	-0.02	100.837
Change		0.09	-0.06	0.12	-0.07	-0.10	0.01	0.00	0.00	0.01	-0.08	-0.01	-0.03	0.00	0.00	0.00	
BO2	Before	20.70	39.18	11.61	0.91	2.39	9.92	0.67	1.30	3.96	0.06	-0.01	0.01	-0.01	0.13	-0.01	99.701
	After	19.24	39.56	11.44	0.89	3.88	10.92	0.66	1.27	4.05	0.06	0.00	0.00	-0.01	0.12	-0.01	100.330
Change		-1.46	0.38	-0.17	-0.02	1.49	1.00	-0.01	-0.03	0.09	0.00	0.01	-0.01	0.00	-0.01	0.00	

Table 21: Treatment efficiency data for six slag samples leached with artificial stormwater

Slag	Al	Sb	As	B	Ba	Be	Cd	Cr	Cu	Pb	Mn	Hg	Mo	Ni	Se	Sn	Zn	N	P	SO$_4$	pH
MS1	87	<DL	97	-1233	-371	<DL	49	95	84	95	-2548	<DL	31	33	<DL	<DL	48	16	84	-2194	N
EAF1	89	<DL	54	-67	-97	<DL	94	-72	96	100	41	<DL	-619	68	<DL	<DL	98	0	30	-375	A
BF1	93	<DL	74	-37	-187	<DL	51	50	85	98	-728	<DL	-109	33	<DL	<DL	53	1	64	-28310	N
BO1	-78	<DL	70	6	12	<DL	99	32	95	88	99	<DL	-213	100	<DL	<DL	92	4	65	-146	SA
BF2	28	<DL	71	18	-4581	<DL	97	45	92	96	97	<DL	-175	100	<DL	<DL	96	2	78	-1072	SA
BO2	32	<DL	86	23	-45	<DL	99	47	95	83	98	<DL	-391	100	<DL	<DL	90	4	69	-93	SA

Some of the slags released contaminants rather than removing them. However, with the exception of barium from BF2, contaminant concentrations remained within ANZECC & ARMCANZ (2000) guidelines or drinking water standards and no environmental impact is expected from these releases. MS1 released barium, boron, manganese and molybdenum. EAF1 released barium, boron, chromium and molybdenum. BF1 released barium, boron, manganese and molybdenum. BO1 released aluminium and molybdenum. BO2 released barium and molybdenum. BF2 released barium. Only the 4 initial samples exceeded the drinking water standard and concentrations rapidly decreased. There is only a potential environmental effect from leachate from BF2 if high concentrations continue. BF2 also released molybdenum but concentrations were below the maximum permitted level in drinking water.

Results from this study are compared with those in laboratory studies reported by Taylor and Trowsdale 2005, Pandey and Taylor (2004a), Clark et al. (1999), and Tenney et al. (1995). In Tenney et al. (1995), treatment efficiency was derived from raw data reported using the same calculation described above. A difference in the studies is that Clark et al. (1999) and Tenney et al. (1995) used stored stormwater in their experiments, while Taylor and Trowsdale 2005, Pandey and Taylor (2004a) and this study used artificial laboratory-made stormwater. Artificial stormwater was chosen to provide controlled experimental conditions. Stored stormwater is not stable, with solid and dissolved fractions of contaminants changing over time (Burton & Pitt 2001).

The permeability of filter medium is of critical importance as the capability to treat large volumes of solution is required (ARC 2003). The pH of treated stormwater should be near neutral (ANZECC & ARMCANZ 2000). The priority elemental contaminants to remove from stormwater in New Zealand are zinc and copper as they have the highest concentrations. The removal of nitrogen and phosphorus is desirable for aesthetic reasons, such as preventing algae blooms (Shaver et al. 2005; ARC 2003). The removal of arsenic, cadmium, chromium, lead and nickel is desirable but, because these contaminants are already at very low concentrations in stormwater, not as essential as the removal of zinc and copper (lead concentrations in stormwater have dropped since the introduction of unleaded petrol) (Shaver et al. 2005; ARC 2003).

Sand is the most common filter medium in filtration devices and has been studied by Clark et al. (1999) and Tenney et al. (1995). Data reported in these two studies does not meet ARC (2003) estimates for Cu, Zn, P and N removal. Sand has been shown to remove contaminants from runoff but to be unable to retain them as the contaminants are “trapped” in the inter-pore spaces and are easily washed out by the next flush of water (Clark et al. 1999). Sand has been coated with mineral oxides to enhance removal of heavy metals (Liu et al. 2001; Sanasalone 1999), but this is currently an expensive option in New Zealand.

3.4 Uses Identified

All the slags tested have potential as stormwater filter media as they reduced the concentrations of arsenic cadmium, copper, lead, nickel, zinc, phosphorus and nitrogen in the artificial stormwater. They are a potential substitute for sand in filtration devices and in infiltration devices such as filter strips. In this laboratory experiment we have tested the ability of slag to remove the most biologically available and most difficult fraction of contaminants to remove, the dissolved fraction. The effect of suspended sediment entrained in stormwater has not been tested here, although in a field test using landfill leachate, Nehrenhiem et al (2005) reported removal of suspended sediment did not affect sorption capacity inside the filters. They also reported that removal rate for suspended sediment to be similar or better than sand (10–30%). The suspended sediment removal rate for sand filters treating road runoff is usually >75% and New Zealand regulations require suspended sediment to be reduced by at least this figure by any alternative stand-alone practice (ARC 2003). Physical clogging of infiltration systems is also very common and has been demonstrated to occur well before the sorptive capacity of the media is reached if runoff is filtered without adequate pre-treatment (McKergow 1994; Clark et al. 1999; Keblin et al. 1997). In one experiment, Tenney et al. (1995) showed that if sediment concentration is reduced in stormwater before it is filtered, filtration systems may work effectively four times longer than when sediment concentration is not reduced before filtration. It is also difficult for any one device to remove all the contaminants found in stormwater. A better approach is integrating several stormwater devices into a comprehensive system. Such systems have been named ‘treatment trains’. The filter media tested here should be employed not in isolation but as part of a treatment train to ensure maximum efficiency and longevity in the urban stormwater treatment system.

Other potential uses are treatment of landfill leachate, agricultural, domestic and industrial waste water treatment, and treatment of acid mine drainage.

Blast furnace slag was investigated in laboratory and pilot field studies by Nehrenhiem et al. (2005) using landfill leachate, and was found to effectively remove metals in solution. However, the columns used were very small (0.15 m diameter by 0.6 m high) and the capacity to remove metals in the field trial was exhausted after only 12 days. Kietlińska and Renman (2005) also carried out a laboratory experiment utilising blast furnace slag in columns to treat landfill leachate. The removal efficiencies over approximately a month of operation were 66 % for copper, 16 % for molybdenum, 19 % for nickel and 62 % for zinc. Depending on the target contaminants to be removed, all or some of the 6 slag tested in our study may be suitable for landfill leachate treatment.

In a review of substrates for phosphorus removal from domestic and dairy wastewater, Johansson Westholm (2006) showed blast furnace and electric arc slag materials in filter boxes or in constructed wetland systems can remove approximately 30–60% of phosphorus. The study period was 3–6 months. However, an 11 year study on phosphorus removal from a domestic wastewater plant incorporating 10 slag filters in parallel and two treatment ponds has been reported (Shilton et al 2006). This paper reports phosphorus concentrations were lowered from about 8 to 2.4 g m^3 for the first 5 years of operation and from the 6th year P removal was severely reduced. In another study, using blast furnace slag in a constructed wetland to treat domestic wastewater, Korkusuz et al (2005) reported removal of suspended sediment (59%), total nitrogen (39%) and phosphorus (4%) after 1 year of operation. The variability of phosphorus removal in these studies may be due to the properties of the wastewater or, more likely, the properties of the slag themselves. Our results presented above also show considerable variability in contaminant removal from the 6 slags tested. However, all six slags in our study retained phosphorus and other metal contaminants and may be suitable for wastewater treatment.

The long-term acid neutralising capacity of steel slag has been reported by Yan et al (2000), while Ziemkiewicz (1998) built slag leach beds to treat acid mine drainage from a coal mine. Reductions of 85% in acidity (pH increased from 3.8 to >5) were achieved over 9 months of operation. Contaminant metal concentrations have also been reduced using slag. Tailing leachate from two Korean gold mines was treated by basic oxygen slag in a laboratory experiment (Ahn et al. 2003), achieving reductions in arsenic to < 0.5 g m^3. Three of the slags we tested (BO1, BF2 and BO2) appear suitable for treating acid mine drainage.

Three of the slags tested in this study (MS1, EAF1 and BF1) removed >85 % of aluminium in stormwater. There may be some application in reclaiming aluminium from Bauxite residue (also known as red mud), a by-product of the Bayer process used in aluminium smelting. There are apparently no studies on this application and feasibility needs to be established.

4. Conclusions

Literature review suggests that despite elevated total concentrations of trace metals in all steel industry slags, very little is likely to leach into the environment and there is minimal environmental or health hazard.

All the six slags tested have potential as stormwater filter media as they reduced the concentrations of arsenic, cadmium, copper, lead, nickel, zinc, phosphorus and nitrogen in the artificial stormwater. Some, but not all of the slag also reduced the concentrations of aluminium, chromium, manganese and molybdenum. Only three slags reduced the concentrations of boron; the other three released boron. All but one slag released concentrations of barium.

The best slags for neutralising the acidity in stormwater are BF1 and MS1 (limited to runoff pH > 4). The MS1 steadily declined in pH value (from 8 to 6) indicating less buffering capacity than the other slags and so should only be used to treat runoff with pH >4 (i.e. not acid industrial runoff). EAF1 is the best slag for use where the receiving waters are already alkaline. Slag with leachate of pH >9 could be used where the receiving waters are already alkaline, such as in areas of limestone. However, site-specific ecological risk assessment may be needed for slag use in and around small water bodies with limited dilution volume due to high pH adversely affecting aquatic plant growth. The slags with leachate above pH 10 are also probably suited to treating highly acidic stormwater such as found in acid mine drainage (Ziemkiewicz 1998).

The hydraulic conductivity for all six slags was greater than could be supplied (K_{sat} > 100 000 mm h^{-1}) and no practical hydraulic restrictions are expected from the slag filters until and unless they become clogged.

No antimony, beryllium, mercury, selenium, and tin were detected in the leachates, indicating little environmental impact from the release of antimony, beryllium, mercury, selenium, and tin by any of the slag tested. The release of aluminium, boron, manganese, molybdenum, in the leachate by some of the slags, and sulphate by all of the slags was below the upper limits in drinking water imposed by Food Standards Australia New Zealand for all samples. Dilution in the receiving environment will reduce the concentrations further and there is unlikely to be any negative environmental effect from the use of these slag materials as stormwater filter media. There is only a potential environmental effect from leachate from the BF2 that barium will accumulate in the bodies of fish and other aquatic species if high concentrations continue. However, as already stated, dilution in the receiving environment will reduce the concentration further and there is unlikely to be significant environmental impact from this release.

Literature research also indicates slag may be suitable for treatment of landfill leachate, domestic, industrial and agricultural wastewater, and acid mine drainage, as well as treatment of stormwater.

5. Specific Recommendations

1. On the basis of the results obtained from this laboratory trial, it is recommend that the most promising media of the 6 slags tested, be field trialled in a stormwater filter to confirm promising initial laboratory results. The filter media tested here should be employed not in isolation, but as part of a treatment train to ensure maximum efficiency and longevity in the urban stormwater treatment system.

2. The slags should be further tested in a controlled field study to assess long-term removal efficiencies as this experiment was designed only to test the short-term removal efficiency.

3. The necessary maintenance regime should be determined by a field study measuring clogging potential of the media.

4. The suitability of the 6 slags tested in our study for landfill leachate treatment and industrial and agricultural wastewater treatment drainage should be determined in pilot-scale field studies, as iron and steel slags already have a track record of successful use, particularly in domestic wastewater treatment.

5. The suitability of the 3 very alkaline slags tested in our study for treating acid mine drainage should be further tested in a laboratory study.

6. The feasibility of using slag to reclaim aluminium in residues from aluminium smelting should be investigated by initiating discussions with those in that industry.

6. General Recommendations

1. Laboratory studies provide an approximation of field conditions, and further testing should be done in a controlled field study because:
    a. depending on the type of construction, slag may retain or provide a suitable surface to degrade other contaminant not tested here, e.g., oils often found in carparks (Bond et al. 1999). The removal of hydrocarbons should be studied.
    b. clogging of the medium may occur due to the retention of sediment. The hydrodynamic performance under sediment loading should be investigated.
    c. the complex interaction between environmental, physical and chemical factors is only accurately testable in a controlled field situation.

2. Cost/benefit should be identified by economic and lifecycle analysis of:
    a. stormwater treatment systems.
    b. wastewater treatment systems.
    c. acid mine drainage treatment systems.

3. Locations should be identified that are suitable for the installation of slag-based:
    a. stormwater treatment systems. The general features of such suitable locations are large paved areas, heavy vehicular traffic, and sites, that use or store contaminants (Pitt 2002).
    b. wastewater treatment systems.
    c acid mine drainage treatment systems.

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