THE INFLUENCE OF ROAD SURFACE CHARACTERISTICS ON RUNOFF QUALITY

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ABSTRACT

A study carried out in the Auckland region found marked differences in the quality of runoff discharged from a site on the northern motorway compared to three other highway sites. Concentrations of total suspended sediments (TSS), total copper and total zinc were lower than at the other sites. These results were unanticipated; given that the site was on one of New Zealand's busiest sections of motorway, it was expected that runoff quality would be relatively poor here.

The better quality of runoff may relate to the recent resealing of the motorway with open graded porous asphalt (OGPA). Unlike other road surfaces, OGPA is designed to allow some infiltration of runoff in order to improve road safety and noise reduction. A by-product of this porous nature is the ability to trap sediments and associated contaminants. However, there is evidence from another site in the study that the ability of OGPA to perform this function reduces over time.

This paper reviews the results of this study and those of others to consider the role that road surfaces play in influencing the generation, transport and removal of contaminants discharged in road runoff.

KEYWORDS

Road runoff, suspended sediments, copper, zinc, road surface, permeable paving, porous asphalt, OGPA.

PRESENTER PROFILE

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1 INTRODUCTION

Roads are a source of stormwater contaminants, particularly the heavy metals copper and zinc and a range of hydrocarbon compounds. A recent study in New Zealand investigated the influence of traffic characteristics on the loads of these contaminants discharged in road runoff (Moores et al., 2010). While the results showed that runoff quality was generally poorer on some roads subject to traffic congestion compared to those with freely flowing traffic, this was not always the case. Other factors appear to be important. This paper examines the role that one of those factors, the characteristics of the road surface, plays in influencing road runoff quality.

There are a number of ways in which the characteristics of a road surface could be expected to influence runoff quality:

- Variations in the composition of the road surface, for example differences in the hydrocarbon compounds present in bitumen or levels of metals found naturally in road aggregate, could contribute to differences in the concentrations of these contaminants in road runoff;

- Variations in the rate of deterioration of the road surface could affect the build-up and wash-off of road sediments;

- Variations in the roughness of the road surface could result in differences in the rates of tyre wear, influencing the quantities of zinc discharged in runoff; and

- Variations in the character of the road surface, and in particular its permeability, could influence the proportion of runoff and associated contaminants discharged into the roadside drainage system.

The first three of these mechanisms relate to the way in which the road surface contributes to the generation of contaminants, while the fourth is associated with the transport and removal of accumulated contaminants from the road. The remainder of this paper reflects this division: Section 2 describes the results of studies into the influence of road surface composition and wear rates on road runoff while Section 3, the main focus of the paper, discusses the influence of road surface permeability on runoff quality.

It is important to recognise the fundamental distinction between road surface types which are explicitly designed to treat road runoff and those which are not, but which may provide runoff quality benefits as a by-product of meeting some other objective. Internationally, there are many examples of the use of permeable paving systems as a measure for managing both stormwater quality and quantity. While this paper does make reference to studies into the performance of such systems, they are **not** the main focus of this review because their application is largely limited to lightly-trafficked areas such as residential roads and car parks.

Instead, the focus here is the way in which the surface characteristics of heavily-trafficked roads can influence runoff quality. In particular, the paper examines the effect of porous asphalt, a surface material developed to meet safety and noise-reduction objectives, on runoff quality. While porous, this type of surface is permeable only to a depth of around 50-100 mm, with the porous upper road surface lying on an impermeable base. In contrast, in a fully permeable paving system, runoff can infiltrate through the base and into the natural ground lying below the road.

This subject is of more than simply academic interest: the surfaces of our motorways, highways and city streets are primarily designed, built and maintained to ensure their durability and safety. If, while meeting these primary aims, a road surface also exerts a positive influence over runoff quality, the possibility arises that road surface design and maintenance can be explicitly recognized and taken into account in the management of road runoff.

2 INFLUENCE ON CONTAMINANT GENERATION

2.1 INTRODUCTION

Road surfaces are classified as either rigid or flexible (Austroads, 2009). Rigid roads typically comprise a concrete pavement with joints and steel reinforcement. Flexible road surfaces are bitumen-based and constructed without joints. They can be further divided into:

- Chip seals, whereby a layer of graded aggregate (rock) is laid on top of a layer of bitumen binder (a process which is repeated in the case of two-coat chip seals); and

- Asphalt, comprising a combination of graded aggregate and a bitumen binder laid as a mix.

As noted above, the characteristics of road surfaces that might be expected to contribute to differences in the generation of contaminants are: their composition; their rate of deterioration; and the amount of tyre wear that they cause.

2.2 ROAD SURFACE COMPOSITION

Both concrete and bitumen-based surfaces contain aggregate and, as a result of the release of this material through surface deterioration and wear, contribute to the discharge of inorganic solids in road runoff (Sansalone and Buchberger, 1997). While aggregate contains a range of trace metals, including copper and zinc, these are present at naturally-occurring background concentrations. Unless aggregate from an area with relatively high background concentrations is used on a road in an area with lower background concentrations, sediment derived from road aggregate is not in itself a source of heavy metal contamination of receiving environments.

Bitumen contains a range of both organic solids inorganic compounds. As part of a suite of studies undertaken for the Ministry of Transport, Kennedy and Gadd (2000) and Kennedy et al. (2002) investigated the levels of organic and inorganic constituents of bitumen used on New Zealand roads. Analysis of raw bitumen for inorganic constituents found only low levels of trace metals, including copper and zinc (Kennedy and Gadd, 2000). Concentrations in samples of used bitumen recovered during road resealing operations were higher, probably reflecting the accumulation of the metals on the road surface from sources such as tyres and brake pads. However, even these concentrations of copper and zinc were 1-2 orders or magnitude lower than in brake pad dust and tyres, respectively. These results indicate that, as is the case for road aggregate, bitumen is unlikely to be an important contributor of heavy metals compared to vehicular sources.

However, asphalt and other bitumen-based surfaces are a potential source of organic solids and other organic compounds in road runoff (Sansalone and Buchberger, 1997). Kennedy and Gadd's (2000) analysis of bitumen samples detected the presence of polycyclic aromatic hydrocarbons (PAHs) at similar levels to those found overseas.

2.3 ROAD AND TYRE WEAR RATES

Road surface wear is a function of traffic volume, fleet composition and road surface type. Kennedy et al. (2002) reported a lack of any quantitative data on the rate of loss of material from road surfaces, noting that particulate emissions models developed in the US and EU ignored the contribution of road wear entirely in estimating total emissions of particulate matter from roads. In the absence of any data, Kennedy et al. (2002) developed a method for estimating road surface wear which reflects the influence of road surface characteristics through the size of the aggregate used: with all other variables held constant, a larger chip size increases the design life of the road and reduces the wear rate. Gardiner and Armstrong (2007) developed a Vehicle Contaminant Load Model

(VCLM) which built on the method of Kennedy et al. (2002) to estimate loads of particulate matter, copper, zinc and PAHs generated by road surface wear, along with those generated from vehicle component wear, exhaust emissions and leaks of fuels and lubricants. The loads of the contaminants generated by road surface wear represent only a minor contribution to the overall contaminant load estimated by this model.

The influence of road surface type on tyre wear is primarily through the roughness of different surfaces. Kennedy et al. (2002) report tyre life being slightly longer (5%) on well-maintained asphalt than on concrete. The authors noted that for urban roads (as opposed to, say, unsealed rural roads) the influence of road surface type on tyre wear rates is small compared to other factors. This is also reflected in Gardiner and Armstrong's (2007) VCLM, in which tyre wear is a function of terrain and traffic conditions, but not of road surface type.

2.4 OBSERVED DIFFERENCES IN RUNOFF QUALITY

There is little in the literature described above to suggest that differences in road surface type exert a strong influence on the generation of contaminants found in road runoff, compared to other factors. The exception is the potential for elevated levels of PAHs in runoff from bitumen-based roads compared to concrete ones.

Despite a wealth of literature on the characterisation of road runoff, few studies have explicitly investigated the influence of road surface type. The results of those that have tend to support the contention that differences between road surface types are less important than other factors such as traffic volumes and behaviour, such as the level of braking and acceleration.

Stotz (1987) reported the results of runoff sampling from two asphalt- and one concrete-surfaced highways in Germany. Levels of suspended solids, copper, zinc and PAHs were similar in samples collected from the two road surface types. Driscoll (1990) compiled a database of road runoff data collected across 31 sites in the US and found that "the available data provide no indication that pavement composition (concrete, asphalt) has any influence on runoff quality and pollutant loads."

Drapper (2000) reported the results of 'first-flush' sampling at 21 highway locations in Queensland, 19 of which were asphalt and two concrete. While zinc and copper concentrations did not appear to be influenced by surface type, the highest and third highest suspended solid concentrations were found in samples collected from the two concrete road sites. Unfortunately, the authors do not discuss these results, other than noting that the concrete-paved roads had the highest vehicle numbers of all roads in the study. They report that vehicle numbers account for 30% of the variation in suspended solid concentrations, which means that other factors (potentially including surface type but also random variations) are responsible for explaining the remaining 70%.

3 INFLUENCE ON CONTAMINANT TRANSPORT AND REMOVAL

3.1 INTRODUCTION

The transport and removal of contaminants in road runoff prior to their discharge to roadside drainage systems is partly a function of a number of factors unrelated to surface characteristics, including rainfall intensity and road slope. However, there is evidence from a number of studies (described below) that the porosity of the road surface is also an important influence on contaminant transport and removal in road runoff. Providing that voids in a porous surface are connected, it is permeable, allowing runoff and entrained contaminants to infiltrate into the road surface. This allows for the removal of contaminants, primarily by the trapping of particulate matter in the void spaces within the road surface. In fully permeable paving systems, further contaminant removal can occur as the runoff continues to infiltrate through an underlying engineered base layer (or layers) and into the natural ground. In contrast, porous roads surfaces used on highways are typically laid on an impermeable base, such that infiltration is limited to the road surface itself. Where runoff meets this impermeable boundary it must flow laterally to be discharged at the road edge, such that any contaminant removal is confined to the road surface itself.

The following sections describe fully permeable paving systems and porous road surfaces in more detail, the results of studies into their performance for contaminant removal and a discussion of the factors which may influence this performance. As noted in the introduction to this paper, of particular interest is the extent to which porous road surfaces can provide water quality benefits in relation to their use on highly-trafficked roads. Firstly, however, the results of research into their performance of fully permeable paving systems are described as this is provides some useful insights relevant to a consideration of the use of porous road surfaces on highways and busy roads.

3.2 PERMEABLE PAVING SYSTEMS

3.2.1 DESCRIPTION

Permeable paving systems were first developed in the 1970s (Cahill and Adams, 2003) and are widely promoted as a measure for reducing stormwater runoff volumes, improving stormwater quality and contributing to groundwater recharge. Most of the guidance material on their design and use comes from the US (Hunt and Collins, 2008; USEPA, 1999; USEPA, 2009), although a number of studies of their performance have also been conducted in Europe (see Section 3.2.2).

Permeable paving systems comprise a porous (and permeable) surface overlying a number of layers of permeable base material. The porous surface can be one of a number of materials: porous asphalt[1]; permeable concrete; permeable interlocking concrete pavers (or blocks); concrete grid pavers; or plastic grid pavers (Hunt and Collins, 2008). Porous asphalt and permeable concrete allow water to infiltrate through connected voids while the various block systems allow water to infiltrate through the spaces between the blocks and, in some cases, through connected voids in the pavers themselves.

USEPA (2009) describes a typical design of the subsurface components of a permeable paving system. The base typically consists of one or more layers of crushed rock. A shallow bed of relatively fine grade rock (6-19 mm diameter) is often used on top of a deeper layer of coarser material (19-63.5 mm diameter) to provide a transition between materials of different infiltration rates. Together, these base layers act as a reservoir to capture and retain runoff infiltrating from above. A 'choke course' of small-sized open-graded aggregate is laid on top of the base material to provide a stable bed upon which the surface material can be laid. Typically, the base layers sit on top of a geotextile to preserve the boundary with the underlying ground surface and prevent soil moving upwards into the base material matrix. Underdrains may be installed above the geotextile to assist with drainage in areas of low-infiltration soils.

The use of permeable paving is generally limited to low-trafficked areas such as car parks and residential roads. Its unsuitability for roads carrying heavy traffic is recognized in guidance material from overseas (Cahill and Adams, 2003; USEPA, 1999; UKHA, 2006), and in the New Zealand Transport Agency's stormwater treatment guidelines (NZTA, 2010). The reasons for this include the lower strength of these systems compared to other

[1] Porous asphalt is described further in Section 3.2.2.

road types and the greater likelihood of pollution spills on roads carrying high volumes of traffic (USEPA, 2009). A particular concern is the potential contamination of groundwater in areas where it is used for drinking water supply (USEPA, 1999).

3.2.2 PERFORMANCE

A number of studies have evaluated the performance of permeable paving systems for the removal of contaminants and improvement of runoff quality. Results on the removal of suspended solids, copper, zinc and hydrocarbons are summarised in Table 1. In the studies reviewed here, levels of sediments (or suspended solids), zinc and copper were as much as 95%, 81% and ≥ 83% lower, respectively, than in runoff sampled from conventional road surfaces or at the point of entry to the permeable paving systems.

Despite the positive nature of these results, three quarters of permeable paving systems are reported to have failed (USEPA, 1999). Causes of failure include poor design, poor construction, low permeability of subsoils, a lack of adequate maintenance and most, frequently, the clogging of the voids in the permeable surface materials (Hunt and Collins 2008; USEPA, 1999; USEPA 2009). Clogging reduces the permeability of the pavement surfaces and typically increases with the age of the system and the accumulation of sediments over time. Other influences can be the surrounding soil type, increased traffic volumes and failure to employ adequate erosion and sediment measures at the time of construction (Hunt and Collins, 2008).

Of course, not all permeable pavement systems have been outright failures: Cahill and Adams (2003) reported on a car park in Philadelphia that was still working well twenty years after it was constructed. Pratt el. (1995) and Brattebo and Booth (2003) reported on systems which were performing well following nine and six years of service, respectively. Abbot and Comino-Mateos (2003) investigated the hydraulic performance of a pavement system in the UK using porous concrete blocks: while the porous blocks became effectively impermeable within 10 months of construction, much higher infiltration rates were measured in the gaps between the blocks and this maintained the overall hydraulic performance of the system.

Regular maintenance is seen as the most important factor in preventing clogging and deterioration of permeability. Guideline documents typically promote vacuum sweeping on a 2-4 times a year basis (Cahill and Adams, 2003; USEPA, 1999; USEPA, 2009). Additional maintenance options include high-pressure washing and removal of the resultant sludge (USEPA, 1999) or, in cases of severe clogging, the drilling of holes through the pavement to re-establish connectivity with the underlying reservoir (USEPA, 2009). A French study found that original infiltration rates could be restored with sweeping and suction, suction alone or high pressure washing (Balades et al. 1995). In contrast, moistening the surface and then undertaking sweeping (but no suction) had a negative effect on permeability.

Table 1: Summary of results of studies to evaluate the effect of permeable paving systems on road runoff quality

Surface Type	Location	Runoff Quality Results[1]	Reference
Porous asphalt	France	Mean concentrations lower than those in urban reference catchment by: • 64% for suspended solids • 72% for zinc Mass balance indicated that less than 2% of total zinc and copper were discharged in drainage from the system (most infiltrates into the soil).	Legret et al. (1996) and Legret and Colandini (1999)
Porous asphalt	Various	Mean removal efficiencies of:	Cahill and Adams, (2003)

		• 91% for sediment • 81% for zinc • 42% for copper	
'Porous pavement' (material not specified)	Maryland and Virginia, US	Removal efficiencies of: • 82-95% for sediment • 'high' for zinc	USEPA (1999)
Concrete blocks	UK	"Consistently low" suspended solid concentrations once effects of construction ceased (4-46 mg/l). Hydrocarbons below detection levels.	Pratt et al. (1995)
Four different plastic grid and concrete block systems	Washington State, US	Mean concentrations lower than those in runoff from standard asphalt by: • ≥ 83% for copper • 39 - 69% for zinc Motor oil below detection levels.	Brattebo and Booth (2003)
Various sites, details of surface type not specified	France	Removal efficiencies of: • 50-90% for suspended solids • 56% for zinc	Balades et al. (1995)

Note

1. Some of these studies also investigated the effects of permeable paving on other constituents of runoff not discussed here. Refer to the original references for further details.

3.3 POROUS ASPHALT ON HEAVILY-TRAFFICKED ROADS

3.3.1 DESCRIPTION

Internationally, porous asphalt has been used for decades to reduce noise and improve road safety by reducing aquaplaning, spray generation and skidding during wet weather (Alabaster and Fussell, 2006; USEPA, 2009). The key difference between it and standard asphalt is the composition of the aggregate used in the mix: porous asphalt contains lower proportions of fine grades of aggregate than standard asphalt. Porous asphalt is referred to as "open graded porous asphalt (OGPA) while mixes containing higher proportions of fine grades are referred to as "dense graded asphalt." The lower proportions of fine aggregates in OGPA gives the material its porous nature and allows water to infiltrate through the network of connected voids.

In New Zealand, porous asphalt comes in a range of mixes, distinguished by variations in its particle size distribution. PA 20 is the traditional mix used on the motorway system since the 1980s and has a void content of 20% total volume (Transit NZ, 2007a and 2007b). Mixes with higher void contents (25-30%) can be used in for enhanced noise reduction. Another alternative is the use of a twin layer of OGPA in which the upper layer has a smaller maximum aggregate size. This system aims to trap debris on the road surface and prevent it from entering the road matrix while the larger voids in the bottom mix maintain the drainage and noise properties of the surface (Transit NZ, 2007a and 2007b).

Porous asphalt layers are typically 50-100 mm thick (USEPA, 2009) and can be laid on a range of base materials including structural asphalt layers or even unmodified existing road seals (Alabaster and Fussell, 2006; Barrett et al., 2006). Guidelines for the use of OGPA in New Zealand emphasise the requirement for an impermeable base material, including both dense-graded asphalt and conventionally designed two-coat chip seals (Transit NZ, 2007c).

3.3.2 PERFORMANCE

While porous asphalt has primarily been employed for its safety and noise reduction properties, a number of authors have recognized its potential benefits for improving road runoff quality. The results of studies undertaken to assess runoff quality from roads surfaced with porous asphalt are summarised in Table 2. In these studies, levels of suspended solids, zinc, copper and PAHs were as much as 94%, 90%, 75% and 96% lower than in runoff sampled from conventional asphalt road surfaces.

In each of these studies, the road surfaces were relatively young (3 years old or less) and this raises a question as to how representative the results presented in Table 2 are of runoff discharged from other (older) roads. The issue of clogging, prevalent in the literature on permeable-paving systems described in Section 3.2.2, is also relevant to the use of porous asphalt as a highway surface. Barrett et al. (2006) comment on the likely result of clogging on runoff quality:

> *"… as particles and particle-associated pollutants accumulate within the pore structure, it seems likely that more runoff will travel on the surface of the pavement, resulting in concentrations that might not be significantly different from those observed in runoff from conventional asphalt pavements …"* (p. 2184)

Berbee et al. (1999) report that clogging is likely to be more prevalent on road shoulders than in vehicle lanes because the turbulence associated with traffic flow tends to transport most of the particulate matter to the sides of the roads. They suggest cleaning 'unused' parts of the highway two times a year with high pressure water systems.

Both sets of authors comment that long-term monitoring is required to establish the extent to which runoff quality changes as porous asphalt road surfaces age.

3.3.3 FINDINGS OF A NEW ZEALAND STUDY

A recent programme of road runoff sampling in New Zealand not only supports the findings of the overseas studies described above but also provides evidence of the effect of age on the quality of runoff discharged from porous asphalt surfaces (Moores et al., 2010). While the objectives of the study were to investigate the influence of traffic behaviour and stormwater treatment on road runoff quality, its results have also provided insights into the possible influence of road surface materials.

Table 2: Summary of results of studies to evaluate the effect of porous asphalt road surfaces on road runoff quality

Description and Age of Road Surface	**Location**	**Runoff Quality Results[1]**	**Reference**
Porous asphalt, 2 ½ years old	Germany	Annual loads lower than impermeable road surface by: • 60% for suspended solids • 31% for copper • 96% for PAHs But zinc load 56% higher.	Stotz and Krauth (1994)
Porous asphalt layer over impervious asphalt, 3 years old.	Netherlands	Median concentrations lower than those in runoff from impermeable asphalt by: • 91% for suspended solids • 67% for copper • 90% for zinc PAHs below detection limits in samples from porous asphalt but detected in	Berbee et al. (1999)

		samples from impermeable asphalt.	
Porous asphalt on bridge deck. Samples collected for 1 year before and after replacement of impermeable asphalt with porous asphalt.	France	Weighted mean concentrations lower than those in runoff from impermeable asphalt by: • 81% for suspended solids • 35% for total copper • 44% for total zinc • 92% for total hydrocarbons	Paggotto et al. (2000)
Porous asphalt, 3 years old. Compared with 4 impermeable asphalt roads and 1 concrete road.	UK	Mean sample concentrations of (compared to other roads shown in brackets): • 51.4 mg/l suspended solids (45.8-318 mg/l) • 23.9 µg/l copper (24.2-67.9 µg/l) • 52.6 µg/l zinc (97.9-221.5 µg/l)	Moy et al. (2003)
Porous asphalt over existing asphalt road seal. Samples collected prior to and within 6 months of construction of porous surface.	Texas, US	Mean event mean concentrations lower than those in runoff from existing asphalt by: • 94% for suspended solids • 75% for total copper • 76% for total zinc PAHs below detection limits.	Barrett et al. (2006)

Note

1. Some of these studies also investigated the effects of porous asphalt on other constituents of runoff not discussed here. Refer to the original references for further details.

Runoff samples were collected at four road locations in the Auckland region, two of which were surfaced with chip seal and two with porous asphalt (see Table 3). Traffic conditions were characterized by estimating an indicator of congestion based on the relationship between road capacity and traffic volumes. Samples were collected from between six and eight rainfall events at each site over the period November 2007 to May 2009 with event characteristics representing a similar range of rainfall depth, duration and antecedent conditions at each site.

Table 3: Description of road runoff sampling sites

Site name and location	**Road description**	**Road surface (and date of last surfacing)**	**Traffic volume[1] (vpd)**	**Indicator of congestion[2] (AADT/Capacity)**
SH 1 (Northern motorway) @ Northcote	Four lane urban motorway (northbound lanes only)	OGPA (2008)	50,849 northbound	0.81
SH 1 (Northern motorway) @ Redvale	Four lane rural motorway	OGPA (2002)	41,541 both directions	0.40
SH 18 @ Westgate	Two lane arterial road, urban fringe	Two-coat chip seal (2005)	36,088 both directions	1.38

SH 16 @ Huapai	Two lane rural highway	Chip seal (unknown)	13,866 both directions	0.52

Notes

1. Annual average daily traffic - AADT (NZTA, 2009), a road with a value of greater than 0.7 is classed as 'congested.'
2. After Gardiner and Armstrong (2007)

Table 4 provides a summary of the results of runoff sampling conducted at each of these four sites. The runoff samples collected at the Northcote site, which had been resealed with OGPA the previous year, had markedly lower suspended solid concentrations than samples collected at the others three sites, with median concentrations between 81 and 92% lower than those at the other sites. Concentrations of total copper and total zinc were also lower in samples collected at this site than elsewhere, although the differences were more marked in relation to maximum concentrations than in median concentrations, particularly for total copper.

Table 4: Median and range (in brackets) of sample concentrations of suspended solids, copper and zinc.

Site	**Number of samples**	**Suspended solids (mg/l)**	**Total copper (µg/l)**	**Total zinc (µg/l)**
SH 1 @ Northcote	59	8.8 (2.7 – 66.7)	15.3 (6.4 – 47.1)	34.0 (18.0 – 155.0)
SH 1 @ Redvale	98	47.4 (2.3 – 2039.4)	15.8 (2.4 – 133.1)	66.0 (6.0 – 1705.0)
SH 18 @ Westgate	68	75.7 (4.0 – 647.8)	25.0 (4.1 – 104.4)	125.0 (15.0 – 719.0)
SH 16 @ Huapai	80	100.8 (1.6 – 1086.9)	18.3 (5.4 – 108.1)	76.0 (11.0 – 442.0)

These results run counter to expectations based on traffic behaviour alone. Based on levels of congestion, runoff quality would have been expected to be worst at Westgate, followed by Northcote, Huapai then Redvale. The markedly different results at Northcote compared to the other three sites are most likely to reflect the influence of the recently-laid OGPA at this location.

Samples collected at Redvale, which had been resealed with OGPA six years prior to sampling, had the second lowest median concentrations of suspended solids, total copper and total zinc. However, samples collected at Redvale also had the highest maximum concentrations of all three constituents collected at any of the sites. Given the lower levels of congestion at Redvale than at Northcote, runoff quality would be expected to be better at the former site, all other things being equal. The sampling results contradict this expectation and indicate that the positive influence of OGPA reflected in the Northcote results had markedly diminished over the 6 years of its use at Redvale. This is likely to reflect the clogging of the road surface and a decrease in permeability at Redvale. The results of an earlier New Zealand study into the infiltration rates of OGPA provide support for this assessment: infiltration rates were found to be markedly lower on roads sealed with OGPA three or more years prior to the study compared to roads sealed more recently (Lane, 2008).

An important aspect of the Northcote results is the way in which the influence of OGPA is less marked on total metal concentrations than on suspended solids. The explanation for this lies in the fact that part of the copper and zinc found in road runoff are in the dissolved phase. The influence of porous asphalt is largely felt by the removal of particulate matter and associated contaminants while dissolved metals remain in solution to be discharged at the road edge.

Median dissolved copper and zinc concentrations in samples from Northcote were higher than those in samples from any of the other three sites (see Table 5). The proportion of each metal that was in the dissolved phase was also markedly higher at Northcote than elsewhere. These results are consistent with those of previous studies, with runoff from porous asphalt reported to contain 71-75% copper and 70-77% zinc in the dissolved phase compared to runoff from impermeable asphalt which contained 24-26% copper and 24-29% zinc in the dissolved phase (Barrett et al., 2006; Berbee et al., 1999). However, previous studies have differed in their findings as to whether there is any reduction in dissolved metals in runoff as a result of infiltration into porous asphalt with Paggotto et al. (2000) reporting an improvement, particularly for dissolved zinc, which they attribute as possibly the result of adsorption on to the road matrix, while Barrett et al. (2006) found no statistically significant difference between dissolved metal concentrations in samples collected from porous and impermeable asphalt.

Table 5: Median sample concentrations of dissolved copper and zinc and median percentage of each metal in the dissolved phase.

Site	**Median dissolved copper concentration (µg/l)**	**Proportion of copper in dissolved phase**	**Median dissolved zinc concentration (µg/l)**	**Proportion of zinc in dissolved phase**
SH 1 @ Northcote	12.0	82%	22.0	69%
SH 1 @ Redvale	6.8	43%	11.0	22%
SH 18 @ Westgate	6.4	26%	19.0	17%
SH 16 @ Huapai	3.7	23%	10.0	14%

4 DISCUSSION

The findings reported above demonstrate that runoff discharged from roads surfaced with porous asphalt can be of better quality than that discharged from impermeable road surfaces but that the difference between the two appears to become less marked over time. This raises a number of questions:

- Can the use of porous asphalt as a surface on heavily-trafficked roads be explicitly recognized as a measure for improving road runoff quality?
- How can its performance be maintained over time?
- What are the implications for the treatment of runoff beyond the road edge?

Clearly, if the results for porous asphalt presented here are widely-representative then it is making a positive contribution to the treatment of road runoff. Runoff at the Northcote site had a median concentration of suspended solids of 81% or more lower than that at any of the other three sites. Overseas studies report removal rates of TSS as high as 94% (Barrett et al. 2006). Results for total metal and hydrocarbon removal are also generally positive.

The key issue in recognizing these benefits is the apparent limit to their longevity. The results from overseas studies all relate to road surfaces aged three years or less while the results from the Redvale site appear to indicate a marked deterioration in effectiveness over a period of six years of use.

As noted in Section 3.3.2, Berbee et al. (1999) advocate twice-yearly high pressure cleaning of road shoulders to maintain permeability. While it is not clear that this would be either sufficient or affordable in New Zealand, results of a high pressure cleaning trial provide encouragement that this method would be effective in maintaining permeability (Lane, 2008). While the objectives of the trial were to assess the extent to which the safety and noise control characteristics of OGPA could be rejuvenated, these features are a direct function of its permeability, such that the method would be equally beneficial for the maintenance of runoff quality benefits. The trials resulted in improvements in permeability of roads of all ages. While the extent of improvement was more marked in older roads (surfaces laid three or more years previously), the permeability of these roads could not be restored to original levels. Cleaning of younger roads was able to increase permeability to levels close to those of the original surface.

While these results suggest that regular high pressure cleaning, commencing early in the life of the surface, can be effective in maintaining the permeability of porous asphalt, it is important to consider the fate of the sediments disturbed by such cleaning processes. A French study analysed sludge recovered from porous asphalt highways and found concentrations of zinc in the range 744-848 mg/kg and copper in the range 230-410 mg/kg (Colandini et al., 1995). The concentrations are 1-2 orders of magnitude higher than background concentrations of soils in the Auckland region (ARC, 2001). Clearly, washing contaminated sediments recovered from the road surface into roadside drainage systems for mobilization and potential delivery to receiving environments could well offset the benefits derived by capturing these contaminants in the road surface. While sediments recovered from road sweeping and roadside catchpits are typically disposed of at landfills at present, Depree (2008) has evaluated the feasibility of their reuse, a line of research which could equally be relevant to the disposal of material recovered from porous asphalt.

The high proportion of dissolved copper and zinc in runoff discharged from porous asphalt may have implications for subsequent treatment of runoff beyond the road edge, irrespective of whether OGPA itself is recognized as contributing to stormwater treatment. The types of device most commonly used to treat road runoff (ponds, swales, sand filters and cartridge filters) primarily operate by promoting the filtration and/or settlement of suspended solids and associated contaminants. They are typically less effective for the removal of dissolved metals. Where a porous asphalt surface is successful in removing a large proportion of solids, this raises the question as to the value of additional traditional forms of treatment.

Barrett et al. (2006) sampled runoff both at the edge of a porous asphalt pavement and 8 metres away from the road edge within a vegetated buffer strip. They reported no statistically significant difference between the runoff quality discharged from the two locations. Berbee et al. (1999) conducted tests to determine the effects of settlement and filtration on runoff samples collected from porous and impermeable road surfaces. Both settling and filtration were found to be less effective on the runoff samples from the porous roads because of its lower suspended solid concentration and the greater proportion of constituents in the dissolved phase. In the light of these results, they suggest that regularly cleaning of porous asphalt roads is more likely to contribute to the maintenance of improved runoff quality than would the provision of additional treatment.

In contrast to these findings, the results of sampling at the Northcote site found additional treatment was beneficial in reducing copper and zinc concentrations, despite the fact that both metals were predominantly in their dissolved form (Moores et al., 2010). Samples collected at the outlet of a roadside swale had lower dissolved copper and zinc concentrations than those in samples collected at the road edge. While the mechanism resulting in these lower concentrations is unclear, it may have been the result of dilution with water discharged into the swale outlet from underdrains, suggesting removal of dissolved metals occurred in association with infiltration of runoff through the swale bed. Despite the contrasting nature of these results with those reported above, all three studies indicate that treatment of runoff from (clean) porous asphalt roads should involve measures which target dissolved contaminants in order to increase the likelihood of improving on the runoff quality discharged from the road surface itself.

5 CONCLUSIONS

Different road surfaces appear to have little influence on the generation of contaminants conveyed in road runoff, compared to other factors such as vehicle numbers and traffic behaviour. Factors which influence the transport and removal of contaminants, and in particular road surface permeability, are more important.

Permeable paving systems have been employed for over 30 years to manage stormwater quality and quantity and enhance groundwater recharge. Studies have shown them to be capable of contaminant removal efficiencies of 90% or higher. However, a key issue has been clogging of the pores, often due to insufficient cleaning.

Porous asphalt laid over impermeable base layers has been used for decades to improve road safety and reduce noise on heavily-trafficked roads. Overseas studies have shown that it can also improve road runoff quality, with upper limit contaminant reductions similar to those reported for fully permeable paving systems. The findings of a New Zealand study have also shown runoff quality to be better from a motorway surfaced with OGPA compared to that from other road surfaces, but results from another site appear to show that effectiveness diminishes over time. As with permeable paving systems, this is probably the result of clogging of the voids in the road surface.

Further research into the potential for OGPA to be recognized as a measure for improving the quality of road runoff should focus on: more detailed characterization of performance over time; ways in which its performance can be maintained; and implications for treatment of runoff beyond the road edge and in particular the removal of dissolved contaminants.

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