Effect of permeable pavement basecourse aggregates on stormwater quality for irrigation reuse

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A B S T R A C T

Urban runoff quality determines its potential for reuse. Permeable pavements, a type of structural water sensitive urban design systems can provide additional opportunities for stormwater harvesting and reuse. This study examined the stormwater quality improvements of three permeable pavement basecourse aggregates compared with control environments and five water storage residence times. The study was a split plot experiment based on a randomized design with four replications. Natural stormwater was used as inflow and was stored for 3 days, 1 week, 2 weeks, 4 weeks and 8 weeks in three model basecourse aggregate reservoirs filled with basalt, quartzite and dolomite. Stormwater stored in an empty simulated reservoir for the defined period of time was used as a control. The water quality measurements were dissolved oxygen (DO), EC, pH and turbidity.

The results showed changes in water quality in the reservoirs. Particularly, there was a decrease in DO and an increase in pH levels in basalt and an increase in turbidity in the dolomite reservoir. DO levels showed a decreasing trend over time, pH showed the highest levels after two weeks and turbidity showed a very large increase after one week water storage. EC changes were functions of interactions between aggregate types and residence times. Comparing the results with current Australian guidelines for water harvesting and reuse revealed permeable pavements with the selected basecourse aggregates and the residence times will generally yield a water quality adequate for reuse for irrigation of green spaces. These results will contribute to sustainable irrigation management of urban green spaces.

1. Introduction

Permeable pavements are becoming significant elements in the urban environment as they provide one of the few opportunities for source control of stormwater through infiltration. Compared with many other water sensitive urban design (WSUD) measures which utilise infiltration, permeable pavements are one of the few opportunities for infiltration that are also fully trafficable. Unlike traditional asphalt and concrete road surfaces, permeable pavements (especially when combined with underlying reservoirs) are designed with environmental considerations. They often form an important component of WSUD systems that provide urban spaces with economic, social and environmental benefits (Ferguson, 2010; Pagotto et al., 2000). Permeable pavements can act as multi-functional landuses providing hydrological control, water quality treatment and traffic load-carrying capacity (Sansalone et al., 2011).

The recent development of permeable pavements and other infiltration systems to harvest and reuse stormwater increases their functionality from that of purely infiltrating stormwater (Schofield, 1993; Pratt, 1999). Permeable pavements with underlying storage reservoirs consist of a relatively thin paver layer laid on top of various aggregate layers. These usually include a fine bedding aggregate layer on top of a larger diameter basecourse aggregate layer. The system is lined with an impermeable membrane to allow storage of infiltrated stormwater in the voids of the basecourse aggregate (Fig. 1).

There have been numerous research studies outlining the potential water quality improvements of permeable pavements (Schofield, 1993; Pratt, 1999; Pratt et al., 1995; Dierkes et al., 2002; Brattebo and Booth, 2003; Myers et al., 2011). Dierkes et al. (2002) report on a study of four different concrete pavers tested for retention capabilities of various heavy metals which showed all
four had pollution retention capabilities of different levels depending on the design of joints and apertures in the pavements. Brattebo and Booth (2003) similarly evaluated the performance of four permeable pavement systems with respect to water quality, showing that the water quality from the pavement, including copper and zinc concentrations, in the infiltrating water was significantly better than that of the surface runoff from a parking area. Myers et al. (2009) investigated whether storage in the basecourse of a permeable pavement impacts the survival of *E. coli*. The results showed that there was no significant difference in the depletion of *E. coli* found in reservoirs without aggregate, and those filled with aggregate. The results indicated that bacteria generally adhere to the surface of the mineral aggregate and to the reservoir walls. Scholz and Grabowiecki (2008) also introduced a combined permeable pavement system and a ground source heat pump system for treating stormwater from nutrient and microbial agents. While such a combined system compared to a single system showed better treatments in some cases in this study, further research is required to fully understand treatment potential of such engineered system. Myers et al. (2011) investigated changes in water quality when water was stored in two types of basecourse aggregate. They found that total zinc, copper and lead were reduced by 94% to 99% in aggregate filled reservoirs compared with controls after 144 h storage.

The aim of the research described in this paper was to investigate the effects over time of several types of basecourse aggregate material, specifically dolomite, quartzite and basalt, on the physical and chemical characteristics of stormwater stored in permeable pavement reservoirs.

The potential applications of the water harvested from underlying storage of permeable pavements were also compared with the following Australian guidelines:

1. Australian guidelines for water recycling: managing health and environmental risks (phase 1) (NRMMC, EPHC and AHMC, 2006)
2. Australian guidelines for water recycling: managing health and environmental risks (phase 2) – stormwater harvesting and reuse (NRMMC, EPHC and NHMRC, 2009)
3. Managing urban stormwater – harvesting and reuse

While these documents have provided guidelines on stormwater reuse applications and storage options such as rainwater tanks and open storages, little has been released on regulations, applications and quality monitoring of stormwater stored in basecourse aggregates of permeable pavements. The current research work will complete these water guidelines on reuse of stormwater stored in underlying reservoirs of permeable pavements.

2. Materials and methods

This research examined stormwater quality effects of three basecourse aggregates of permeable pavements, namely basalt, quartzite and dolomite after being stored for durations of 72 h (3 days), 168 h (1 week), 336 h (2 weeks), 672 h (4 weeks) and 1344 h (8 weeks). The experimental design was split plot based on a randomized design with residence time as the main plot treatment factor and the basecourse aggregate types as subplot treatment factor. The experiment had four replications.

2.1. Construction of the model permeable pavement reservoirs

To conduct the experiment, model permeable pavement reservoirs were constructed using polyethylene containers (250 mm × 300 mm × 750 mm). These containers were selected due to their size, dark in color and opaque and their lids, to simulate subsurface conditions and to restrict interaction with air flow and thus limit transpiration and aerosol dispersal. Prior to the experiment, the containers were checked for any leaking. These permeable pavement reservoir model configurations were based on an earlier model constructed by Myers (2010).

To construct the reservoirs, PVC standpipes (40 mm wide × 200 mm long and 40 mm wide × 1000 mm) were prepared by drilling 10 mm diameter holes at 50 mm intervals along the standpipe between the base of the reservoir and the surface of the basecourse aggregate. The standpipe was designed for water sampling and extraction of water (Fig. 2).

The model reservoirs were filled with a non-washed basecourse aggregate. This material, therefore, included some fine materials attached to the surface of the basecourse matter. The unwashed nature of the basecourse aggregates simulate the environment of aggregates used in permeable paving, as they are delivered. The use of unwashed basecourse aggregate materials in the construction of permeable pavements is reported to occur in other studies (Pratt et al., 1995).
The experimental design was a split plot with four replicates and with residence time as the main factor and the aggregate type as the sub-plot as described in the following sections.

2.2. Aggregate types

Three types of basecourse aggregates were used in this research, namely dolomite, quartzite and basalt. The size of the three aggregate types was 20 mm, and they were sourced from Montacute Quarry, Athelstone, South Australia; Boral Quarry at Blacktop, South Australia; and Moore Quarry, Victoria, respectively. These cover the dominant type and size of aggregates which are available for paving construction in Australia.

2.3. Stormwater and the residence times

Stormwater harvested from a rooftop was used in this research to ensure that adequate amounts of water of a consistent quality could be applied throughout the entire experiment. The water was harvested from a polyethylene tank that collected stormwater from a galvanised iron roof. The pH level of the source harvested stormwater at the beginning of the experiment was 8.07, EC was 20.48 μS/cm, dissolved oxygen was 4.3 mg/l and turbidity was 15.27 NTU. The roof run off was selected as it is usual to collect stormwater in external rainwater tanks in the gardens in arid and semi-arid cities. However, this experiment aimed to investigate the potential of underlined reservoirs of permeable pavements as a replacement for external rainwater tanks which usually occupy useful spaces in urban environments and have impact on local amenity.

The constructed permeable pavement reservoir models were filled slowly with the stormwater via a standpipe and were left for durations of 72 h (3 days), 168 h (1 week), 336 h (2 weeks), 672 h (4 weeks) and 1344 h (8 weeks) in the selected basecourse aggregates. Similar containers were used as controls where stormwater was kept for the same periods of times as those kept in the basecourse aggregates. These containers were a simple container filled with stormwater and could provide a basis for comparisons of stormwater qualities in the simulated reservoirs.

2.4. Water quality analyses

For each residence time, the pH, temperature (°C), electrical conductivity (μS/cm), dissolved oxygen (mg/l) and turbidity (NTU) were measured directly in the sample pipe using an electric meter (TPS 90-FLT Field Lab Analyser, TPS Inc.). The measurements were conducted at the two-thirds point on the base of the water sampling standpipe in each reservoir. This depth was selected to ensure water sampling could be feasible even if most of the reservoirs were not filled. The pH and EC are important quality parameters for irrigation water which affect health and survival of plants. Dissolved oxygen is considered as an important water quality parameter for health of ecosystems and microorganisms. Turbidity is also an important factor affecting the esthetic quality of water. If it is increased, it may cause clogging in the irrigation system. The analyser and all probes were calibrated daily for all three pH, conductivity and DO measurements. Turbidity was measured using an ENC turbidity sensor (TPS Inc., 125187). The meter was regularly calibrated prior to analysis.

2.5. Data analysis

The measurements were analysed using the statistical software package of SPSS v.19 (SPSS Inc., 2010). The stormwater quality, based on pH, EC, DO and turbidity were measured from samples collected from each basecourse aggregate reservoir and control reservoir. These measurements were compared in the three basecourse aggregate types, basalt (B), quartzite (Q) and dolomite (D) and the control (C) reservoir, over an eight week testing period using analysis of variance. Two assumptions of ANOVA, namely normality of the distribution of errors and homogeneity of variance were tested using Shapiro Wilks and Levene’s tests, respectively. Pairwise comparisons were made using least significant difference (LSD) tests between each two aggregate types and residence times. Changes of the values of pH, EC, DO and turbidity were graphically presented using line graphs to better show the continuous nature of the time data of residence times and bar graphs were used to better show the discrete nature of the data for aggregate types.

3. Results

The results of the analysis of variance of dissolved oxygen (DO), pH, EC and turbidity as a function of aggregate types and residence times have been shown in Table 1.

3.1. Dissolved oxygen

The analysis of variance showed significantly different effects of residence times (P < 0.01) and similarly of basecourse aggregate types (0.01 < P < 0.05) on DO levels. No interaction effects were found between the basecourse aggregate types and the residence times as can been seen in Table 1.

LSD pair-wise comparison values of dissolved oxygen showed significantly lowest numbers for basalt basecourse aggregates (Mean (M) = 6.45 mg/l) compared with these values in dolomite or quartzite-based aggregates or even in the control reservoir (M = 7.01 mg/l). However, the values for this factor were not significantly different in the water stored in any other two reservoirs of quartzite and dolomite (Fig. 3a).

The value of dissolved oxygen showed the highest amounts in 3 days residence time of the stored water (M = 7.64 mg/l) but this value although was significantly different compared with similar values in other residence times, it was not significantly different from the value of dissolved oxygen of the water stored for one week.

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom (df)</th>
<th>Mean square</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DO</td>
</tr>
<tr>
<td>Residence time</td>
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</tr>
<tr>
<td>Error type 1</td>
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<td>0.41</td>
</tr>
<tr>
<td>Aggregate type</td>
<td>3</td>
<td>1.43*</td>
</tr>
<tr>
<td>Error type 2</td>
<td>45</td>
<td>1.01</td>
</tr>
<tr>
<td>Aggregate type * residence time</td>
<td>12</td>
<td>0.34*</td>
</tr>
</tbody>
</table>

* ns, non-significant.

* Significant in 99% confidence level.

* Significant in 95% confidence level.

Table 1
Analysis of variance (ANOVA) for levels of dissolved oxygen (DO) (mg/l), pH, EC (μS/cm) and turbidity (Tb) (NTU) as a function of aggregate type and residence time.
in the reservoirs. Dissolved oxygen had a decreasing trend as residence time increased to the extent that it significantly decreased down to an average of 6.1 mg/l in 8 week period of keeping water in the reservoirs (Fig. 3b).

### 3.2. pH

The analysis of variance showed significantly different effects of residence times ($P < 0.01$) and basecourse aggregate types ($P < 0.01$). However, no interaction influences between these two factors on pH levels were observed (Table 1).

According to LSD pair-wise comparisons between aggregate types, pH showed significantly different values in water stored in basalt-filled reservoirs ($M=8.63$) compared with the values in other three reservoir types including the control reservoir ($M=8.07$). There were, however, no significant differences among pH in any other two reservoir types (quartzite and dolomite and the control) (Fig. 4a).

Pair-wise comparisons of pH in different residence times also showed that there were significant differences between pH in 2 weeks as the highest value ($M=8.57$) and 4 weeks as the lowest values ($M=8.04$) and also between 2 weeks and 3 days ($M=8.07$) residence times. However, the difference between pH after 3 days and 4 weeks residence times were non-significant. The pH in 1 week and 8 weeks residence time were between the previous values and comparing to each other, there were non-significant in terms of pH values of the stored water (Fig. 4b).

### 3.3. EC

ANOVA showed a significant difference in the levels of EC among the residence times ($P < 0.01$) and aggregate types ($P < 0.01$). There were also significant interactions between these two factors ($P < 0.01$) (Table 1).

The interaction effects of different aggregate types and residence times on EC are shown in Fig. 5. The highest level of EC was shown in dolomite aggregate combined with 8 week residence time (least square mean = 512.5 μS/cm) and this was significantly different from the same value in all other combinations of aggregate types and residence times. The second highest EC level was measured in basalt aggregate after 8 week residence time (least square mean = 426 μS/cm) and this was followed by the EC level in quartzite and 8 week residence time (least square mean = 341.25 μS/cm).

The lowest EC levels were observed in the control reservoir and these levels mostly showed a constant trend with non-significant differences in different residence times in the control permeable pavement model (Fig. 5).
The analysis of variance showed a significant effect of residence times \((P < 0.01)\) and basecourse aggregate types \((0.01 < P < 0.05)\) on turbidity levels. However, no interaction between basecourse aggregate types and residence times were observed as shown in Table 1.

LSD pair-wise comparisons of turbidity values in basecourse aggregates showed highly significant differences in turbidity between dolomite basecourse aggregate \((M = 252.19 \text{ NTU})\) and the control reservoir \((M = 11.96 \text{ NTU})\). The values of turbidity for basalt- and quartzite-filled aggregates were between these two mentioned extreme values (Fig. 6a).

The line graph of comparisons of turbidity in different residence times showed how turbidity in the basecourse aggregates dramatically increased in one-week residence time \((M = 400.84 \text{ NTU})\). This increase in turbidity was to the extent that made this residence time significantly different in term of this measurement from similar measurements in all other residence times. It should be noted that there was no known external source of agitation or additional sediment between 3 days and 1 week. Despite this, no other two residence times showed significant differences in terms of turbidity (Fig. 6b).

4. Discussion

4.1. pH

Guideline recommendations for pH typically suggest most appropriate pH levels for irrigation of between pH 6.5 and pH 8.5. However some have suggested that up to pH 9 is also appropriate for surface water sources ([ANZECC and ARMCANZ, 2000]). However, the pH of most supply waters is recommended to be between pH 6.5 and pH 8.5 to prevent rusting and corrosion of pipes ([NRMMC, EPHC and AHMC, 2006]). It is important to note that the levels of pH in a water source can affect other water quality parameters. Examples of these parameters include ammonia and other nutrients ([NRMMC, EPHC and AHMC, 2006], citing Glendinning, 1999), \(\text{CO}_2\) ([Australian and New Zealand Environment and Conservation Council, Agriculture and Resource Management Council of Australia and New Zealand, 2000]) and even the availability of heavy metals. Heavy metals attached to soils or roof tops have been shown to mobilise with in low pH solutions \((\text{pH} \sim 4.0)\), thereby becoming a potential threat to groundwater resources ([Gong and Donahoe, 1997]). The biological availability of nutrients after the application of low pH solutions is shown to restrict plant fertility and thus compromise the effectiveness of irrigation ([NRMMC, EPHC and AHMC, 2006], citing Glendinning, 1999).

The pH levels of water following storage in basalt-filled reservoir models were always higher than the levels of pH of the water stored in other reservoir types. These results were similar to those found in other studies of permeable pavements ([Pratt et al., 1995]). The increase in pH of water stored with basalt aggregate can be attributed to the minor constituents at the surface of the aggregate particles, typical of non-washed aggregate of this
type used in permeable pavement storage systems. On the other hand, it appears that the effect of permeable pavements with underlying storage on the pH of stored water is considered beneficial particularly when acidic rainfall conditions prevail.

The pH was highest after 2 weeks storage time ($M = 8.57$) and the lowest after 3 days or 4 weeks residence times. Although such high pH levels are not considered dangerous to human or plant health, there is a potential for fouling to occur in irrigation systems at pH levels higher than pH 9.0 if the source of the harvested stormwater also adds to the water alkalinity (ANZECC and ARMCANZ, 2000).

Regardless of the residence time, the pH level of the harvested stormwater used in this study was 8.07 in the control reservoir while it is usually expected that pH of pure stormwater to be nearly neutral or acidic. Although, there is little evidence to confirm the source of this high pH, it could have been the rainwater (though not likely), the rooftop or storage in the polyethylene tank which caused the pH to increase. It is expected that if low pH water enters the reservoir, the increase of pH of the water in the reservoirs, disregarding of the type of the basecourse aggregates of the pavements, can still provide water appropriate for irrigation of sensitive plants to higher pH levels. However, if lower acidity of the stored water is the aim, it is more appropriate to collect the stored water under the basecourse aggregates after 3 days or keep it for a four-week period especially if the permeable pavement with underlying reservoir has been constructed using basalt as the basecourse aggregate.

4.2. Electrical conductivity

Electrical conductivity is commonly used to determine the soluble salt concentration of a solution and is specified under various guidelines for Australia (NRMNC, EPHC and AHMC, 2006; ANZECC and ARMCANZ, 2000). Australian guidelines recommend salinity levels based on a crop’s ability to tolerate levels of salt. The growth of salt-sensitive crops requires irrigation water with salinity of no more than 700 $\mu$S/cm (NRMNC, EPHC and AHMC, 2006; ANZECC and ARMCANZ, 2000; Hassani and Kazemi, 2012). Typically the levels of conductivity and salinity are not suggested to be of risk to human health. However, an upper limit of 1000 $\mu$S/cm is usually specified as an aesthetic guideline.

This research found that the conductivity of water increased due to storage in all three basecourse aggregate types (basalt, quartzite and dolomite), when compared with the control reservoir. These increases in conductivity can be attributed to the dissolution of ions and other mineral fractions on the surface of aggregate particles in the reservoirs (Myers et al., 2009). EC tended to increase with time over the period of this study (8 weeks). The highest levels of EC were recorded after the longest residence time (8 weeks) in all cases, reaching a mean value of 512.5 $\mu$S/cm in the dolomite basecourse aggregate after an eight week residence time. Even at this salinity level, there is no risk posed for the irrigation of plants which are sensitive to irrigation water salinity based on the current Australian guidelines for salinity sensitive, ornamental and native plants of Australia (NRMNC, EPHC and AHMC, 2006). However, it is clear that EC with increasing the storage time of water in the basecourse material and particularly in the dolomite reservoirs does increase. This might be explained by solubility of the aggregates and their cation exchange capacities (Grissi et al., 2009). Where particularly sensitive plants are used, it is recommended that a basecourse aggregate of quartzite be utilised for storage of the stormwater as it produced the lowest EC values of the three basecourse aggregates tested in this study.

4.3. Turbidity

Turbidity is an important consideration for stormwater harvesting and reuse where treatment of microorganisms is required, as particles causing increased turbidity can block UV light used to treat water (NRMNC, EPHC and NHMRC, 2009). Acceptable levels of turbidity depend on the disinfection system design. Some guidelines specify that turbidity should be less than 1 NTU for adequate UV disinfection. However, more recent research has shown that standard UV disinfection systems can operate effectively for waters with a median turbidity of up to 2 NTU, with occasional peaks of up to 5 NTU (NRMNC, EPHC and NHMRC, 2009). Also, provided the disinfection system can respond accordingly to changes in turbidity, water with median turbidity levels of up to 25 NTU (and occasional peaks of up to 100 NTU) may be adequately treated with UV disinfection (NRMNC, EPHC and NHMRC, 2009).

In this experiment, a distinguishably high turbidity was shown after one week storage of water in the reservoirs. This might imply that this time is critical for water collection as it might have effects on water reuse or on the irrigation or water collection system. Even disregarding of the highest turbidity levels which was shown in one week residence time in this study, the turbidity levels were still relatively low (75 NTU in other residence times, which means that the effectiveness of UV disinfection would be questionable. Therefore, detailed microbial investigations would be required before consideration could be given to reusing, for potable purposes, water stored in the permeable pavement basecourse materials used in this experiment. The highest turbidity was observed in dolomite aggregate compared with the reservoir which might need to be taken into consideration if water reuse purpose of the reservoir requires low turbidity of the stored water.

4.4. Dissolved oxygen

The depletion of DO is apparent in basalt aggregate compared with other reservoir types. Little scientific evidence was found to justify such depletion but this attribute might be connected to the nature and biochemistry of basalt. Also, disregarding of the type of basecourse aggregates, depletion in dissolved oxygen was also apparent as the residence time of the stored water increased. This might be associated with the development of anaerobic conditions in water stored for long periods of time. Although these anaerobic conditions could be beneficial in terms of nitrate removal the potential odors associated with anaerobic conditions may not be acceptable in the open urban environment (Bachand and Horne, 1999). Although, there is some research-based evidence that confirm low DO levels have negative effects on organisms and ecosystems, most such documentations reveal that DO levels above 3 mg/l are less harmful for the ecology and the environment (Belanger, 1991). Further, no evidence was found to prove that there will be any impact on plant growth and survival at the measured DO levels. Strategies for aeration such as recirculation of storage waters could be investigated if required. DO levels may also increase in water pumped to the surface and emitted via an irrigation system which can be considered in irrigation strategies.

5. Conclusions

The experiment showed that there were changes in water quality when stormwater was stored in the basalt, quartzite and dolomite basecourse materials that commonly underlie permeable pavements. The comparisons that were made with current Australian guidelines for water harvesting and reuse lead to conclusions that these systems will generally yield a water quality adequate for reuse for irrigation of green spaces. This result is
consistent with findings of Nnadi et al. (2015) in which they confirmed disregarding the type of basecourse aggregates of permeable pavements, they have the capacity to recycle stormwater for agricultural irrigation even in nutrient leaching or oil dripping conditions to these systems.

All in all, in this research no water quality changes was found that would be considered as a barrier to the use of stormwater stored under the permeable pavement for green space irrigation. This conclusion was based on the regulatory limits of the current stormwater guidelines as described in Section 4.

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