Experience with Pervious Paving

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Abstract

A research project established in South Australia in 2009 investigated whether a gravel base layer beneath pervious paving could deter shallow tree root growth and minimise pavement damage. The experiment found that persistent roots with potential to damage the pavement surface were fewer and they were deeper in the subgrade beneath the pervious paving than beneath impervious paving. Root growth in the pervious pavement's gravel base layer was restricted to short-lived, fine roots which withered and died at 2 mm in diameter or less through the natural process of fine root turnover, but roots beneath impervious paving increased in diameter sufficiently to damage the pavement. This experience has led the City of Mitcham to use pervious paving as a mainstream component in its capital works programs, with over 20,000 m^2 now incorporated into its footpath network. Investigation of pervious paving for vehicular traffic applications is also underway in the City of Mitcham, with over 1200 m^2 of pervious vehicular paving laid in recent years over low-permeability, moderately reactive silty clay subgrade in working demonstrations in residential streets and carparks. This paper summarises some pervious paving research and experience over the past decade, and adds the findings of a recent examination of root development beneath pervious paving after ten years of tree growth.

1. INTRODUCTION

Pervious paving can be substituted for impervious pavement to manage stormwater *in-situ*; a major attraction being that it can deliver water quantity and quality benefits and other ecosystem services without requiring additional land (Beecham 2009; Sharma et al. 2016). A primary goal of many pervious pavements is to infiltrate water into the subgrade to reduce runoff and associated pollution, erosion and other impacts (Beecham et al. 2012; Thelen et al. 1972). Pervious paving can also help to restore ecosystem services in urban areas by replenishing aquifers and soil moisture, reducing potable water demand and mitigating heat island effects. The durability and scale of city pavements mean these benefits can be significant and enduring (Eisenberg et al. 2015).

Investigations in recent years have revealed potential benefits through synergies between trees and stormwater management (Grey et al. 2018; Szota et al. 2019; Szota et al. 2018). Trees can help to manage stormwater quality and quantity; they intercept rainfall (Xiao & McPherson 2011), increase infiltration to the soil (Day & Dickinson 2008) and then convey much of what is detained back to the atmosphere. Pollutants that can be toxic to aquatic and marine life nourish trees and aid their growth (Denman et al. 2006). Links between stormwater infiltration and better hydrated and nourished street trees are clear (Chen et al. 2015; US EPA 2013). Synergies between trees and pavements are not as obvious, but a footpath that had been severely damaged by roots after only 20% of its expected service life led to the pervious paving trials detailed in this paper.

Pavement damage can occur when pressure exerted by tree roots exceeds the shear strength of subgrades, base materials and surfaces (Grabosky et al. 2011; Ishihara et al. 2012). Approaches reported in literature to prevent damage include planting smaller species further from infrastructure (Wagar & Barker 1983), and an increasing reluctance to plant trees was noted (Lucke et al. 2011). These approaches are in conflict with contemporary directions toward increased tree planting for community and environmental reasons. Research identified that a gravel layer was 'One of the most effective means of controlling tree root growth' (Coder 1998), so it appeared that pervious paving with its gravel base layer might offer a potential solution.

Use of pervious paving remains limited to date, due in part to lack of local information on its performance. When pervious paving was first considered in 2008 for managing root-related footpath damage the potential for problematic ground movement, clogging, poor infiltration in low permeability soils, and saturation reducing subgrade strength were all raised as concerns. Literature informs some of these, but little information was available regarding tree root growth beneath pervious paving and none was identified which reported empirical data relating ground movement and infiltration. An experiment was designed to inform these knowledge gaps. To update findings published to date, experimental pavements were excavated in 2019 to observe root development after ten years of growth; these most recent findings are presented in this paper. Some previously published information and results are summarised to provide context to this update. Details of pervious road pavements which have been functioning for several years are also presented.

2. LITERATURE REVIEW

2.1. Clogging of pervious pavements

Experience with pervious paving spans decades and clogging, hydraulic conductance and maintenance needs have been investigated and reported. Sediment and organic matter can effect hydraulic conductance, with clogging varying with pavement type, age and the nature of the surroundings (Lucke & Beecham 2011; Lucke et al. 2013). Pervious asphalt and concrete have lower initial conductivity than permeable interlocking concrete paving (PICP), and conductance diminishes more slowly with time in PICP than in pervious asphalt and concrete (Borgwardt 2006). Over two decades porous asphalt's conductivity diminished from its initial 290 mm min^{-1} to 0.22 to 0.50 mm min^{-1} (13 to 30 mm hr^{-1}), but infiltration up to 6.5 mm min^{-1} (390 mm hr^{-1}) could be restored by cleaning (Al-Rubaei et al. 2013). Hydraulic conductivity of pervious concrete can exceed 500mm min^{-1} when new (Schaefer et al. 2006), but typically varies from 12 to 32 mm min^{-1} (Tennis, Leming & Akers 2004).

Infiltration rates in PICP after eight to ten years of service have been reported at or above 100 mm hr^{-1} (Beecham et al. 2009), however Kresin et al. (1997) measured <15 mm hr^{-1} for pavements one to three years old and Drake and Bradford (2011) reported <50 mm hr^{-1} in a seven year old pavement. In explaining these, James and Gerrits (2003) indicated that minimising the entry of fines from the surrounding environment was critical. Borgwardt (2006) indicated that after about ten years of service, PICP infiltration would be 18% of its value when constructed. Mullaney and Lucke (2014) suggested the majority of pavements remained functional beyond their 15 year design life, while Shackel et al. (2008) suggested a design life of 20 years was reasonable. Boogaard et al. (2014) supported this, agreeing that most pervious pavements were still effective after many years of service. While maintenance equipment including vacuum trucks, high pressure water cleaners and street sweepers has been tested and recommended (Drake et al. 2011), other researchers question the need for such maintenance if designs are based on the lower infiltration rates which typically plateau after the first decade (Beecham et al. 2009). Some clogging of PICP is to be expected during operation due to the filtering action which delivers much of its environmental benefit, but under reasonable site conditions (in the absence of excessive fines, or wind-blown sand in coastal regions, for example) it has been shown that stormwater management can be achieved without requiring excessive maintenance.

2.2. Infiltration into low-permeability subgrades

Literature identifies that pervious paving can contribute to stormwater management on low permeability soils due to its detention capacity (Mullaney et al. 2015). Collins et al. (2008) found that catchment outflow reductions of 67% were possible for rainfall events of less than 50 mm by using permeable pavements built over clay subgrades. Other researchers drew a similar conclusion:

> …permeable pavement appears to be an effective tool for hydrologic mitigation of storms from "every day events" up to the 10-year, 24-h ARI [Average Recurrence Interval], even on steep slopes located over impermeable soils and subject to frequent

rainfall.

(Fassman & Blackbourn 2010)

2.3. Subgrade saturation

Roads and footpaths need adequate support from their underlying soils. Soil strength relates to the nature and arrangement of mineral particles, and increasing the mechanical interface between grains and aggregates through compaction increases soil strength. Soil strength is inversely proportional to water content (Shackel et al. 2008), so high strength to support pavements is typically achieved by compacting the soil subgrade and base materials and sealing the surface to prevent water entry. The resulting soil conditions restrict tree root growth, however.

Trees need soil which combines air, water and organic matter between the grains and aggregates. Compacted, dry, high strength soil prevents root penetration (Smith et al. 2001; Watson et al. 2014) and compromises the stormwater management benefits that trees and soils offer (Berland et al. 2017; Day & Dickinson 2008). Various approaches have been developed to support pavements and root growth, including structural soil (Grabosky et al. 2009; Riikonen et al. 2009), structural cells (Ow & Ghosh 2017) and suspended pavements (Plant 2002). Pervious pavements on gravel bases designed to distribute traffic loads over low-strength and occasionally saturated subgrades are another option.

Pervious paving does not conform to accepted pavement design methods. As stated by Borgwardt (1995): 'the traditional principle of road construction, to keep away all water from the loadbearing layers, must be departed from…'. Furthermore, recent literature suggests that to preserve infiltration capacity pervious pavement subgrades should not be compacted (Drake et al. 2013), with Eisenberg et al. (2015) advocating the use of machinery with tracks or over-sized tyres to avoid incidental compaction. By using conservative moduli and determining subgrade strength in its uncompacted, saturated state, pervious pavements can be designed to successfully support vehicular traffic. Literature reports that pervious paving can also support heavy traffic in applications including bus terminals, loading bays and container handing ports (Knapton & Cook 2000).

2.4. Root deterrent properties of gravel

A gravel base layer has been shown to limit shallow root growth beneath concrete pavement (Costello & Jones 2003). Sycamore roots grew deeper near a 150 mm thick gravel layer beneath a concrete footpath, the gravel deterring root growth more effectively than impenetrable plastic root barrier treatments (Gilman 2006). The effect was also observed with London Plane growing near a concrete pavement with a 100 mm thick gravel layer base (Smiley 2008). Similar results were reported with other species including Linden and Ash (Kristoffersen 1999), Norway Maple (Bassuk et al. 2011), and Euramerican poplar (Kopinga 1994). These results followed investigations by environmental scientists seeking to prevent buried low-level nuclear and toxic waste material being transported to the surface through roots; a gravel layer in the waste's clay capping prevented penetration by roots of Sagebrush and grasses (Cline et al. 1980; Hakonson 1986; Reynolds 1990).

The gravel layer's root deterrent effect is due to desiccation of root tips in air-filled voids in the gravel matrix (Reynolds 1990) and to mechanical impedance (Kristoffersen 1999). Gravel's high void ratio makes it ideal to detain stormwater beneath pervious pavements (Beecham et al. 2012; Eisenberg et al. 2015), and in Adelaide's semi-arid climate it seemed likely that a pervious surface above it might also reduce condensate formation at the underside of the wearing layer (Morgenroth 2010), to further reduce shallow root growth (Barker 1988; Randrup et al. 2001). The experiment described in this paper was designed to investigate and demonstrate the reported root-deterrent capacity of the gravel layer in a working pervious pavement.

3. MATERIALS AND METHOD

3.1. Pervious footpath pavement

Twelve pervious pavement sections 4 m long and 2 m wide were built in suburban Kingswood, South Australia, in 2009. Six replicates of each of two different base designs were built; one with a 150 mm thick layer of 20 mm gravel on level subgrade (‘perm-level’) and one with the gravel layer increasing to 300 mm thickness in the centre of the footpath (‘perm-swale’) (Figure 1). 80 mm thick Ecotrihex permeable interlocking concrete block pavers (PICP) were laid directly onto a 50 mm thick bedding layer of 5-7 mm gravel above the 20 mm gravel. Geotextile was used at the subgrade but not between the gravel base and bedding layers. The pervious paving sections were built into an existing impervious concrete block footpath which served as the control. The pre-existing impervious footpath’s subgrade had been compacted during its construction in 1999, but newly-exposed subgrade was not compacted prior to constructing the pervious pavement gravel bases in 2009.

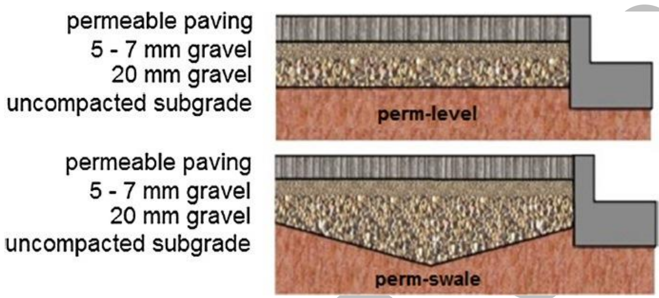

Figure 1. Experimental pervious pavements had gravel bases formed of 20 mm gravel 150 mm thick on level subgrade (perm-level) and formed as a gravel-filled swale 300mm deep at the centre (perm-swale).

Tree planting pits measuring 1.6 m long and 0.6 m wide were built into the pavement sections (Figure 2). Callery pear trees (Pyrus calleryana ‘Chanticleer’) were planted in September 2009. After five years a trench was excavated across the footpath one metre south of three trees in each paving treatment. Root diameter, depth and location were recorded. Linear mixed model analyses were conducted in the R statistical computing environment (R Development Core Team 2017) using ASReml (Butler et al. 2017) and asremlPlus (Brien 2017a) software to investigate effects of pavement design on tree root quantity, diameter and depth.

Figure 2. Pervious paving sites 4 m long and 2 m wide included a tree pit measuring 1.6 m by 0.6 m. (Site 3, 29th October 2010)

3.2. Pervious road pavement

Trials to investigate suitability of pervious paving for vehicular traffic included construction of 580 m^2 of PICP in 2016 in Kegworth Road in Melrose Park, South Australia (Figure 3), to manage stormwater at a site which flooded occasionally. Surface runoff from a residential catchment area pooled at the intersection of Kegworth and Wheaton Roads, where at times it exceeded 300 mm deep and extended across adjacent private properties. To maintain maximum stormwater infiltration the silty clay subgrade was not compacted. In its saturated state the subgrade had a Californian Bearing Ratio of 3%. Drainage installed in the gravel base (Megaflo 170, Geofabrics Australasia) allowed infiltration but conveyed water during intense rainfall to leaky wells in road verges and soakage trenches on an adjacent reserve; overflows discharged into the pre-existing stormwater network. 80 mm thick Ecotrihex pavers were used above a 50mm thick bedding layer of 5-7 mm screenings and 175 mm thick base layer of 20 mm screenings (Figure 4). 2-3 mm sand was used as jointing sand between the pavers and to fill the voids.

In 2017 PICP was built to replace asphaltic concrete road pavement in Brookside Road in Springfield, South Australia (Figure 3). The PICP's gravel base was similar to the design for Kegworth Road (Figure 4) but with the addition of a geogrid (100 mm deep Geoweb Cellular Confinement System, Geofabrics Australasia) in the 20 mm gravel layer as part of the pavement structural design.

Figure 3. Pervious road paving in Brookside Road in Springfield, South Australia (left) and in Kegworth Road, Melrose Park, South Australia (right)

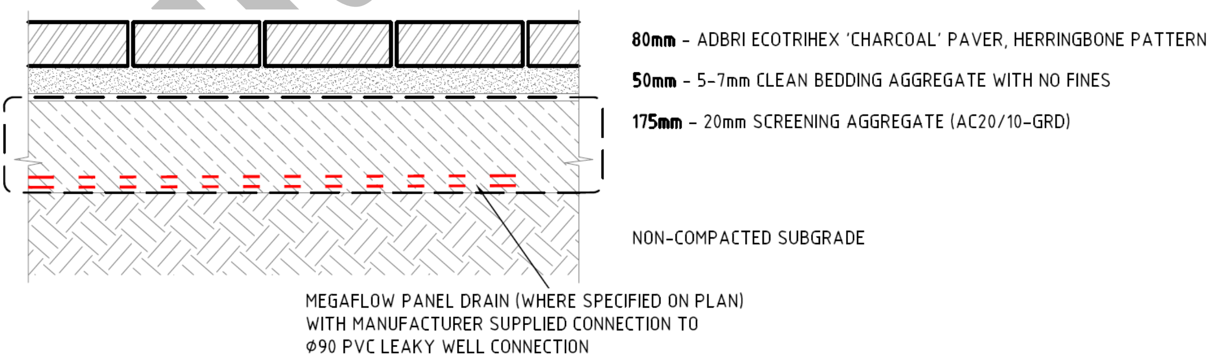

Figure 4. Pervious road base detail as constructed in 2016 in Kegworth Road, Melrose Park, South Australia

4. RESULTS

After five years of growth *in-situ*, roots <2 mm in diameter were abundant and in good health in PICP footpath gravel base layers and near the surface of the uncompacted subgrade. Dead and decaying roots of up to 2 mm in diameter were also observed throughout the gravel. Beneath the gravel, roots which had grown to 5 mm or more in diameter were fewer and deeper in the subgrade beneath perm-level paving than beneath impervious paving (Figure 5). Further detail is available in Johnson et al. (2019).

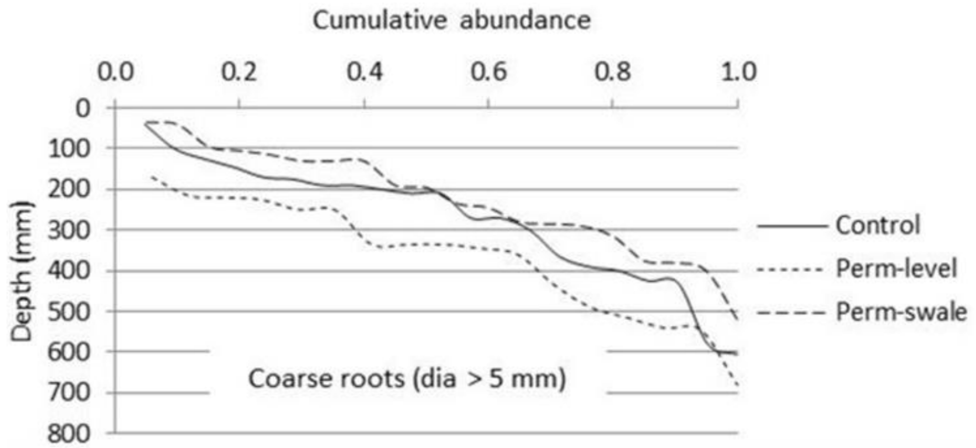

Figure 5. Cumulative abundance of roots greater than 5mm in diameter relative to depth beneath the subgrade surface (from Johnson 2017).

After ten years of growth, at sites with impervious paving the structural roots near the trees' trunks had grown in and near the sand bedding layer and dislodged the surface to the extent that tripping hazards had formed and maintenance was required (Figure 6). The root growth habit shown in Figure 6 was representative of the three impervious sites which were excavated. At sites with pervious paving, structural roots had also lifted the pavement but to a smaller extent, and the rounded form of the displacement did not present a tripping hazard (Figure 7). Maintenance was not required at pervious pavement sites. At pervious sites roots had not persisted in the gravel base layer (Figure 8), and the gravel was easily removed with a vacuum.

Figure 6. Impervious pavement damaged after ten years due to shallow root growth. The level is on the alignment of the edge of the tree pit; scale shows cm. (Site 18, 16 April 2019).

Figure 7. At pervious pavements root growth had caused only minor lifting.

Figure 8. Root growth had not persisted in pervious pavement gravel base layers.

Some roots had entered the pervious pavement gravel base layer across the top of the geotextile, others had grown through the geotextile; these roots were stunted and growth had ceased within centimeters of the edge of the gravel (Figure 9). Roots which had grown large enough at pervious sites to provide structural support to the tree had descended outside the edge of the gravel base layer and were distributed through the subgrade beneath the gravel layer (Figure 10).

Roots shown in images up to and including Figure 10 supported Chanticleer callery pear street trees. A small-leaved native fig (*Ficus* sp.) had been planted in an adjoining front garden in 2009. Roots from this tree grew beneath the pervious paving and the adjacent impervious paving (Figure 11). Beneath impervious paving the *Ficus* root growth habit was similar to the growth of Chanticleer callery pear beneath impervious paving, with shallow growth (Figure 12) requiring roots to be cut and removed to enable footpath repair. A larger root of the same *Ficus* tree grew beneath pervious paving approximately 3.5 m to the north of the root shown in Figure 12. Beneath the pervious paving this root grew at the interface of the gravel and subgrade (Figure 13).

Figure 9. Roots which grew through and over the geotextile were stunted and were confined to the outer few centimetres of the gravel layer (Scale shows cm and inches).

Figure 10: Structural roots had persisted only outside and beneath the pervious pavement subgrade. The string shows the position of the tree pit edge.

Figure 11. Roots from an Australian native fig (*Ficus* sp., identified by the arrow in the right image) had damaged the pervious footpath (left) and the nearby impervious paving (right).

Figure 12: Shallow *Ficus* root growth beneath impervious concrete block paving

Figure 13: Deep *Ficus* root growth beneath pervious paving with a gravel base layer

5. DISCUSSION

Tree root diameter, abundance and depth in the subgrade were affected by pavement surface type and base design. The gravel layer beneath pervious paving effectively prevented growth of large, shallow roots over the ten year period of the experiment. 'Fine root turnover' is the term given to the death following their naturally short life cycle of the fine roots that are responsible for most of a tree's water and nutrient uptake. Fine root turnover limited growth in the gravel to roots which were too small to affect the paved surface. From the perspective of tree growth the gravel layer functioned like a layer of mulch; it supported root growth only for short periods when conditions were suitable. Fine root turnover is likely to enhance the hydraulic conductance of the soil, thus improving the stormwater infiltration capacity of the pervious pavement subgrade.

Beneath the gravel layer, large roots which might dislodge pavers at the surface were deeper in the subgrade and were fewer in number beneath pervious paving than beneath impervious paving, making trip hazard development less likely in pervious paving. This is consistent with recent findings in relation to Prickly paperbark (*Melaleuca quinquenervia*) growing in subtropical Australia at the Sunshine Coast, where annual rainfall averages 1700 mm (Lucke & Beecham 2019). Literature reports this gravel-layer root deterrent effect beneath impervious concrete poured onto a gravel base layer, so the use of a pervious surface may not be essential, but reduced condensate formation and evaporation from beneath pervious paving are likely to enhance the root-deterrent effect. This root-deterrent effect has been shown for a limited number of tree species and under a limited number of climatic conditions so, whilst these results are promising, further investigation is warranted.

Soil moisture and ground movement were measured and analysed with respect to the different pavement treatments as part of this experiment. Full results are available in Johnson (2017). A journal paper is currently in press which shows that infiltration through pervious paving did not exacerbate problematic ground movement in reactive soil when there were trees in proximity. This finding seems reasonable, as trees are known to increase shrinkage of reactive soil by extracting water. Infiltrating stormwater through pervious paving or other means could help to offset the water extracted by trees and, therefore, potentially mitigate both tree root-related and reactive soil-related infrastructure damage. These results mean that tree root-related pavement damage may be managed through the informed selection of open graded base layer materials, with the use of pervious pavement materials potentially helping to reduce problematic ground movement in the presence of trees.

Pervious paving has not been widely applied as a stormwater management tool, possibly because its cost remains marginally higher than conventional concrete block paving and the value of its environmental and water management benefits can be difficult to quantify. Paving maintenance, liability insurance and injury claims-related expenses are readily available however, and these may justify the use of pervious paving with a gravel base layer.

Pervious paving has performed well under vehicular traffic for decades in places such as Smith Street, Manly, New South Wales, where the pavement described by Beecham et al. (2009) received torrential rain in February 2020, so the effective service demonstrated by the recently constructed pavements in Kegworth and Brookside Roads is expected to continue. The use of pervious paving in Kegworth Road was not a fair test of the technology however, as it was applied to address a flooding problem rather than to perform the function for which it was designed – to manage rain where it falls. Ideally, additional pervious paving and other WSUD devices will be used to increase infiltration across the catchment and not just at locations where runoff concentrates and becomes problematic. However, under these less-than-ideal conditions the pavement has performed well; it managed two extreme rainfall events a few weeks apart during spring in 2016, without localised flooding where there would otherwise have been deep ponding.

The Kegworth Road pervious pavement shows how water sensitive urban design can be effective and save public funds when project planning takes a holistic approach. Kegworth Road's pervious paving cost $30,000 more than resurfacing the road with asphalt, which may have resulted in renewal of the asphalt if the focus had been limited to pavement cost alone. The project in total, including the pervious paving, leaky wells, soakage and distribution systems in the nearby reserve, cost $200,000. This represented a considerable benefit in comparison with the $1.2M estimated cost of upgrading the conventional pit and pipe network to address the local flooding issue. Pervious paving reduced the funding needed to resolve this flooding issue by $1M when compared with a 'business as usual' upgrade of the pit and pipe drainage network.

6. CONCLUSIONS

Pervious paving has been shown to provide stormwater quality and quantity benefits but uptake remains slow despite Australian experience which shows that it can cost-effectively accommodate pedestrian and vehicular traffic on low-strength, reactive subgrades. Although infiltration has been shown to decrease with time due to clogging, pervious paving's infiltration capacity remains sufficient in most urban environments to manage high-intensity rainfall events. In applications in close proximity to street trees additional benefits have been identified: pavement damage, trip hazard formation, liability, injury and tree and pavement life cycle costs can be reduced by the root-deterrent function of gravel base layers. Larger trials and working demonstrations of pervious paving are warranted, in collaboration with researchers, to increase knowledge and evaluate their performance in different soils and climatic zones and in association with different tree species.

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