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Manuscript title: The role of engineered tree pit solutions in nature-positive civil engineering

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Abstract

Successfully establishing and growing street trees presents significant challenges and traditional techniques are associated with elevated tree mortality. Moreover, securing appropriate soil volumes for trees is a substantial challenge, particularly in modern street engineering where the grey infrastructure is prioritised over tree success. Engineered tree pit solutions can counteract this situation. They enable trees and grey infrastructure to coexist, providing improved rooting environments, load-bearing structural support conforming to engineering specifications, and the ability to manage stormwater runoff within one tree pit design. This article presents a literature-informed overview of the current technologies applicable to new-build and retrofit scenarios that integrate street trees and pavements, enabling nature-positive, resilient tree pit designs conducive to tree growth. We focus on the solutions most commonly employed in practice – structural growing media and crate systems – outlining their constituents, construction and considerations for success. This article informs built environment practitioners, policymakers and researchers on innovations translatable into practical techniques to enhance tree pit design and optimise street trees as multifunctional nature-based solutions.

Keywords: environmental engineering, pavement design, soils and ground conditions, vegetation, structural soils, tree substrates, biochar, soil cells, suspended pavement, urban forestry, green infrastructure, SuDS, ecological engineering

Introduction

The benefits of street trees are now widely understood. However, establishing street trees presents significant technical challenges and traditional techniques are often unsuitable in meeting the adverse growing conditions of urban environments (Jim, 2022). Street trees grow in the presence of many stressors, comprising a litany of subterranean and subaerial constraints. However, inadequate soil volumes and soil compaction are repeatedly reported to be key constraints affecting street tree growth and survival (Jim, 2022; references therein). These constraints do not exist in a vacuum; rather, they are inherent consequences arising from highway engineering practice.

A major challenge in growing street trees is the need to resolve the conflicting engineering and biological demands of soils. As an engineering substrate, soils are compacted to within at least 95% of their peak bulk density (PBD) to prevent settling. Conversely, as a biological medium, soil requirements include low bulk densities, a distribution of pore sizes providing adequate storage capacity for plant-available water, good drainage, aeration and fertility (Hirons and Percival, 2012). These characteristics require both macro- and micro-pore sizes and therefore a well-structured and aggregated soil. However, the PBD required in pavement design ultimately demands a compaction level beyond that conducive for root growth (Grabosky and Bassuk, 2017).

Street trees have traditionally been planted in small cutouts in the pavement with no additional measures to prevent soil compaction. The perimeter of these pits is frequently blocked by concrete and utility runs and encased by compacted roadbed materials inaccessible to root penetration (Jim, 2017). The rooting volume available for trees is therefore commonly restricted due to conventional engineering design, and traditional approaches are widely considered inadequate in supporting tree longevity (Urban, 1992; Hirons and Thomas, 2018).

To overcome this conflict, engineered tree pit solutions integrate engineering and tree requirements within a shared design. This is achieved through either a load-bearing soil (structural growing media: sand- or aggregate-based substrates) or a physical structure (crate systems) in the root zone. This article provides an overview of structural growing media and crate systems and their role in enhancing the load-bearing capacity of tree pits, whilst simultaneously improving tree growth. It seeks, via a literature review, to answer the question: What is the impact of engineered tree pit solutions on street tree growth and survival? Although these solutions include patented products, this article focusses on the general principles of the technologies instead of specific products. For the first time, this article brings together a simple overview of load-bearing tree pit types underpinned by current research and international practice.

Approach to the research

The typology of engineered solutions follows TDAG (2014): Structural growing media with sand-based substrates and aggregate-based substrates, and crate systems (**Table 1**). This is expanded through a state-of-the-art literature review drawing on published academic literature, conference proceedings and practitioner guidance on the performance of these load-bearing solutions. Each engineered solution is introduced, and evidence related to the impact on tree growth and survival are presented. Comparative evidence is then provided from studies that have examined the impact on tree performance in the solutions. Finally, some conclusions for research and practice are summarised.

Structural growing media

Principles

Structural growing media retain the qualities required for tree growth when compacted for load-bearing support. The fundamental concept is the development of structural skeleton, achieved through sand or aggregate, that provides air and water in balance with root penetrability post-compaction.

Sand-based substrates

Overview

Sand-based substrates (SBS) contain approximately 90% sand, 4-5% organic matter and 2-4% clay w/w (TDAG, 2014). They must be mixed to tight tolerances and within a narrow and uniform distribution spread. The sands comprise medium coarse silica sand, free of salts, with a median particle size of 0.2-2.0 mm, and the organic matter and clay components must have <2 µm sized particles (Roberts, Jackson and Smith, 2006). The sand facilitates load-bearing and supports the organic matter and clay to add capacity for water and nutrient retention (Couenberg, 1994; **Figure 1**). The mixture must strictly contain only 2-4% clay to prevent the clogging of pores between the sand particles (Couenberg, 1994).

The organic matter must be thoroughly decomposed to prevent further decomposition causing a high oxygen demand. SBS are premixed in an industrial blender and installed in two lifts of 400-500 mm to a maximum depth of 1 m, as aeration is inadequate for root growth at greater depths (TDAG, 2014; **Figure 2**). Compaction in each lift is monitored in terms of resistance, measured in megapascals (MPa) via a cone penetrometer. The typical required penetration resistance for SBS to perform both structurally and biologically is 1.5-2.0 MPa, equating to approximately 70-80% PBD (Roberts, Jackson and Smith, 2006). Consequently, SBS are only applicable where relatively low load-bearing is expected; they are not appropriate as an alternative base for highway pavements (TDAG, 2014).

Considerations

SBS have been a successful growing medium for street trees when compacted to 80% PBD (Couenberg, 1994). Over-compacting SBS can reduce drainage efficiency, leading to anaerobic conversion of the organic matter and reductions in tree growth (Kristoffersen, 1999). Accordingly, during installation, construction practices must receive rigorous oversight to ensure the degree of compaction meets the small threshold in which SBS support tree growth (TDAG, 2014). In the US, a SBS has been proposed as a paving sub-base intended to support root growth when compacted to 95% PBD (Urban, 2008). Although this approach has been used in practice no controlled studies have verified tree performance. Over compaction of SBS is common during installation if clay or organic matter content exceeds 4% or 5% respectively (Couenberg, 1994). Increasing organic matter may also reduce soil pH and constrain tree species selection. Understanding the age and quality of the organic matter is necessary as this influences its acidity and oxygen usage as it further decomposes following placement. If mature and stable organic matter derived from compost cannot be sourced, an aeration system should be used (TDAG, 2014).

SBS were pioneered in Amsterdam, which sits on a high water table with minimal seasonal fluctuation (Voeten, 2014). The water table is reportedly consistent between 1-1.2 m, above which is a 100-200 mm saturation zone, overlaid with a compacted layer of non-saturated sand (Goodwin, 2017). SBS are typically installed above this compacted layer, which enables the groundwater to infiltrate into the substrate via capillary action, facilitating soil water recharge (Urban, 2008). However, places without high water tables often experience comparatively dry soil conditions due to the low water-holding capacity of coarse sand creating sensitivity to drought (Hirons and Thomas, 2018). Consequently, SBS are best suited to sites with high rainfall, or the provision of supplementary irrigation is required to meet tree water demands.

In addition, SBS may struggle to support tree longevity due to the vulnerability of sand to rapid drying and leaching of nutrients (Urban, 2008). Thus, trees may experience water and nutrient deficiencies, leading to substrate “burnout”, particularly as maturing canopies begin to demand greater volumes of water (Hirons and Thomas, 2018). The evidence for the efficacy of SBS on tree growth is mixed; for example, studies have reported both reduced and comparable performance relative to compacted loam soils (Kristoffersen, 1999; Rahman, Stringer and Ennos, 2013; Buhler, Kristoffersen and Larsen, 2007).

However, reports from the Netherlands suggest that when specifications are followed, SBS can support tree growth under light pedestrian traffic loads including footways, cycleways and parking for light vehicles (Moll and Batenburg, 2020). Ultimately, SBS provide a rooting environment compatible with modest load-bearing and a solution to extend tree pits across a larger area than is traditionally achieved.

Aggregate-based substrates

Principles

Aggregate-based substrates (ABS) are designed for use under pavements, parking areas, plazas and highways. There are two categories: medium-sized aggregate substrates and large-stone skeletal substrates (TDAG, 2014). The general principles for load-bearing and tree growth are consistent; the substrates combine angular stones with a growing medium. When the aggregate is compacted for load-bearing, friction at contact points between the aggregates locks them together. In engineering terms, ABS can be described as an open-textured sub-base layer, enabling compaction to 95% PBD. Due to aggregate angularity, voids remain after compaction, and the interstitial space is occupied by a growing medium (see below) to support root growth (**Figure 3**). The intention of ABS is to “suspend” the media between the aggregates without overfilling the voids, which would render the substrate neither structurally-sound nor biologically-viable.

Medium-sized aggregate substrates

Overview

Medium-sized aggregate substrates (MSAS) use highly angular aggregates (20-40 mm) with no fines (**Figure 4**). The growing medium comprises 20% clay and 2-5% organic matter w/w (Grabosky and Bassuk, 1996). Load-bearing ability is more sensitive to mixing ratios than tree growth; however, aggregate characteristics can influence growth. Narrow particle size distribution, and angular aggregates with at least three sheared faces provide larger void space once compacted compared to the wide-sized distribution through aggregate nesting (Shergold, 1953). Further, cubical, as opposed to prismatic, aggregate shapes provide higher void volume thereby accommodate more soil (Grabosky and Bassuk, 2017). The stability of the mixture prior to compaction can be temperamental; to prevent separation, some MSAS use hydrogel (0.025%) for stabilisation (Bassuk et al., 2015).

A MSAS tree pit requires a minimum depth of 0.6 m, preferably 0.7-0.9 m to increase water-holding capacity (Bassuk, 2013; **Figure 5**). The substrate is installed in 150 mm lifts to the surfacing course level. Ideally, the substrate should also form the surfacing course sub-base (Goodwin, 2017). Trees are planted either directly into the substrate or into a specific planting hole containing topsoil. The latter serves to extend the accessible rooting volume and would support transplant recovery by encouraging early root growth (Watson and Himelick, 2014). As MSAS are free-draining, and the subgrade is highly compacted, it is advised to install positive drainage to prevent saturation (Urban, 2008). The substrate can also be used in sustainable drainage systems (SuDS), bringing additional benefits besides tree growth (Day and Dickson, 2008).

Considerations

MSAS enable compaction to greater densities than in SBS. Therefore, they are more applicable in areas subject to greater loading, such as highway pavements, and can be installed in tight, contorted spaces, fills around utilities and adjacent to building foundations (Urban, 2008). Determining the precise quantity of soil in the mixture is critical for MSAS success. The clay fractions enable a greater water-holding capacity, increase drought tolerance and soil fertility (Grabosky and Bassuk, 1995; 1996). A clay of approximately 20% also “coats” the aggregates, providing a greater surface area for roots to acquire moisture (Bassuk et al., 2015).

Quality control of MSAS mixing and installation is a strong determinant of success (Trowbridge and Bassuk, 2004). Erroneous construction can impair tree growth and decrease nutrient concentration, and overly-compacted lifts form a barrier to root extension (Buhler et al., 2017). Conversely, when specifications are followed, abundant root growth has been observed (Grabosky et al., 2001; Grabosky, Haffner and Bassuk, 2009).

As with SBS, MSAS are vulnerable to water and nutrient deficits due to high aggregate proportions, particularly as trees mature (Hirons and Thomas, 2018). Nutrient deficits are also greater due to the influence of aggregate on rooting zone chemistry. In limestone-based systems, pH typically peaks at 8.0-8.2, regardless of soil pH at mixing (Trowbridge and Bassuk, 2004). High pH blocks a tree’s absorption of vital nutrients, reducing root growth (Kristoffersen, 1999). Consequently, preference is given to granitic aggregates as they are relatively inert and thus do not significantly alter pH (Grabosky and Bassuk, 2017). However, tree species selection is important to avoid nutrient deficits and approved species lists exist (e.g. Bassuk et al., 2015).

To support load-bearing, approximately 80% of MSAS volume must comprise aggregate, leaving a 20% growing medium (Urban, 2008). It is suggested trees will grow at reasonable rates until the soil is exhausted, and that soil burnout may occur within 5-10 years of planting (Ow et al., 2018), perhaps sooner in tree species without periods of dormancy (Ow and Ghosh, 2017). It is argued that MSAS are 20% as effective as uncompacted loam soil (Urban, 2008), principally based on the mixture comprising 80% aggregate. However, this may be a too simplistic view, as tree roots do not necessarily colonise soil volumes on an efficiency basis (Salisbury and Grabosky, 2020). Future predictive mixture designs should focus on repeatability and optimisation to learn from past successes and failures and develop substrates to best support street trees.

The long-term nutritional status of MSAS is therefore likely to restrict tree growth. It is plausible the demands of the roots will exceed attainable conditions, and nutritional supplements may be required (Hirons and Thomas, 2018). In addition to the stabilising benefits, a by-product of using hydrogel is their capacity to absorb and release large amounts of water and make this available to the roots for uptake (Agaba et al., 2010). The incorporation of biochar (see below) may also alleviate water and nutrients deficits in MSAS. Similarly, incorporating irrigation into MSAS or combining with a SuDS to recharge soil water is recommended (TDAG, 2014). This could be achieved by channelling runoff harvested from surrounding roofs, pavements and roads and diverting this into the tree pit (as is standard for large-stone skeletal substrates; see below).

Large-stone skeletal substrates

Overview

Large-stone skeletal substrates (LSSS) differentiate from MSAS by using larger angular stones and routinely incorporating nutrient-enriched biochar, aeration mechanisms and stormwater interception for use by the tree. The original design comprised an extensive base formed by layers (250-300 mm) of large angular stones (100-150 mm) to a minimum depth of 0.6 m (Embren et al., 2009; **Figure 6**). Each layer was compacted systematically prior to being flushed with soil at ≤20 mm intervals, where each cubic metre of stone required 0.25 m^3 of soil (Embren et al., 2009). However, the design evolved as follows. The first approach, the “Stockholm method”, uses (screened) hard angular aggregates (90-150 mm) such as crushed granite, basalt or recycled concrete installed in 200-250 mm lifts and compacted (Embren and Alvem, 2017). The growing media is then flushed, as above. The latest approach, building on the “Stockholm method”, is biochar macadam, composed of 85% v/v clean stone (32-63 mm) mixed with 15% nutrient-enriched biochar and compost at 1:1 (**Figure 7**), which are typically mixed with the macadam prior to installation and installed in 200-250 mm lifts (Embren and Alvem, 2017; **Figure 8**).

An important feature of both evolved designs is an aeration layer providing a “terrace” above the compacted substrate. The top 200 mm beneath the surfacing course comprises clean stone (32-63 mm) followed by a non-woven separation geotextile to prevent fines migrating into the tree pit and settling into the voids. Vertical aeration wells are also installed within the substrate, providing pathways for air and water. The tree is planted into a modular concrete frame that sits above the compacted substrate and diverts root growth away from the surface.

More so than for MSAS, fundamental to LSSS is providing pathways for stormwater to enter the tree pit and hydrate the growing media (Embren et al., 2009). Accordingly, tree pits are designed to capture runoff from adjacent roofs, roads and pavements via surface and kerb inlets. To ensure trees can effectively regulate incoming water, the perimeter of the tree pit is often tanked, and underdrainage installed to accommodate water outflow.

Considerations

The definitive switch to nutrient-enriched biochar and compost in lieu of soil is considered a primary reason for enhanced tree growth (Embren, 2016). Biochar is a highly stable storage site that maintains and increases soil fertility over time (Batenburg, 2021). Compared to initial designs, biochar macadam has improved the substrate's void ratio and resistance to compaction, increasing porosity to 40% (Embren, 2016). Porosity is integral to LSSS to facilitate effective permeability and support root growth.

Trees growing in biochar macadam are reported to have an average annual height growth of approximately 1 m; greater than that achieved in traditional tree pits across Stockholm, Sweden (Embren, 2016). Reportedly, 6-year-old trees have grown five times larger than 30-year-old trees planted in traditional tree pits (Embren, 2016). Biochar macadam has also resulted in trees of notable uniformity when planted in linear trenches along streets in Stockholm (personal observations [Bell]); these trenches are intentionally designed to intercept stormwater, and thus hydrate the substrate. Careful design is required to provide a sufficient volume of water to meet tree species demands and the substrate drainage rate must be known to prevent tree pits from inundation (TDAG, 2014).

Unfortunately, the current lack of commercial pyrolysis plants mean that it can be challenging to source biochar cost-effectively. In Stockholm, the municipality built their own pyrolysis plant and convert green waste generated by residents and municipal operations into biochar for use in urban tree pits and the district heating system (Bloomberg Cities Network, 2021). The feedstock used to create biochar is also important for tree growth. Biochar is not a singular product, but a family of products, whereby feedstock should be viewed as specific to the application; for enhanced tree growth, evidence suggests that a wood-based biomass should be used (Schaffert et al., 2022).

As with MSAS, LSSS are vulnerable to water deficits. However, they are typically constructed at low points in the pavement to optimise water interception and are more commonly used in bioretention tree pits (BTP), whereby stormwater enters through aeration wells or permeable pavement and can be held at the base of the tree pit acting as a reservoir to support the tree during times of drought. BTP typically use ABS that include a biochar and compost blend, but not the aeration layer above the substrate. Instead, the water retention zone in BTP comprises compacted clean stone with a porosity of 30-40%, enabling air and water circulation and the storage of up to 400 litres of water per cubic metre of the drainage layer. With appropriate design, this water can be used by the tree and discharged to the conventional sewage system in a controlled manner.

Monitoring during construction and a common understanding of the design principles are critical for LSSS success, and installation handbooks have been produced (Embren et al., 2009; Embren and Alvem, 2017). Erroneous construction is the factor most likely to affect tree growth (Embren and Alvem, 2017). A common mistake is the inclusion of fines in the aggregate mix; consequently, it is important to control aggregate grading. If aggregates are inconsistent, interstitial spaces are lost and the substrate will not support root growth. If LSSS are mixed on-site, it is important that the growing media flushed into the matrix is homogenous and evenly distributed (Embren et al., 2009). Frequently, contractors incorrectly position the geotextile between the compacted substrate and aeration layer (Embren and Alvem, 2017), which impairs air and water diffusion, curbing root growth.

A significant number of street trees in Stockholm have successfully established in LSSS (Embren, 2016). Consequently, the City of Stockholm now retrofit the solution around existing trees to reinvigorate tree growth (Embren and Alvem, 2017). To recreate the successes in Stockholm, it would invariably be necessary to imitate the entire solution and not only the biochar-aggregate mix. That is, to ensure stormwater interception, include mechanisms for aeration serving the entire tree pit, and quality control substrate mixing and installation. There is great potential for LSSS in hybrid tree pit designs to create effective root breakout zones under pavement. This is especially true given LSSS's low-tech approach, similarity with pavement construction methods, and minimal reliance of patented products allowing for flexible designs.

Crate systems

Overview

Crate systems are modular structural cells that support pavement design loads and act as a vault to support a large volume of uncompacted soil (**Figure 9**). The cells transfer the weight from the point of loading across the lattice structure and down into the subgrade, bypassing the soil. The system foundation is a layer of aggregate resting on the compacted subgrade. Subgrade compaction levels, type, and thickness of base coarse aggregate are dependent on the soil conditions encountered and load-bearing requirements (Urban, 2008).

Most crate systems, including latest innovations, are constructed from polypropylene. Polypropylene has several advantages, including elasticity, toughness, and resistance to fatigue and chemicals. Therefore, it can retain its shape after considerable torsion, bending and/or flexing-induced stress (GreenBlue Urban, 2018a). The interlocking prefabricated modules are available in different sizes to suit site circumstances, and most designs can be stacked to achieve increased depth (**Figure 10**). The resulting rigid lattice can withstand heavy vertical and lateral loads (Grabosky and Bassuk, 2017). The surfacing course is separated by an open-grid geotextile covering the crate matrix to prevent migration of granular material. Aeration inlets are typically fitted at regular intervals throughout the system to enable effective gaseous exchange (TDAG, 2014).

Considerations

The principal benefit of crate systems is in accommodating a larger soil volume compared to structural growing media. Typically, 90% of the void space within crate systems is available for uncompacted soil (Hirons and Thomas, 2018), supporting a range of soil types. Clay and organic matter content can be increased by up to 15% v/v and soil structure is conserved (Urban, 2008).

Several crate systems have been designed to enable encasement of utilities in the tree pit (GreenBlue Urban, 2019; DeepRoot, 2020). They can also function as SuDS as stormwater can be routed through a crate system for detention and treatment achieving consistent decreases in pollutant concentrations from inlet to outlet (Page, Winston and Hunt, 2015), corresponding with the performance of bioretention systems (Tirpak et al., 2019).

Polypropylene crate systems can yield good tree growth (discussed below); however, their long-term performance is yet to be fully understood. Manufacturers' case studies of the earliest installations suggest crate systems can sustain tree growth (e.g. www.greenblue.com/gb/case-studies; www.deeproot.com/case-studies/silva-cell).

Crate systems incur around 25% greater upfront costs compared to structural growing media (TDAG, 2023). Consequently, their use has typically been concentrated in prestigious developments. However, manufacturers argue, through a cost-benefit analysis, that tree growth, survival and ecosystem services delivery are increased when trees are planted in crate systems compared to traditional tree pits (GreenBlue Urban, 2018b).

Current comparative evidence of tree growth in engineered tree pit solutions

Following the overview of each engineered solution, the next section examines studies that have directly compared the efficacy of different solutions. Smiley et al. (2006) conducted a comparative study on tree growth in structural growing media and crate systems in controlled experimental plots at the Bartlett Tree Research Laboratories, North Carolina, US. Tree root and shoot growth of *Prunus serrulata* and *Ulmus parvifolia* planted in uncompacted loam soil in crate systems was the largest, fastest and healthiest 14 months after planting compared to the structural growing media. Chlorophyll content was also greatest in crate systems, reflective of tree vitality, where the crate systems provided more visually healthier trees than in the structural growing media treatments (Smiley et al., 2006).

Another trial at the Bartlett Laboratories reported crate systems containing low density soil media provided the best tree growth and visual health in *Liriodendron chinese* when compared to SBS, ABS and compacted control tree pits over a 4-year period (Smiley, Urban and Fite, 2019). Overall root growth, weight and penetration depth, and the number of roots in proximity to the tree stem was significantly greater when trees were grown in crate systems compared with the alternative tree pits. Using mean visual colour ratings as a proxy for physiological health, SBS consistently performed the worst, with crate systems and an open control tree pit performing the best (Smiley, Urban and Fite, 2019).

In London, UK, street trees planted in crate systems achieved greater changes in trunk diameter and tree height between growth years 1 and 2 after planting and increased tree survival compared to traditional tree pits, indicating crate systems can accelerate the transplant recovery period for street trees (Bell, 2024). In a separate London study, street tree growth was assessed over a single growth period for trees growing in crate systems, crate systems backfilled with SBS, SBS, concrete sewer rings, traditional tree pits, tree pits in lawn and soft plant beds. Changes in trunk diameter and tree height were significantly greater in crate systems compared to all other tree pit types, and changes in growth were greater when trees were planted in SBS protected by a crate system compared to the use of SBS alone (Bell, 2024). These results correspond to a global survey of built environment professionals, where practitioners reported high satisfaction with tree growth rates in crate systems, greater satisfaction with crate systems compared to SBS, and ranked crate systems as the top engineered solution for securing the best growth and survival rates in trees (Bell, 2024).

A study in Singapore reported greater tree performance and increased growth for *Samanea saman* and *Peltophorum pterocarpum* planted in crate systems compared to MSAS and tree pits in open space without physical rooting confinement over a 6-year period (Ow and Ghosh, 2017). Crate systems enabled both species to achieve greater trunk diameter, height and basal expansion, deeper root colonisation and increased folia ratings by 9-16% (Ow and Ghosh, 2017), attributed to the greater soil volume in crate systems. Whilst growth in the MSAS did occur, it was not significantly different to the trees growing without rooting confinement.

A parallel study in Singapore assessed tree growth and health eight years after planting across sixteen urban tropical species planted in traditional tree pits in roadside verges and open urban parkland, MSAS, biochar-stone mixes and crate systems (Ow et al., 2018). The approaches were found to result in tree growth and health in the order of: crate systems > biochar-stone mixes > MSAS > traditional tree pits. Trunk diameter growth in crate systems was 37% greater than in the traditional tree pits, and health ratings were significantly better in crate systems compared to the other tree pit types (Ow et al., 2018).

Kristoffersen (1999) reviewed the performance of structural growing media on the growth of test plants comprising one-year grafts on four-year-old root stock for *Tilia* x *vulgaris* ‘Pallida’, *Fraxinus excelsior* ‘Westhof’s Glorie’ and *Acer platanoides* ‘Emerald Queen’ grown in experimental containers in Horsholm, Denmark. ABS produced comparable growth relative to the sole use of loam soil as the growing media. However, root:crown ratios decreased when ABS were used, indicating reduced shoot growth in each volume of ABS when compared to a mirrored volume of uncompacted loam soil. A diminished root:shoot ratio was also reported in a *Ficus benjamina* container-grown experiment at Cornell University, US, as well as lower leaf nitrogen content and slower growth rates of trees planted in MSAS compared to those in uncompacted loam soil (Loh, Grabosky and Bassuk, 2003).

Tree growth and vitality was found to be greatest in “super planting pits” compared with MSAS, SBS and traditional tree pits installed in urban streets and paved squares in Copenhagen, Denmark (Buhler, Kristoffersen and Larsen, 2007). The super planting pits did not include load-bearing layers but instead provided the largest soil volume, in combination with a large, unsealed surface. Their superiority over the structural growing media pits may be due to the increased water and nutrient availability coming from the deeper soil profile (Buhler, Kristoffersen and Larsen, 2007). Noteworthy is that the conditions created by the super planting pits can be achieved by crate systems, which have the added benefit and arguably necessity of load-bearing support for urban streets.

Many of the existing studies highlight the limitations of ABS, and particularly MSAS, suggesting that concerns for the potential for substrates to burnout are well founded. The incorporation of an aeration layer is now deemed critical for tree growth in ABS (Embren and Alvem, 2017), whereas this was absent from early installations of these substrates, including those in research studies. Therefore, these findings may not reflect the present-day efficacy of the solutions. There also remain complicating factors of comparability between different ABS mixes and installation methods. Grabosky (2015) proposed using a void analysis methodology to better compare the impact of the various stone-soil blends; however, no such studies currently exist. Applying such a methodology and using a common set of parameters in future studies would be beneficial in capturing the impact of new innovations and move ABS away from user-driven improvements and towards optimal substrate design.

Further, the impact of incorporating nutrient-enriched biochar into ABS has undergone limited peer-reviewed research, particularly over the longer term. However, it is reported that biochar, and specifically wood biomass-based biochar, has the potential to greatly enhance tree growth and survival (Schaffert et al., 2022). For example, observations include a 20% reduction in mortality, an increase in crown size by 28%, and a 32% improvement in leaf photosynthetic efficiency when transplanting *Pyrus communis* into biochar-amended soils compared with untreated trees (Schaffert and Percival, 2016). Similar improvements are reported in aboveground growth when biochar was added to LSSS to establish *Khaya grandifolia*, *Khaya senegalensis* and *Samanea saman* compared to untreated traditional tree pits in Singapore (Ow et al., 2018). In combination with the observations from Stockholm, these studies indicate there is a key role for biochar in ABS. However, although an increase in growth in biochar-stone mixes has been observed, the current evidence suggests they will still be outperformed by crate systems (Ow et al., 2018).

Conclusions

Historically, the space beneath the pavement has been a zone where strict engineering parameters are achieved with disregard to tree requirements (Blunt, 2008). However, now more than ever we require integrated designs underpinned by scientific research to address the climate and ecological emergencies. This article provides an important and timely contribution that bridges the research-practice interface, covering deployable technologies towards achieving this goal. Although long-term studies exploring tree growth and survival in engineered tree pits are limited, we found that there is consistent evidence that crate systems enhance tree performance. In structural growing media, ABS appear to increase tree performance compared with traditional tree pit designs, with LSSS perhaps being most effective. Whereas the evidence related to the efficacy of SBS is mixed, and further research is needed to explore their performance in areas without a high water table. Crate systems and newer modifications to ABS, such as the use of biochar, also show promise but longer-term trials on a range of species are required to demonstrate their sustained performance. Similarly, the use of hybrid systems, for example, crate systems with a LSSS root breakout zone should also be explored. We only explored these solutions from the perspective of their load-bearing capabilities and tree performance; therefore, this review could be further expanded to consider their impact on ecosystem services delivery, including stormwater management. Finally, the climate is changing, and the urban heat island will make street trees particularly vulnerable; greater research is needed to test how these engineered solutions perform under future climate scenarios to ensure that their positive impacts on tree growth and survival are resilient.

Engineered tree pit solutions challenge traditional approaches and can overcome many subterranean constraints imposed on street trees, offering key design solutions to put trees on an equal footing with grey infrastructure. However, to optimise success, practitioners should understand each solution’s limitations, apply science to policy and practice and demand multidisciplinary collaboration – especially between arboricultural and engineering professionals – to overcome the constraints of urban paved sites. This understanding could then be incorporated into policy and design guidance, for example, for new development or green infrastructure standards, building on the guidance for collaboration set out in TDAG (2014). This is especially important given that flourishing street trees are essential for delivering ecosystem services necessary for liveable cities. The mantra of “right tree, right place” is now widely appreciated. However, we must not ignore the importance of providing the *right infrastructure*, to encompass the load-bearing structures and media.

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Tables

Table 1: Summary of key characteristics, advantages and limitations of the engineered tree pit solutions

Solution	Key characteristics	Advantages	Limitations
Sand-based substrates	•90% sand, 4-5% organic matter, 2-4% clay w/w •Sand facilitates load-bearing •Organic matter must be fully decomposed •Installed in two lifts of 400-500 mm •Maximum depth: 1 m •Typical penetration resistance 1.5-2.0 MPa	•40+ years' implementation history •Compatible with modest load-bearing •Patented or unpatented versions •Successful growing medium for street trees	•Not suitable in highway pavements •Over-compaction is common and can reduce drainage and tree growth •Use may be restricted to areas with high water table or rainfall •Liable to nutrient and water deficits •Risk low soil pH •Handling and mixing requires good technical knowledge
Medium-sized aggregate substrates	•Highly angular aggregates (20-40 mm) with no fines •20% clay and 2-5% organic matter w/w •Installed in 150 mm lifts •Recommended depth: 0.7-0.9 m	•20+ years' implementation history •Suitable for areas with greater loading •Can be installed in tight, contorted spaces and around utilities •Support reasonable tree growth within 5-10 years of planting •Patented or unpatented versions •Can be incorporated into SuDS	•Stability of mixture can be temperamental, but this can be overcome with hydrogel •Over compaction can inhibit root growth •Vulnerable to water and nutrient deficits, but alleviated by hydrogel and incorporation into SuDS •Stone type affects pH •Handling and mixing requires good technical knowledge

Large-stone skeletal substrates	•Original design: 250-300 mm layers of large angular stones (100-150 mm), compacted and flushed with soil •Modern design: 85% v/v clean stone (32-63 mm) mixed with 15% nutrient-enriched biochar and compost at 1:1, installed in 200-250 mm lifts and compacted •Aeration layer beneath surfacing course •Minimum depth: 0.6 m	•Withstand heavy loads •Routinely incorporate nutrient-enriched biochar, aeration and stormwater interception •Designed to capture runoff from roofs, roads and pavements •Biochar results in enhanced tree growth •Less prone to water and nutrient deficiency •Minimal reliance on patented products •Similar construction to existing pavement engineering •Can be retrofitted around existing mature trees	•Can be difficult to cost-effectively source aggregates and wood-based biochar •Aggregate consistency and exclusion of fines is essential •Monitoring during construction is critical •Newer solution, therefore limited data, but early case studies are promising
Crate systems	•Modular polypropylene structural cells that support load-bearing and uncompacted soil •Sit on a layer of aggregate and compacted subgrade •Can be stacked to increase depth	•Withstand heavy loads •Suitable for utilities •Accommodate larger soil volume compared with other solutions •Early research suggests greatest tree growth •Can be incorporated into SuDS •Existing soil can be reused if appropriate	•Expensive •Only patented versions •May be difficult to extricate should access be required •Newer solution, so more long-term research is required

Figure captions

Figure 1: View of a SBS during tree trench installation. Reproduced by permission of Tim O'Hare Associates LLP.

Figure 2: Example tree pit design using a SBS under pavement. "Compacted structural soil" represents the substrate profile. Reproduced by permission of Christopher Gower.

Figure 3: Conceptual diagram of ABS. Reproduced by permission of Nina Bassuk.

Figure 4: MSAS pre- (**a**) and post (**b**) addition of soil fractions. Reproduced by permission of Nina Bassuk.

Figure 5: Example tree pit design using a MSAS under pavement in the US. Reproduced by permission of Nina Bassuk.

Figure 6: Angular stones (100-150 mm) used in the original LSSS design to accommodate load-bearing. Reproduced by permission of Bjorn Embren.

Figure 7: Biochar macadam tree pit design. Key: 1= pavement with base course, 2= stormwater channel, 3= aeration well for infiltration of stormwater and gaseous exchange, 4= surface grate, 5= tree guard; 6= root collar placed at same level as in the nursery, 7= stone mulch – macadam 4-8 mm, 8= macadam 2-6 mm + 25% v/v nutrient-enriched biochar and compost at 1:1, 9= modular concrete frame, 10= separation geotextile, 11= levelling stones – macadam 8-11 mm, 12= aeration layer – macadam 32-63 mm, 13= biochar macadam – macadam 32-90 mm + 15% v/v nutrient-enriched biochar and compost at 1:1, 14= layer of biochar, 15= gaseous exchange (Embren and Alvem, 2017). Reproduced by permission of Bjorn Embren and Hildegun Nilsson Varhelyi.

Figure 8: Premixed biochar macadam placed within a highway excavation in Stockholm, Sweden. Reproduced by permission of Bjorn Embren.

Figure 9: Example tree pit design using a crate system under pavement. Reproduced by permission of GreenBlue Urban Ltd.

Figure 10: Illustration of a crate system under pavement accommodating a large soil volume and underground utility. Reproduced by permission of GreenBlue Urban Ltd.

Fig. 1

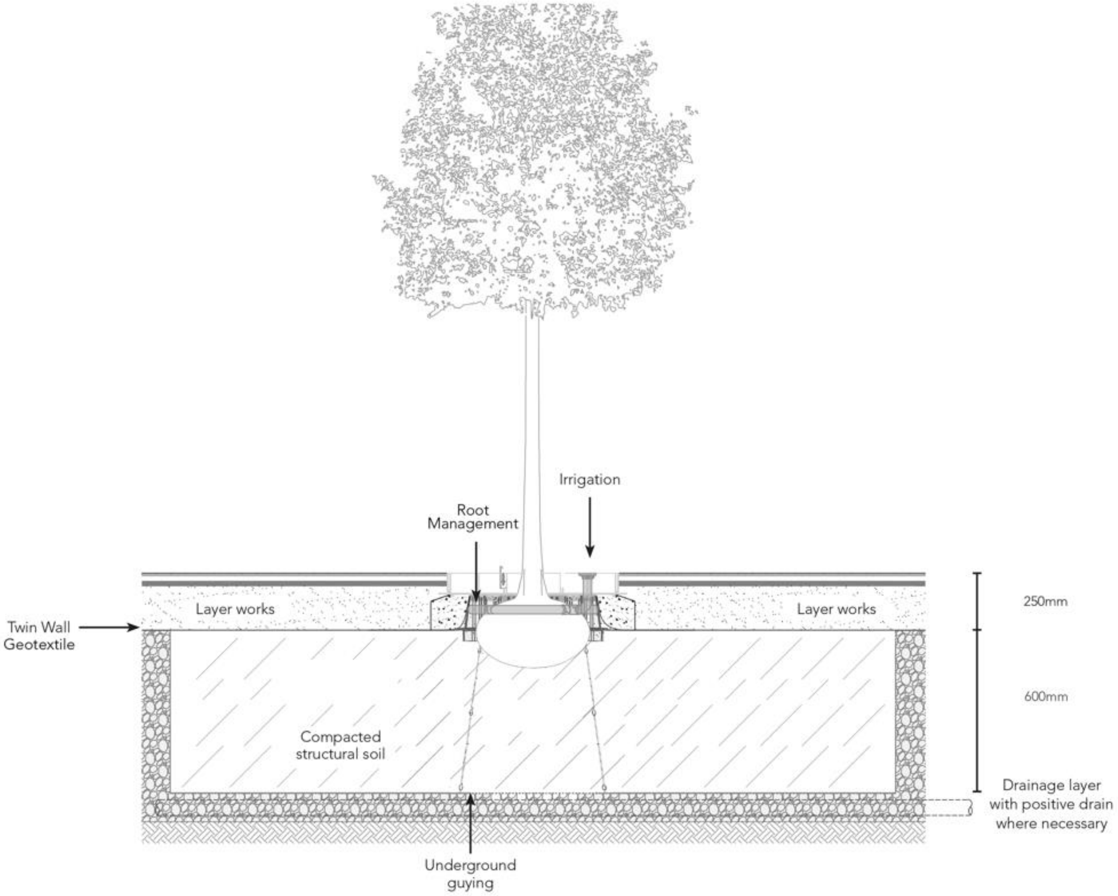
Irrigation
Root
Management
Layer works
Layer works
Twin Wall
Geotextile
250mm
600mm
Compacted
structural soil
Drainage layer
with positive drain
where necessary
Underground
guying

Fig. 2

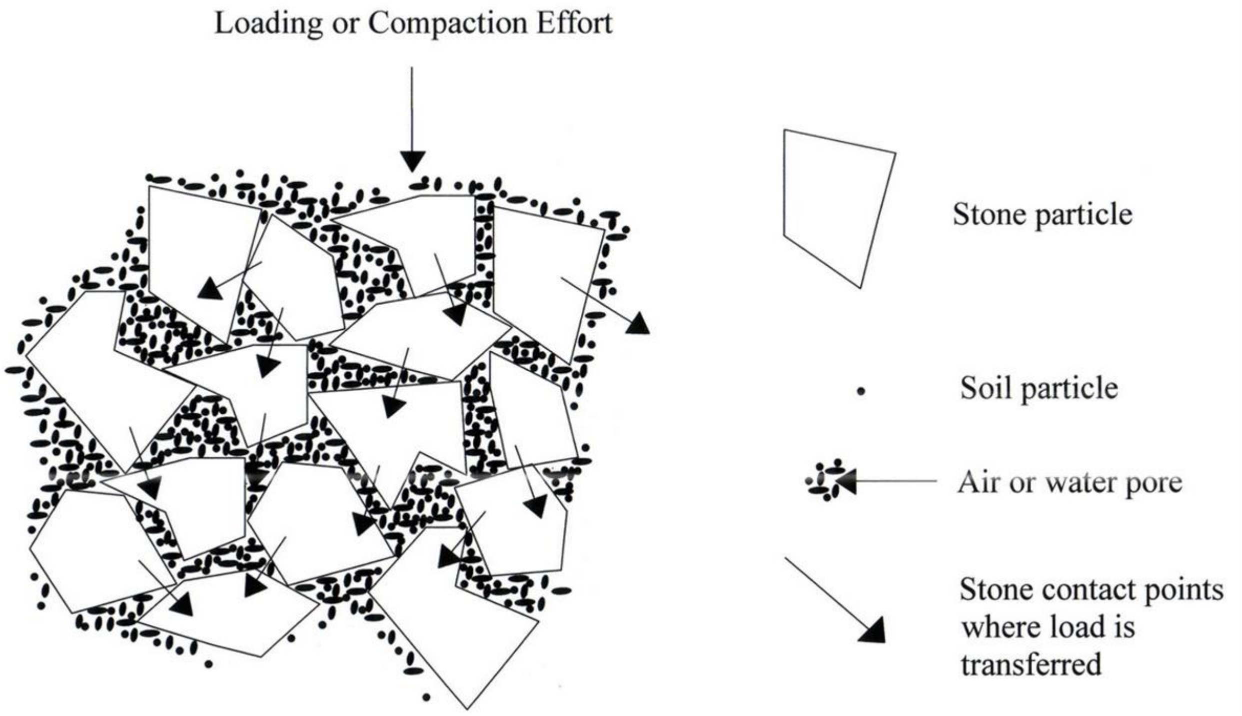
Loading or Compaction Effort
Stone particle
Soil particle
Air or water pore
Stone contact points where load is transferred

Fig. 3

Fig. 4a

Fig. 4b

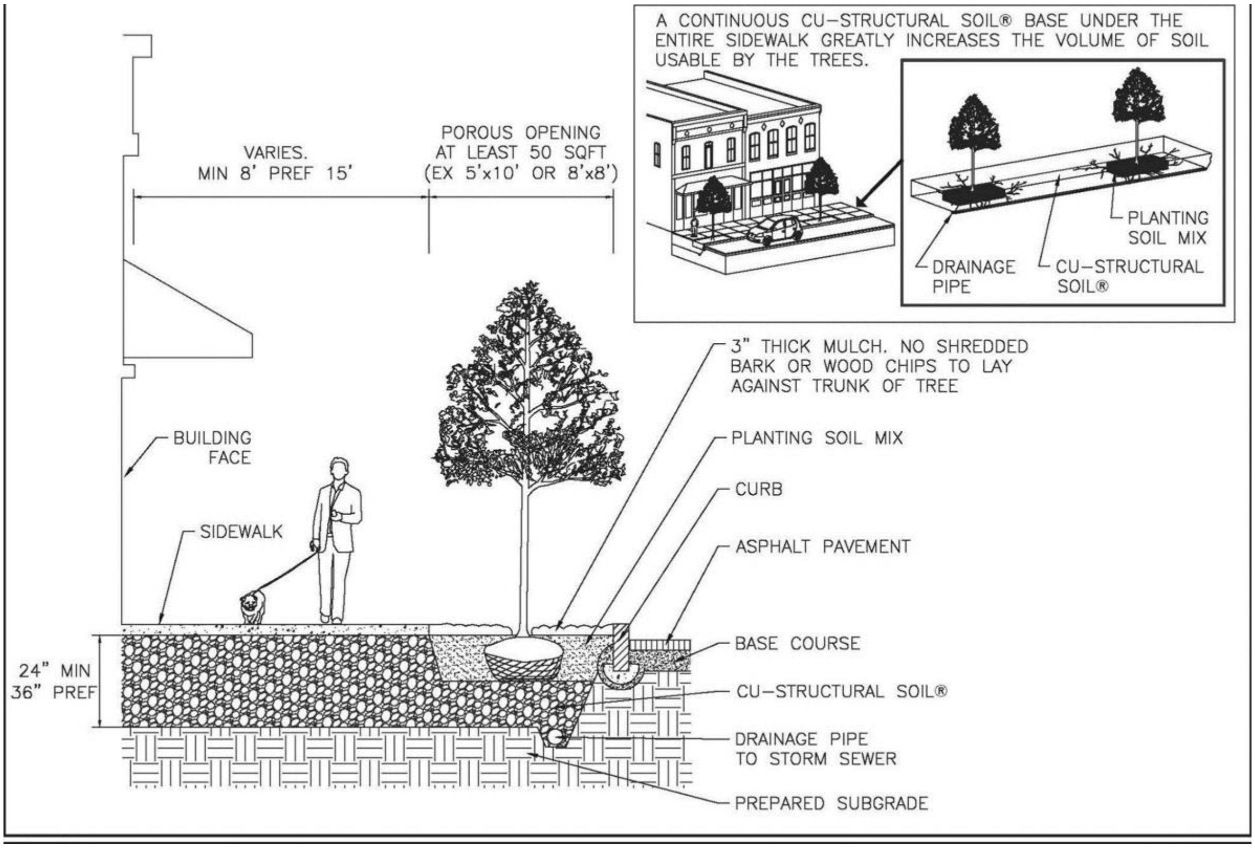
A CONTINUOUS CU–STRUCTURAL SOIL® BASE UNDER THE ENTIRE SIDEWALK GREATLY INCREASES THE VOLUME OF SOIL USABLE BY THE TREES.
PLANTING SOIL MIX
DRAINAGE PIPE
CU–STRUCTURAL SOIL®
VARIES. MIN 8' PREF 15'
POROUS OPENING AT LEAST 50 SQFT (EX 5'x10' OR 8'x8')
3" THICK MULCH. NO SHREDDED BARK OR WOOD CHIPS TO LAY AGAINST TRUNK OF TREE
PLANTING SOIL MIX
BUILDING FACE
CURB
SIDEWALK
ASPHALT PAVEMENT
24" MIN
36" PREF
BASE COURSE
CU–STRUCTURAL SOIL®
DRAINAGE PIPE TO STORM SEWER
PREPARED SUBGRADE

Fig. 5

Accepted manuscript doi:
10.1680/jcien.24.00962

Fig. 6

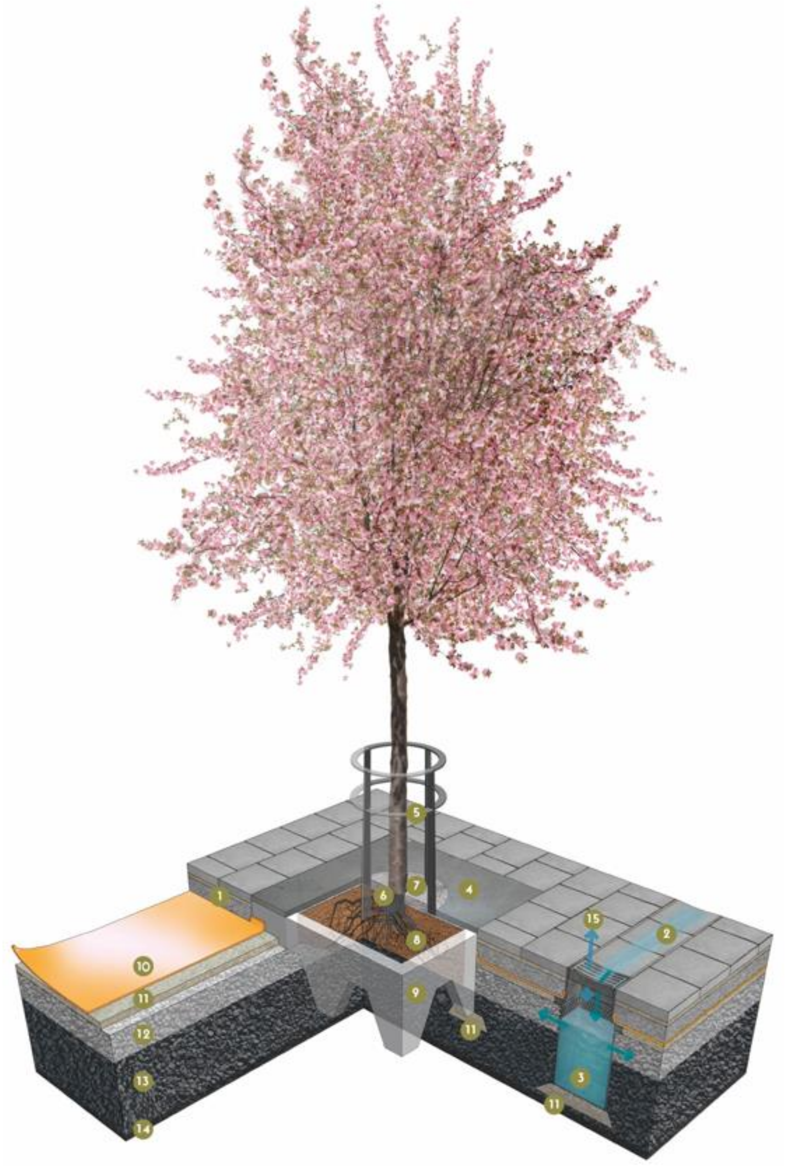

Fig. 7

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Fig. 8

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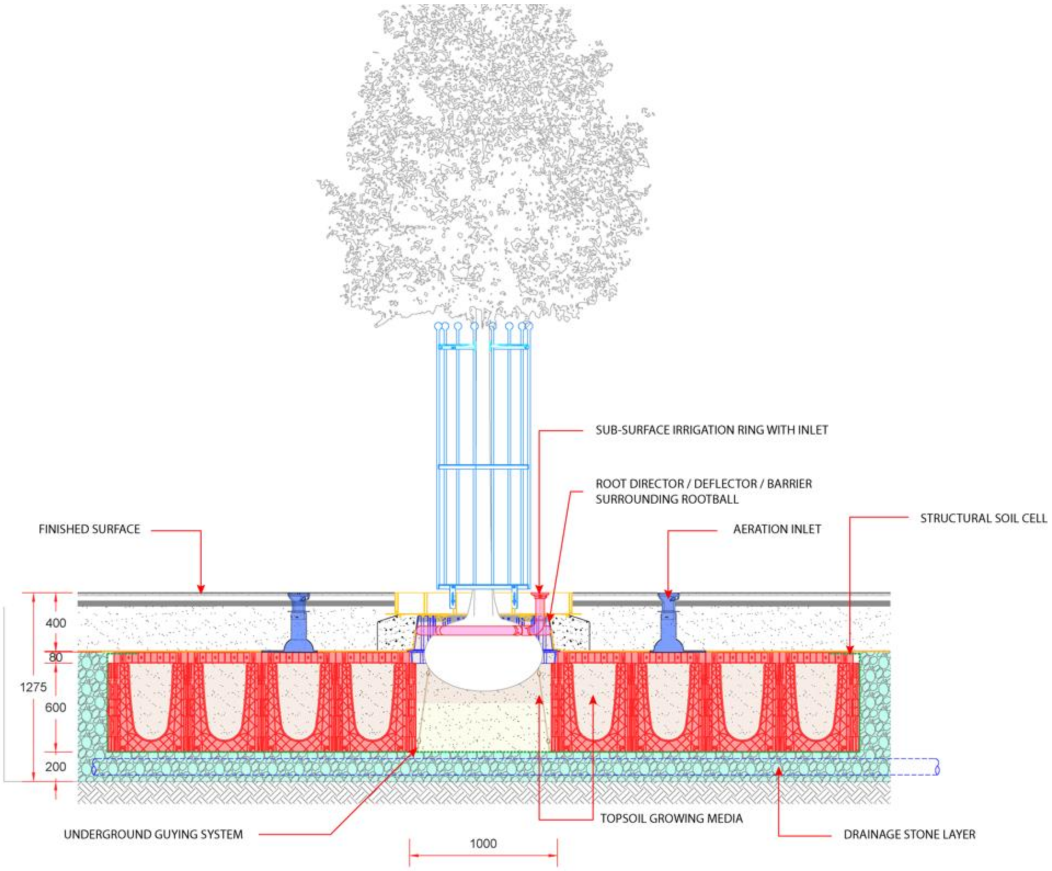

Fig. 9

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Fig. 10