Permeable Clay Brick Pavements

Abstract: This *Technical Note* describes the proper design and construction of permeable pavements made with clay pavers on an aggregate setting bed, an open-graded aggregate base, and an open-graded subbase. The purpose and performance of this type of paving in environmental protection and stormwater management are discussed. Options for stormwater design are reviewed, and guidance is given in material selection and installation.

Key Words: Best Management Practice (BMP), detention, exfiltration, infiltration, LEED, low impact development, paving, permeable paving, runoff, stormwater, sustainability.

SUMMARY OF RECOMMENDATIONS:

Stormwater Design
- A permeable pavement is part of a site's drainage and stormwater management system and must be designed as a part of that system by a qualified engineer

Pavement Thickness
- Use the greater of the thicknesses calculated for structural and hydrologic (stormwater management) requirements; both the base and subbase can contribute to the required thickness

Clay Pavers
- Use clay pavers meeting ASTM C902 or C1272 as appropriate for the traffic application
- Use clay pavers that have lugs or are shaped to accommodate open joints between adjacent pavers of at least ¼ in. (6.4 mm) wide for adequate permeability, but not more than ½ in. (13 mm) wide where universal accessibility is required

Joints
- Aggregate:
  - Do not fill joints with sand
  - Fill joints with a washed, open-graded, permeable aggregate such as ASTM D448 No. 8, No. 9, No. 89 or its local equivalent
- Thickness:
  - Install pavers with joints at least ¼ in. (6.4 mm) wide for adequate permeability, and not more than ½ in. (13 mm) wide where universal accessibility is required

Setting Bed Aggregate
- Use a washed, open-graded, permeable aggregate such as ASTM D448 No. 8 or its local equivalent; crushed, angular aggregate is preferred over rounded aggregate
- Do not use sand as a setting bed material

Edge Restraints
- Use edge restraints appropriate for the traffic application as described in *Technical Note* 14A, or use edge restraints specifically designed for permeable pavements

Base Course Aggregate
- Use a washed, open-graded, permeable aggregate, such as ASTM D448 No. 57 aggregate
- Choose crushed, angular aggregate over rounded aggregate

Subbase Course Aggregate
- Use open-graded, permeable aggregate such as ASTM D448 No. 2, No. 3 or its local equivalent

Geotextile
- Consider placing a geotextile over subgrades containing significant amounts of clay or silt or when other jobsite issues require it

Maintenance
- Vacuum affected areas when clogging sediment (mud, sand, organic matter or detritus) is visible on the joint-fill aggregate or when water percolation through the aggregate is visibly slow to restore permeability
- Do not power wash a permeable pavement

INTRODUCTION

Permeable clay brick pavements are an effective method of meeting stringent stormwater management requirements in communities while taking advantage of the natural benefits of clay pavers. Many Best Management Practices (BMPs) and low-impact developments (LIDs) use permeable clay brick pavements in fulfilling requirements for managing stormwater runoff and protecting water quality. Municipalities use permeable clay brick pavements to reduce the need for combined sewer overflows (CSOs) and to minimize localized flooding by infiltrating and treating stormwater on site. Permeable clay brick pavements aid in the health of street trees by allowing air and water to reach the roots easily. Permeable pavements do not increase the temperature of the runoff, minimizing the damage to aquatic life. The use of permeable clay brick pavements has shown to be cost-effective in new development and redevelopment since such pavements reduce or eliminate the need for storm sewers and detention ponds, while providing more land for buildings and other structures.

Permeable paving with clay pavers is appropriate in any public or private setting where impervious cover is to be limited or stormwater is to be managed under contemporary environmental requirements and traffic load is pedestrian or light vehicular (low volume). To a permeable pavement, clay pavers bring texture, traditional appearance, craftsmanship, color, durability and strength. Permeable clay brick pavements are still a small proportion of all paving installations, but their use is growing rapidly under today's environmental requirements.

Photo courtesy Whitacre Greer Company

Photo 1
Permeable Clay Brick Pavement Reduces Runoff at Youngstown State University

The distinctive, defining features of permeable clay brick pavements are the relatively wide joints between the pavers and the open-graded aggregate (Photo 1) — not sand or dense-graded material — making up the pavement's subbase, base, setting bed and joint fill. Both the traffic-bearing capacity and the stormwater management success of a permeable clay brick paving system depend on the total pavement section and not just the surface layer of clay pavers. These systems differ from those with clay pavers set in sand. Correct installation of a permeable clay brick pavement is not more difficult than that of sand-set systems, but its distinct design and installation requirements must be strictly adhered to.

The highly permeable aggregate that fills the joints is what gives the pavement surface as a whole its permeability, rather than the shape of the paver. In permeable pavements, spacers (lugs) on clay pavers are larger to maintain a uniform joint width of ¼ in. (6.4 mm) or wider. In contrast, pavements made with a sand setting bed have sand-filled joints as narrow as ¹⁄₁₆ in. (1.6 mm), which makes them comparatively impermeable. Alternatively, the shape of the paver may allow water to pass through openings formed by its edges or within its body. The pattern in which clay pavers are laid provides adequate opening area for drainage.

Permeable clay brick paving systems' limits on traffic type and speed are the same as those for other vehicular paving systems as described in *Technical Note* 14. Most individual clay pavers have high compressive strengths and, with sufficient thickness and proper installation, can develop interlock with surrounding pavers to help support vehicular loads. Strong, durable aggregate compacted into the stable base and subbase courses distributes any traffic loads.

Slip resistance, skid resistance and hydroplaning are comparable to those of sand-set paving systems, except during wet weather, when a permeable paving system makes a better drained surface with potentially improved safety for pedestrians and vehicles. Accessibility is comparable to that of sand-set pavers when the selected permeable pavement has joints no wider than ½ in. (13 mm). The use of pavers that form wider joints or openings should be limited to areas where accessibility is not required. In these cases, universal accessibility can be provided on nearby pathways constructed to comply with the Americans with Disabilities Act accessibility guidelines [Ref. 4].

Refer to *Technical Note* 14 for clay paver design considerations, including traffic, site conditions, drainage and appearance. Refer to *Technical Note* 14E for information about the design of accessible clay pavements.

FEATURES OF PERMEABLE PAVEMENTS

The purpose of this type of construction is to provide permeability through the entire pavement section without compromising structural capacity. Much of the information presented herein is based on information presented in *Permeable Interlocking Concrete Pavements* [Ref. 9]. Most of the principles and concepts for permeable segmental paving systems made with concrete paver units can be used in the design and construction of systems using clay paver units, since the modulus of elasticity and compressive strength of the units are comparable. The system relies upon permeable aggregate in the joints, setting bed, base and subbase courses, while maintaining paver interlock and base course stability. An engineer should be consulted for structural design and hydrology.

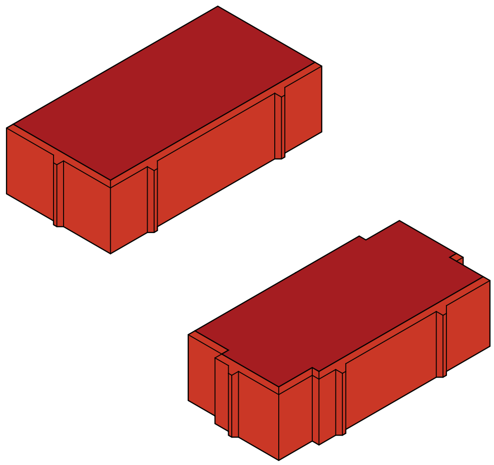

Figure 1
Typical Shapes Used for Permeable Pavements

Photo courtesy General Shale Brick, Inc.

Photo 2
Permeable Clay Pavers with Openings at Corners

Hydrologic Design

The pavement as a whole is designed as a component of the site's drainage and stormwater management system or BMP, contributing pervious land cover, detention and water quality treatment. Although the paver units are impermeable, the pavement surface is highly permeable because of the highly permeable aggregate used in the joints and openings. The pavers' lugs leave joints ¼ in. (6 mm) wide or wider, not the 1⁄16 in. (1.6 mm) to 3⁄16 in. (5 mm) joints familiar in impervious sand-set construction. Typical paver shapes are shown in Figure 1 and Photo 2. Joints and openings typically occupy approximately 10 percent of the finished pavement area.

The aggregate in the joints conforms to ASTM D448, *Standard Classification for Sizes of Aggregate for Road and Bridge Construction* [Ref. 1] Sizes No. 8, No. 89 or No. 9. Each of these gradations is considered "open-graded" because it specifies a relatively narrow range of particle sizes where no fine particles fill the voids. While the numeric designations for jointing, bedding, open-graded base and subbase aggregate gradations are found in ASTM D448, the same gradations can be found in ASTM C33, *Standard Specification for Concrete Aggregates* [Ref. 2] or AASHTO M43, *Sizes of Aggregate for Road and Bridge Construction* [Ref. 1]. Many of the numeric designations for aggregates are supplied by local quarries and may use local nomenclature.

The joint fill aggregate's permeability is more than 2000 in./hr (50.8 m/h), which gives the surface as a whole potential permeability of hundreds of inches per hour (tens of meters per hour). In the setting bed, similar aggregate transmits water rapidly into the base and subbase courses. The setting bed thickness is usually 2 in. (51 mm), but its thickness is not taken into account when determining the hydrologic capacity. Fine aggregates (often referred to as concrete sand) conforming to ASTM C33 are not recommended because of the fine particles within not allowing infiltration.

The pavement's base and subbase courses are often collectively called the "base reservoir" because they have a hydrologic function in addition to the structural function as a pavement layer. The base reservoir is made of larger open-graded aggregate that is even more rapidly permeable than the aggregates in the joints and setting bed. It is not the dense-graded aggregate used in the base course of typical sand-set construction. The ASTM D448 No. 57 aggregate commonly used in a permeable base has particles mostly about ½ in. (13 mm) to 1 in. (25 mm) in size. Large open voids between the particles give the material permeability of thousands of inches per hour (hundreds of meters per hour). The pavement's subbase course is often combined with the base course when determining the reservoir capacity, but it is often a coarser material than the base course. ASTM D448 No. 2 stone is usually more economical than No. 57 stone and is 1½ in. (38.1 mm) to 2 ½ in. (63.5 mm) in size. As will be explained, the permeable base and subbase aggregates are also a substrate for microorganisms that improve water quality. When excess water occurs in the base reservoir, the material transmits it readily to a designed discharge point, where it exits at a controlled rate.

Structural Design

In a permeable paving system, clay pavers make a segmental, flexible wearing course, as they do in other clay paver systems. The paver unit is strong and durable, meeting the same ASTM standards as pavers in other clay paver systems. The joints between pavers transfer horizontal and vertical forces, producing interlock from paver to paver and between aggregate and pavers.

Just as importantly, the aggregate material in the base and subbase courses is strong and durable, and compacted in lifts. Stone-to-stone interlock makes a stable structural skeleton, while the material's pores remain open and permeable. The base and subbase courses are well drained due to their very high permeability. Sufficient thickness of subbase, base and paver layers spread out traffic load and inhibit pavement deformation, even when the subgrade soil is wet from the pavement's retained water.

APPLICATIONS

Permeable clay brick pavements are appropriate where traffic loads are not excessive and where reduction of runoff and improvement of water quality would be beneficial. In many land use districts, pavements are two-thirds of the potentially impervious land cover (the other one-third is roof area), so making pavements permeable greatly improves the water quality and stormwater management for an entire site or district.

Permeable clay brick pavements are applicable in a wide range of land use or neighborhood contexts. On residential sites, they are suitable for driveways, patios and walkways. In commercial and public areas, they serve as parking lots, sidewalks, plazas, courtyards and walkways. They are also appropriate on city streets, parking lanes and other pavements subjected to vehicular traffic. For the heaviest vehicular loadings, the pavers and supporting pavement layers are increased in thickness.

Photo 3

Permeable Clay Brick Street Installed as Part of a CSO Reduction Program

Retrofit of existing city streets is a growing municipal application of permeable clay brick pavements that provides the advantages of improved drainage, stormwater management and combined sewer overflow (CSO) reduction. Retrofit requires removing the old impervious pavement and its impervious base layers and replacing them with an entirely new permeable clay brick paving system, as described in this *Technical Note*. An example of a retrofit installation is shown in Photo 3.

The underlying subgrade soil may dictate the type of permeable system that is appropriate for an application. On rapidly permeable sandy soil, most water exfiltrates to the subgrade even during large storms, so additional detention to control peak runoff rates may not be necessary. Such need depends on the project's land use and jurisdictional requirements.

On clay soil, or where there is a shallow water table and water cannot be rapidly exfiltrated to the subgrade soil, a perforated drainage pipe is ordinarily required to discharge excess water from large storms after it has been treated and detained in the pavement. Further detention may be necessary to control peak downstream flows, depending on the project's land use and jurisdiction. A permeable pavement over clay soil can:

- reduce impervious cover;
- reduce runoff coefficient;
- detain peak flows;
- treat water quality; and
- recharge aquifers by gradual exfiltration of rainwater from small, numerous, year-round storms.

Where a permeable pavement is used, do not allow water to exfiltrate from the base reservoir into the soils of septic tank leaching fields, brownfield soils with leachable toxins, water supply wells or steep unstable slopes.

Instead, in those conditions, line the base reservoir with an impermeable geomembrane to prevent exfiltration while continuing to take advantage of the permeable system's stormwater detention and treatment. The water table should be 1 to 2 ft (305 to 610 mm) below the bottom of the permeable pavement system.

Permeable clay brick pavements' environmental advantages are given credit in the U.S. Green Building Council's LEED rating system [Ref. 10] for sustainable development. LEED points that are related to the use of clay pavers are listed in Table 1. Other rating systems, such as the Sustainable Sites Initiative, NAHB's National Green Building Standard and ASHRAE 189.1, provide points for permeable clay brick pavements for managing stormwater on site and protecting water resources and water quality.

TABLE 1
Potentially Available Points in the LEED Rating System for New Construction

Sustainable Sites		
Credit	**Item**	**Permeable Paving's Potential Role**
5.1	Protect or restore habitat	Reduce space developed for retention basin, and increase success of trees
6.1	Control stormwater quantity	Decrease impervious cover, and reduce stormwater volume
6.2	Control stormwater quality	Reduce suspended solids, and infiltrate water
7.1	Reduce heat island	Support tree shade, and select paver with high Solar Reflectance Index
Water Efficiency		
Credit	**Item**	**Permeable Paving's Potential Role**
1.1 & 1.2	Reduce irrigation water use	Keep water on site
Materials and Resource		
Credit	**Item**	**Permeable Paving's Potential Role**
4.1	Recycled content	Select recycled aggregate
5.1	Local sources of materials	Select local aggregate or locally manufactured pavers

MATERIALS AND INSTALLATION

The entire pavement section is designed and constructed for structural stability with permeability. A typical permeable clay brick pavement section is shown in Figure 2.

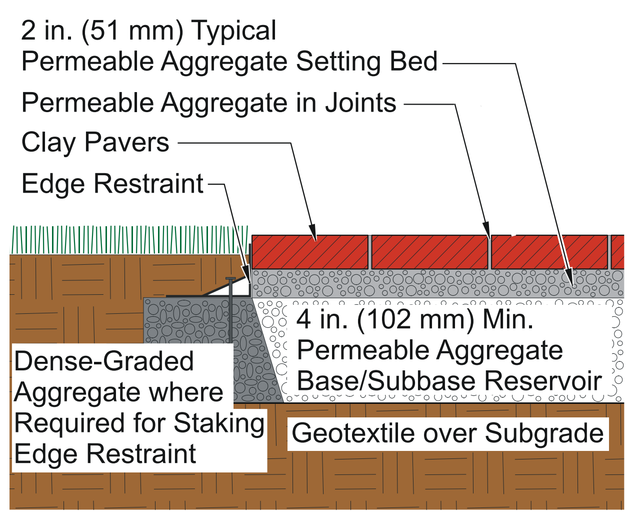

Figure 2
Typical Pedestrian Section

Subgrade

Compaction of the subgrade as described in *Technical Note* 14 may be performed if required by site condition tests because it increases strength, limits future settlement, reduces freeze-thaw action and is low-cost; however, compaction reduces the soil's infiltration rate. Some projects have specified limited compaction, such as a minimum of 92 percent standard Proctor and a maximum of 96 percent. This limited compaction ensures a degree of compacted stability while retaining some favorable infiltration capacity. Swelling soils must be compacted and stabilized as they are under any other structure. Organic material or other material unsuitable for supporting a pavement structure should be removed and replaced with open-graded aggregate subbase. For maximum infiltration of the subgrade, use an adequate subbase and an uncompacted subgrade.

Geotextiles

Geotextiles are not typically usually used in permeable pavement applications because they are easily clogged. However, it may be beneficial to use a geotextile conforming to AASHTO M288, *Standard Specification for*

Geotextile Specification for Highway Applications, Class 2 [Ref. 1] to separate subgrade soil, especially plastic clay or silt soil, from the void spaces in the open-graded base or subbase aggregate. Without the separation, plastic soil could flow into the base's void spaces, compromising the base reservoir's capacity and integrity.

Base and Subbase Aggregate

Base and subbase materials must be open-graded so they can store and convey water. These are not the same dense-graded aggregate as used in sand-set pavements. The gradations in successive aggregate layers must satisfy "filter criteria" so small particles in one layer will not migrate significantly into the void spaces of a lower layer. The most common base material is washed ASTM D448 No. 57 aggregate. Its particles are approximately ½ to 1 in. (13 to 25 mm) in size. The material is compacted in lifts up to about 4 in. (102 mm) thick. The 4 in. (102 mm) thick base is combined with an appropriately thick subbase for the loading conditions. The base can be used alone when supporting a pedestrian pavement application with well-drained native soils and approved by an engineer as stable. To deepen the section for frost protection, additional hydraulic capacity or structural capacity, a minimum 6 in. (152 mm) subbase should be added below the base with larger-sized No. 2 aggregate. Properties of the base and subbase aggregates used in permeable pavements are shown in Table 2. By comparison, the ASTM D2940 dense-graded aggregates used in non-permeable paving systems have maximum permeabilities that are estimated to range from approximately 5 to 1000 in./hr for base aggregates and from 1 to 4400 in./hr for subbase aggregates, both of which are significantly lower than the estimated minimum permeabilities of open-graded aggregates. The correct permeable aggregate must be clearly specified by the designer and exclusively followed by the installer. No soil, sand, fill, dense-graded aggregate or any material other than the specified open-graded aggregates must be used to replace these aggregates for any part of the subbase or base. These open-graded aggregates should be angular (90 percent fractured) in structure, not rounded.

TABLE 2

Properties of Permeable Base and Subbase Aggregates[1]

Open-graded aggregate used in permeable construction (ASTM D448)			
Designation	**Approximate size range**	**Porosity (vol/vol)**	**Permeability (in./hr)**[2]
No. 57	¾ in. to ½ in.	0.38 to 0.44	27,000 to 155,000
No. 2	2½ in. to 1½ in.	0.43 to 0.46	1.8 M to 5.0 M

1. Unclogged porosity and permeability estimated with formulas of Kasenow, 2002, Eqs. 10.2 and 11.1 [Ref. 6]; estimated aggregate characteristics are subject to verification by testing of actual aggregate from specific sources.
2. 1 in./hr = 25.4 mm/h

Edge Restraint

To maintain paver position and interlock, edge restraints such as those described in *Technical Note* 14A must be present in permeable clay brick paving systems. Where the edge restraint is not provided by a curb or other fixed structure adjoining the pavement, a restraint can be added in the form of a concrete band or a manufactured metal or plastic edging. Proprietary edge restraints specially designed for permeable pavements are available from several manufacturers. The restraint must rest on or be adjacent to the dense-graded base course material so that it restrains both the pavers and the setting bed. When using spiked-in-place edge restraints, open-graded base aggregates should be replaced with dense-graded aggregates along the edge of the pavement to provide adequate support (see Figure 2).

Setting Bed Aggregate

The setting bed is made of permeable open-graded aggregate, rather than the sand used as bedding in more common systems using clay pavers. Table 3 lists gradations commonly used. No. 8 aggregate has particles small enough to provide a level for paver setting but large enough to meet filter criteria over No. 57 base aggregate. The particles interlock with one another and with the underlying base aggregate. The aggregate is commonly specified to be washed free of clinging particles. Unwashed aggregates will compromise the performance of the pavement.

The typical thickness of the setting bed is 2 in. (51 mm) to accommodate variations in the paver and some minor variances in the base. The setting bed aggregate is screeded moist into the top of the No. 57 base. Properties

TABLE 3

Properties of Permeable Setting Bed and Joint Fill Aggregates[1]

Permeable systems' joint-fill and setting bed aggregates (ASTM D448)			
Designation	**Approximate Size**	**Porosity (vol/vol)**	**Permeability (in./hr)**[2]
No. 8	⅜ in. to No. 4 sieve	0.39 to 0.45	8000 to 60,000
No. 89	⅜ in. to No. 16	0.39 to 0.45	2000 to 15,000
No. 9	No. 4 sieve to No. 8 sieve	0.39 to 0.45	2000 to 15,000

1. Unclogged porosity and permeability estimated with formulas of Kasenow, 2002, Eqs. 10.2 and 11.1 [Ref. 6]; all estimated aggregate characteristics are subject to verification by testing of actual aggregate from specific sources.
2. 1 in./hr = 25.4 mm/h

of open-graded aggregate used for permeable setting beds, joints and openings are shown in Table 3. C33 concrete sand used to fill joints in other pavements is not appropriate because it has significantly lower permeability, estimated to range between approximately 10 and 335 in./hr in sand-set construction. The correct permeable aggregate must be clearly specified by the designer and exclusively followed by the installer. Soil, sand, fill, dense-graded aggregate or any material must not replace the specified open-graded aggregates to bring any part of the pavement up to grade or for any part of the setting bed.

Photo courtesy Boral Bricks, Inc.

Photo 4

Joints Filled with Permeable Aggregate

Pavers

Permeable clay brick pavers are shaped to leave joints or openings that give the pavement surface its permeability. A paver must be selected for its irregular shape or lugs, producing joints ¼ in. (6.4 mm) wide. These joints are wider than the joints between pavers intended to be placed on a sand setting bed, which are usually no wider than $\frac{3}{16}$ in. (4.8 mm). Joints ¼ in. (6.4 mm) wide are sufficiently wide to receive Nos. 8, 89 and 9 permeable joint fill aggregate (Photo 4).

Clay pavers used in these paving systems should comply with ASTM C902, *Standard Specification for Pedestrian and Light Traffic Paving Brick* [Ref. 2], or ASTM C1272, *Standard Specification for Heavy Vehicular Paving Brick* [Ref. 2]. Clay pavers that comply with either ASTM standard can support light vehicular loads when properly installed. The most common thickness is 2¼ in. (57.2 mm), but other thicknesses are available. Other characteristics that may be considered in paver selection are described in *Technical Note* 14, including texture, color, edge treatment and bond patterns. Pavers can be installed using mechanical installation techniques when available.

Joint Fill Aggregate

The joint fill aggregate for permeable pavements is open-graded for high permeability, with particles small enough to fit into the paver joints but large enough to meet filter criteria with the underlying setting bed aggregate. This is the same No. 8 aggregate (or No. 89 or No. 9 stone) commonly used in the setting bed of clay paver systems that have joints filled with sand. The aggregate is commonly specified to be washed free of clinging particles. It is swept into the paver joints and openings, and the pavers are vibrated to level. The joints must not be left unfilled. One of the purposes of the aggregate is to trap sediment and debris near the pavement surface, where it can be removed by vacuuming, as described below under "Maintenance." The correct permeable aggregate must be clearly specified by the designer and exclusively followed by the installer. Soil, sand, fill, dense-graded aggregate or any material other than the specified open-graded aggregate must not be used to fill any part of the joint.

ENVIRONMENTAL PERFORMANCE

Research has been conducted and experience has been gained in segmental permeable pavements and other types of permeable pavements in many places in North America and around the world. The results have been scientifically monitored. Observed results defeat false rumors and make misconceptions unnecessary. The following results apply to permeable clay brick pavements that are correctly designed, installed and maintained as described in this *Technical Note*.

Surface Infiltration Rate

Permeable segmental paving systems that are properly designed, installed and maintained have high surface infiltration rates (surface permeabilities) of 40 to 2700 in./hr (1 to 68.6 m/h). At these rates, essentially all rainwater passes through the surface and into the pavement system. Poorly maintained pavements that are clogged with sediment have infiltration rates as low as 1 to 10 in./hr (25.4 to 254 mm/h). The absorption of water into the paving system is effective irrespective of the underlying soil type. Several studies demonstrating infiltration rates in installed pavements are accessible through the North Carolina State University's permeable pavement research website [Ref. 7].

Runoff Coefficient

Permeable paving has a low runoff coefficient, which is defined as the percentage of the total rainfall that will become runoff. The runoff coefficient is used in the rational method of analysis. The most frequent runoff coefficient that has been measured with natural rainfall on properly built and maintained permeable paving systems is zero. There is no runoff because the surface permeability is so high compared with natural rainfall rates, but in a long, intense storm, the base reservoir may become saturated and the water may overflow across the surface or through a perforated drainage pipe if one is provided. At that point the pavement would in effect be generating runoff. So when designing or evaluating a permeable clay brick pavement, it is prudent to use some positive number — not zero — for the runoff coefficient. For example, set the runoff coefficient equal to that of the local jurisdiction's "predevelopment" condition, which might be forest, meadow or grass. Reasonable values for the runoff coefficient, C, are 0.25 for high-infiltration soils and 0.4 for low-infiltration soils. While this method can be used to design permeable pavements, it does not accurately account for permeable clay brick pavement's retention capacity [Ref. 9].

Perviousness

The word "perviousness" means the ability to pass water into and through the material or structure, so it is equivalent to permeability. In jurisdictions that regulate pervious and impervious cover, permeable paving meets objective criteria for a completely pervious surface. Properly constructed and maintained permeable pavement's infiltration rate is higher than that of almost any natural soil and greater than the rate of almost any natural rainfall. It is more pervious than anything that is already called "pervious," so a surface of this type meets the criteria to be given complete credit for "100 percent perviousness," as does a meadow or a forest.

Detention/Retention

Reduction of stormwater runoff flow rate is expected in most contemporary stormwater requirements in order to protect downstream drainage systems and water bodies. This effect is vitally important in old neighborhoods with CSO where lower runoff rates can reduce the frequency of overflows. In permeable clay brick pavements like the one shown in Photo 5, the base and subbase aggregate's void space is a reservoir in the same sense as any other stormwater detention/retention reservoir. The base and subbase reservoir stores storm flows until it exfiltrates or the

Photo courtesy Pine Hall Brick Company, Inc.

Photo 5
Permeable Paving Providing Stormwater Retention at Luray, VA Train Depot

water leaves at a rate controlled by the outlet. The peak outflow rate is lower than the peak rainfall rate entering through the surface, and it occurs later in time. The total amount of discharging water is less than the amount entering through the surface, because some water remains clinging to the reservoir aggregate's particles, where it later evaporates.

Water Quality

Water quality improvement is one of the fundamental purposes of contemporary stormwater requirements. Oil from vehicles is the most generic pollutant originating on city pavements. In a permeable pavement, the open-graded base and subbase aggregate is a suitable substrate for natural water quality treatment. Oil that enters through the surface clings to the aggregate particles. It then migrates slowly down and has an extended residence time in the pavement structure. Naturally occurring microorganisms ingest the oil and biodegrade it, thereby reducing the oil's hydrocarbons to their simpler chemical constituents. The pavement's interior is aerated, it is moistened from time to time, and its temperature is moderate and stable compared with that at the surface; so it is a favorable place to support this natural microecosystem. What used to be oil goes off into the atmosphere and ceases to exist as a water quality pollutant before it can reach the bottom of the pavement section. The pavement's water quality benefit occurs within the pavement system, without regard to the underlying soil; the soil is only a redundant "backup" system. Other benefits may include the reduction of zinc, copper, phosphorous and total suspended solids [Ref. 8].

Exfiltration

Exfiltration of water from the base and subbase reservoir into the subgrade soil reduces the total volume of runoff, eases the loads on city sewers and stream channels, further improves water quality in the soil, and replenishes groundwater aquifers with clean water. Some water exfiltrates from permeable pavements even where the subgrade is low-permeability clay. For example, monitoring in North Carolina [Ref. 3] observed that water exfiltrated into a clay soil at a slow rate — less than 0.1 in./hr (2.5 mm/h) — but it continued every hour of the day, as long as the water was in contact with the soil at the bottom of the pavement. Over a period of days, this added up to a substantial amount of exfiltrated water, restoring the base reservoir's capacity to receive water from the next rainstorm. It accounted for a large portion of all the rainwater over a period of months.

Development Cost

Some form of stormwater management is required in almost any contemporary development. In developments with impervious pavements, stormwater management consists of inlets, culverts, swales, retention ponds and detention basins, and the land to place those items on. Permeable pavement is a completely different approach in which stormwater is absorbed into pavement that is built as part of the development. Because permeable pavement effectively manages stormwater, it reduces or eliminates the need for specialized stormwater facilities. Where a permeable pavement is used intelligently in a development to absorb and treat stormwater, and the municipality gives credit for its stormwater functions, total development cost is commonly reduced. Absorbing the stormwater management function into a permeable pavement can increase the amount of development possible on a given property and make otherwise unusable lands developable, by letting the whole site be used for necessary construction up to the zoning jurisdiction's full regulated density.

DESIGN CONSIDERATIONS

The pavement thickness is designed for both structural and hydrologic (stormwater management) requirements. The structural and hydrologic theories underlying thickness calculations are the same for clay pavers as for pavers made of other materials. Structural design takes into account traffic level, soil bearing capacity and strength of pavement materials. Wet subgrade conditions should be assumed, as is common in all pavement design. Stormwater design uses the pavement's runoff coefficient. Capacity and sizing take into account the local storm intensity and soil type, and the hydraulic capacity in the pavement's void space. The amount of water entering a pavement varies with precipitation in the pavement's region, and the size of any area draining in laterally. The proportion of the rainwater to be stored varies with jurisdictional requirements. A pavement's required thickness is the greater of the two thicknesses calculated for structural and hydrologic design. The structural and hydrologic implications of several alternative thicknesses are listed in Table 4. Available software for permeable segmental pavement design is listed in Table 5.

TABLE 4

Minimum Base and Subbase Thicknesses Under Certain Conditions[1]

Base Thickness	Structural Capacity	Hydrologic Capacity
6 in. (152 mm) No. 57 base	Pedestrian traffic, on soil with soaked California Bearing Ratio (CBR) of 4 to 10	2.1 in. (53 mm)
4 in. (102 mm) No. 57 base + 6 in. (152 mm) No. 2 subbase	50,000 ESALs or residential driveway, on soil with soaked CBR of 4 (poor)	3.8 in. (97 mm)
4 in. (102 mm) No. 57 base + 13 in. (330) No. 2 subbase	200,000 ESALs (busy street with some truck traffic), on soil with soaked CBR of 4 (poor)	6.6 in. (167 mm)
4 in. (102 mm) No. 57 base + 22 in. (560) No. 2 subbase	600,000 ESALs (parking lot traffic), on soil with soaked CBR of 4 (poor)	10.2 in. (259 mm)
4 in. (102 mm) No. 57 base + 11 in. (279) No. 2 subbase	600,000 ESALs (parking lot traffic), on soil with soaked CBR of 10 (good)	5.8 in. (147 mm)

1. Structural capacity from the Interlocking Concrete Pavement Institute, Figure 3-1; structural capacity assumes lifetime equivalent single axel loads (ESALs) with 10 percent commercial vehicles; hydrologic capacity assumes 35 percent void space in No. 57 aggregate, and 40 percent in No. 2.

TABLE 5

Available Software for Permeable Segmental Pavement Design

Name	Design role	Source contact
Lockpave Pro with PCSWMM	Hydrologic & structural	www.uni-groupusa.org
Lockpave-Permpave	Hydrologic & structural	www.cmaa.com.au
PCSWMM Permeable Pavement Wizard	Hydrologic	www.chiwater.com
Permeable Design Pro	Hydrologic & structural	www.icpi.org

DETAILING CONSIDERATIONS

A permeable clay brick pavement requires a few simple but important special detailing considerations, because it is both a pavement structure and a drainage and stormwater management device.

Excess water must be permitted to discharge from the reservoir. Three forms of outlet are shown in Figure 3: no exfiltration, partial exfiltration and full exfiltration. Where a perforated pipe is placed at the floor of the pavement, all water is treated and detained in the paving system, then discharged laterally out of the pipe. This type of system is referred to as no exfiltration, since exfiltration to the subgrade is only incidental. The lateral outflow rate can be controlled by an orifice or weir at the pipe's outlet. Where a perforated pipe is placed at an intermediate level in the base reservoir, all water is treated and detained, and a substantial portion is forced to exfiltrate into the subgrade. In the event that water rises above the pipe's elevation, it discharges laterally out of the pipe after being treated and detained in the pavement system. Full exfiltration is where overflow occurs from the surface only at the pavement's low edge, a substantial portion of water is forced to exfiltrate and the excess overflows after being treated and detained.

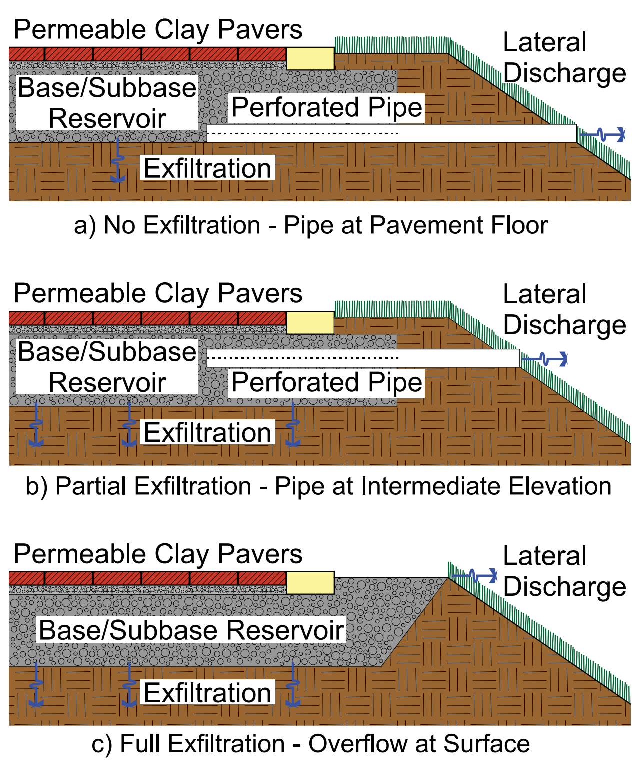

Figure 3

Base Reservoir Drainage Design Options

On a long, sloping pavement, the base reservoir should be divided into cells to prevent water from concentrating in the pavement's low edge, where it would fail to use the entire base reservoir for storage, fail to use the entire subgrade surface for exfiltration, and overflow frequently. As shown in Figure 4, add subsurface trenches, berms or geomembranes to divide the base reservoir into cells where water is forced to be stored and cannot flow downslope. The subgrade typically has a maximum 5 percent slope.

Surface overflow may occur in any permeable pavement configuration, as in any component of a drainage or stormwater management system. In all cases it is vital to identify the point where surface overflow is likely and to make sure that that point is safe from clogging and is non-erodible in an overflow event.

In many instances the minimum surface slope can be as little as zero percent — dead level — because drainage is primarily vertically through the pavement, not laterally across the surface. A level "floor" has the advantage of holding water in contact with subgrade soil for exfiltration. An important exception is at the edges of buildings, where, to protect the building from inadvertent overflows, the slope should be 2 percent or more away from the building for at least 6 in. (152 mm) downward. In addition, to protect the foundation, the subgrade slope should be downward away from the building wall for at least 3 ft (0.9 m) horizontally, and until the subgrade is 6 in. (152 mm) lower than at the wall. In this sloping area, the subgrade must be compacted to prevent water infiltration. Where the building is poorly waterproofed, it should be protected by an impermeable geomembrane placed against the building wall, down the sloping subgrade soil, and into a trench to prevent water penetration. These measures are shown in Figure 5.

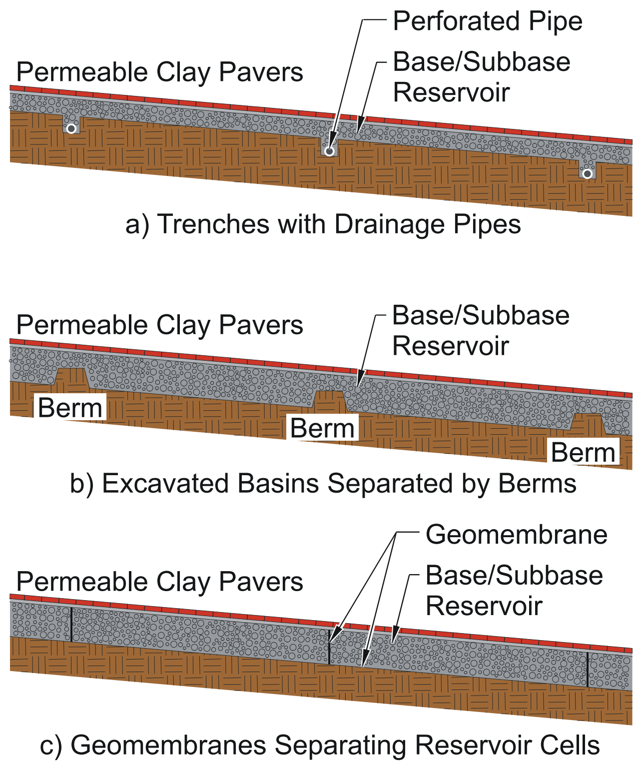

Figure 4
Water Control on Long Sloping Pavements

Pavements often border, or are bordered by grass or plantings, as shown in Photo 6. Earth adjacent to permeable pavements should be shaped and sloped downward away from every pavement edge where possible to prevent sediment from washing onto the pavement. Soil can erode and generate pavement-clogging sediment. Where necessary, add a swale to divert inflowing runoff and sediment. Runoff from adjacent vegetated areas impervious roofs or pavements may be drained onto a permeable pavement, since vegetated areas, roofs and pavements do not produce sediment the way soil does.

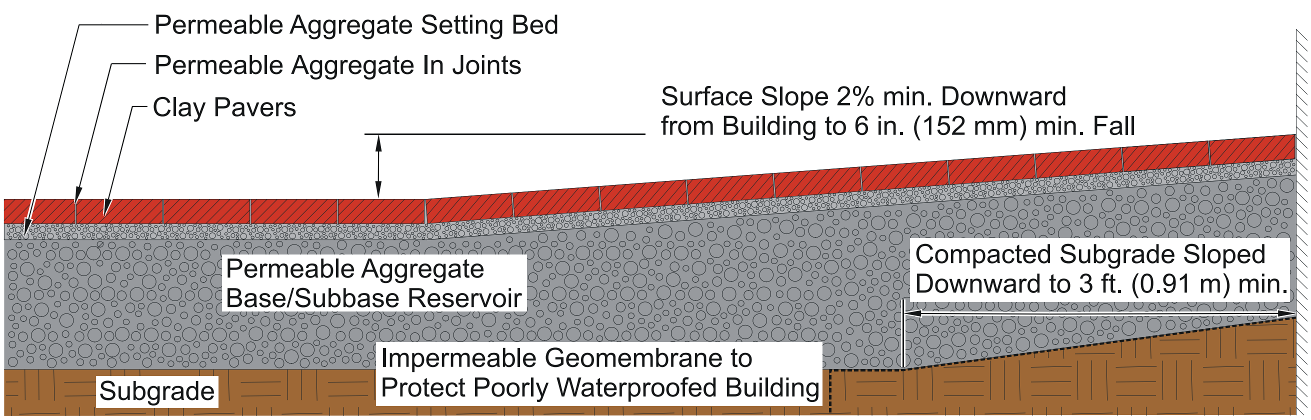

Figure 5
Pavement Detailing at Building Edge

Where a permeable pavement adjoins a conventional impervious pavement, the impervious pavement was probably not designed to have water in it, and it must be protected from subsurface water migrating out of the permeable pavement. This can be accomplished with a concrete grade beam or impermeable plastic sheet (geomembrane) separating the two sections, as shown in Figure 6.

If a hazardous or toxic chemical is spilled on the pavement surface, immediate and complete cleanup is necessary. No pavement or drainage system is designed for this contingency, with the exception of industries that produce such chemicals.

CONSTRUCTION

During construction, the pavement must be protected from construction-related sediment. There must be no dropping, tracking or storing of sand, mud, mulch, soil or other potentially clogging material on the pavement's subbase, base course, setting bed or surface during any stage of construction or after construction is complete. Temporary storage of soil, sand or mulch on the pavement is possible if a plastic sheet is placed to protect the pavement and carefully pulled up afterward to prevent spillage. In the event of tracking or spilling of sediment onto the pavement, the affected area must be vacuumed immediately as described below.

The subgrade is typically not compacted unless a need for doing so is established, since compaction reduces the soil's infiltration rate. The base and subbase aggregates are installed in lifts and compacted to the design thickness prescribed. Proper compaction is often measured with a nuclear density instrument (backscatter mode) or stiffness gauge. Setting bed aggregate is often best installed when moist but should not be compacted until after the pavers have been placed. Pavers can be installed manually or mechanically when possible (Photo 7). Pavers should be installed in the designated pattern so that no cut pavers are less than one-third of a paver. The pavers are compacted after the joints have been filled with aggregate. To prevent pavers from chipping during vibration, the underside of the plate compactor can be fitted with a rubber mat. Pavers may also be covered with a sheet of geotextile or sheets of plywood during vibration.

MAINTENANCE

Sediment that can clog a pavement's pores can come from construction sand, muddy construction traffic, eroded soil, grit applied to pavements for

Photo courtesy Glen-Gery Brick

Photo 6
Mulch Runoff Can Clog Permeable Pavements

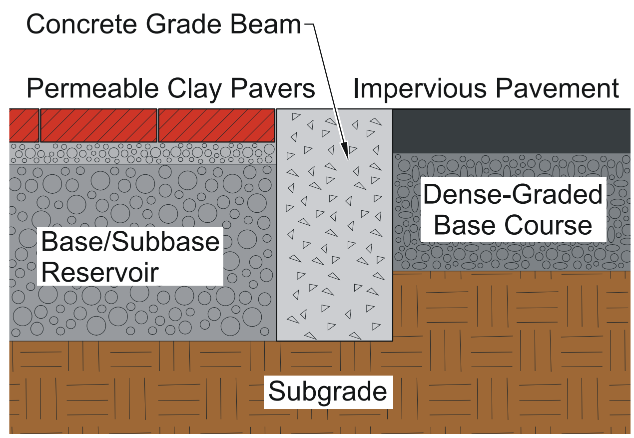

Figure 6
Separation of Differing Pavements

Photo courtesy Belden Brick Company

Photo 7
Mechanical Installation of Permeable Pavers

winter traction and overhanging trees. Nevertheless, with proper maintenance, a properly designed and installed permeable clay brick paving system should remain permeable indefinitely.

The key process for maintaining a permeable pavement is vacuuming. Vacuum equipment is either truck-mounted or walk-behind. Most urban municipalities and most large property management companies already own the required type of equipment. Sediment accumulates mostly in the uppermost 1 in. (25 mm) of joint aggregate, where it is accessible by vacuum suction. Vacuuming lifts sediment out and restores the pores to their original open condition. The surface should be dry when cleaning; vacuuming should not be accompanied by washing. Vacuuming may pull up some joint-fill aggregate with the sediment; vacuum strength settings can be adjusted for pulling up of sediment alone, or sediment plus aggregate. The aggregate can be replenished immediately after vacuuming. Washing the pavement is not an acceptable alternative to vacuuming; it would only drive sediment farther down into the pores.

It is easy to monitor a pavement's relative permeability and need for vacuuming over time. The simplest method is a visual inspection. When a properly constructed permeable pavement is clean and unclogged, the space between open-graded aggregate particles in joints and openings is clearly visible; if the open space within the aggregate is not visible, then sediment is clogging the pavement. A simple confirming test is to pour water from a bottle gently onto the middle of a paver. If the water disappears rapidly and completely into the first joint or opening it finds, then the pavement has relatively high permeability and requires no maintenance. However, if the water flows over a number of joints and openings before completely infiltrating, then the aggregate is clogged and it is time for vacuuming. More sophisticated testing can be completed with infiltrometers, if necessary.

Grit or sand should not be applied to the pavement for winter traction. Instead, rely only on snow removal and deicing agents. In a municipality where grit or sand is spread on public streets, vehicles can track it onto parking lots and driveways. The material tends to concentrate where piles of snow are pushed during the winter. Vacuuming will be necessary at least once per year: in the spring, following snowmelt. Where appropriate, No. 8 or No. 9 aggregate can be used for traction control. Deicing salt does not clog permeable clay brick pavements, nor cause any deterioration to the pavers. Deicing agents dissolve readily and then flush through with meltwater, without accumulating in the pavement. Research at the University of New Hampshire suggests that permeable pavements require less salting than impervious pavements or none at all, because meltwater drains away so readily through the pores.

A permeable pavement that is free from eroding soil and winter sanding may not need vacuuming for many years. Instead, vacuuming may be needed only in isolated instances such as construction vehicles tracking mud onto the surface. In this case, the vacuuming should be limited to the pavement area actually affected by sediment. Local clogging of one area of a pavement does not reduce the permeability of other parts of the system. Seasonal blowing to remove surface debris such as tree litter, mulch and loose dry soil is also beneficial and reduces the need for, or the required frequency of, vacuuming.

SUMMARY

Permeable clay brick pavements provide a cost-effective way of meeting stringent stormwater management requirements. When properly designed and constructed, the permeable aggregate in joints and openings provide high permeability, low runoff, stormwater detention and water quality treatment without compromising pavement stability under traffic. This *Technical Note* provides the basic information required to properly select pavers and permeable aggregate materials and to design, construct and maintain permeable clay brick pavements. It is recommended that an engineer be consulted, as these systems are very site specific. Further information about the properties of other brick pavements and concepts not unique to permeable pavements is discussed in the *Technical Notes* 14 series.

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