# Problems with and Alternatives to Permeable (Open-Graded) Subbases for Use in Jointed Plain Concrete Pavement Structures

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**Abstract**

Due to their intuitive advantage to quickly remove water from a pavement structure, permeable (open-graded) subbases (subbases with a permeability greater than about 350 ft/day (107 m/day) in laboratory tests) have been a common design element in jointed plain concrete pavement structures since the 1990s. Despite this assumed advantage, permeable subbases are no longer recommended for inclusion in jointed plain concrete pavement structures for various reasons discussed in this paper. Free-draining subbases (subbases with more fines than permeable subbase and, thus, with a permeability less than 350 ft/day (107 m/day) in laboratory tests) that are daylighted are the reasonable alternative to permeable subbases with edge drainage systems.

## Introduction

Permeable subbases, also known as drainable or open-graded subbases, are subbases with a permeability greater than about 350 ft/day (107 m/day) in laboratory tests, although permeability values typically are closer to 1,000 ft/day (305 m/day) in laboratory tests and some permeable subbases have been constructed with a permeability as high as 20,000 ft/day (6,100 m/day) in laboratory tests (Crovetti and Dempsey 1991). These subbases are generally characterized as a crushed stone (sometimes stabilized with cement or asphalt) with a reduced amount of fines, creating a mixture with many large voids that water can easily drain through.

Table 1 shows gradation ranges for unstabilized and stabilized permeable subbases that have been used by various state agencies across the United States. Also listed in this table is the permeability of each sample subbase gradation. As shown in the sample gradations, limiting the percent passing the No. 4 and No. 200 sieves may greatly increase the permeability of a subbase.

Because it was assumed that the ability to remove water rapidly from a jointed plain concrete pavement structure would mitigate most deterioration mechanisms, permeable subbases became a very popular design element for many state agencies in the 1990s (FHWA 1992). According to a 2005 national survey of state agencies, over 60% of responding agencies allowed the use of some form of permeable

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*Table 1. Free-draining, unstabilized permeable, and stabilized permeable subbase gradations that have been used by various state agencies (After FHWA 1992 and Munn 1990).*

| | Percent Passing | | | | | | |
|---|---|---|---|---|---|---|---|
| **Sieve Size** | **Free-Draining** | **Unstabilized Permeable** | | | | **Stabilized Permeable** | |
| 2 in. | - | - | 100 | - | - | - | - |
| 1 1/2 in. | - | - | - | 100 | - | - | 100 |
| 1 in. | 100 | 100 | - | 95-100 | 100 | 100 | 95-100 |
| 3/4 in. | - | - | 52-100 | - | 90-100 | 90-100 | - |
| 1/2 in. | 60-90 | - | - | 60-80 | - | 35-65 | 25-60 |
| 3/8 in. | - | - | 35-65 | - | 20-55 | 20-45 | - |
| No. 4 | 35-60 | - | 8-40 | 40-55 | 20-55 | 0-10 | 0-10 |
| No. 8 | - | 10-35 | - | 5-25 | 0-5 | 0-5 | 0-5 |
| No. 10 | - | - | - | - | - | - | - |
| No. 16 | - | - | 0-12 | 0-8 | - | - | - |
| No. 30 | 10-35 | - | 0-8 | - | - | - | - |
| No. 40 | - | - | - | - | - | - | - |
| No. 50 | - | 0-15 | - | 0-5 | - | - | - |
| No. 200 | 0-15 | 0-6 | 0-5 | - | - | 0-2 | 0-2 |
| *Permeability (feet/day)* | *150* | *500* | *1,000* | *2,000* | *18,000* | *15,000* | *20,000* |

subbase (ACPA 2008). Despite their widespread use, permeable subbases have had a problematic history for many reasons, including:

- Instability as a construction platform.
- Loss of support due to breakdown and compaction of the aggregate.
- Early age cracking due to mortar penetration.
- Potential for increased curling.
- Loss of support and decreased permeability due to infiltration of fines from below.
- Problems associated with an edge drainage system.
- Increased cost without a comparable increase in pavement life/performance.
- Poor overall field performance.

Thus, the inclusion of a permeable subbase with an edgedrain is no longer recommended in jointed plain concrete pavement structures, a potentially significant departure from current allowances in many states of the U.S. Free-draining daylighted subbases (subbases with a permeability less than 350 ft/day (107 m/day) in laboratory tests, but with a typical target permeability between 50 and 150 ft/day (15 and 46 m/day) in laboratory tests) have proven to be a suitable alternative. Because of their increased fines content (see Table 1), free-draining subbases have the requisite stability that is necessary for construction activities and long term durability, but free-draining subbases are still effective at quickly removing water from the pavement system.

The following sections discuss the mechanism behind many of the hypothesized problems with permeable subbases, as well as results from one of the most comprehensive reviews of the performance of jointed plain concrete pavement structures that include permeable subbases.

**Instability as a Construction Platform**

Subbase material stability is an important consideration for paving operations. Many contractors and state agencies have reported that unstabilized permeable subbases may cause difficulties during paving due to the weight of the construction equipment, difficulties in anchoring dowel baskets and/or tie bar chairs, and unacceptable final concrete pavement smoothnesses (ACPA 2007; FHWA 2002; Long and Ioannides 2007; and Reed 1995). Dense-graded granular subbases, free-draining subbases, and subbases stabilized with cement or asphalt are all examples of subbases that create a support condition that is more conducive to construction activities (ACPA 2007).

The profile pan (the part of a slipform paver that controls the pavement surface) typically references its position from sensors that follow stringlines placed along the grade, usually on both sides of the paver. The stringlines are not necessarily parallel to the grade, but rather are set to form the concrete pavement in the proper location regardless of the grade elevation below the stringline. A well-positioned stringline can help to overcome some minor surface deviations in a subbase or track line, but it is not a substitute for smooth, stable track lines built to a tolerance. The hydraulic systems that control a slipform paving machine's profile pan cannot adjust quickly enough to significant variations in the machine's vertical position caused by settlement of an unstable subbase or track line. An unstable track line may cause the profile pan to continually attempt to adjust its position relative to the machine's frame. If too abrupt or frequent, these types of mechanical adjustments may cause bumps or dips in the pavement surface.

Layers with high permeability coefficients often do not have the in-place stability necessary to enable contractors to build consistently smooth concrete pavement surfaces. Also, agencies must consider if specifying an unstabilized permeable subbase will limit the option to haul concrete to the paving site due to the high potential of rutting of the surface by the construction equipment. Because of their increased fines content, free-draining subbase materials will be more stable during construction activities, making them the reasonable alternative to permeable subbases in regard to in-place stability.

**Loss of Support Due to Breakdown and Compaction of the Aggregate**

Starting in 1996, the American Concrete Pavement Association (ACPA) began to observe cracks and early faulting of joints on concrete pavements placed on unstabilized permeable subbases with coefficients of permeability around 1,000 ft/day (305 m/day) or higher. The cause of this cracking was typically believed to be the break down of material at the joints, which created a non-uniform support condition between the ends of the slab (joints) and the center of the slab. The primary mechanism for this deterioration is hypothesized to be crushing of the aggregate in the subbase below pavement joints because of higher relative deflections at the joint compared to the center of the slab and high point-to-point contact pressure between neighboring aggregate particles in the unstabilized permeable subbase (Figure 1). When this contact pressure becomes high enough to fracture an aggregate, the crushed aggregate particles fall into the open void structure of the permeable subbase and the subbase eventually will undergo secondary consolidation at the joint (reorientation and recompaction of the aggregate due to roadway vibrations and loading might also aid the secondary consolidation), leaving the ends of the slab unsupported and often resulting in faulting and/or corner cracking (Wei et al. 2005).

Though this phenomenon has primarily occurred on unstabilized permeable subbases, it has also occurred on asphalt-treated permeable subbases (Long and Ioannides 2007). Theoretically, it could also occur on a cement-stabilized permeable subbases if the cementing action between particles were to break down, although this has yet to be observed in the field. Also, it should be noted that secondary consolidation of permeable subbases may occur even if the subbase material is properly compacted to specification during construction. In fact, over-compaction of a permeable subbase during construction, whether by accident or in an attempt to meet a compaction specification, may cause the aggregate in a permeable subbase to begin to breakdown even before the pavement section is placed into service.

Common recommendations previously made by various state agencies to prevent aggregate breakdown were that, if an unstabilized subbase is to be used, 90-100% crushed stone be used (and not crushed gravel or recycled concrete aggregate) and a

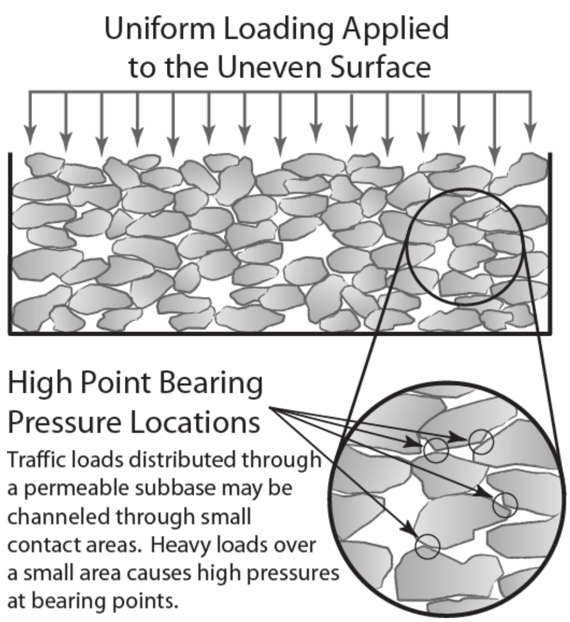


*Figure 1. Illustration of the phenomenon of high bearing stresses in unstabilized permeable subbases.*

maximum LA Abrasion of 40 to 45 percent be allowed (Baumgardner 1992 and FHWA 1992).

Because of their increased fines content, free-draining subbase materials will mitigate this mechanism of support loss by increasing the points of contact between aggregate particles and reducing point-to-point bearing pressures between particles, making free-draining subbases the reasonable alternative to permeable subbases in this regard.

**Early Age Cracking Due to Mortar Penetration**

Early age cracking due to penetration of mortar from the concrete pavement into the subbase is a problem that can occur on permeable subbases. Because of the openness of the permeable subbase structure, the mortar portion of the fresh concrete mixture can be forced into or may migrate into the voids as the concrete is vibrated and consolidated, creating high friction at the slab/subbase interface once the concrete sets. Table 2 shows typical coefficient of friction values for various subbase materials, where asphalt-treated and cement-treated permeable subbases are shown to have significantly higher friction values at the slab/subbase interface than other subbase types. This increased friction may cause early erratic cracking in the concrete pavement, may alter the structural section/the required jointing pattern, and/or may result in early mid-panel cracking on properly sized slabs.

Because of their increased fines content and more well-graded nature, the surface of a free-draining subbase will not be as open (e.g., have as many voids) as that of a permeable subbase, so the effects of mortar penetration can be greatly negated. This makes free-draining subbases the reasonable alternative to permeable subbases in regards to mortar penetration.

**Potential for Increased Curling**

Although it has been shown in environmentally controlled testing that concrete slabs should curl more when placed on a dense-graded subbase than when on an open-

*Table 2. Coefficient of friction for various subbase materials (ACPA 2002).*

| Subbase | Coefficient of Friction |
|---|---|
| Natural Subgrade | 1.0 |
| Chemically-Modified Clay Soil | 1.5 |
| Unstabilized (Granular) Subbase | 1.5 |
| Bituminous Surface Treatment | 3.0 |
| Unstabilized Crushed Stone Subbase | 6.0 |
| Asphalt-Treated Subbase (smooth) | 6.0 |
| Cement-Treated Subbase | 10.0 |
| Asphalt-Treated Subbase (rough) | 15.0 |
| Lean Concrete Subbase (Econocrete) | 15.0 |
| *Cement-Treated Permeable Subbase* | 15.0 |
| *Asphalt-Treated Permeable Subbase* | 15.0 |

graded subbase due to the increased subbase support provided by the dense-graded subbase (Childs and Kapernick 1963), it has been found that concrete pavements constructed on an unstabilized permeable subbase may exhibit excessive built-in and thermally-induced curl in the field (Beckemeyer et al. 2002). Any increase in curling deflections and stresses increases the probability of mid-slab cracking. As was concluded in the field investigation conducted by Beckemeye et al., limiting the joint spacing to 15 ft (4.6 m) or less, the common recommended maximum joint spacing amongst most state agencies (ACPA 2008), can greatly minimize the probability of top-down cracking caused by excessive curl.

**Loss of Support and Decreased Permeability Due to Infiltration of Fines from Below**

Loss of support due to infiltration of the subgrade and/or a subbase immediately below the permeable subbase into the permeable subbase is believed to occur primarily due to traffic loading or vibrations, causing the entire slab to settle (Figure 2). A filter-separator layer (i.e., geotextile) is necessary to prevent the migration of fines (minus No. 200 [75 µm] material) into the permeable subbase from below (Gisi et al. 2004). When this infiltration occurs, the pavement section settles to a degree that matches the infiltration. Though this can occur with both unstabilized and stabilized permeable subbases, it has been observed that stabilized subbases can worsen the effect because temperature related volume changes in the subbase may aid in the working of subgrade material up into the subbase.

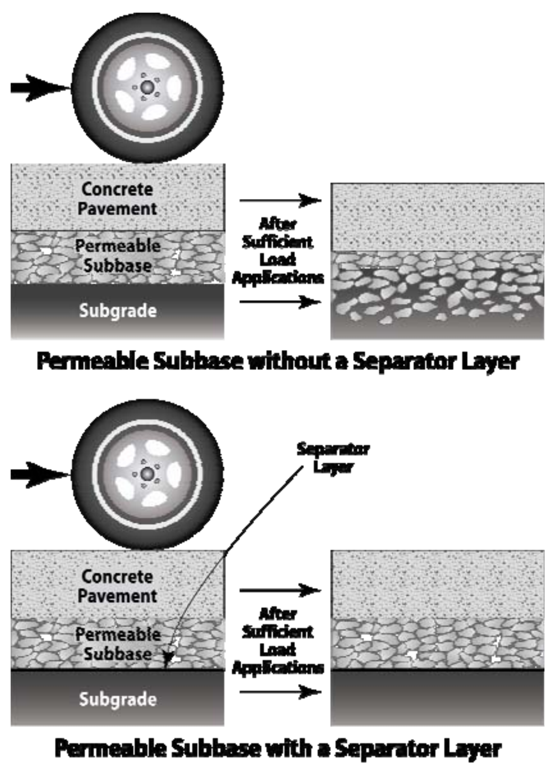


*Figure 2. A permeable subbase with and without a separator layer. Note the infiltration of the subgrade into the permeable subbase and resultant settlement of the pavement in the case without a separator layer.*

The loss of support due to infiltration of fines from below may result in an overall nonuniform support condition, which can result in overall roughness, slab cracking, and/or faulting. Also, the introduction of fines into the permeable subbase eventually may decrease the permeability of the layer to the point where it becomes clogged and traps water inside the jointed plain concrete pavement structure.

Because of their increased fines content and less open-graded character, free-draining subbases will not be as prone to the infiltration of fines from below and, if of concern, a geotextile may be used to prevent infiltration of fines from below.

**Problems Associated with an Edge Drainage System**
Permeable subbases are generally used in conjunction with edge drainage systems; in theory, a permeable subbase will serve as a means for any water that enters the jointed plain concrete pavement structure to travel to an edge drain and an edge drain will collect the water and feed it to an outlet along the roadside. Figure 3 illustrates a cross-section of an edge drainage system. Where edge drains are used, the hydraulic capacity of longitudinal edge drains and outlet laterals must be high enough to drain 50% of the free water within the pavement structure within 2 hours of rain cessation to be considered to have an excellent quality of drainage (FHWA 1992).

Although an edge drain system is a sound method of removing water from a jointed plain concrete pavement structure in theory, many problems arise due to settling, crushing, and plugging of both newly constructed and retrofitted edge drain pipes during installation and service. These problems may be caused by several of the previously mentioned methods of failure of a permeable subbase, but the end result is typically an edge drainage system that is partially or completely clogged, thus trapping water in the pavement structure (Baumgardner 2002).

Even if an edge drainage system is installed correctly and the permeable subbase around it does not cause it to clog for any reason, free material inside the pavement structure (i.e., pieces of aggregate from the permeable subbase that are broken off due to bearing stresses, particles from the subgrade, etc.) can migrate into the edge drainage system and this action alone may eventually cause the system to partially or completely clog. FHWA has even stated that, "if a state highway association does

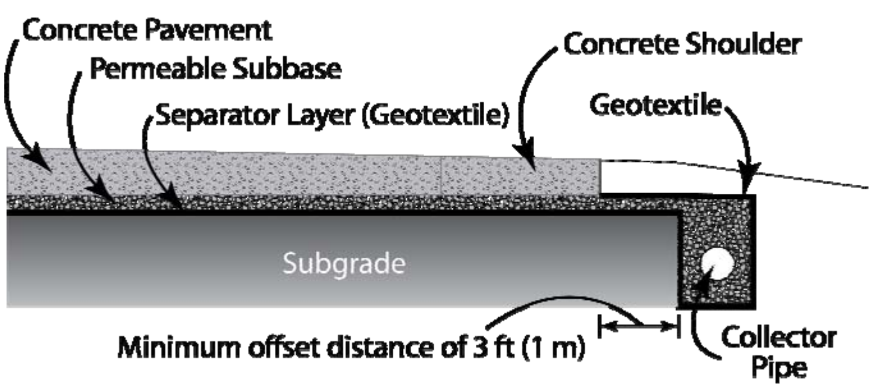


*Figure 3. Detail for an edge drainage system, typical with permeable subbases.*

not have a commitment to maintenance, permeable [sub]bases should not be provided" (FHWA 1992). Regardless, problems have arisen when regular scheduled maintenance is deferred or, even worse, when no maintenance is programmed for an edge drainage system. Lack of maintenance of the edge drain system is cited by almost all state highway agencies that have constructed permeable subbases as a prime reason for clogging problems (Baumgardner 2002).

The practical alternative to expensive edge drainage system is a free-draining daylighted subbase (Figure 4). In such a setup, water and any free material that finds its way into the free-draining subbase will have many paths to follow that could potentially lead out of the pavement structure. Studies have found that flexible pavements sections with daylighted bases (without edge drains) performed as well as (or better than) any other flexible pavement section (NCHRP 2002). Similar performance should be expected with concrete pavements. Also, no regular scheduled maintenance is required for a daylighted subbase.

**Increased Cost without a Comparable Increase in Pavement Life/Performance**
The increased cost of a permeable subbase is not clearly justified by a comparable increase in pavement life or performance. Figure 5 shows the relative cost comparisons for different types of subbases that are used under jointed plain concrete pavements (Cole and Hall 1996). On average, unstabilized permeable subbases add approximately 15% to the cost of jointed plain concrete pavements relative to a jointed plain concrete pavement structure that utilizes a dense-graded unstabilized subbase, which may be free-draining; asphalt-treated and cement-treated permeable subbases add approximately 25% to the cost of jointed plain concrete pavement due to their additional requirements for layers, materials and edge drainage systems. Other studies estimate the cost differential for these stabilized permeable subbases at over 30% (Hoerner at al. 2004). A cost-benefit analysis will show that permeable subbases need to extend pavement life by between 8 and 15 years in a life cycle cost analysis to be considered cost effective (ACPA 2007). Experience over the past two decades indicates that permeable subbases do not provide that level of impact, and the positive impacts of drainage can be provided more effectively with a daylighted free-draining subbase layer. Therefore, installation of a permeable subbase carries with it a substantial risk that the system will not function properly over the life of the pavement and will not extend pavement life enough to be considered cost effective, negating the beneficial concept of this drainage feature (NCHRP 2002).

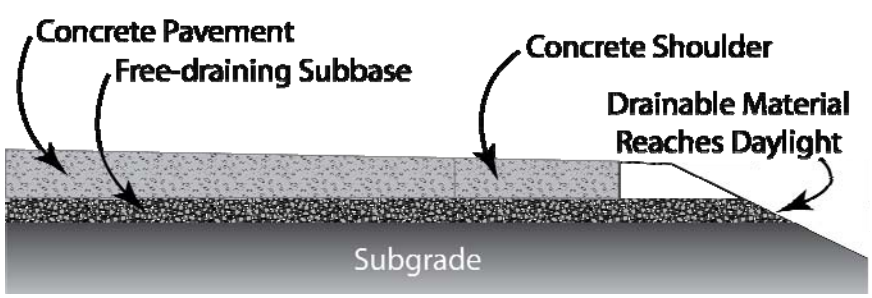


*Figure 4. Detail for a daylighted free-draining subbase system.*

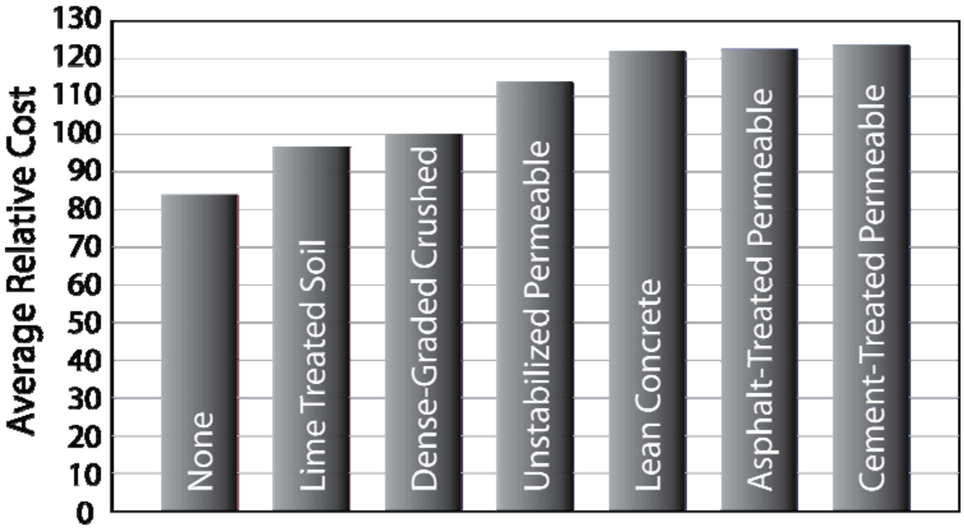


*Figure 5. Relative total construction cost for various subbase types, with dense-graded crushed aggregate subbase assigned the relative cost of 100 percent.*

**Poor Overall Field Performance**

The most comprehensive study of the performance of permeable subbases in jointed plain concrete pavement structures came to the following conclusions (NCHRP 2002):

- For properly designed, doweled, jointed concrete pavements, joint faulting in general is fairly low and a permeable subbase has a relatively small effect on reducing joint faulting further. When a dense-graded subbase exists, edge drains were not found to have a significant effect on reducing doweled joint faulting. Dowel bars greatly minimize differential deflections across joints, thus reducing the potential for pumping and erosion.
- For non-doweled, jointed concrete pavements, joint faulting in general is much higher and a permeable subbase has a significant effect in reducing joint faulting. However, the permeable subbase must be well designed or it can become contaminated by fines, allowing faulting to develop. The edge drains must also be maintained properly or they will clog and any potential benefits in pavement performance will be lost.

**Summary and Conclusions**

Permeable subbases are no longer considered a cost effective design element for jointed plain concrete pavement structures. This conclusion was reached through experiences with poorly performing jointed plain concrete pavements built on permeable subbase layers. It is further supported by several performance evaluation studies that concluded that these systems do not have a significant positive influence on concrete pavement performance for many design conditions (Hall and Crovetti 2007; NCHRP 2002). Without contributing appreciably to the performance of the typical jointed plain concrete pavement, it is difficult to justify the high cost (as much as 25% more) of these rapid-draining permeable subbase systems (further research is necessary to determine if D-cracking can be mitigated in jointed plain concrete pavements built on permeable subbases, as has been suggested elsewhere [Mathis 1989], to decide if they might be a cost effective solution in such a scenario).

Free-draining subbases have enough fines that they are not as susceptible as permeable subbases to problems such as instability as a construction platform, loss of support due to aggregate breakdown, and loss of support and due to infiltration of fines from below. Also, because free-draining subbases are less open-graded, they are not as prone to mortar penetration and the associated problems of having high friction at the slab/subbase interface. Daylighted subbases provide as much, if not better, long-term drainage potential as edge drainage systems do, but daylighted subbases do not rely on the interconnectivity and cleanliness of several components (Gisi et al. 2004). Thus, free-draining and daylighted subbases are the reasonable alternatives to rapidly draining permeable subbases with an edge drainage system.

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