PERVIOUS CONCRETE PAVEMENT—HOW IMPORTANT IS COMPRESSIVE STRENGTH?

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INTRODUCTION

As asphalt becomes more expensive and in short supply, and as the need to manage stormwater runoff increases, designers must revisit old assumptions and take a fresh look at how pavements need to work in a sustainable environment, and how to design and specify for them. Pervious pavements are a recent addition to the list of viable paving options, but as yet, there have been few ways to design them and to effectively predict their performance. This article offers some help to accomplish those tasks.

Pavement designers have one goal in mind: to carry the traffic load smoothly, reliably and cost effectively for a long period of time. We know that in order to accomplish that goal, a pavement has to meet several criteria.

- It has to distribute the applied load over a wide enough area so that it does not fail the underlying soil support system.
- It has to be durable to withstand the abrasive nature of the traffic, and environmental conditions.
- It has to resist damage so that it does not have to be repaired or replaced within a reasonable lifespan.
- It needs to be strong.

We also know that the most sustainable pavement is the one that lasts longest, requires the least maintenance, and carries the widest range of loads for the longest time. What we have found is that if we make it strong enough, we usually attain all the other goals along the way.

No mystery; End of story?

Not quite, especially in the case of pervious concrete used as a paving material. We need to look into this "needs to be strong" statement just a little bit more to get a full understanding of pervious concrete as a paving material, and to understand how to design and construct it cost-effectively and reliably.

Engineers are interesting people. We start each problem with a notoriously negative look at life, by asking ourselves one simple question, "What is the worst thing that can happen?" When we have engineered against that however unlikely occurrence, we move on to the "What is the next worst thing that can happen?" question, and ensure that our design prevents that situation. We repeat this process until we can ensure that the design will prevent or withstand all of the "Oh-My-Gods," and that we have found a cost-effective solution with an acceptable level of risk.

In the case of a pavement, we know that if we make a pavement very thick and strong, let's say 10 feet thick, it will never fail. We know that if we make it 5 feet thick, it will likely never fail. We can guess that if we make it say 1″ thick, it probably won't work. The question then becomes how thin and how strong can we make it and have it still work. As part of that question, we have to figure out how much the answer will cost, and we should find out the lowest cost alternative that still solves the problem. Anyone can build a pavement 10 feet, or even 5 feet thick, but it takes an engineer to understand the relationship between thickness of pavement, strength of material, and cost of the pavement system. It takes an engineer who does understand these relationships to design a reliable, cost effective pavement system. That is the purpose of this article.

We have some tools at our disposal. We have years of anecdotal evidence. We have a good basic understanding of rigid pavement material—concrete. We have some concrete pavements that have been in

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service for many years under severe traffic loading. We have pavement design procedures that have been shown to be conservative and reliable. And, we have built a number of pervious and conventional concrete pavements, and have had an opportunity to observe them. As a result, we have a place to start.

Conventional concrete is what we know and recognize as sidewalks, curbs, retaining walls, foundations, etc. By design and construction, conventional concrete is dense and impermeable. Pervious concrete is the same material, but without the sand, and it is intentionally permeable to allow water to pass through it unimpeded. Pervious concrete is a recent development, driven by sustainability and changes in stormwater management laws. Although pervious concrete looks different, it still has known and predictable engineering properties that allow the use of conventional wisdom for design and construction.

What do we know about concrete? We know that strength is a function of the water cement ratio (w/c ratio)—lower w/c equals higher strength. We know that the minimum cement content for durability—the ability to resist abrasion—is 5.5 sacks of cement per cubic yard (517 lb. per CY). We know that if we give water a place to expand when it freezes, we can prevent it from damaging the concrete.

We know that pavements do not fail in compression. Pavements have two primary failure modes—fatigue and erosion. A fatigue failure is how you break a coat-hanger wire by bending it repeatedly. Pavements fail the same way, by repeatedly loading it with repetitive wheel loads.

An erosion failure is when the pavement does not break or crack, but its support system is compromised by the loss of support beneath it. For a pavement, the way that support system is compromised is by "pumping." For a "pumping" condition to exist, you need three things to exist in conjunction: a fine grained soil that will go into suspension with water, a source of water, and movement to pressurize the water and make it move.

The way to prevent a fatigue failure is to make the concrete thick enough so that the applied load over its expected life does not exceed the fatigue capacity of the pavement section. The way to resist erosion failure is to make the pavement thick enough that the interlocking fractured face between the jointed panels is sufficient to transfer load, and enable both sides to move together, thus preventing differential movement.

Another key factor in the analysis and design of a pavement is the fact that the pavement section strength is proportionate to the square of the thickness, but only linear with respect to strength of the concrete. More on this later.

When we look at the fatigue and erosion issues, what we see is that both are addressed by thickness, and that strength doesn't really enter into that analysis, as long as the concrete is strong enough. A good question is: how strong is strong enough? In order to answer that, we need to look at some calculations.

The basis for the design comparisons I use is the StreetPave program, which is available from the American Concrete Pavement Association. Its engine is based on the PCAPAV program that is in the public domain, and was copyrighted by the Portland Cement Association in 1986. It is a time-tested program that returns conservative results and pavements that have outperformed their anticipated lives. Don't be concerned with the absolute values returned from these calculations; it is the relative values that really tell the story, and that I call to your attention.

In the design of pavements, we need to identify some fairly universal parameters. First is that the thickness of concrete pavements is designed to the next half inch increment greater than or equal to the calculated design thickness. So, a pavement calculation that results in 7.01″ would be identified as a 7.5″ design.

The next issue is that of how strength of pavement is entered. The concrete strength parameter that is used is the flexural strength of the concrete, not compressive. It is fair to ask, "Why, then, do we measure and use compressive strength?" The answer is that while the compressive strength test has its issues, it is much more repeatable and consistent than the results of the flexural strength test procedures we have developed. In fact, when we make flexural strength beams from a single batch of concrete, the results typically plot as a bell curve normally associated with random data, not data from what should be a single uniform source. So, even though compressive strength isn't the parameter of concern, we use it because we have more faith in the accuracy of the test result. We have attempted to correlate flexural strength of concrete by using the results of the compressive strength test. Empirical data analysis tells us that the flexural strength of concrete can be approximated by the equation:

$$MR = k\sqrt{(fc')}$$

where

MR = Modulus of Rupture (flexural strength)
k = a constant with value in the range of 8–10
fc′ = compressive strength of the concrete

For the purpose of our calculations, we are going to assume our concrete has a constant value of k = 9.0, which means that at 3000 psi, the flexural strength is 493 psi; at 6000 psi, the MR = 697 psi, and so forth. To quantify the relative importance of the strength of the concrete, let's take a look at some examples noting how the load carrying capacity of the pavement changes with strength of concrete, and thickness of section under the following conditions:

Traffic = collector street with 100 trucks per day average, 2% growth per year.
Soil CBR = 2, k = 161
E (modulus of elasticity) = 6750 × MR
30 yr. design life, 85% reliability, no dowels, with edge support

At fc′ = 4,000 psi, (MR = 550 psi) a run-of-the-mill commercial/residential ready mixed concrete, it takes a 6″ thickness of concrete to carry the load. If we want to save the cost of 1″ of concrete, the analysis shows that we would have to increase the concrete strength to fc′ = 7,000 psi (MR = 750 psi). When we consider the increased cost of all the concrete on the project and the relatively fixed costs of placing, forming, grading, and finishing, it is unlikely that the materials volume savings will offset the increased materials cost. In fact, typical field experience confirms this assumption.

Now let's take a look at what it would take to increase the load carrying capacity of the pavement to 750 trucks per day (750 ADTT) load on a 6″ section. We would have to increase the concrete strength from fc′ = 4000 psi (MR = 550) to fc′ = 8000 psi (MR = 800 psi)! But if we keep the concrete strength at fc′ = 4000 psi (MR = 550 psi), we find that we only need an additional half inch thickness of concrete. Again, the cost benefit of strength vs. thickness shows that the cost-effective solution is to increase thickness, not increase strength.

"How can this be?" you may well ask. Here is where the discussion about the influence of pavement thickness and strength of materials on strength of section we saw earlier comes into play. The strength of the section is proportionate to the square of the thickness, but varies directly proportionate to the flexural strength of the concrete. What this means is that a small change in thickness has a great influence on load carrying capacity, while a relatively large change in psi results in a relatively small change in load carrying capacity. When applied to costs associated with pavement construction, the costs of increasing all the concrete on the job to a very high strength is almost always higher than the cost of increasing the thickness of the lower strength concrete.

How does this relate to pervious concrete? Pervious concrete is concrete. In fact, it is a high quality concrete. Typical pervious mixes have around 6 sacks (564 lb. / CY) of cement per cubic yard, and typically have a w/c ratio of around 0.30, which is normally associated with conventional concrete mixes showing very high strengths, in excess of fc′ = 10,000 psi. But, when we intentionally make holes in any material, it has to be weaker than the same material without holes. And, it is the holes (interconnected pores, or voids) that make pervious concrete pervious. It is the pervious attribute of pervious concrete that makes it desirable. If it were not so sought after, we would likely use conventional concrete.

FIGURE 1. Pervious concrete pavements are able to pass flows of water in excess of even the most severe storm rainfall intensities.

For design purposes, we can effectively ignore the erosion part of the analysis, because pervious concrete will not be able to pressurize and move the water like conventional concrete does—the water simply runs through the concrete. The design procedure will still perform the erosion analysis, but will accurately predict that the fatigue analysis controls, and that erosion will not be the failure mode at the end of the service life.

At this point, we encounter an issue. There are no approved methods for characterizing the strength of pervious concrete. An ASTM committee is currently working on developing this test procedure, but it will be some time before there are any developed and adopted. So, how then do we accurately characterize the strength of the pervious concrete materials?

When tested under the procedures approved for conventional concrete, we find what we have learned to expect from other low strength construction materials made with Portland cement—a high degree of variability of strengths. We find that it is notoriously difficult to control strengths of low strength materials within a narrow range. We find that there is an inverse relationship between density and strength—you can't have high strength without decreasing voids, and you can't have voids without decreasing strength.

This brings us to the crux of the issue. If you make the decision to control your pervious paving project by strength of the pervious concrete material, you have to be willing to place the pervious attribute of the concrete at risk, and that attribute is precisely why we selected pervious concrete in the first place.

What then is the answer? If we can't verify strength of materials, how can we ensure quality, cost-effective projects? The answer lies in the discussion above. Although the results of the non-standard tests are highly variable and by definition inaccurate, we do find that compressive strengths of pervious concrete with voids in the plastic concrete within the range of 15% to 21%, a typical specified range, generally are in excess of fc′ = 2000 psi. Flexural strength likewise showed strengths generally in excess of MR = 400 psi. We have to keep in mind that when we make the decision to make concrete pervious, part of that decision is that we have decided to make it weaker.

As we have learned, there is typically a relatively small penalty to be paid for designing to a lower strength material. If we make the assumption of a pervious concrete strength well below what experience shows we can expect, even at the low end of the range of measured and expected values, pavement thicknesses are still in the range of very cost-effective pavement alternatives.

Let's take a look at the example we started with, and make the assumption of an MR = 375, which equates to an fc′ of approximately 1400 psi. This is typically the value I use for design of a pervious concrete pavement. An additional assumption we must make for pervious concrete is that the soil support value is poor because we will be intentionally allowing water to get into the soil, and weaken it if it can be weakened. For this example, I use a CBR = 1, or k = 100. For an ADTT of 100, the resulting pavement thickness is 7.5″, or an increase of 1.5 inches. For an ADTT of 750, the design returns a thickness of 8.1″, or an increase of 1.6″ (this would be rounded up to 2″ increase, in this case). This is within the typical range observed, and is also confirmed by observing pavements placed in the Puget Sound region I am familiar with.

In this region, there are regulations limiting impervious surface lot coverage and also requiring very large stormwater retention/detention facilities. The use of pervious concrete pavements reduces both impervious surface coverage, and the amount of land

FIGURE 2. City of Seattle's High Point Project—pervious concrete street pavement and pervious concrete sidewalk.

FIGURE 3. Stratford Place in Sultan, WA. All surfaces in the development—streets, sidewalks, and driveways—are constructed with pervious concrete. Colored pervious concrete delineates walkways. Use of pervious surfaces replaced stormwater retention pond, and saved the owner over $250,000.

required for the stormwater ponds. The result is a significant cost benefit and incentive to the owner/developer by using pervious concrete as a pavement material. Even with very conservative strength assumptions, the increased thickness of pervious concrete paving required is still a cost effective solution.

We have been able to observe a number of installations across the country that have been installed and designed "by the seat of the pants." We have observed gross violations of both mix and construction practices. The failures observed have been readily apparent at the plastic concrete stage and include premature drying, insufficient consolidation, and over compaction resulting in plugging by sealing the voids. Although installation expertise has varied widely, as well as the visual appearance of the pavement surfaces, these pervious concrete pavements have held up structurally. There have not been experiences of fatigue failures, sudden failures under large loads, or displacements at cracks or joints. These pervious concrete pavements have performed above expectations. In this region, the interest in pervious concrete pavements has grown, fueled in large part by increasing stormwater management regulations. The use of pervious pavements is growing, and has progressed from small residential parking areas to streets and commercial parking lot installations, with a number of projects exceeding an acre in size.

Until we have more reliable methods of quantifying strength characteristics of pervious concrete, we have little choice but to design very conservatively. As testing methods become more refined and adopted, we may be able to reliably reduce the thickness of pervious pavement without compromising

FIGURE 4. Sketch of typical pervious pavement/sidewalk installation.

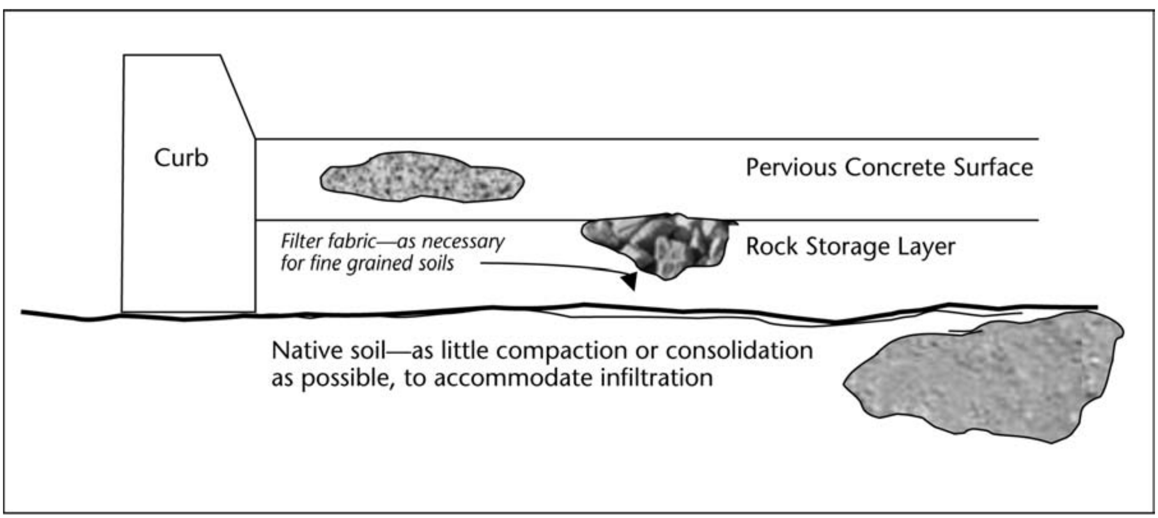

FIGURE 5. Snoqualmie Gourmet Ice Cream, pervious concrete parking area. (AM Photo)

the performance or the permeability of the paved surface. Until then, conservative strength assumptions will result in reliable, cost-effective pavement thicknesses while preserving the permeability of the pavement. Use of strength as an acceptance criterion places the permeability of the pervious concrete at risk—you can't make pervious concrete stronger without removing the voids. As plastic concrete void content approaches about 11%–12%, the voids become disconnected, and the pavement becomes impermeable. ACI 522.1-08 is a pervious concrete specification that affords the designer with a good, reliable construction specification, and is a specification I endorse. It specifies control and acceptance of the pavement by voids content, compliance with mix design, and by visual observation of the installation. Anomalies in installation can be identified and corrected while the mix is in a plastic state.

What we have found, when pervious concrete is designed and constructed in compliance with ACI 522.1-08 is that it generally has a permeability greater than 200 in/hr. and up to 1000 in/hr. through the concrete. The result is that the concrete will never impede the rainfall reaching the soil, so the rainwater can infiltrate into the soil as it did before the pavement was built, effectively replicating a pre-development condition.

In addition, it provides storage for excess stormwater, and it reduces runoff velocities so less pollution is carried downstream when runoff from extreme events does occur. Other pavement systems such as asphalt require ongoing and routine maintenance—overlays, sealcoats, etc. Porous asphalt pavements are no different. So, not only are there additional costs, and additional commitment of aggregate and petroleum products, once a porous concrete is overlaid or sealcoated, it is no longer porous.

Portland Cement Concrete is a highly sustainable building material; pervious concrete is even more so. Concrete pavements should be designed for a minimum 30-year design life, and we find that concrete pavements routinely and usually last much longer. There are concrete streets in the NW approaching 100 years in age that have received no maintenance of any kind, and are still in service carrying greater loads than were even possible at the time of their construction.

Concrete surfaces are lighter colored, which makes them reflect solar radiation rather than absorb it, and results in mitigating for urban heat island effect. Concrete, both conventional and pervious, uses post-industrial and post-consumer recycled materials such as fly ash, granulated ground blast furnace slag, and recycled concrete aggregates. Pervious concrete may help qualify a project for LEED points in the areas of stormwater management and urban heat island effect, and will result in a lighter surface at night with less applied lighting.

FIGURE 6. "F. E. Nelson Spokane, Wash. 1908"—An example of old concrete pavement with no maintenance in 100 years.