Villanova Urban Stormwater Partnership

Lessons Learned - Porous Concrete Demonstration Site

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Executive Summary:
This document explores the lessons learned from the construction of the porous concrete surface for the Villanova University Porous Concrete Best Management Practice. At the time of construction, this site was the first to use this material in the region. Considerable knowledge was gained in the construction and reconstruction of the surface. The initial installation occurred during August 2002, and due to failure of the original surface, was resurfaced in May 2003. The initial failure was caused by a number of elements, the most significant being a lack of understanding of the impact the porous concrete material properties had on construction practice. The site was redesigned and resurfaced in May of 2003, incorporating the lessons learned during the initial failure. The second attempt has been successful to date.

Project Overview:
A porous concrete infiltration "Best Management Practice" (BMP) was constructed during the retrofit of an existing paved area in the center of the campus of Villanova University. The contributing watershed is approximately 50,000 ft^2 and is highly impervious, consisting of pedestrian walkways, rooftops and some grass areas. The rooftops and some adjacent paved areas are directly connected to three separate rock storage beds (four feet deep) that underlay the porous concrete surface. The rock beds are linked through piping systems to distribute the runoff between beds and allow for overflow for major storm events. The original porous concrete surface was edged using decorative pavers. Installation involved demolishing the original site, extensive regrading, and construction of the infiltration BMP. The site was designed to capture and infiltrate the first two inches of runoff, thereby reducing downstream stormwater volumes, stream bank erosion, and non-point source pollution. The project joins the Villanova University "Best Management Practice Demonstration Park" as both a research and demonstration site (Traver 2002). Funding for the project was through the Pennsylvania Non-Point Source Pollution Section 319 Program, and the site has been designated as a National Monitoring site by the EPA. Further information on this and other projects can be found through the Villanova Urban Stormwater Partnership website (www.villanova.edu/VUSP).

Figure 1 – BMP – Initial Surface

Initial Pour Observations:

The original design consisted of three large porous surfaces bordered with pavers as shown in Figure 1. The original plan was for the material to be batched offsite, poured and spread, and then leveled using a traveling vibratory screed, hand compacted, and finally covered. An admixture to improve bonding and thus strength of the concrete was to be added to the drum at the site prior to pouring. Before construction a small test pad (130 ft^2) was poured from a visual inspection appeared to be satisfactory in porosity and strength. The chief concern from the test pad experience was the cosmetic appearance of the material. Two tamping methods (hand, vibratory) were tried.

The weather during pouring was extremely hot (95 -105 degrees Fahrenheit). The concrete was provided by a concrete plant located approximately 45 minutes away from the construction site; however, this travel time was unpredictable due to traffic congestion. Once the truck arrived at the site, the admixture was added, mixed thoroughly for approximately 15 to 20 minutes, and then poured.

Figure 2 - Initial Pour and Hand Tamping

Figure 3 - Vibratory Tamping

The first truckload of concrete lacked the desired consistency. The concrete resembled wet, loose gravel and was discarded. It was assumed that too much water had been added which prevented the concrete from curing properly. The second truckload of concrete arrived shortly thereafter and appeared to have a better consistency. It was poured and then spread by shovels and rakes. The vibratory screed was not useful because of the poor workability of the material (stiffness). Once spread, a vibratory tamper was used to smooth and lightly compact the concrete. Originally a hand tamper was used. Unfortunately, hand tamping proved to be time consuming and the laborers could not keep up with the pour. Later, a vibrating push tamper was modified with a larger bottom plate and used to finish the concrete behind the screed. This technique was successful because the compaction was distributed over a larger area thereby improving the final surface appearance. It was observed that there was a small window of opportunity in which the concrete maintained its workability.

The third truckload became unworkable before it was completely poured. The contractors and the admixture industry representative discussed the issue and decided to dispose of the remaining material. At this time the fourth truckload had already arrived on site and had been sitting for some time. The material had already lost its workability when it was time for it to be poured and could not be used.

At the end of each day the porous concrete was covered with plastic sheets, but these sheets were extremely difficult to hold in place due to the size of the pour and gusting winds. They blew off long before the recommended 48 hour cure time.

Similar events unfolded in the days that would follow. To better control and predict the workability of the concrete it was decided that the trucks should bring the concrete mix to the site without the addition of any water. The water would then be added on site, thereby eliminating some of the uncertainties in travel and mixing times. Occasionally the mix consistency would be acceptable for placement, but often the material would become unworkable. Portions of the material that did appear to be acceptable at the time of placement did not cure properly. These portions were removed and replaced the following day. After consultation with the concrete plant, it was discovered that a retardant had been added by the plant to delay setup due to the excessive heat and dry conditions. This retardant was not documented on the delivery sheets.

Once the entire site was constructed it was clear that the final finish of the porous concrete would not be acceptable. In many locations the surface of the concrete was rutted while other areas did not set up at all and resembled loose gravel. It was theorized there may have been cement remaining in the concrete that had not yet hydrated. The contractor brushed and wet the concrete to in an attempt to promote hydration. Many of the areas of loose gravel were removed and patched with another batch of porous concrete. This created a tremendous variation in color and texture of the concrete as shown in Figure 4. Due to the start of classes, there was no time left for further repairs.

Figure 4 – Patched Surface

Speculations:

Construction was restricted to the summer months due to the vacancy of the adjacent dormitories. Pouring began on July 30th 2002 and was completed on August 20th. The pour occurred in the midst of a severe heat wave with temperatures consistently in the upper 90's to low 100's. This environmental factor made the installation of the porous concrete extremely difficult. The mixing process on site was unpredictable and caused curing to occur much too quickly. The freshly poured concrete

Figure 5 – Ineffective Covering

was covered with plastic sheets; however, the covers were not secured adequately and blew off the concrete soon after being laid down. The large size of the pour made covering extremely difficult. Therefore the concrete that was poured was not allowed to properly hydrate, which contributed to the observed surface failure.

There were many inconsistencies between the different loads including travel and mix times. Some of the loads had the concrete sitting for over two hours before the pour began. To eliminate the influence of variable travel times on the concrete reaction time, it was decided to add water on site (after the first day). This also allowed the workers to have better control on the amount of water added per truck. Due to the extreme heat and often long travel times, the plant had added a retardant to some of the trucks to slow the reaction in the mix, a standard practice with conventional concrete. However, the workers at the site were not made aware of the retardant, and its affect on porous concrete containing a bonding agent were not known. It was also later found (after construction was completed) that the aggregate used was not washed as specified and contained excessive fines. These fines absorbed water thereby increasing the amount of water required. Because the composition of each load varied (i.e. additives, fine content, etc.), it was impossible to determine the proper volume of water to add. The inability to accurately know and control the mix contributed to the surface failure.

The traveling vibratory screed used to level and compact the concrete proved to be cumbersome and ineffective. The screed was used because the pours were 15-25 feet wide. Simply moving the concrete material side to side was extremely difficult. The setup speed was extremely fast compared to conventional concrete, and often the end of a full drum's pour was extremely difficult to work, leading to irregularities in the surface appearance and ruts.

Covering of the concrete to promote proper hydration was ineffective. After the concrete had been poured and compacted, it was sprayed with the additive and water mixture as per the specification and then covered with large sheets of plastic. The plastic was not put down until 15 or 20 minutes (or later) after compaction. During the heat of the day, this delay in covering the fresh material may have played a significant role in the failure of the surface. While this was apparently "normal" construction practice for regular concrete, the large void spaces in porous concrete may accelerate the drying process. Once placed, the plastic sheets were held down at the edges by rocks, cinder blocks, buckets, and pieces of wood. Often during the 24 hours after pouring, the plastic sheets came loose, causing the concrete to dry too quickly.

Most of the problems that occurred during the construction were not anticipated. As the construction team had built a satisfactory test pad, the only concern at the start of the pour was the surface appearance. Unfortunately, there was no extra time built into the construction schedule due to the projects relatively small construction window. The failure of the first truckload of porous concrete caught the team by surprise. As the team was unaware of the plant additives and unwashed aggregate, the changes to the water mixture were by trial and error, causing mixed results. Adding to the mix design difficulties, the inability to properly cover the material, and the short construction window, it is clear that failure of the surface was due to multiple factors.

While the surface was not satisfactory in appearance or durability, porosity was not a problem. The surface drained quickly and easily, without significant ponding. The porosity did not diminish over the one year before replacement.

Reconstruction:
Due to the surface failure, the porous concrete site was redesigned and resurfaced in the spring of 2003. Lessons learned from the initial construction and visits to other sites were included in the redesign and construction.

Figure 6 –Visitor Center Sidewalk

Figure 7 - UNC Parking Lot

Three existing sites were visited by representatives from Villanova University and the contactor prior to the redesign. The first visit to the Centre County Visitor Center adjacent to Pennsylvania State University was encouraging. Porous concrete (no admixture) had been used to construct a sidewalk, which had been rolled during construction. The surface was smooth and durable, but the color variation of each pour was evident. Two sites were visited near Raleigh North Carolina. The first was an older site where the driveways and a cul-de-sac were all porous concrete. Again, the surface was durable. The second site was a very large parking area at the University of North Carolina that had included an admixture. The surface appeared durable, but the cosmetic appearance was inconsistent. While this was acceptable for a parking area, it was not acceptable for a central pedestrian mall that was to be a showcase on Villanova's campus.

Based on the site visits, it was decided to construct several concrete test pads to give the contractor more experience and to check durability and surfacing techniques. The first 200 ft^2 (built in the fall of 2002) was acceptable for durability, but the surface color varied excessively (partially because the contractor tried several compaction techniques during the pour). To provide a "larger" test, four 100 ft^2 porous concrete dumpster pads were installed at various locations on campus prior to the start of reconstruction as shown in Figure 8. This was done to compare two mix designs as well as compaction methods. As will be discussed below, several new quality control measures were imposed on the batch plant. Two of the pads were constructed using a bonding agent and two without that admixture. A vibrating plate tamper was used to compact two of the test pads and a 50 gallon, 48" wide, plastic drum roller filled with water was used on the other two. Following construction of the test pads, each was inspected and core samples

Figure 8 - Test Pad

taken for compaction strength testing. Each test pad's porosity was verified by pouring water on the pad and observing how quickly it infiltrated. From the test pad trials it was determined that the mix containing a binding agent and compacted with the roller provided the best results. The roller was filled with water to exert a 10 psi load. The mix containing bonding additive was judged to be more uniform in color and produced higher strength concrete. An important advantage for the admixture was that the manufacturer had experience and effective field supervision available to train the contractor's crew.

From initial data and observations of the site it was determined that the original design had more than enough porous concrete surface, and this area could be decreased without effecting the site's performance. Therefore a new layout was designed which included narrow strips of porous concrete around the perimeter of each bed with conventional concrete replacing the porous concrete in the middle. Pavers remained along the perimeter. The impervious concrete was crowned along the center strips to promote drainage toward the porous strips on the perimeter. These narrow strips allowed the concrete to be compacted using the 50 gallon roller instead of the vibratory screed. The roller covered the entire width of the surface, and limited the amount of distance the concrete had to be spread.

Figure 9 - Redesigned Site

Several Villanovans had complained that the original surface was too rough. The aggregate used in the original mix was relatively sharp crushed rock. A smoother "river pebble" was used for the reconstruction. Review of the batch plant's practices resulted in the new aggregate being fully washed and dried before introduction into the drum. The mix was to be delivered dry with no admixtures introduced.

The reconstruction began on May 19th, 2003 with the first day of pouring occurring two days later. The spring weather was much more favorable than the hot summer conditions during the initial construction. During the reconstruction the temperatures remained cool with high in the mid 70s. Many days were overcast with occasional drizzle. The high humidity and cool temperatures were ideal for concrete hydration.

Applying the lessons learned from the first pour, no water was added to the concrete mix until it reached the site. This gave the workers total control over what was added to the mix and the mixing times.

Consistency of the mix was assured through pre-inspection of the concrete plant. The bonding admixture's representative was in charge of on-site concrete mixing and pouring.

From the moment the concrete truck arrived, the foreman was in charge of what, how much, and when to add the water and admixture. He carefully inspected the concrete to ensure it had the consistency to properly consolidate. When a problem arose, he decided the proper course of action. The representative trained one of the contractor's foremen to recognize and produce the proper mix consistency for later pours.

Each truckload contained 6-7 yd^3 of material. Ten gallons of water per yard of concrete were typically used, but this varied from nine to eleven depending on weather conditions. The foreman remained at the top of the truck so that he could see into the drum and examine the mix's consistency (Figure 10). Batching typically lasted between five and ten minutes. After adding the water, the admixture was slowly introduced. The specifications call for 3.3 gallons of admixture per yard of concrete. Once this was added, the concrete was thoroughly mixed again for approximately five minutes before reversing the drum so it could be released into the chute. The batches were often "hand-sampled" to visually determine slump. It was at this point that the foreman would decide if the consistency was correct or if it needed more water or mixing. He would periodically "feel" the hydration rate (heat) inside the drum by laying the palm of his hand on the rotating drum's exterior. If it was satisfactory, the material was poured. If not, steps were taken to remedy the situation until the desired consistency was achieved. The entire process of mixing took an average of 20 minutes from the introduction of water into the drum to release for pouring. This relatively quick mixing process may have played a key role in maintaining the concrete's workability during the pour. While the workability was greatly improved, it did prove difficult at the end of each load as the concrete began to hydrate. This is why a drum's maximum 9 yd^3 capacity was not utilized.

Figure 10 -Concrete Truck and Foreman

Figure 11 – Rolling

Rakes were used to move the concrete horizontally no more than 24 in. Excessive movement within the pour resulted in a blotchy surface. Troweling or movement with shovels was not permitted, as they left spots of "glazed" surface. The rolling compaction technique proved to be far superior to the vibratory screed and plate tamper used in the initial construction. The narrow pour widths allowed the crew to quickly prepare the concrete for rolling and cover. It was found that wetting the 50 gallon roller prior to and during the compaction process helped keep the concrete from sticking to its face. Immediately after rolling, the concrete was covered with plastic sheets and properly secured. This process was maintained throughout the pour duration. The plastic was not removed until at least 48 hours later.

Current State:
The reconstruction was completed on May 30, 2003. This process went much smoother than the initial effort. There were no areas that needed to be patched, removed, or repaired. However, one truckload was rejected due to poor consistency. It was speculated that moisture left in the truck from a previous job caused early hydration. Overall, the surface of the porous concrete met expectations. The appearance of the site is greatly improved over the original design, and the surface is durable to date. The new "river pebble" aggregate provides a smoother and more aesthetically pleasing surface. The site has been observed during multiple rainfall events and is porous.

The redesigned site provides for the center (impervious) concrete areas to drain toward the porous concrete border. In some locations the runoff from the conventional concrete is concentrated due to both the slopes and decorative grooves. This concentrated flow sometimes exceeds the capacity of the porous concrete strip's width during periods of intense rainfall.

Figure 12 - Non-Porous Area

Some minor inconsistencies remain. In a few areas the concrete appears to be almost glazed over with excess cement. While these areas are probably the most durable and strong, they have little or no porosity as the voids have been clogged. This could be a result of the mix being too wet. Observations made during the construction seem to support this theory.

Figure 13 - Elevation Differences

In some areas where the porous concrete meets either conventional concrete or the decorative pavers there are slight differences in elevation. This difference is likely a result of excess material prior to compaction. Before compacting the concrete, the material was intentionally elevated approximately ½'' such that the material, when sufficiently compacted, ideally would reside at the same level as its border. With too much excess material, the drum roller would compact the material, but still leave the material above its intended finished elevation. This protruding edge could create a vulnerable spot where the concrete could be chipped.

Material Testing:

On May 29, 2003, four sample cylinders were molded to conduct compressive strength tests. There is no ASTM standard procedure for molding porous concrete cylinders so a method developed by Eco-Creto of Texas, Inc. was used. The method involved filling a standard six inch diameter cylinder with concrete in three lifts. Each lift was compacted using a six inch diameter tamp struck with six firm blows. The cylinders were then covered and allowed to cure. Two of the cylinders were broken on July 3, 2003. The results of the two breaks were 3,460 psi and 3,412 psi. However the samples taken from that truck appeared to be too wet and therefore the concrete did not appear to have sufficient void space. This may have accounted for the high compressive strengths. The remaining two cylinders are being kept for future testing.

Figure 14 - Test Cylinder Preparation

Reconstruction Result:

In conclusion, the reconstruction of the porous surface was successful. The surface is porous, durable, smooth and attractive.

Figure 15 – Reconstructed Surface

Design Recommendations:

- Design the porous surface as a series of narrow strips to promote surface uniformity. Narrowing the width of the pour reduces movement during placement of the material, allows for rolling the complete width with each pass, provides the opportunity for immediate coverage to promote even hydration, and minimizes visual ridges resulting from uneven rolling.

- Use a series of perimeter strips, and design the non-porous surface to drain as sheet flow into the porous concrete surface. The incredible infiltration capacity of porous concrete makes it unnecessary for the whole area to be porous. It must be cautioned that concentration of runoff can overload the capacity of the porous concrete surface. We found that runoff from the regular concrete follows the expansion joints and can, during severe weather, concentrate and overload the porous concrete. A better design to capture more runoff from intense rainfall periods would be to have the runoff cross multiple porous strips, and to anticipate the channeling effect of the expansion joints. This would also provide redundancy to protect against areas that clog over time.

- This type of BMP should be located in areas that have a low risk of hazardous spills. Villanova's site is a pedestrian mall, located in the center of campus. There is virtually no risk of catastrophic chemical spills, etc. on the site. The only recourse for such spills would be total site reconstruction.

- Generic concrete specifications will not be adequate for inexperienced contractors to perform a satisfactory porous concrete installation. Either the consulting engineer or contractor should enlist the assistance of industry manufacturers' reps to specify batching and placement techniques as well as formulation. Mistakes are irreversible and thus costly because this concrete system has no "give" (due to low initial slump and fast set-up times).

- The material specification must be enforced. Mix proportions, additives, and composition are critical. Do not assume your concrete plant operator understands the importance of washed aggregates, additives, etc. Water should be added at the site. The water volume and contact time is critical.

- Owners should enter into a general construction type of contract rather than attempt to perform the work on a multiple-prime basis. Having single-point accountability makes the general contractor responsible for all tolerances, coordination of excavation and bed preparation, and concrete mixing/placement activities.

Construction Recommendations:
Consultants and contractors must recognize batching and placement practices for porous concrete vary greatly compared to those for conventional (impervious) structural concrete.

- Regarding batching:
  - Concrete batches should be in 5-7 yd^3, not the 9 yd^3 capability of most drums.
  - Delivery of dry-mix is necessary. It must be batched in dry (not "washed-out") drums.
  - If a binder admixture is specified, no other "conventional" concrete admixture should be introduced without consent of bonding agent's manufacturer.
  - Aggregates must be fully washed and dried before batching. Excessive fines diminish the function of porous concrete and affect field-introduction of water and bonding agent.
  - Field introduction of water and bonding agent should only be performed by experienced porous concrete personnel. Due to the product's very low slump, its workability must be determined visually before mix is "run down the chute." Adjustments in water quantity, number of drum rotations, and admixture introduction must be performed quickly to insure workability. Hydration heat monitoring in drum is important.

- Regarding placement practices:
  - Multiple test pours are strongly recommended using the same foreman and crew as will be used for actual construction. Test pads should be at least 200 ft^2 to detect surface unevenness.
  - Properly-batched mix cannot be moved horizontally more than a couple of feet from point of placement. This is a major contrast to conventional concrete exhibiting typical 3-5 inch slumps.
  - Use rakes instead of flat devices such as shovels, screed boards and trowels should not be used to shift or level concrete. Using such devices will produce "splotchy" surfaces.
  - Installers must carefully plan and execute placement to affect the items above. In conventional concrete practice concrete leaves the chute and forms "puddles" which are first "worked" by laborers several feet horizontally, screeded and then troweled smooth by cement finishers. Its lack of slump and fast set-up characteristics requires steady movement of porous concrete chutes to replace manual "working", so placement is not in pools, rather in continuous bands that need minimal "working" before rolling. Such placement requires laborers to develop a cement finishers' eye for "level" and an understanding of the drum's discharge rate down the chute. Critical is the degree of communication between the laborers and person (foreman) responsible for field mixing at the truck's drum.
  - Rolling is the preferred compaction method. Vibratory tampers create ridges that are difficult to detect visually until after concrete has hydrated.

Careful hand tamping may be necessary in areas where rollers cannot reach. Rollers will also leave small ridges that are difficult to detect in unhydrated concrete.

- Concrete must be tightly covered for a minimum 48 hours after placement.

- Existing concrete material specifications and testing standards are inadequate for both batch plants not experienced with porous concrete and when "proprietary" binding admixtures are used. Our experience indicates the only people capable of insuring proper batching and placement are the bonding admixture manufacturers or contractors with a proven porous concrete installation track record.

- Flexibility must be included in the construction schedule. Porous concrete is less forgiving than regular concrete. You cannot take short cuts, and pouring in extreme weather conditions is not an option. Some loads may have to be discarded. Extra time must be built into the construction schedule.

- Smaller pour volumes are better. The material should be rolled and covered immediately. The fast setup requires timely placement, rolling and covering. Our experience was that the material was most difficult to move at the end of the pours (7 yds^3), and that the appearance was not as good.

Villanova Urban Stormwater Partnership

The mission of the Villanova Urban Stormwater Partnership is to advance the evolving comprehensive stormwater management field and to foster the development of public and private partnerships through research on innovative SWM Best Management Practices, directed studies, technology transfer and education. We invite firms interested in joining the partnership to contact us through the VUSP website. (www.villanova.edu/VUSP)

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