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# **FINAL REPORT**

## **A PERMEABLE ACTIVE AMENDMENT CONCRETE (PAAC) FOR CONTAMINANT REMEDIATION AND EROSION CONTROL**

**SERDP (SEED) ER-2134**

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**Anna Sophia Knox**

**Michael H. Paller**

**Kenneth L. Dixon**

**Savannah River National Laboratory (SRNL), Aiken, SC, USA**

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## LIST OF ACRONYMS

A – apatite

ANOVA – one-way analysis of variance

As – arsenic

CCME – Canadian Council of Ministers of the Environment

Cd – cadmium

Co – cobalt

Cr – chromium

Cu – copper

DGT - diffusive gradients in thin films

DoD – Department of Defense

DOE – Department of Energy

EPA – U.S. Environmental Protection Agency

ER – Environmental Restoration

Hg - mercury

ICP-MS – inductively coupled plasma – mass spectrometry

$K_d$  – partition coefficient

Ni – nickel

Mo – molybdenum

PAAC – permeable active amendment concrete

Pb – lead

Se – selenium

SERDP – Strategic Environmental Research and Development Program

SON – Statement of Need

SRNL – Savannah River National Laboratory

TCLP – toxicity characteristic leaching procedure

Zn – zinc

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## EXECUTIVE SUMMARY

The final project report for SEED SERDP ER - 2134 describes the development of permeable active amendment concrete (PAAC), which was evaluated through four tasks: 1) development of PAAC; 2) assessment of PAAC for contaminant removal; 3) evaluation of promising PAAC formulations for potential environmental impacts; and 4) assessment of the hydraulic, physical, and structural properties of PAAC.

Conventional permeable concrete (often referred to as pervious concrete) is concrete with high porosity as a result of an extensive and interconnected void content. It is made from carefully controlled amounts of water and cementitious materials used to create a paste that forms a coating around aggregate particles. The mixture has a substantial void content (e.g., 15% - 25%) that results in a highly permeable structure that drains quickly. In PAAC, the aggregate material is partly replaced by chemically-active amendments that precipitate or adsorb contaminants in water that flows through the concrete interstices. PAAC combines the relatively high structural strength, ample void space, and water permeability of pervious concrete with the contaminant sequestration ability of chemically-active amendments to produce a new material with superior durability and ability to control contaminant mobility. The high surface area provided by the concrete interstices in PAAC provides significant opportunity for contaminants to react with the amendments incorporated into the concrete matrix. PAAC has the potential to immobilize a large variety of organic and inorganic contaminants by incorporating different active sequestering agents including phosphate materials (rock phosphate), organoclays, zeolite, and lime individually or in combinations.

The results of this work can be summarized as follows:

1. Active amendments were successfully incorporated into permeable concrete (PC). PAACs with apatite, zeolite, organoclay or limestone and apatite effectively removed metals.
- 2 The replacement of small amount of crushed stone by amendments (e.g., 10%) is sufficient to effectively remove metals from the aqueous phase.
3. A static column study was conducted with PAAC containing 20% apatite (PAAC – A), PAAC containing a mixture of 10% apatite, 5% zeolite, and 5% MRM (PAAC – AZM), and permeable concrete without amendments (PC)]. This study showed that concentrations of metals were significantly ( $P < 0.05$ ) lower in leachates from PC, PAAC-A, and PAAC-AZM than in control leachates (uncapped sediment) for a test period of five months. The sediments beneath the PAAC caps were analyzed for the bioavailable pool of metals using diffusive gradients in thin films (DGT) probes. DGT can measure labile species that correspond closely to bioavailable contaminant fractions in sediments. The DGT results for showed that the concentrations of Cd, Co, Pb, and Zn in the sediment beneath the caps (down to 5 cm) were substantially lower than in uncapped sediment.

4. Three flow-through columns (PAAC – A, PAAC – AZM, and PC) were tested under saturated conditions at flow rates of 0.2 ml/min and 1.0 ml/min. Leachates from the three columns were analyzed for concentrations of As, Cr, Co, Cd, Cu, Ni, Se, Pb, and Zn for six weeks. All tested materials removed almost 100% of all metals from the spike solution at low flow rates through the column. There was no difference between the tested materials except that PAAC – AZM was more effective at removing As and Se. Desorption experiments showed that there was very high retention of all elements. After the low flow study, the columns were leached at a higher flow rate (1.0 ml/min) with a low pH (2.53) spike solution containing about 10 mg/l of all tested elements. At the high flow rate, concentrations of Cr, Cd, Co, Ni, Pb, and Zn in the leachates from the PC column increased to levels found in the spike solution. However, the PAAC-A column effectively removed up to about 40 percent of almost all tested metals. These results contrasted with the findings of the static column study in which all treatments (PC, PAAC-A, and PAAC-AZM) performed similarly. The better performance of PAAC-A was the result of better metal binding sites in this material. The flow-through column study indicated that PAAC-A constitutes a better capping material than PC (permeable concrete without amendments) because its metal removal capacity is greater – a factor that could be important over long periods of time or in situations where there is substantial movement of water through a cap.
5. PAAC exhibited high retention (90% or more) of most tested metals indicating low potential for remobilization based on the Toxicity Characteristic Leaching Procedure (TCLP) and 1 M MgCl<sub>2</sub> desorption data.
6. All developed PAAC materials exhibited high porosity and hydraulic conductivity values compared to ordinary concrete, and the observed property ranges are consistent with typical permeable concrete. The PAAC-AZM formulation exhibited the highest porosity and hydraulic conductivity. Substantial porosity and high hydraulic conductivity make PAAC ideal for flow through treatment of waters contaminated with heavy metals. PAAC porosity could be modified by changing the ratio of crushed stone to sand.
7. PAAC has the potential to create structural barriers that contain contaminants while resisting physical disturbance and permitting the passage of water.

## TECHNICAL APPROACH

In situ management of contaminated sediments is potentially less expensive and risky than ex situ management, but there are relatively few alternatives for in situ treatment and some are still under development. Among the more promising alternatives for in situ treatment are active capping technologies. However, apart from the types of amendments to be used in active capping, little is known regarding amendment application techniques, application rates, and amendment combinations that will maximize sequestration, immobilization of contaminants, and resist erosion. A selected set of active capping treatment technologies has been demonstrated in the field as part of the Anacostia Active Capping Demonstration Project (Reible et al., 2006) and at the Savannah River Site (Knox et al., 2011). Knox's field deployment (Knox et al., 2011) showed that active amendments such as apatite or organoclay can effectively immobilize contaminants but are subject to erosion in dynamic stream environments.

The design of sediment caps must consider a wide variety of factors, including the mobility of the contaminants, burrowing habits of potential receptors, erosive forces acting on the surface of the cap, and geotechnical characteristics of the native sediment (Palermo et al., 1998). Diffusion or advection of contaminants as well as bulk movement of contaminated sediment must both be considered as potential routes of contaminant migration. The thickness of the cap and appropriate capping materials are selected based on an evaluation of these factors and site-specific modeling (Knox et al., 2011). In the long-term the cap must provide an effective barrier to contaminant migration, a barrier to penetration by burrowing organisms, and must remain stable in flowing water and where waves or propeller-generated currents move fine grained capping materials. The design of the cap must consider these erosive forces, and adequately sized materials must be selected to resist them. Capping materials that help to resist erosion may also be effective in resisting penetration by burrowing organisms. The cap must use a sufficiently coarse substrate or be sufficiently thick so that organisms are discouraged from burrowing into the cap or are still separated from contaminants by clean cap material. At the same time, the surface of the cap may need to be designed to encourage recolonization if maintenance or restoration of habitat is required. These design constraints often work in opposition. Furthermore, traditional in situ caps composed of granular materials (i.e. sand, gravel, and rock) may be difficult to install in certain settings, such as channels with high surface-water velocities and/or areas with weak, fine-grained native sediment. The accurate placement of fine-grained capping material in a high velocity stream may be difficult to achieve without the loss of a significant amount of capping material, which could drive up costs as well as cause turbidity problems during construction.

Consideration of the preceding facts suggests that there is a need for capping technologies that can sequester organic and inorganic sediment contaminants and create a reliable, stable, and long-lasting cap in a range of aquatic environments. Current technologies typically produce caps with limited physical stability that are suitable primarily for low-energy, depositional aquatic environments. However, depositional environments can become erosive

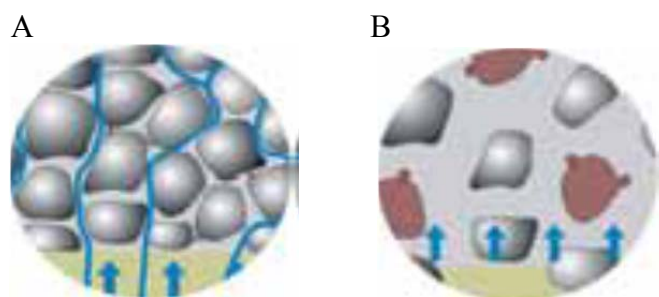
as a result of unpredictable natural events such as floods and storms as well as anthropogenic actions such as boating and construction activities. Under such conditions, caps can be rapidly compromised resulting in the mobilization of contaminated sediments. Therefore, current capping technologies, both passive and active, often fail to represent a secure, long-term solution to sediment contamination because of their likelihood of physical failure under extreme conditions. In recognition of this limitation, we developed a PAAC cap that combines the desired features of improved physical stability with the capability of chemically sequestering both organic and inorganic sediment contaminants.

Permeable concrete (often referred to as pervious concrete) is concrete with high porosity as a result of an extensive and interconnected void content. Permeable concrete is made from carefully controlled amounts of water and cementitious materials used to create a paste that forms a coating around aggregate particles. Unlike conventional concrete, the mixture contains little or no sand, creating a substantial void content – between 15% to 25% in typical applications (Figure 1 A). Using sufficient paste to coat and bind the aggregate particles together creates a system of highly permeable, interconnected voids that drain quickly. The low mortar content and high porosity combine to reduce the compressive strength compared to conventional concrete, but sufficient strength is easily achieved for many applications. Permeable concrete is used for a variety of environmental applications. Because typical mixtures allow the rapid passage of water (3 to 8 gallons per minute per square foot), permeable concrete is used to facilitate rainwater infiltration into the ground and control storm water runoff. In addition, permeable concrete filters have been used to control acid mine drainage and treat potable water in developing countries.

Capping technologies can result in modifications of the benthic habitat that affect the abundance and distribution of bottom organisms. This has led to the suggestion that a “habitat layer” composed of sand or a similar material, should be applied over active caps to encourage the development of communities of benthic organisms. Such habitat layers may encourage colonization by some types of infauna (organisms that live within the substrate) but would provide poor habitat for epifaunal organisms that colonize benthic habitats by attachment to solid substrates. In contrast, research shows that many types of epifauna will colonize pervious concrete. A study comparing pervious concrete, conventional concrete, and natural substrates in a riverine environment showed that pervious concrete was colonized by a variety of organisms and that the number of families, number of taxa, number of individuals, total weight, and diversity of the benthos was greatest in the permeable concrete (Zouaghi et al., 2003). These results suggest that permeable concrete can act like an artificial reef, contributing to local increases in the productivity and standing stocks of some types of organisms. However, permeable concrete cannot be penetrated by burrowing organisms, thereby eliminating bioturbation as a means of contaminant release.

In this research we combined the relatively high structural strength, ample void space, and water permeability of permeable concrete with the contaminant sequestration ability of selected amendments to develop a new capping technology, PAAC, with superior durability and ability to control contaminant mobility. We believed that the high surface area provided

by the concrete interstices would provide significant opportunity for contaminants to react with amendments incorporated into the concrete matrix. In addition, the cementitious materials used in PAAC can, in themselves, exhibit significant metal binding capability. Installation of a PAAC cap in the aquatic environment would be possible using existing concrete pouring techniques for underwater applications. PAAC could be delivered to bottom habitats using a chute, concrete pump, or in fabric formwork bags. Rigid concrete formworks, as used in typical construction applications, would not be required because the proposed application does not require the strength and uniformity necessary for structural applications. Alternatively, tiles composed of PAAC could be constructed on the land and later delivered to contaminated sediment sites.



**Figure 1. Pervious concrete (A) and PAAC (B). Red material in B represents active amendments. In PAAC, aggregate materials (crushed stone) are partly replaced by active amendments that precipitate or adsorb contaminants released from sediments.**

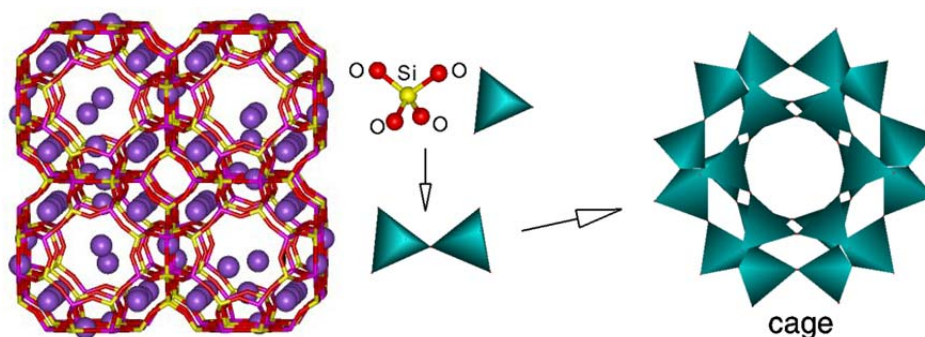
This project focused on developing a PAAC for the in situ remediation of a broad range of contaminants including metals (e.g., As, Cd, Cr, Co, Cu, Hg, Ni, Mo, Se, Pb, and Zn) and organics (e.g., PAHs). The proposed PAAC technology has the potential to stabilize a large variety of organic and inorganic sediment contaminants by incorporating different active sequestering agents such as phosphate materials (rock phosphate), organoclays, zeolite, and lime individually or in combinations. The abilities of phosphate based materials to stabilize metals, organoclays to stabilize nonpolar pollutants (e.g., PAHs), and lime to immobilize metal are well known. PAAC can also include new varieties of organoclay that stabilize Hg and As as well as zeolites that have the potential to sequester P as well as metals. Also, Portland cement by itself is an effective amendment for stabilization of metals and can effectively treat Hg when mixed with zeolite (Zhang et al., 2009).

The following amendments were evaluated in this project: apatite (rock phosphate from North Carolina, Florida or other suitable sources), organoclays (CETCO and Biomin, Inc.), zeolite (clinoptilolite), and lime. These amendments were selected because of their combined ability to remediate the mixture of metals, metalloid, and organic contaminants (especially PCBs and PAHs) likely to occur in many contaminated sediments (Knox et al., 2008 a and b).

Apatite is a commonly used surface and subsurface amendment (Knox et al., 2004) that effectively immobilizes Pb and other constituents (e.g., Cd, Ni, Zn, and U) in contaminated soils/sediments (Knox et al., 2000 a, b; Knox et al., 2003 and 2004; Ma et al., 1995, 1997; Singh et al., 2001), thus offering an economical, simple, and environmentally friendly alternative for treating contaminated environments. Properly selected P amendments, individually or in a mixture with other amendments, may effectively reduce metal mobility, bioavailability and toxicity in contaminated sediments.

Organoclays consist of bentonite that is modified with quaternary amines. The bentonite becomes organically modified by exchanging the nitrogen end of a quaternary amine onto the surface of the clay platelets through cation exchange, (Lagaly, 1984). Organoclays are particularly effective at removing non-polar pollutants such as oil, polychlorinated biphenols, chlorinated solvents, and polycyclic aromatic hydrocarbons (Xu et al., 1997; Alther, 2002; Knox et al., 2008 b). In this project, we used organoclay MRM (CECTO Company), a high-capacity organic adsorptive material designed to adsorb Hg and As from contaminated sediments.

Zeolites are by definition crystalline hydrated alumino-silicate minerals of the alkaline and alkaline-earth metals. The fundamental units of a zeolite crystal are  $\text{SiO}_4$  tetrahedra, which are linked to form a complex 3-dimensional framework (Armbruster and Gunter, 2001). The structure of the zeolites is remarkably open resulting in a highly porous mineral with microscopic cavities in the form of channels and cages (Figure 2). In zeolites these cavities are sufficiently large to contain water molecules and extra-framework cations. The water and the cations are only loosely bonded to the zeolite framework and can be removed or exchanged with other ions from the environment. These minerals can remove cationic substances such as  $\text{NH}_4^+$ , P, and metals such as Cu, Zn, Cd, Co, and Ni from the water. The uptake of these metals leads to the release of biologically acceptable cations such as Na, K, Mg, Ca or protons residing on the exchange sites of the mineral (Kallo, 2001; Stefanakis et al., 2009). In this project the natural zeolite, clinoptilolite, was incorporated in a PAAC matrix individually and mixed with other amendments.



**Figure 2. Zeolite structure.**

Limestone is a carbonate rock consisting principally of the minerals calcite and aragonite,



both having the chemical formula  $\text{CaCO}_3$ , and dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ) (Dixon and Weed 1989). Calcite, which is the principal component of limestone rocks, neutralizes acidity because it dissolves under consumption of protons ( $\text{H}^+$ ). Limestone rocks are common in nature. Crushed limestone rocks can be substituted for aggregate such as crushed stone in the PAACs.

PAAC will have potential to resist erosion and bioturbation due to its high structural integrity relative to more traditional capping approaches. PAAC could be applied as a slurry directly on the top of contaminated sediments or in solid phase as blocks (e.g., 2 inch thick tiles). A cap composed of PAAC could be deployed in any type of benthic habitat considered for conventional capping applications and additionally could be used in high energy environments and sloping habitats, such as contaminated river banks, lakes or shores. In the latter case, it may reduce or stop the release of contaminants from sediments as well as prevent sediment erosion and contaminant runoff, tasks for which conventional capping technologies are unsuitable.

The objective of this project was to develop a permeable active amendment concrete (PAAC). The objectives were accomplished in four tasks:

- 1) development of PAAC
- 2) assessment of PAAC for contaminant removal
- 3) evaluation of promising PAACs for potential environmental impact
- 4) assessment of the hydraulic, physical, and structural properties of PAAC.

## MATERIALS AND METHODS

### TASK 1. DEVELOPMENT OF PERMEABLE ACTIVE AMENDMENT CONCRETE (PAAC)

#### Experiment 1. Development of PAAC with different ratios of crushed stone/amendment to cement

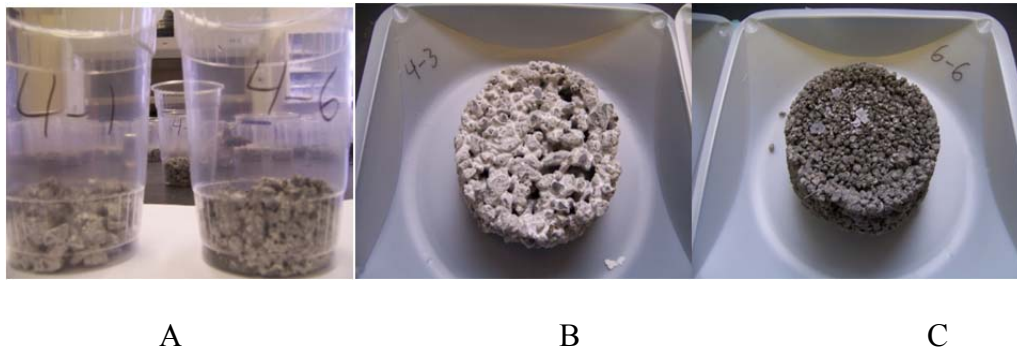
This task started with experiments to identify combinations of cementitious material, crushed stone, sand, and amendments that result in an amendment modified concrete with acceptable permeability, ability to remove contaminants, and structural integrity. The primary variable under investigation was the ratio of crushed stone/amendment to cement and sand to cement. Three types of PAAC with apatite were developed with the following ratios of crushed stone/amendment to cement: 4.5, 4.25, and 3.88 by volume (Table 1). Sand was added to the PAAC to modify permeability; the following ratios of sand to cement were tested: 0, 0.4, and 0.75 (Table 1).

In these experiments, the amendments substituted for crushed stone were apatite (rock phosphate from North Carolina) and limestone. The amendments were added individually or in mixtures at rates of 0, 10, and 25 % in each type of PAAC. PC with 0% amendment served as a control. Mixtures of PAAC with apatite are shown in Table 2. Similar experiments were conducted with lime.

During preparation of PAAC materials, each component was measured in a graduated cylinder to the nearest mL. To make PAAC, Portland cement, sand, crushed stone, and amendment (excluding controls; i.e., 0% amendment) were mixed in the appropriate amounts, and then water was added (Picture 1 and Table 1). The mixtures were shaken vigorously by hand for at least one minute. Each treatment had three replicates. Treatments were water hardened and air hardened. Treatments that were water hardened had parafilm placed over the top of the container after mixing. These procedures were used to produce one inch thick PAAC discs (Picture 1B and 1C) for evaluation of contaminant sequestration capacity.

**Table 1. Ratios of cement to other components in three types of PAAC (M1, M2, M3).**

PAAC components	Ratios		Amount		Ratios		Amount	
	M1		M2		M3		M3	
		(%)		(%)		(%)		(%)
Cement	1.00	16.9	1.00	16.4	1.00	16.0		
Crushed Stone/Amendment	4.50	76.3	4.25	69.7	3.88	62.0		
Sand	0.00	0.0	0.40	6.6	0.75	12.0		
Water	0.40	6.8	0.45	7.4	0.63	10.0		



**Pictures 1. Pervious concrete components before hardening (A) and pervious concrete discs after hardening (B pervious concrete, C pervious concrete with apatite).**

**Table 2. Development of three types of PAAC with apatite.**

Major concrete components	Permeable concrete with 0% apatite	Permeable concrete with 10% apatite	Permeable concrete with 25% apatite
<b>M1</b>			
Cement	16.9	16.9	16.9
Crushed Stone (CS)	76.3	66.3	51.3
Apatite (A)	0.0	10.0	25.0
Sand (S)	0.0	0.0	0.0
Water	6.8	6.8	6.8
<b>Total</b>	<b>100</b>	<b>100</b>	<b>100</b>
<b>M2</b>			
Cement	16.4	16.4	16.4
Crushed Stone (CS)	69.7	59.7	44.7
Apatite (A)	0	10	25
Sand (S)	6.6	6.6	6.6
Water	7.4	7.4	7.4
<b>Total</b>	<b>100</b>	<b>100</b>	<b>100</b>
<b>M3</b>			
Cement	16	16	16
Crushed Stone (CS)	62	52	37
Apatite (A)	0	10	25
Sand (S)	12	12	12
Water	10	10	10
<b>Total</b>	<b>100</b>	<b>100</b>	<b>100</b>

## Experiment 2. Development of PAAC with proportions of rock and cement typically used in pervious concrete

In this PAAC design, active amendments were added at rates of 10, 25, and 40% to proportions of rock and cement typically used in pervious concrete (Table 3 and 4). From a structural standpoint, the active amendment acted as a fine aggregate that decreased the void content and increased strength while still permitting substantial water flow. These materials were tested in trial sorption and desorption batches to establish proper proportions and determine expected behavior.

**Table 3. Typical ranges of material proportions in pervious concrete**

	<b>Proportions (lb/yd<sup>3</sup>)</b>	<b>Proportions (kg/m<sup>3</sup>)</b>
<b>Cementitious materials</b>	450 to 700	270 to 415
<b>Aggregate</b>	2000 to 2500	1190 to 1480
<b>Water:cement ratio (by mass)</b>	0.27 to 0.34	-----
<b>Aggregate:cement ratio (by mass)</b>	4 to 4.5:1	-----
<b>Fine:coarse aggregate ratio (by mass)</b>	0 to 1:1	-----

The following amendments were tested: North Carolina apatite (Aurora, NC), organoclay MRM (CETCO), organoclay PM-199 (CETCO), and clinoptilolite (zeolite) (Steelhead Specialty Minerals, Spokane, WA). During preparation of the PAAC materials, each component was measured in a graduated cylinder to the nearest mL. To make PAAC, Portland cement, sand, crushed stone, and amendment (excluding controls; i.e., 0% amendment) were mixed in the appropriate amounts, and then water was added. The mixtures were shaken vigorously by hand for at least one minute. Each treatment had three replicates. Treatments were water hardened. Parafilm was placed over the top of the container after mixing. These procedures were used to produce one inch thick PAAC discs for evaluation of structural integrity.

Table 4. Development of PAACs with 10, 20, and 40% amendments.

Treatments			Volumetric milliliters of additives							
% volume amendment rep.	Cement	Crushed stone	Water	Clinoptilolite	Apatite	PM 199 Organoclay	MRM Organoclay	Sand	Integrity	
<b>PAAC with zeolite clinoptilolite (zc)</b>										
10 zc 1	18.7	60	10	13.8					very good	
10 zc 2	18.7	60	10	13.8					very good	
10 zc 3	18.7	60	10	13.8					very good	
20 zc 1	16	51	12	26.5					very good	
20 zc 2	16	51	12	26.5					very good	
20 zc 3	16	51	12	26.5					very good	
40 zc 1	11.1	36	14	49					poor	
40 zc 2	11.1	36	14	49					poor	
40 zc 3	11.1	36	14	49					poor	
<b>PAAC with apatite (a)</b>										
10 a 1	19.8	61	8		8.9				very good	
10 a 2	19.8	61	8		8.9				very good	
10 a 3	19.8	61	8		8.9				very good	
20 a 1	17.8	57	8		18.1				very good	
20 a 2	17.8	57	8		18.1				very good	
20 a 3	17.8	57	8		18.1				very good	
40 a 1	13.7	44	8		37				poor	
40 a 2	13.7	44	8		37				poor	
40 a 3	13.7	44	8		37				poor	
<b>PAAC with organoclay PM-199 (oc)</b>										
10 oc 1	18.8	61	8			13.4			very good	
10 oc 2	18.8	61	8			13.4			very good	
10 oc 3	18.8	61	8			13.4			very good	
20 oc 1	16.1	52	8			25.8			good	
20 oc 2	16.1	52	8			25.8			good	
20 oc 3	16.1	52	8			25.8			good	
40 oc 1	11.3	36	8			48.1			poor	
40 oc 2	11.3	36	8			48.1			poor	
40 oc 3	11.3	36	8			48.1			poor	
<b>PAAC with organoclay MRM (mrm)</b>										
10 mrm 1	18.8	61	8				13.4		very good	
10 mrm 2	18.8	61	8				13.4		very good	
10 mrm 3	18.8	61	8				13.4		very good	
20 mrm 1	16.1	52	8				25.8		poor	
20 mrm 2	16.1	52	8				25.8		poor	
20 mrm 3	16.1	52	8				25.8		poor	
40 mrm 1	11.3	36	8				48		poor	
40 mrm 2	11.3	36	8				48		poor	
40 mrm 3	11.3	36	8				48		poor	
<b>PC without amendments</b>										
control 1	19.7	63	8					9.5	very good	
control 2	19.7	63	8					9.5	very good	
control 3	19.7	63	8					9.5	very good	

## **TASK 2. ASSESSMENT OF PAAC FOR CONTAMINANT REMOVAL**

This task was accomplished with sorption/desorption experiments and column studies.

### **Sorption experiments on PAAC with different ratios of crushed stone/amendment to cement**

In the sorption tests, PAAC discs incorporating different amendments (Tables 1 and 2) were placed in contact with a spike solution for a period of one day. The ratio of liquid to solid was 10:1. The liquid phase was separated and analyzed for pH and metal content by ICP-MS. The metal concentration data obtained in this experiment were used to calculate percent sorption and partition coefficient ( $K_d$ ) values, defined as the ratio of the concentration of solute sorbed to the solid divided by its concentration in solution. Each treatment in the preceding experiment had three replicates. The following metals were analyzed: As, Cd, Cr, Co, Cu, Ni, Pb, and Zn. The metals were tested jointly. The concentration of each metal in the spike solution was  $5 \text{ mg L}^{-1}$ .

### **Sorption experiments on PAAC with proportions of rock and cement typically used in pervious concrete**

In this design to the PAAC structure the active amendments were added at rates of 0, 10, 25, and 40% to proportions of rock and cement typically used in pervious concrete. These materials were tested in trial sorption and desorption batches to establish proper proportions and determine expected behavior of the PAAC materials.

Sorption tests were conducted to assess the metal removal ability of the PAACs. In these tests a constant amount of Portland cement (0.5 g) was added to 0.1, 0.25, and 0.5 g of three different individual amendments together with sufficient sand to bring the total to 1.0 g (Tables 5, 6, and 7). The following three amendments were tested: North Carolina apatite (Aurora, NC), organoclay MRM (CETCO), and clinoptilolite (zeolite, Steelhead Specialty Minerals, Spokane, WA). PAAC reactive components (cement and amendments) were placed in contact with a spike solution for one week. The ratio of liquid to solid in this experiment was 30:1. Each treatment in the preceding experiment had three replicates. The following metals were tested: As, Cd, Cr, Co, Cu, Ni, Mo, Pb, Se, and Zn. The metals were tested jointly. Each metal concentration in the spike solution was  $5 \text{ mg L}^{-1}$ . After one week of contact, the liquid phase was separated from the PAAC reactive components and analyzed for pH and metal content by ICP-MS.

**Table 5. The PAAC reactive components (cement and organoclay MRM) tested in the sorption and desorption study; 0, 25, and 50% addition of MRM.**

Treatments	Replicates	Cement	MRM	Sand	Total
		[g]	[g]	[g]	[g]
CS-MRM0%	1	0.50	0.00	0.50	1.00
	2				
	3				
CS-MRM10%	1	0.50	0.10	0.40	1.00
	2				
	3				
CS-MRM25%	1	0.50	0.25	0.25	1.00
	2				
	3				
CS-MRM50%	1	0.50	0.50	0.00	1.00
	2				
	3				

**Table 6. The PAAC reactive components (cement and clinoptilolite - zeolite) tested in the sorption and desorption study; 0, 25, and 50% addition of clinoptilolite.**

Treatments	Replicates	Cement	Clinoptilolite	Sand	Total
		[g]	[g]	[g]	[g]
CS-ZC0%	1	0.50	0.00	0.50	1.00
	2				
	3				
CS-ZC10%	1	0.50	0.10	0.40	1.00
	2				
	3				
CS-ZC25%	1	0.50	0.25	0.25	1.00
	2				
	3				
CS-ZC50%	1	0.50	0.50	0.00	1.00
	2				
	3				

**Table 7. The PAAC reactive components (cement and North Carolina apatite) tested in the sorption and desorption study; 0, 25, and 50% addition of North Carolina apatite.**

Treatments	Replicates	Cement	Apatite	Sand	Total
		[g]	[g]	[g]	[g]
CS-A0%	1	0.50	0.00	0.50	1.00
	2				
	3				
CS-A10%	1	0.50	0.10	0.40	1.00
	2				
	3				
CS-A25%	1	0.50	0.25	0.25	1.00
	2				
	3				
CS-A50%	1	0.50	0.50	0.00	1.00
	2				
	3				



A desorption study was run on the PAAC reactive components following the sorption experiment. The residues from the sorption study were washed twice with deionized water and extracted with 1 M MgCl<sub>2</sub> to determine the readily available pool of sorbed metals. After one hour, the liquid samples were taken and analyzed for metals by ICP-MS. The results from the sorption and desorption experiments were used to calculate contaminant removal and retention of sorbed metals by the PAAC reactive materials.

### Control of metal release – static column studies

Static column studies using two PAAC materials were conducted for five months to investigate metal release from contaminated sediments via diffusion (Table 8). Five cm (350 g) layers of contaminated sediment from Tims Branch, a stream on the Savannah River Site near Aiken, SC were placed at the bottom of clear plastic tubes and covered with caps composed of different types of PAAC (Picture 2). The tested PAACs included PAAC with 20% North Carolina apatite (A) and PAAC with a mixture of 10% A, 5 % zeolite clinoptilolite (Z), and 5% organoclay (MRM). Permeable concrete without amendments (PC) was also evaluated. The control treatment consisted of uncapped sediment. The PAACs and PC were prepared in glass beakers and then poured on the top of the sediments to form a layer about 0.5 inch thick. Then 700 mL of DI water was gently added to each tube, and all tubes were covered with a plastic cap to avoid evaporation. Leachate samples from above the sediment or caps were collected three times from the first leachate (after two days, then weekly). The leachate was then discarded, and 700 ml of DI water was again added to each tube. Leachate samples were subsequently collected every week and then every month. This process was repeated for five months. Leachate samples were analyzed for pH and metals content by ICP-MS.

The experiment was terminated after the fifth leachate. The PAAC caps were separated from the sediment beneath the cap. The sediment was split into two layers: layer A (0-2.5 cm) and layer B (2.5-5 cm). The sediment from both layers was analyzed for pH and the bioavailable pool of metals. The bioavailable pool of metals in the sediment was evaluated by diffusive gradients in thin films (DGT) probes (Pictures 3 A-D). DGT can measure labile species that correspond closely to bioavailable contaminant fractions in sediments. We used wet sediment (ratio 1:1.15; i.e., 5 g of dry sediment and 5.75 mL of water) to evaluate the bioavailable pool of metals with DGT. Equation 1 was used to ensure that the mass of wet sediment versus water was consistent:

$$\text{Amount of wet sample} = 5 \text{ gram of dry sediment} / (1 - \text{moisture content}) \quad \text{Equation 1.}$$

The disc-shaped DGT probes were placed onto the surface of wet sediment with the open end against the sediment and then pressed firmly into the sediment until the open window was fully covered (Picture 3 B). The samples were covered with parafilm to prevent evaporation of water from the slurry. After seven days the DGT probes were removed and rinsed with deionized water to remove residual sediment. Then the collected resin-gel from the DGT probes (Pictures 3 C and D) was extracted with 1 M HNO<sub>3</sub> for 24 hours, diluted five times

with deionized water, and analyzed for metals by ICP-MS. The resulting concentration from the diluted aliquot was adjusted for dilution to determine the concentration of metals in the 1M HNO<sub>3</sub> elution, C<sub>e</sub>. The mass of metal accumulated in the resin gel layer (M) was calculated using Equation 2 for each metal:

$$M = \frac{C_e * (V_{NO_3} + V_{gel})}{f_e} \quad \text{Equation 2,}$$

where V<sub>NO<sub>3</sub></sub> equals the amount of nitrate added (750 μL, based on the amount of nitric acid required to submerge the resin-gel layer), V<sub>gel</sub> equals the volume of the resin gel, or 810 μL, and f<sub>e</sub> is the elution factor of 0.8 (Zhang and Davison, 1995 and 2001). The concentration of metal measured by each DGT unit (C<sub>DGT</sub>) was calculated using Equation 3:

$$C_{DGT} = \frac{M * \Delta g}{D * t * A} \quad \text{Equation 3,}$$

thickness of the diffusive layer and filter layer (0.096 cm) (Zhang and Davison, 1995 and 2001), D is the diffusion coefficient of each metal at the retrieval temperature, t is the deployment time, and A is the exposed area of the DGT unit.

**Table 8. Experimental design of static column studies for control of metal release from contaminated sediments by PC and PAACs.**

ID	Treatments	Replicates	Sediment	Water to leach	PAAC constituents						
					Cement	Crushed stone	Sand	Apatite (A)	Zeolite (Z)	MRM	Water
			g	ml	ml	ml	ml	ml	ml	ml	ml
1	Control*	1	350	700							
2		2	350	700							
3		3	350	700							
4	PAAC - 20%A	1	350	700	17.8	57		18.1			8
5		2	350	700	17.8	57		18.1			8
6		3	350	700	17.8	57		18.1			8
7	PAAC - 10%A/5%Z/5%MRM	1	350	700	16.9	54		8.6	7	6.7	8
8		2	350	700	16.9	54		8.6	7	6.7	8
9		3	350	700	16.9	54		8.6	7	6.7	8
10	PC without amendments	1	350	700	19.7	63	9.5				8
11		2	350	700	19.7	63	9.5				8
12		3	350	700	19.7	63	9.5				8

\*Control – uncapped sediment; PAAC - Permeable Active Amendment Concrete; PAAC -20% - PAAC with 20% apatite; PAAC - 10%A/5%Z/5%MRM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.



**Pictures 2. Columns with two PAAC materials, PC, and uncapped contaminated sediment.**



A



B



C



D

**Pictures 3. DGT analysis.**

### Transport of metals through PAAC – flow through column studies

Laboratory column experiments were conducted to evaluate the effectiveness of selected PAACs in the sorption, desorption and retention of various metals (As, Cd, Co, Cr, Cu, Se, Ni, Pb, and Zn). Three flow-through columns were tested under saturated conditions, one packed with PAAC containing 20% apatite, a second packed with PAAC containing a mixture of 10% apatite, 5% zeolite, and 5% MRM, and a third with PC as the control (Picture 4). The control consisted of Portland cement, aggregate, sand and water mixed in a commonly used mass ratio of 1:4:0.75:0.4 respectively, or expressed as a percentage: 16%:65%:12%:7% (Table 9). The acrylic glass (Lucite) columns used in the experiments were 5 cm in diameter and 10 cm in length.

**Table 9. Composition of PAACs for evaluation of metal sorption and retention in flow through studies.**

Treatments	Cement	Stone	Sand	Apatite	Zeolite	MRM	Water
PC without amendments	16%	65%	12%				7%
PAAC - 20%Apatite	15%	59%		20%			6%
PAAC - 10%A/5%Z/5%MRM	15%	59%		10%	5%	5%	6%

PC - permeable concrete; PAAC - Permeable Active Amendment Concrete; PAAC -20% - PAAC with 20% apatite; PAAC - 10%A/5%Z/5%MRM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM).



**Pictures 4. Flow column experiment.**

After a curing time of 28 days, the columns were leached with a spike solution containing approximately 10 ppm of each metal under low (0.2 ml/min) and high (1 ml/min) flow. Each flow condition was continued for two weeks in an effort to determine metal removal from the spike solution under different flow regimes. A peristaltic pump was used to maintain the inflow of spike solution through each column. To determine the retention of sorbed metals on the PAAC materials after the two-week low flow (0.2 ml/min) experiment, the spike solution was replaced by tap water pumped at a flow rate of 0.2 ml/min to evaluate the desorption of sorbed metals from the PAAC. After the two-week desorption experiment, the columns were leached again with the same spike solution, but the flow was maintained at about 1 ml/min for another two weeks. The high flow experiment was conducted to see if metals would be removed from the spike solution at low pH and high flow. Samples of effluent from the columns were collected for ICP-MS analysis using an auto-sampler (5 ml per sample).

### **TASK 3. EVALUATION OF PAAC FOR POTENTIAL ENVIRONMENTAL IMPACT**

The EPA toxicity characteristic leaching procedure (TCLP) (U.S. EPA, 1992) is a regulatory test widely used to classify materials as hazardous or nonhazardous (U.S. EPA, 1992). Selected PAAC materials with apatite and limestone were extracted using the TCLP. The TCLP leaching solution was comprised of 0.1 M glacial acetic acid and 0.0643 M NaOH, with a final pH of 4.93. One inch PAAC discs (about 100 g) were added to two liters of leaching TCLP solution; the mixture was agitated on a shaker for 18 hours at 25°C, and then 10 mL solution subsamples was taken. These solution subsamples were filtered through 0.22 µm pore-size polycarbonate filters, acidified with HNO<sub>3</sub>, and analyzed for metals with ICP-MS.

In these experiments, the amendments substituted for crushed stone were apatite (rock phosphate from North Carolina) and limestone. Apatite was added at rates of 0, 10, and 25 % in each type of PAAC (Table 2). PC with 0% amendment served as controls. Similar experiments were conducted with limestone.

Static bioassays employing *Hyaella azteca* as the test organism were conducted to assess the potential toxicities of several PAAC formulations. Materials tested in these studies included conventional concrete (i.e., not pervious) with 0%, 10%, or 25% apatite; PC (no amendments); PAAC with 10% or 25% apatite; and PAAC with limestone and 10% or 25% apatite. Limestone was substituted for crushed rock in PAAC with limestone. The bioassays were conducted in 500 ml beakers, each containing a 120 g disc of PAAC or conventional concrete and 200 ml of overlying water obtained from Steel Creek, a local stream. All treatments were represented by three replicates. The test organisms were periodically fed small amounts of ground commercial fish food during the tests. The duration of all tests was 10 days. Water hardness, alkalinity, and pH were measured during the test period. A second series of tests were conducted in larger beakers containing 1000 rather than 200 ml of water together with PAAC and PAAC with limestone.



**TASK 4. ASSESSMENT OF THE HYDRAULIC, PHYSICAL, AND STRUCTURAL PROPERTIES OF PAAC**

The objective of this task was to determine the hydraulic, physical, and structural properties of PAAC. Hydraulic and physical properties measured included saturated hydraulic conductivity, porosity, dry bulk density, and specific gravity. Three inch diameter by six inch long mold samples of PAAC described in Table 9 were prepared for testing following method ASTM C 192 (2005). The mold samples were cured for 28 days in a temperature and humidity controlled environment prior to testing. These samples were tested for saturated hydraulic conductivity following method ASTM D 5084 (2003) using a flexible wall permeameter. Because of the expected high permeability of the PAAC, a falling head/constant tailwater pressure test method was used (ASTM D 5084, Method B, 2003). The dry bulk density and porosity of each sample tested for saturated hydraulic conductivity was measured per ASTM C 642 (1997). All tests were conducted with tap water.

## RESULTS

### **TASK 1. DEVELOPMENT OF PERMEABLE ACTIVE AMENDMENT CONCRETE (PAAC)**

#### **Experiment 1. Development of PAAC with different ratios of crushed stone/amendment to cement**

This research project was initiated with the development of PAAC with apatite and limestone, which replaced a portion of the crushed stone or sand in traditional concrete. The results from Task 1 indicated that

- 1) amendments that sequester and retain metals can be successfully incorporated into permeable concrete (PC) (Tables 1 and 2 and Picture 1),
- 2) PAAC porosity can be modified by changing the ratio of crushed stone to sand,
- 3) replacement of crushed stone by different amounts of apatite does not substantially change the physical properties of PAAC.

#### **Experiment 2. Development of PAAC with proportions of rock and cement typically used in pervious concrete**

The PAACs in which active amendments were added at rates of 0, 10, 20, and 40% to proportions of rock and cement typically used in pervious concrete (Table 4) were tested for structural integrity and physical strength. PAACs with the best performance were those with 10 and 20 % zeolite (clinoptilolite) and apatite (Pictures 5 and 6). When the amounts of each amendment increased to 40%, the PAACs lost their strength and structural integrity (Table 4). In the case of organoclays PM-199 and MRM, the greatest amount of amendment that could be added without loss of structural integrity was 10% (Pictures 7 and 8).



**Pictures 5. PAAC with addition of 10 and 20% zeolite clinoptilolite.**



**Pictures 6. PAAC with addition of 10 and 20% apatite.**



**Pictures 7. PAAC with addition of 10 and 20% organoclay (PM-199).**

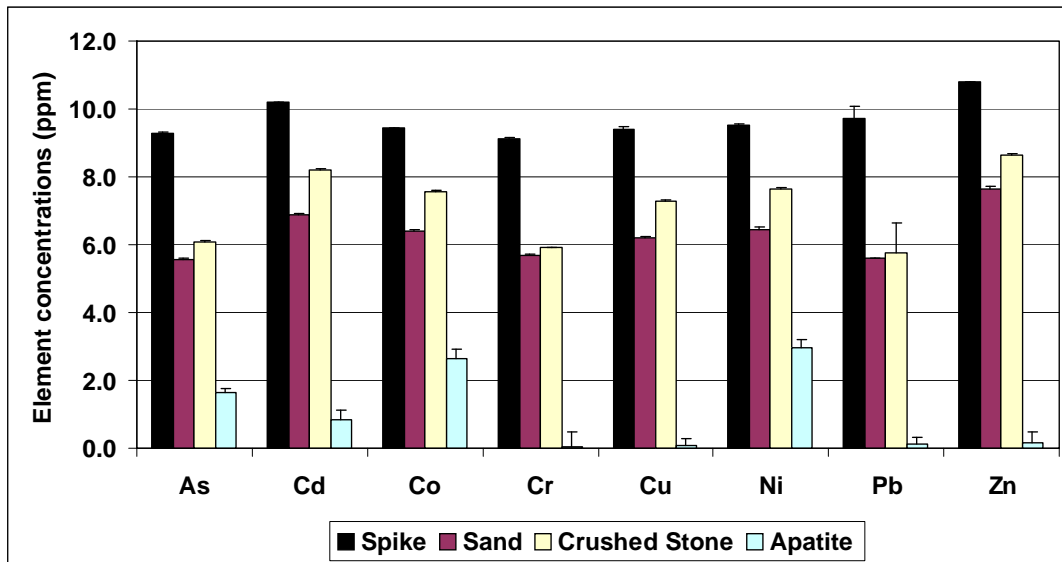


**Pictures 8. PAAC with addition of 10 and 20% organoclay (MRM).**

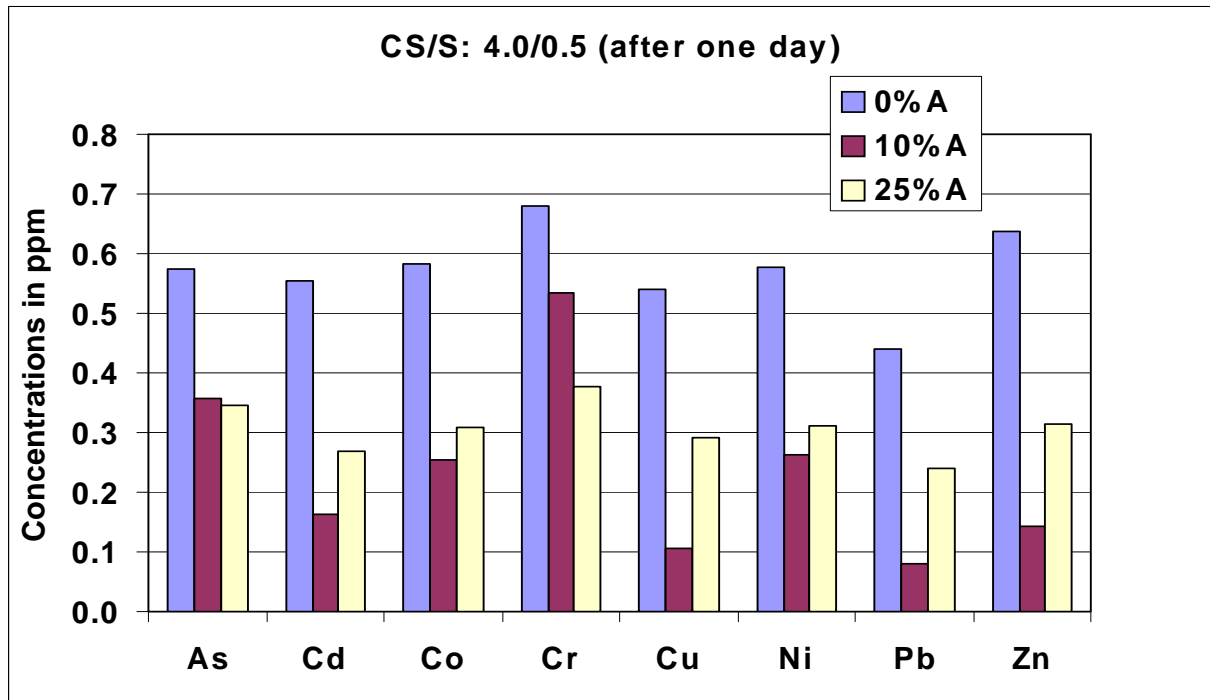
## TASK 2. ASSESSMENT OF PAAC FOR CONTAMINANT REMOVAL

### Sorption experiments on PAAC with different ratios of crushed stone/amendment to cement

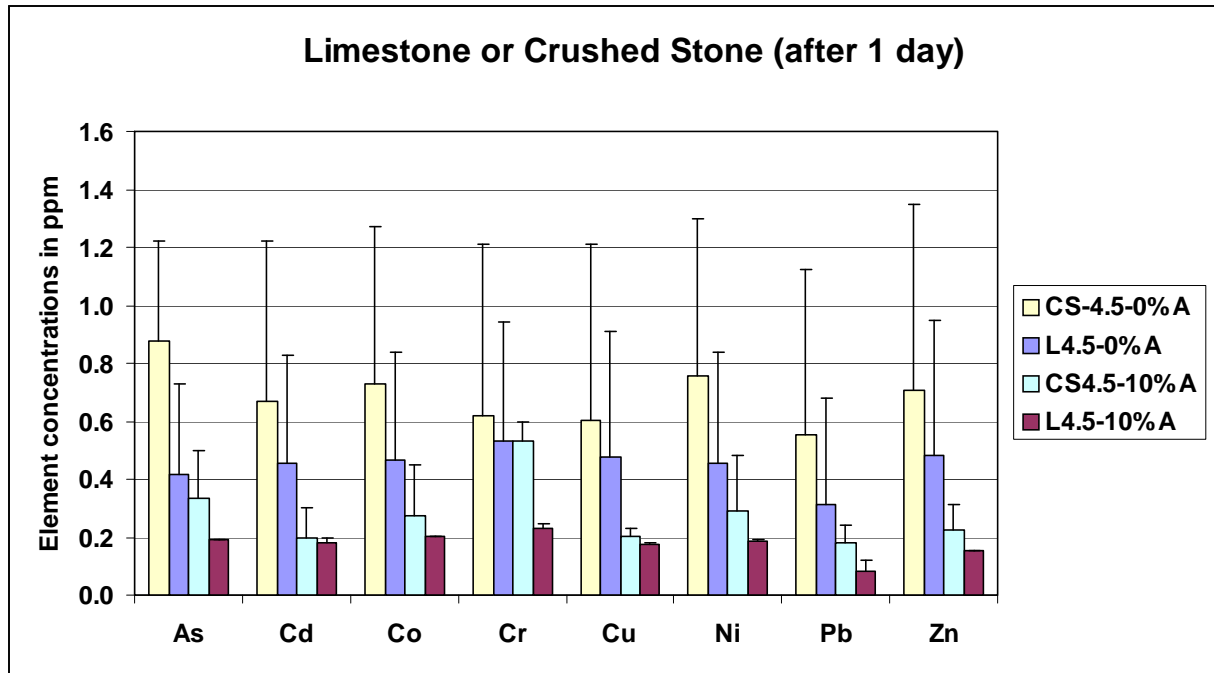
The sorption experiments under Task 2 evaluated the PAAC developed under Task 1 for stabilization of metals including As, Cd, Cr, Co, Cu, Ni, Pb, and Zn. The apatite in PAAC with apatite, removed more than 80% of all tested metals from the spike solution (Figure 3). Other PAAC components including sand and crushed stone removed lesser amounts of the metals. PAAC with apatite or limestone and apatite was more effective at removal of metals than PC. The substitution of small amounts of crushed stone by amendments (e.g., 10% of apatite from North Carolina) was sufficient to effectively remove metals from the aqueous phase (Figures 4 and 5).



**Figure 3. Metal concentrations in a spike solution after contact for 24 hours with individual components of PAAC.**



**Figure 4. Metal concentrations in a spike solution after contact for 24 hours with PAAC containing apatite; metal concentrations in the spike solution were ~ 10 ppm; A – apatite, CS – crushed stone, S – sand.**

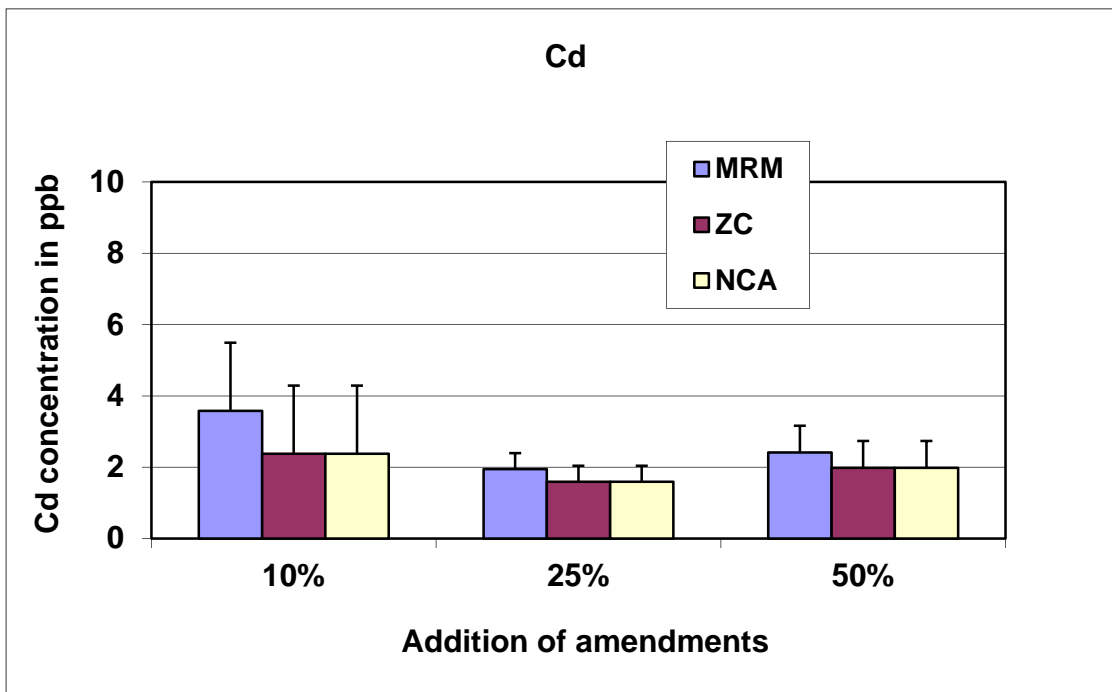
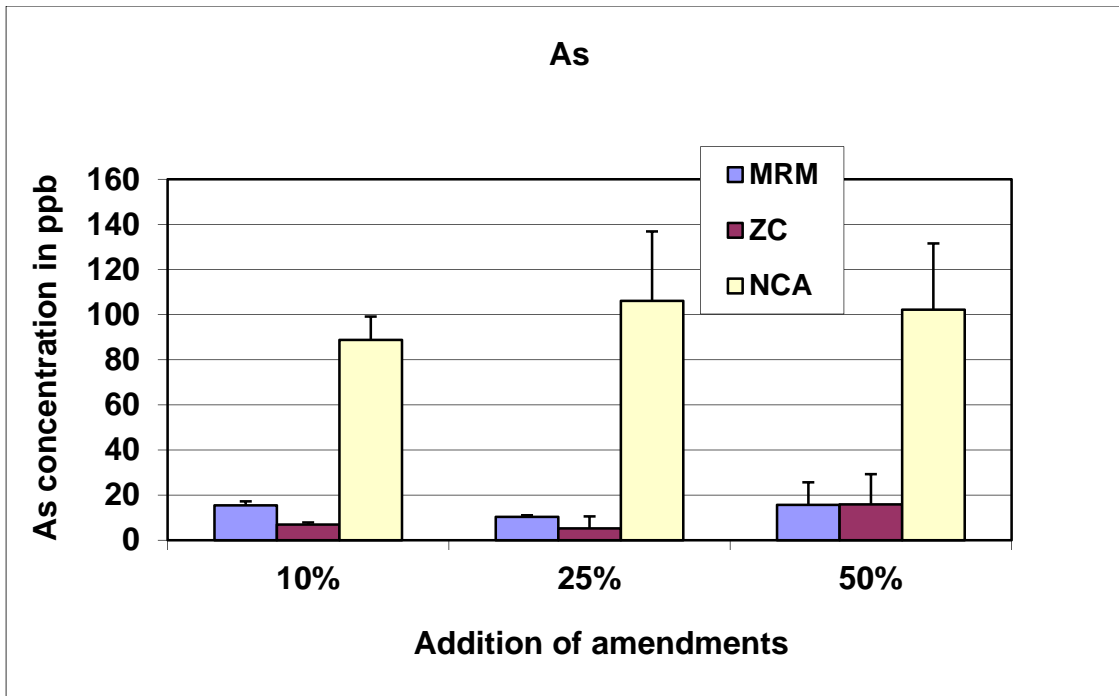


**Figure 5. Metal concentrations in a spike solution after contact for 24 hours with PAAC with limestone and apatite; metal concentrations in the spike solution were ~ 10 ppm; A – apatite, CS – crushed stone, L – limestone.**

#### **Sorption experiments on PAAC with proportions of rock and cement typically used in pervious concrete**

PAAC designs with proportions of rock and cement typically used in pervious concrete indicated that only small amounts of amendments need to be incorporate into the structure of PAAC to obtain very high metal removal This was initially investigated by mixing amendments (in the proportions to be used in PAACs) with sand (Figures 6, 7, 8 and 9). The removal (sorption) of Cd, Co, Cu, Pb, Se, and Zn from spike solutions was very high for all three tested amendments (Figures 6, 7, 8 and 9) and for all rates of amendment addition. Also, cement by itself efficiently removed metals from the spike solution indicating its effectiveness as a sequestering agent.





**Figure 6. Sorption of As and Cd in fresh water by organoclay (MRM), zeolite (clinoptilolite - ZC), and North Carolina apatite (NCA); concentration of each metal in the spike solution was  $\sim 5 \text{ mg L}^{-1}$ .**

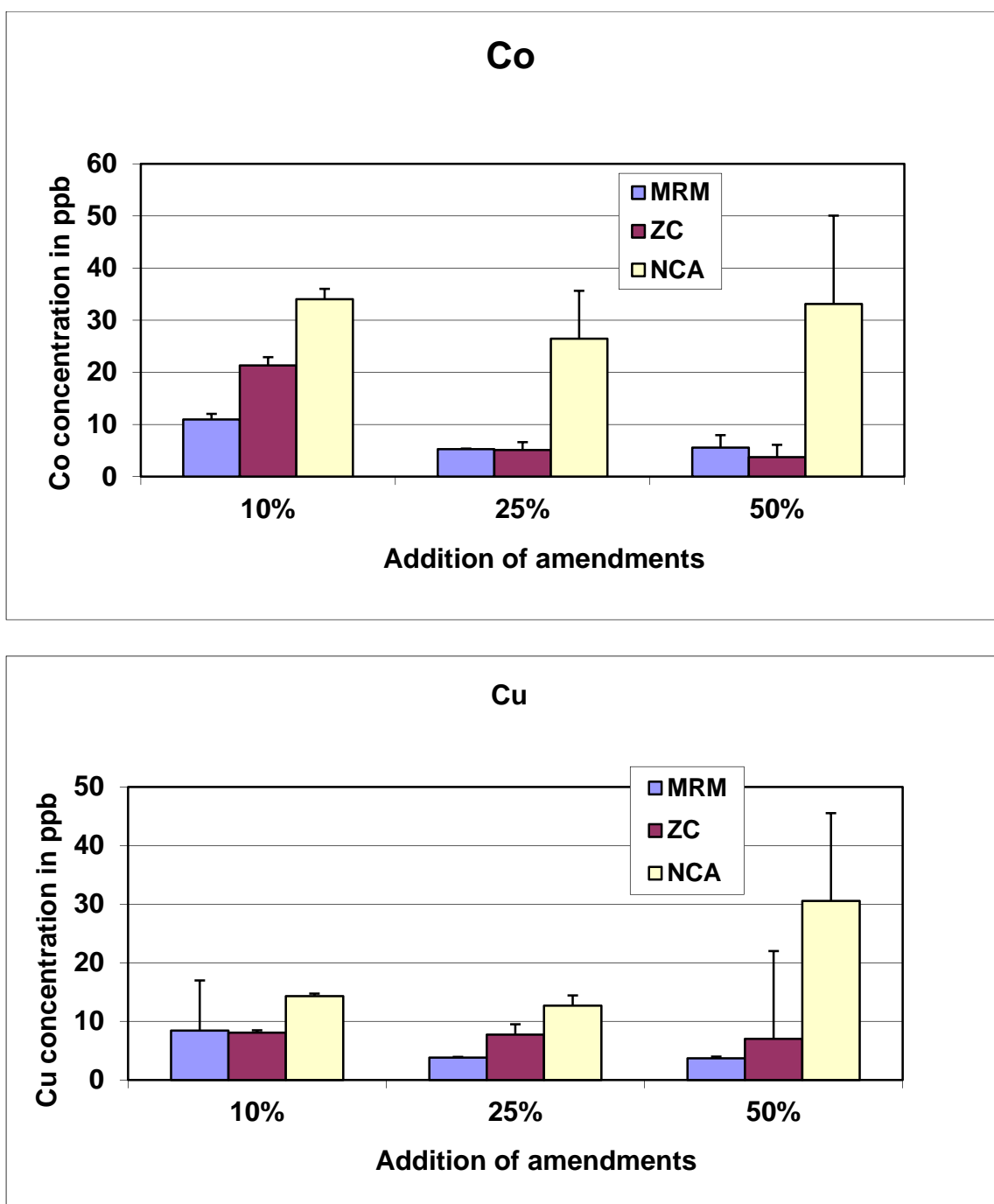


Figure 7. Sorption of Co and Cu in fresh water by organoclay (MRM), zeolite (clinoptilolite - ZC), and North Carolina apatite (NCA); concentration of each metal in the spike solution was  $\sim 5 \text{ mg L}^{-1}$ .

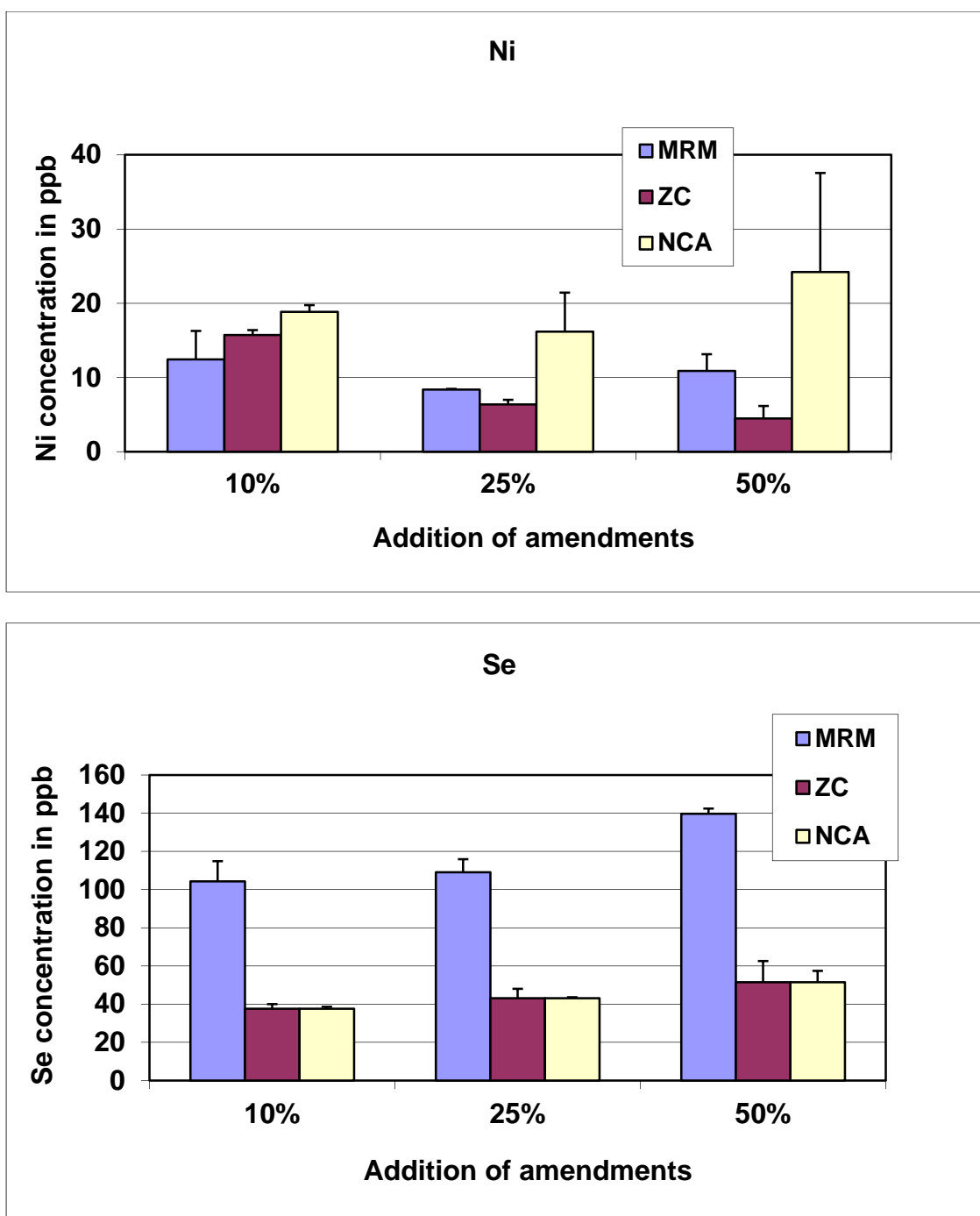
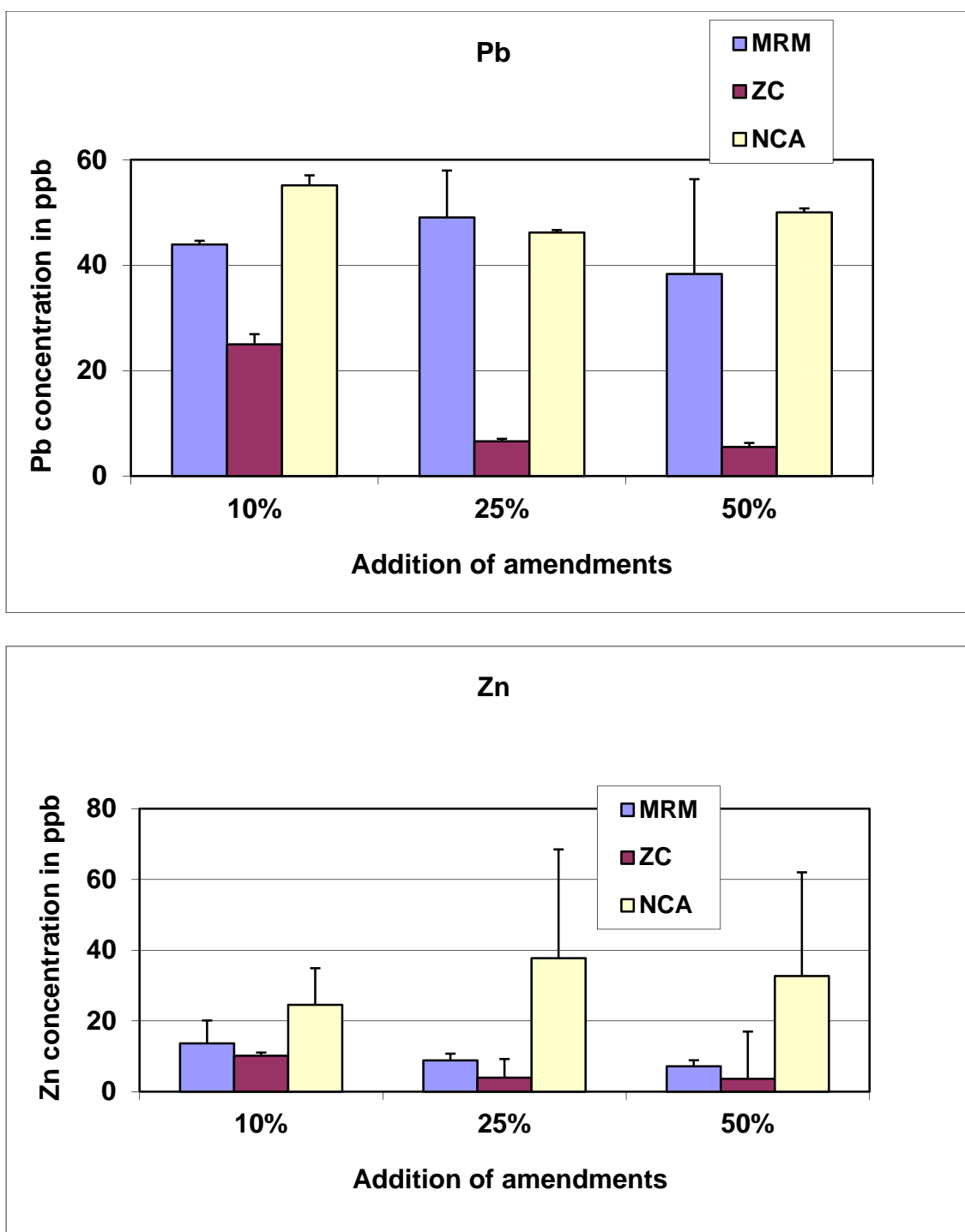


Figure 8. Sorption of Ni and Se in fresh water by organoclay (MRM), zeolite (clinoptilolite - ZC), and North Carolina apatite (NCA); concentration of each metal in the spike solution was  $\sim 5 \text{ mg L}^{-1}$ .



**Figure 9. Sorption of Pb and Zn in fresh water by organoclay (MRM), zeolite (clinoptilolite - ZC), and North Carolina apatite (NCA); concentration of each metal in the spike solution was  $\sim 5 \text{ mg L}^{-1}$ .**

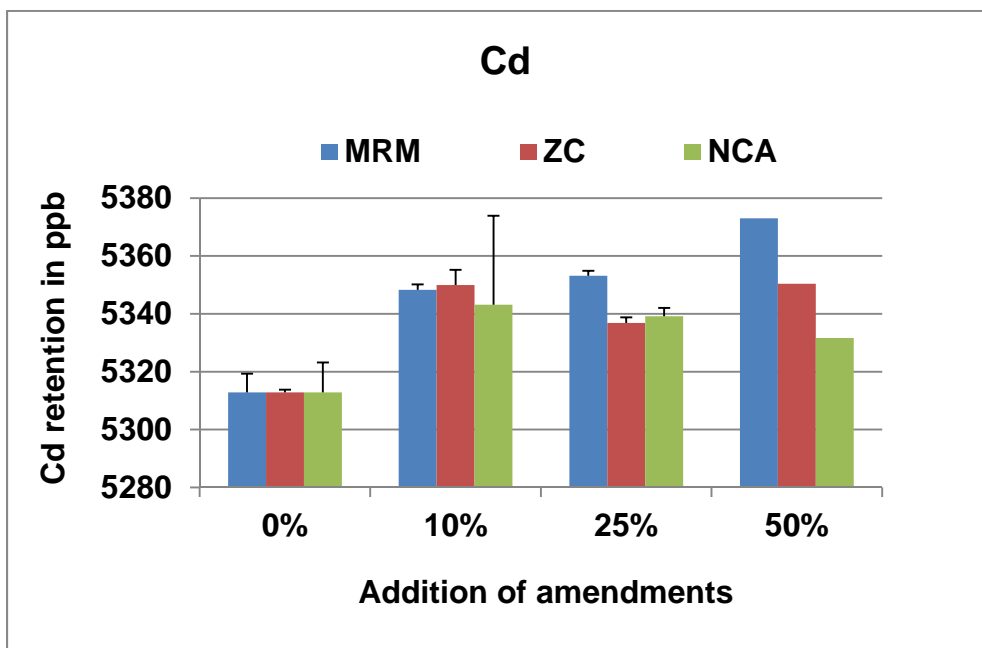
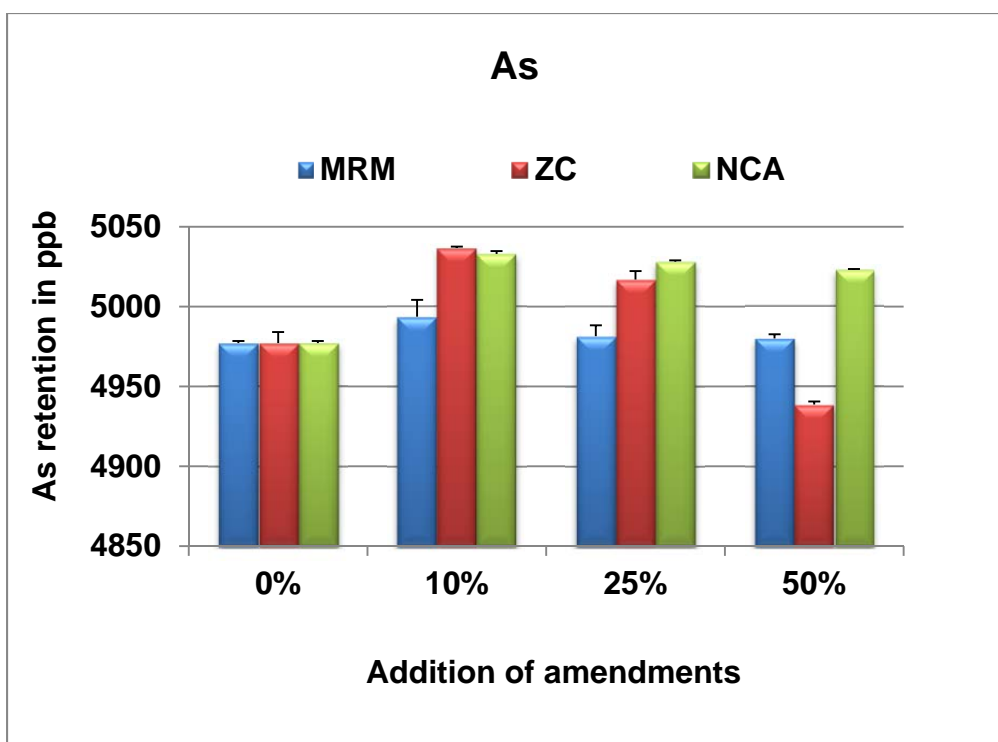
Retention of removed metals by the amendments was evaluated in a series of desorption experiments in which the residue from the sorption studies was extracted with 1 M MgCl<sub>2</sub> solution, which is commonly used to determine the bioavailable and mobile pool of metals (Tessier et al., 1979). The desorption studies determined how strongly metals were bound to the amendments in fresh water. Scientific understanding of binding strength and the irreversibility of reactions is essential to obtain regulatory approval of in-situ immobilization as an acceptable remediation strategy because these variables have a direct effect on bioavailability and mobility. Although amendments remove contaminants from water very efficiently, subsequent contaminant remobilization from the amendments can release contaminants back to the water or treated sediments. The manner in which an amendment desorbs contaminants depends on its binding capacity and retention. Choosing the most appropriate treatment requires an understanding of how amendments bind contaminants and the conditions under which they could release the removed metals back into the water column.

Figures 10 and 11 show metal retention by the tested amendments in fresh water. Retention was calculated following equation number 4.

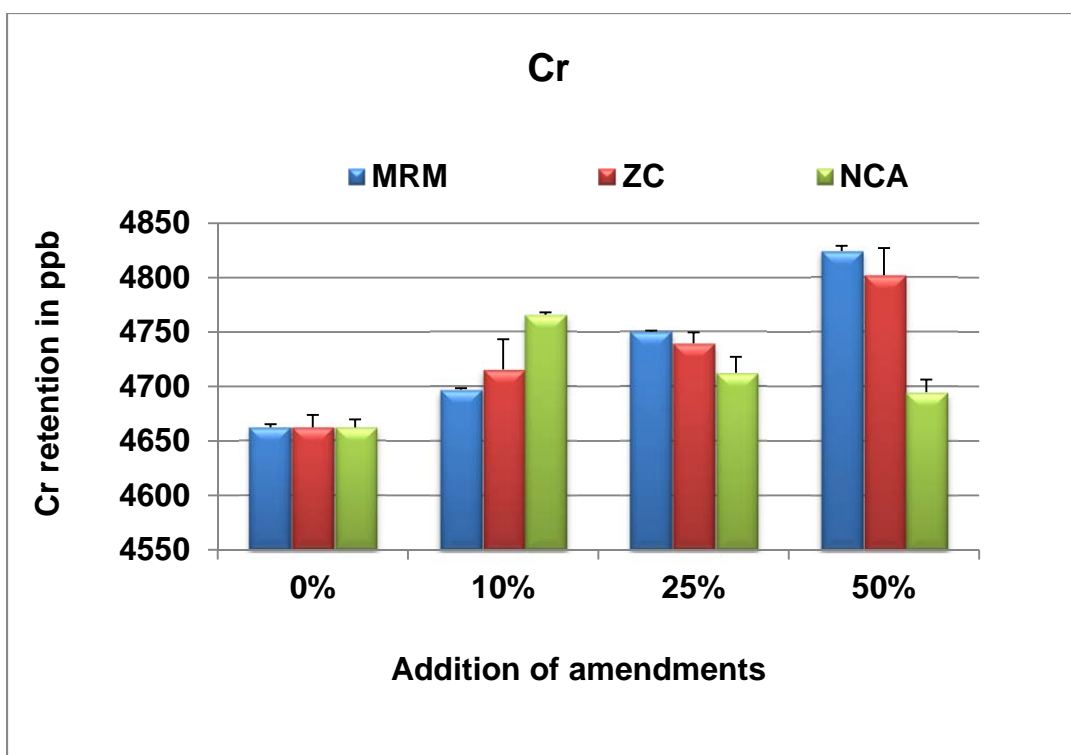
$$\text{retention} = [(C_{\text{adsorbed}} - C_{\text{desorbed}})/C_{\text{spike}}] \quad \text{Equation 4,}$$

where  $C_{\text{desorbed}}$  is the concentration of metal desorbed at the end of the desorption experiment,  $C_{\text{adsorbed}}$  is the concentration of metal adsorbed at the end of the adsorption experiment, and  $C_{\text{spike}}$  is the concentration of metal in the spike solution.

All amendments including cement showed high retention of the tested metals. The addition of amendments to PC improved the retention of As, Cd, and Cr (Figures 10 and 11).



**Figure 10. Retention of As and Cd in fresh water by organoclay (MRM), zeolite (clinoptilolite - ZC), and North Carolina apatite (NCA); concentration of each metal in the spike solution was  $\sim 5 \text{ mg L}^{-1}$ .**



**Figure 11. Retention of Cr in fresh water by organoclay (MRM), zeolite (clinoptilolite - ZC), and North Carolina apatite (NCA); concentration of each metal in the spike solution was  $\sim 5 \text{ mg L}^{-1}$ .**

#### Control of metal release – static column studies

The description of the two types of PAAC materials that were evaluated in the static column study for the removal and retention of contaminants is presented in Table 8. The two tested PAAC materials were PAAC with 20% apatite (PAAC-A) and PAAC with 10% apatite, 5% zeolite and 5% MRM (PAAC-AZM). Both types of PAAC and PC increased the pH values of all leachates in comparison to the control treatment consisting of uncapped sediment (Tables 10 and 11, Figure 12). PAAC and PC increased the pH values of the first leachate from about 4.7 to 12 compared with uncapped sediment (Tables 10 and 11, Figure 12). After each month the leachate was discharged and replaced with about 700 ml of fresh DI water. The pH of leachates from the sediment capped with PAAC and PC decreased from about 12 to 10 after two months but still remained much higher than in the control treatment until the end of this experiment (Tables 10 and 11, Figure 12).

**Table 10. The pH of leachates collected over five months; raw data.**

Treatments	Replicates	pH measurements of each sampling											
		First leachate			Second leachate			Third leachate		Foruth leachate		Fifth Leachate	
		9/23/2011	9/27/2011	10/4/2011	10/5/2011	10/11/2011	10/26/2011	11/4/2011	12/7/2011	1/6/2012	1/10/2012	1/24/2012	
Control	1	4.73	4.84	4.84	5.05	4.66	4.73	4.84		missing sample	missing sample	missing sample	
	2	4.82	4.67	4.82	5.05	4.79	4.77	5.64	5.86	5.17	6.36	5.96	
	3	4.7	4.71	4.84	4.92	4.55	4.61	5.78	5.81	5.41	6.22	6.01	
PAAC - 20%A	1	11.59	12.38	12.21	9.94	10.36	9.98	10.01	9.92	9.95	10.14	9.68	
	2	12.1	12.22	12.31	10.44	10.06	10.19	9.58	10.35	10.14	10.13	9.92	
	3	12.32	12.3	12.4	10.32	10.21	10.76	9.97	10	10.53	10.24	10.79	
PAAC - 10%A/5%Z/5%MRM	1	11.99	11.86	11.81	9.81	9.75	10.37	9.6	9.73	9.45	9.96	9.37	
	2	12.32	11.85	11.12	9.96	9.68	10.25	9.51	9.72	9.6	9.74	9.64	
	3	12.26	12.25	12.17	10.53	9.84	10.39	9.97	10	9.91	9.83	9.88	
PC without amendments	1	12.01	12.14	12.07	9.73	9.75	10.3	9.71	9.63	9.53	9.84	9.51	
	2	12.14	11.93	12.1	10.39	9.98	10.39	9.92	10.12	9.96	10.16	9.81	
	3	12.09	11.91	12.12	10.45	11.43	11.52	10.18	10.88	10.04	10.27	9.83	

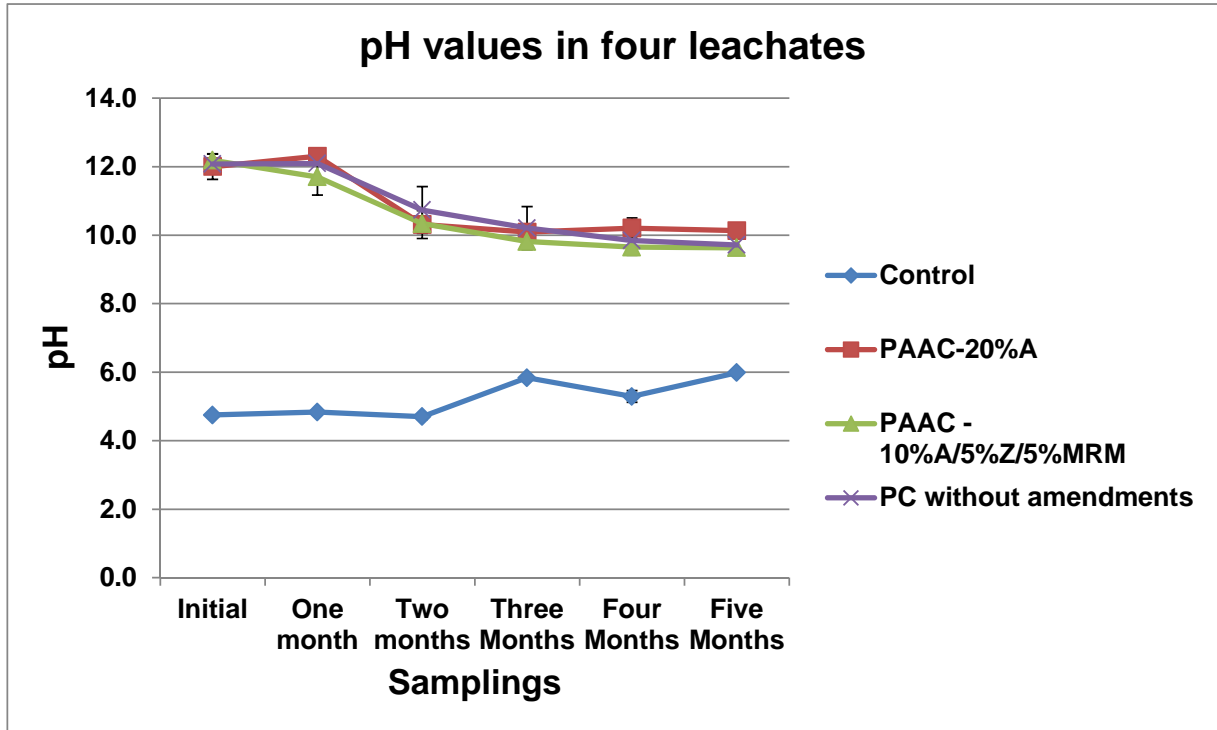
Control – uncapped sediment; PAAC - Permeable Active Amendment Concrete; PAAC -20% - PAAC with 20% apatite; PAAC - 10%A/5%Z/5%MRM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.



**Table 11. The average pH of leachates collected over five months.**

Treatments	pH measurements of each sampling										
	First leachate		Second leachate			Third leachate		Fourth leachate		Fifth leachate	
Sampling date	9/23/2011	9/27/2011	10/4/2011	10/5/2011	10/26/2011	11/4/2011	12/7/2011	1/6/2012	1/10/2012	1/24/2012	
AVG											
Control	4.75	4.74	4.83	5.01	4.67	4.70	5.42	5.84	5.29	6.29	5.99
PAAC-20%A	12.00	12.30	12.31	10.23	10.21	10.31	9.85	10.09	10.21	10.17	10.13
PAAC - 10%A/5%Z/5%MRM	12.19	11.99	11.70	10.10	9.76	10.34	9.69	9.82	9.65	9.84	9.63
PC without amendments	12.08	11.99	12.10	10.19	10.39	10.74	9.94	10.21	9.84	10.09	9.72
STDEV											
Control	0.06	0.09	0.01	0.08	0.12	0.08	0.51	0.04	0.17	0.10	0.04
PAAC-20%A	0.37	0.08	0.10	0.26	0.15	0.40	0.24	0.23	0.30	0.06	0.58
PAAC - 10%A/5%Z/5%MRM	0.18	0.23	0.53	0.38	0.08	0.08	0.24	0.16	0.23	0.11	0.26
PC without amendments	0.07	0.13	0.03	0.40	0.91	0.68	0.24	0.63	0.27	0.22	0.18

Control – uncapped sediment; PAAC - Permeable Active Amendment Concrete; PAAC -20% - PAAC with 20% apatite; PAAC - 10%A/5%Z/5%MRM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.



**Figure 12. Effect of PC and PAACs on pH values of the leachates over five months (n = 3 replicates). Control – uncapped sediment; PAAC - Permeable Active Amendment Concrete; PAAC -20% - PAAC with 20% apatite; PAAC - 10%A/5%Z/5%MRM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.**

A two-way repeated measures analysis of variance (ANOVA) was used to investigate the significance of changes in leachate pH over time and determine whether these changes differed significantly among treatments. The ANOVA indicated a significant ( $P < 0.001$ ) interaction between treatment and leachate, reflecting the fact that pH changes over time differed among treatments. Further investigation using Holm-Sidak pairwise multiple comparison tests showed that pH did not change significantly in the leachates from the control. In contrast, most pH differences between leachates were significant for PC and PAAC as a result of a decline in pH over time in the leachates from these treatments. These results suggest that the effects of PC and PAAC on pH may decline with continued flushing as would typically occur in the field.

Metal concentrations in the leachates from the static columns were analyzed after one, two, three, four, and five months (Tables 12, 13, 14, 15, and 16). Differences among treatments in each set of measurements were tested for significance ( $P < 0.05$ ) using one-way analysis of variance (ANOVA) (Table 17). Concentration data for some of the elements were  $\log_{10}(X +$

1) transformed to meet the assumptions of ANOVA (normality and homogeneity of variance). Analysis of the first set of leachates (collected after one month) showed that the concentrations of Co, Ni, Zn, As, and Cd were significantly ( $P < 0.05$ ) lower in leachates from PC, PAAC-A, and PAAC-AZM than in leachates from the controls (i.e., uncapped sediment, Table 17).

Results from the final set of leachates collected after five months were generally similar to the results from the first, second, third, and fourth set except that differences among treatments were no longer statistically significant for Zn and Pb. In the case of Zn, lack of significance was due to a reduction in Zn concentration in leachate from the control (uncapped) sediment. Zn concentrations declined in successive leachates from the uncapped sediment as a likely result of removal by leaching (Tables 16 and 17). Co, Ni, As, Se, and Cd concentrations were significantly lower in all leachates from the PAAC and PC treatments than in leachates from the controls (Tables 16 and 17).

Table 12. Metal concentrations in leachates after one month.

Treatments	Co ppb	Ni ppb	Zn ppb	As ppb	Se ppb	Mo ppb	Cd ppb	Pb ppb
Control	134.1	126.4	124.9	11.0	12.0	1.9	33.2	0.5
	178.4	158.6	156.2	9.8	13.3	1.0	43.8	0.4
<b>Average</b>	<b>156.3</b>	<b>142.5</b>	<b>140.6</b>	<b>10.4</b>	<b>12.7</b>	<b>1.4</b>	<b>38.5</b>	<b>0.4</b>
<b>Stdev</b>	<b>22.1</b>	<b>16.1</b>	<b>15.7</b>	<b>0.6</b>	<b>0.7</b>	<b>0.5</b>	<b>5.3</b>	<b>0.1</b>
PAAC - 20%A	2.1	3.3	1.0	0.9	5.6	22.4	0.3	0.2
	1.9	5.7	0.7	2.6	12.3	21.5	0.0	0.4
<b>Average</b>	<b>2.0</b>	<b>4.5</b>	<b>0.9</b>	<b>1.7</b>	<b>8.9</b>	<b>21.9</b>	<b>0.2</b>	<b>0.3</b>
<b>Stdev</b>	<b>0.1</b>	<b>1.2</b>	<b>0.1</b>	<b>0.8</b>	<b>3.4</b>	<b>0.4</b>	<b>0.2</b>	<b>0.1</b>
PAAC - 10%A/5%Z/5%MRM	0.5	8.5	0.5	2.8	7.7	20.3	0.0	0.0
	0.2	0.9	0.8	2.8	5.9	10.2	0.0	0.0
	3.5	7.0	1.4	2.4	4.9	19.1	0.0	0.0
<b>Average</b>	<b>1.4</b>	<b>5.4</b>	<b>0.9</b>	<b>2.7</b>	<b>6.1</b>	<b>16.5</b>	<b>0.0</b>	<b>0.0</b>
<b>Stdev</b>	<b>1.8</b>	<b>4.0</b>	<b>0.4</b>	<b>0.2</b>	<b>1.4</b>	<b>5.5</b>	<b>0.0</b>	<b>0.0</b>
PC without amendments	0.8	4.7	0.3	2.4	8.4	12.3	0.0	0.4
	2.7	4.8	1.8	3.8	11.8	15.8	0.0	0.9
	3.3	9.7	0.8	3.3	11.8	16.8	0.0	0.4
<b>Average</b>	<b>2.3</b>	<b>6.4</b>	<b>1.0</b>	<b>3.2</b>	<b>10.7</b>	<b>15.0</b>	<b>0.0</b>	<b>0.6</b>
<b>Stdev</b>	<b>1.3</b>	<b>2.8</b>	<b>0.8</b>	<b>0.7</b>	<b>1.9</b>	<b>2.4</b>	<b>0.0</b>	<b>0.3</b>

Control – uncapped sediment; PAAC - Permeable Active Amendment Concrete; PAAC -20% - PAAC with 20% apatite; PAAC - 10%A/5%Z/5%MRM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.

Table 13. Metal concentrations in leachates after two months.

Treatments	Co ppb	Ni ppb	Zn ppb	As ppb	Se ppb	Mo ppb	Cd ppb	Pb ppb
Control	31.5	50.3	24.6	22.9	17.4	3.3	8.8	0.8
	31.1	46.8	28.1	8.0	9.6	2.1	12.3	1.3
	39.0	67.3	21.4	47.2	13.0	1.2	4.4	2.1
<b>Average</b>	<b>33.8</b>	<b>54.8</b>	<b>24.7</b>	<b>26.0</b>	<b>13.3</b>	<b>2.2</b>	<b>8.5</b>	<b>1.4</b>
<b>Stdev</b>	<b>4.5</b>	<b>10.9</b>	<b>3.3</b>	<b>19.8</b>	<b>3.9</b>	<b>1.0</b>	<b>4.0</b>	<b>0.7</b>
PAAC - 20%A	0.1	0.4	0.0	1.3	9.0	1.1	0.0	0.4
	0.1	0.0	1.3	1.1	6.7	0.9	0.1	0.2
	0.6	0.3	0.0	1.3	6.4	1.6	0.0	0.5
<b>Average</b>	<b>0.3</b>	<b>0.2</b>	<b>0.5</b>	<b>1.2</b>	<b>7.4</b>	<b>1.2</b>	<b>0.0</b>	<b>0.4</b>
<b>Stdev</b>	<b>0.3</b>	<b>0.2</b>	<b>0.8</b>	<b>0.1</b>	<b>1.4</b>	<b>0.4</b>	<b>0.0</b>	<b>0.2</b>
PAAC - 10%A/5%Z/5%MRM	0.1	1.4	0.0	1.1	6.1	3.1	0.0	0.5
	0.3	4.1	0.0	1.5	6.2	2.7	0.1	0.5
	0.2	1.1	0.0	1.1	5.3	1.8	0.0	0.2
<b>Average</b>	<b>0.2</b>	<b>2.2</b>	<b>0.0</b>	<b>1.3</b>	<b>5.9</b>	<b>2.5</b>	<b>0.0</b>	<b>0.4</b>
<b>Stdev</b>	<b>0.1</b>	<b>1.7</b>	<b>0.0</b>	<b>0.3</b>	<b>0.5</b>	<b>0.7</b>	<b>0.0</b>	<b>0.1</b>
PC without amendments	0.2	3.1	0.9	2.2	7.7	4.1	0.0	0.1
	0.1	0.3	0.0	1.0	6.7	0.9	0.0	0.2
	0.3	2.3	0.0	1.0	7.7	1.3	0.0	0.4
<b>Average</b>	<b>0.2</b>	<b>1.9</b>	<b>0.3</b>	<b>1.4</b>	<b>7.3</b>	<b>2.1</b>	<b>0.0</b>	<b>0.2</b>
<b>Stdev</b>	<b>0.1</b>	<b>1.4</b>	<b>0.5</b>	<b>0.7</b>	<b>0.6</b>	<b>1.8</b>	<b>0.0</b>	<b>0.2</b>

Control – uncapped sediment; PAAC - Permeable Active Amendment Concrete; PAAC -20% - PAAC with 20% apatite; PAAC - 10%A/5%Z/5%MRM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.

Table 14. Metal concentrations in leachates after three months.

Treatments	Co ppb	Ni ppb	Zn ppb	As ppb	Se ppb	Mo ppb	Cd ppb	Pb ppb
Control	missing	missing	missing	missing	missing	missing	missing	missing
	16.48	32.04	19.55	18.97	5.131	1.236	4.523	4.886
	10.81	25.35	16.52	21.31	4.627	0.984	6.634	7.214
<b>Average</b>	<b>13.6</b>	<b>28.7</b>	<b>18.0</b>	<b>20.1</b>	<b>4.9</b>	<b>1.1</b>	<b>5.6</b>	<b>6.1</b>
<b>Stdev</b>	<b>4.0</b>	<b>4.7</b>	<b>2.1</b>	<b>1.7</b>	<b>0.4</b>	<b>0.2</b>	<b>1.5</b>	<b>1.6</b>
PAAC - 20%A	0.078	0.548	5.559	0.935	0.24	1	0.026	0.083
	0.031	0.406	8.432	0.495	0	0.772	0.013	0.096
	0.165	2.649	5.931	1.537	0.448	0.955	0	0.003
<b>Average</b>	<b>0.1</b>	<b>1.2</b>	<b>6.6</b>	<b>1.0</b>	<b>0.2</b>	<b>0.9</b>	<b>0.0</b>	<b>0.1</b>
<b>Stdev</b>	<b>0.1</b>	<b>1.3</b>	<b>1.6</b>	<b>0.5</b>	<b>0.2</b>	<b>0.1</b>	<b>0.0</b>	<b>0.1</b>
PAAC - 10%A/5%Z/5%MRM	0.282	3.017	6.918	2.781	1.032	1.727	0	0.149
	0.856	7.906	3.723	1.929	0.654	2.052	0	0
	0.207	1.444	0.576	2.527	1.232	1.544	0	0
<b>Average</b>	<b>0.4</b>	<b>4.1</b>	<b>3.7</b>	<b>2.4</b>	<b>1.0</b>	<b>1.8</b>	<b>0.0</b>	<b>0.0</b>
<b>Stdev</b>	<b>0.4</b>	<b>3.4</b>	<b>3.2</b>	<b>0.4</b>	<b>0.3</b>	<b>0.3</b>	<b>0.0</b>	<b>0.1</b>
PC without amendments	0.299	2.649	7.202	1.734	0.331	2.348	0	0
	0.036	0.436	1.024	0.671	0.283	0.881	0	0
	0.141	1.057	6.91	1.355	0.289	0.402	0	0
<b>Average</b>	<b>0.2</b>	<b>1.4</b>	<b>5.0</b>	<b>1.3</b>	<b>0.3</b>	<b>1.2</b>	<b>0.0</b>	<b>0.0</b>
<b>Stdev</b>	<b>0.1</b>	<b>1.1</b>	<b>3.5</b>	<b>0.5</b>	<b>0.0</b>	<b>1.0</b>	<b>0.0</b>	<b>0.0</b>

Control – uncapped sediment; PAAC - Permeable Active Amendment Concrete; PAAC -20% - PAAC with 20% apatite; PAAC - 10%A/5%Z/5%MRM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.

Table 15. Metal concentrations in leachates after four months.

Treatments	Co ppb	Ni ppb	Zn ppb	As ppb	Se ppb	Mo ppb	Cd ppb	Pb ppb
Control	missing	missing	missing	missing	missing	missing	missing	missing
	10.61	23.97	7.444	57.71	2.087	0.37	1.113	2.848
	8.106	20.09	6.601	9.251	4.172	0.277	6.083	2.526
<b>Average</b>	<b>9.4</b>	<b>22.0</b>	<b>7.0</b>	<b>33.5</b>	<b>3.1</b>	<b>0.3</b>	<b>3.6</b>	<b>2.7</b>
<b>Stdev</b>	<b>1.8</b>	<b>2.7</b>	<b>0.6</b>	<b>34.3</b>	<b>1.5</b>	<b>0.1</b>	<b>3.5</b>	<b>0.2</b>
PAAC - 20%A	0.081	0.687	0.618	0.971	0.366	0.644	0	0
	0.05	0.649	0	0.521	0.33	0.513	0	0
	0.256	3.773	0	1.163	0.255	0.893	0	0
<b>Average</b>	<b>0.1</b>	<b>1.7</b>	<b>0.2</b>	<b>0.9</b>	<b>0.3</b>	<b>0.7</b>	<b>0.0</b>	<b>0.0</b>
<b>Stdev</b>	<b>0.1</b>	<b>1.8</b>	<b>0.4</b>	<b>0.3</b>	<b>0.1</b>	<b>0.2</b>	<b>0.0</b>	<b>0.0</b>
PAAC - 10%A/5%Z/5%MRM	0.083	0.855	2.169	1.613	0.176	2.355	0.012	0.353
	0.804	5.712	0.236	1.95	0.424	2.072	0	0
	0.043	0.38	0.158	0.729	0	1.096	0	0
<b>Average</b>	<b>0.3</b>	<b>2.3</b>	<b>0.9</b>	<b>1.4</b>	<b>0.2</b>	<b>1.8</b>	<b>0.0</b>	<b>0.1</b>
<b>Stdev</b>	<b>0.4</b>	<b>3.0</b>	<b>1.1</b>	<b>0.6</b>	<b>0.2</b>	<b>0.7</b>	<b>0.0</b>	<b>0.2</b>
PC without amendments	0.159	1.257	0	0.786	0.106	1.881	0	0
	0.012	0.199	2.5	0.541	0	0.757	0.002	0.125
	0.267	2.048	2.491	1.139	0.294	0.454	0	0.816
<b>Average</b>	<b>0.1</b>	<b>1.2</b>	<b>1.7</b>	<b>0.8</b>	<b>0.1</b>	<b>1.0</b>	<b>0.0</b>	<b>0.3</b>
<b>Stdev</b>	<b>0.1</b>	<b>0.9</b>	<b>1.4</b>	<b>0.3</b>	<b>0.1</b>	<b>0.8</b>	<b>0.0</b>	<b>0.4</b>

Control – uncapped sediment; PAAC - Permeable Active Amendment Concrete; PAAC -20% - PAAC with 20% apatite; PAAC - 10%A/5%Z/5%MRM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.

Table 16. Metal concentrations in leachates after five months (final measurements).

Treatments	Co ppb	Ni ppb	Zn ppb	As ppb	Se ppb	Mo ppb	Cd ppb	Pb ppb
Control	missing	missing	missing	missing	missing	missing	missing	missing
	3.485	7.669	2.899	6.969	1.148	0.362	1.417	1.071
	2.58	8.627	3.522	5.784	2.275	0.32	2.64	1.441
<b>Average</b>	<b>3.0</b>	<b>8.1</b>	<b>3.2</b>	<b>6.4</b>	<b>1.7</b>	<b>0.3</b>	<b>2.0</b>	<b>1.3</b>
<b>Stdev</b>	<b>0.6</b>	<b>0.7</b>	<b>0.4</b>	<b>0.8</b>	<b>0.8</b>	<b>0.0</b>	<b>0.9</b>	<b>0.3</b>
PAAC - 20%A	0.08	0.614	0.267	0.642	0.127	0.653	0.002	0.009
	0.015	0.555	0.081	0.245	0	0.432	0	0
	0.23	3.566	0	0.726	0.169	1.064	0	0
<b>Average</b>	<b>0.1</b>	<b>1.6</b>	<b>0.1</b>	<b>0.5</b>	<b>0.1</b>	<b>0.7</b>	<b>0.0</b>	<b>0.0</b>
<b>Stdev</b>	<b>0.1</b>	<b>1.7</b>	<b>0.1</b>	<b>0.3</b>	<b>0.1</b>	<b>0.3</b>	<b>0.0</b>	<b>0.0</b>
PAAC - 10%A/5%Z/5%MRM	0.06	0.709	0.695	1.078	0	0.789	0	0.15
	0.296	2.458	0.14	1.369	0.181	0.717	0	0
	0.05	0.423	0.285	0.243	0	0.413	0	0
<b>Average</b>	<b>0.1</b>	<b>1.2</b>	<b>0.4</b>	<b>0.9</b>	<b>0.1</b>	<b>0.6</b>	<b>0.0</b>	<b>0.1</b>
<b>Stdev</b>	<b>0.1</b>	<b>1.1</b>	<b>0.3</b>	<b>0.6</b>	<b>0.1</b>	<b>0.2</b>	<b>0.0</b>	<b>0.1</b>
PC without amendments	0.078	0.882	0.814	0.68	0.017	0.858	0	0
	0.01	0.292	1.286	0.217	0	0.242	0	0.201
	0.156	1.541	0.158	0.425	0	0.168	0	0.051
<b>Average</b>	<b>0.1</b>	<b>0.9</b>	<b>0.8</b>	<b>0.4</b>	<b>0.0</b>	<b>0.4</b>	<b>0.0</b>	<b>0.1</b>
<b>Stdev</b>	<b>0.1</b>	<b>0.6</b>	<b>0.6</b>	<b>0.2</b>	<b>0.0</b>	<b>0.4</b>	<b>0.0</b>	<b>0.1</b>

Control – uncapped sediment; PAAC - Permeable Active Amendment Concrete; PAAC -20% - PAAC with 20% apatite; PAAC - 10%A/5%Z/5%MRM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.



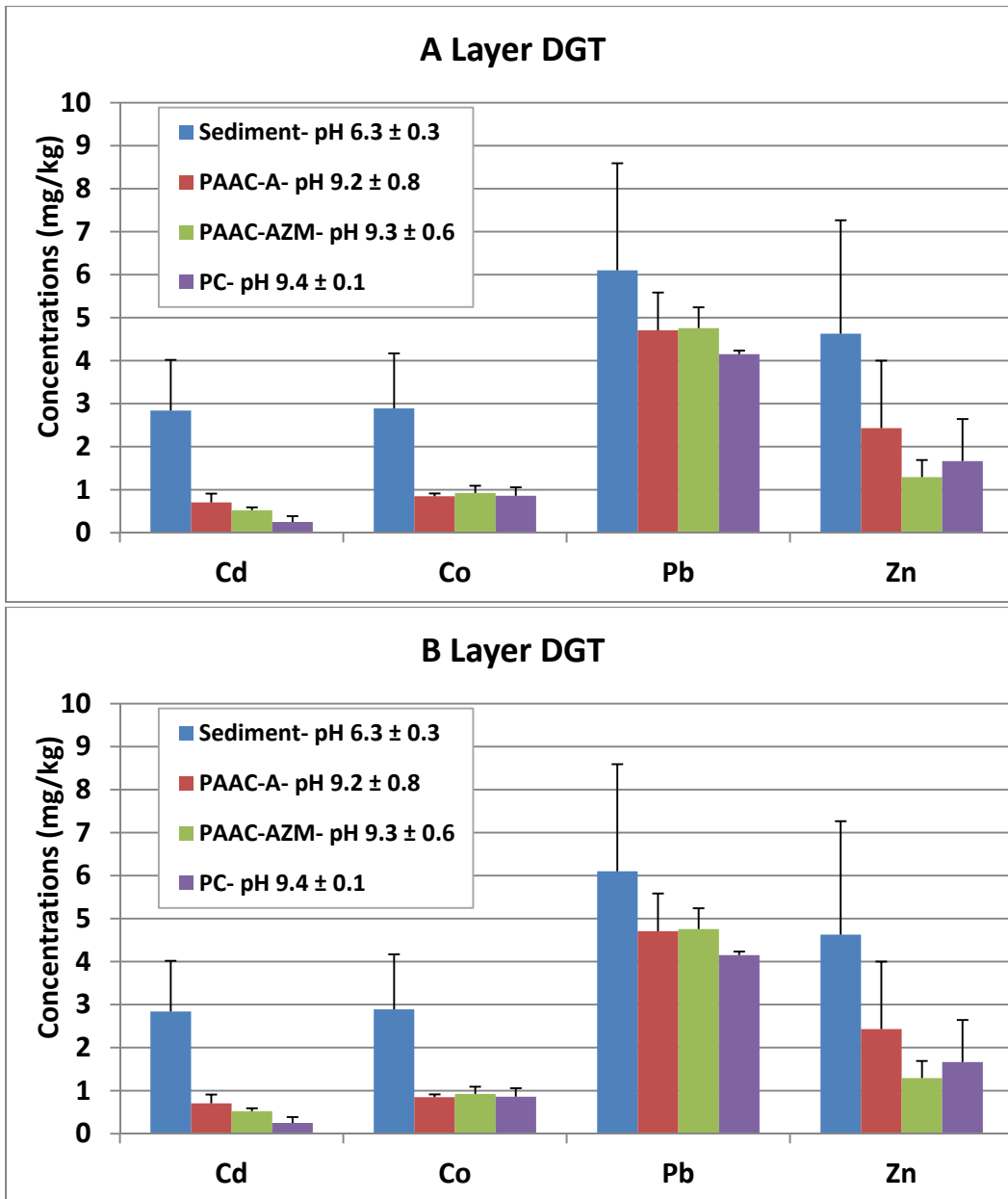
**Table 17. Geometric means of metal concentrations in leachates after one, two, and five months. Means connected by the same line are not significantly different ( $P < 0.05$ , ANOVA followed by Holm-Sidak test,  $n=3$  per treatment, metal concentration data were  $\log_{10}(x+1)$  transformed as necessary to meet the assumptions of ANOVA).**

METAL	One month				Two months				Five months (final)			
Co	C*	P-A	PC	P-AZM	C	P-AZM	P-A	PC	C	P-AZM	PA	PC
	154.68	3.21	2.07	1.03	33.66	0.24	0.21	0.16	3.01	0.13	0.10	0.08
Ni	C	PC	P-A	P-AZM	C	P-AZM	PC	P-A	C	P-A	P-AZM	PC
	141.59	6.07	4.37	4.19	54.14	1.93	1.60	0.96	8.14	1.25	1.03	0.83
Zn	C	P-A	PC	P-AZM	C	P-A	PC	P-AZM	C	P-A	PC	P-AZM
	139.68	1.44	0.91	0.85	24.54	0.34	0.24	0.00	3.20	1.73	0.69	0.35
As	C	PC	P-AZM	P-A	C	PC	P-AZM	P-A	C	P-AZM	P-A	PC
	10.40	3.12	2.69	2.20	20.80	1.35	1.24	1.21	6.35	0.83	0.52	0.43
Se	C	P-A	PC	P-AZM	C	PC	P-A	P-AZM	C	P-A	P-AZM	PC
	12.64	11.91	10.56	6.05	12.99	7.33	7.30	5.85	1.65	0.10	0.06	0.01
Mo	P-A	P-AZM	PC	C	P-AZM	C	PC	P-A	P-A	P-AZM	PC	C
	23.87	15.87	14.85	1.39	2.46	2.08	1.83	1.15	0.70	0.63	0.39	34
Cd	C	P-A	PC	P-AZM	C	P-AZM	P-A	PC	C	P-A	PC	P-AZM
	38.12	0.10	0.02	0.00	7.90	0.03	0.02	0.01	1.97	0.0	0.0	0.0
Pb	PC	P-AZM	C	P-A	C	P-AZM	P-A	PC	P-A	C	PC	AZM
	0.56	0.49	0.41	0.24	1.32	0.40	0.35	0.23	1.97	1.25	0.08	0.05

\*C – Control (uncapped sediment); PAAC - Permeable Active Amendment Concrete; P-A: PAAC-A with 20% apatite; P – AZM: PAAC – AZM with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.

***Effect of PAAC materials on metal bioavailability***

The static column study was terminated after the fifth leachate. The PAAC caps were separated from the sediment beneath the cap. The sediment was split into two layers: layer A (0-2.5 cm) and layer B (2.5-5 cm). The sediment from both layers was analyzed for pH and the bioavailable pool of metals. The bioavailable pool of Cd, Co, Pb, and Zn in the sediment was evaluated by diffusive gradients in thin films (DGT) probes. DGT can measure labile species that correspond closely to bioavailable contaminant fractions in sediments. The DGT results showed that the concentrations of all tested metals in the layer of sediment just beneath the cap (layer A) and in the deeper sediment layer (layer B) were substantially lower than in uncapped sediment (Figure 13).



**Figure 13. Metal concentrations measured by DGT in untreated sediment and in sediments located 0 – 2.5 cm (A layer) and 2.5 – 5 cm (B layer) beneath three types of sediment caps. Control – uncapped sediment; PAAC-A - Permeable Active Amendment Concrete with 20% apatite; PAAC-AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete without amendments.**

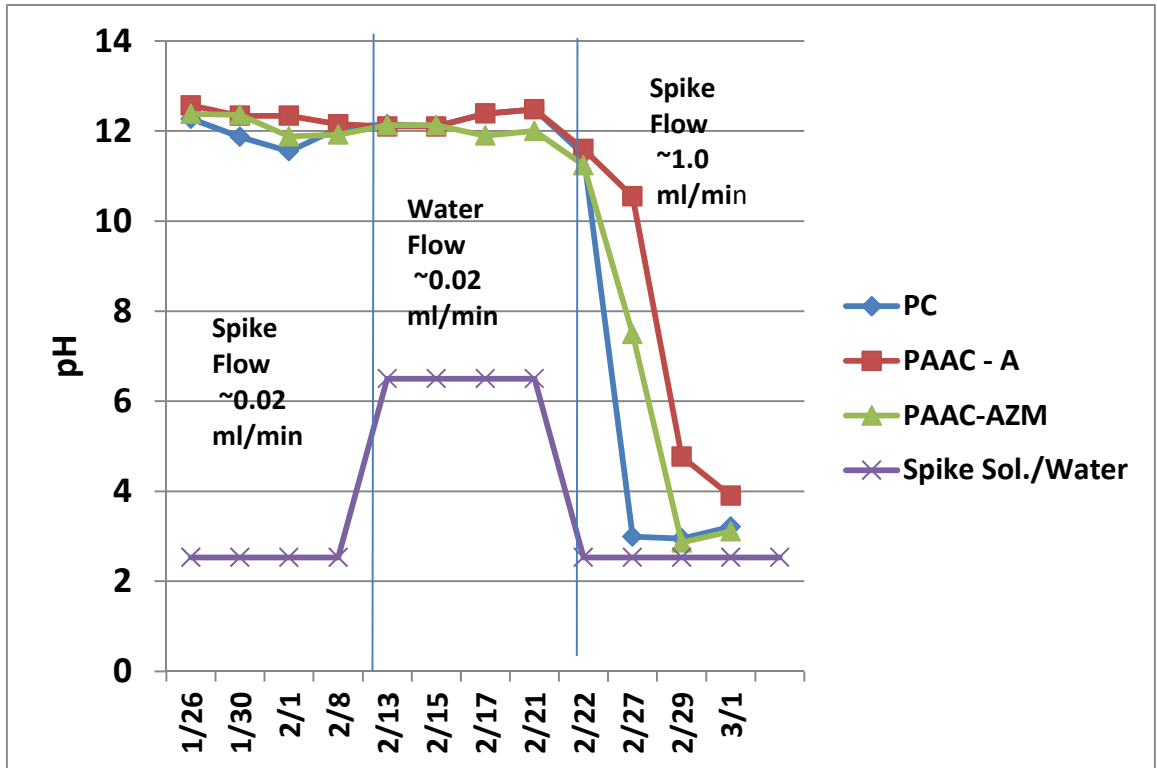
### **Transport of metals through PAAC – flow through column studies**

Three flow-through columns [PAAC containing 20% apatite (PAAC – A), PAAC containing a mixture of 10% apatite, 5% zeolite, and 5% MRM (PAAC – AZM), and PC as control (PC)] were tested under saturated conditions at flow rates of 0.2 ml/min and 1.0 ml/min (Picture 4). The objectives of the study were to investigate the ability of PAAC to remove metals from the spike solution under low and high flows and to investigate the retention of the removed metals on the tested materials.

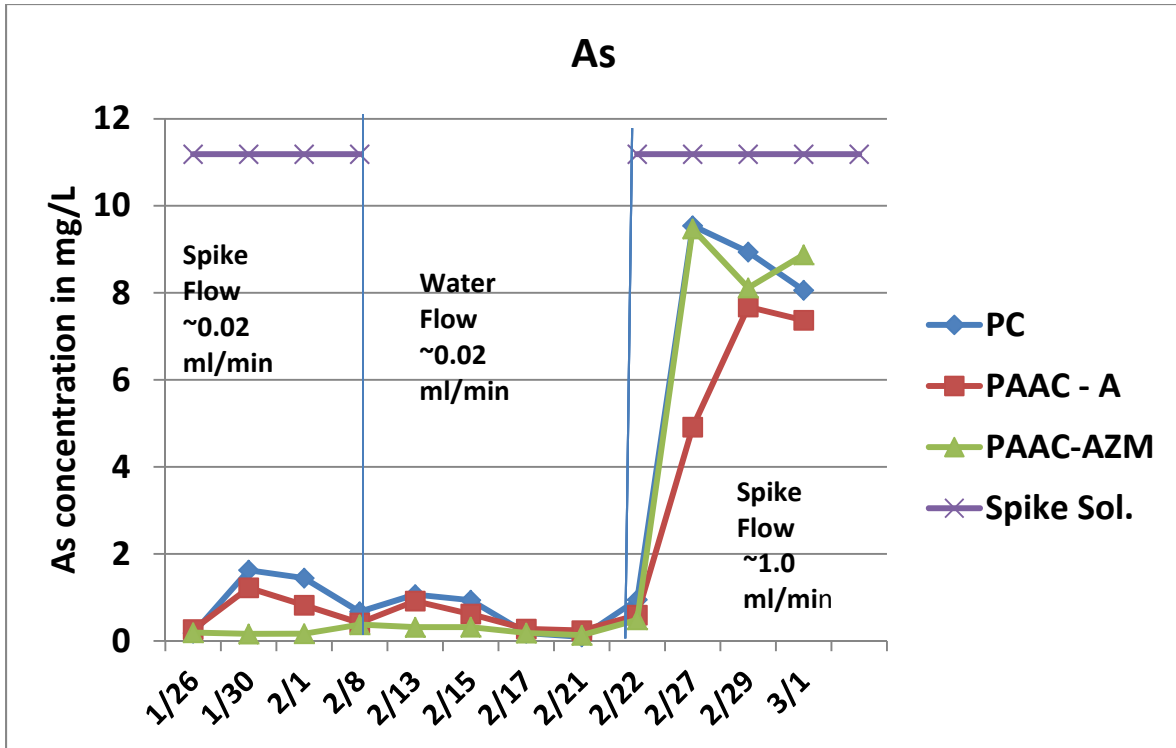
The pH of the spike solution was very low (2.53) but increased to 12 or more after leaching through PAAC and PC at a flow rate of 0.2 ml/min (Figure 14). The pH of the leachates from all three tested materials did not change when the spike solution was replaced by tap water (Figure 7). However, when the tap water was replaced by the spike solution, and the flow increased from 0.2 to 1 ml/min, the pH of the leachates decreased to 3.0 or less within one week for PC and PCCA – AZM (Figure 14). The pH of leachates from the PAAC- A column decreased more slowly and remained slightly higher than the pH in the leachates from PC and PCCA- AZM (Figure 14).

Leachates from the three columns were analyzed for concentrations of As, Cd, Co, Cr, Cu, Ni, Se, Pb, and Zn for a period of 6 weeks. All tested materials removed almost 100% of all metals from the spike solution under low flow (0.2 ml/min) (Figures 15, 16, 17, 18, 19, 20, 21, 22, and 23). As a result of this very high removal, there was no difference among the tested materials, except for As and Se. PAAC – AZM was more effective at removing these two elements than PC and PAAC- A (Figures 15 and 22). After the two week sorption experiment, we tested the PAAC materials for metal retention by running tap water through the column for two weeks. The results of this desorption experiment showed that there was very high retention of all tested elements (Figures 15-23).

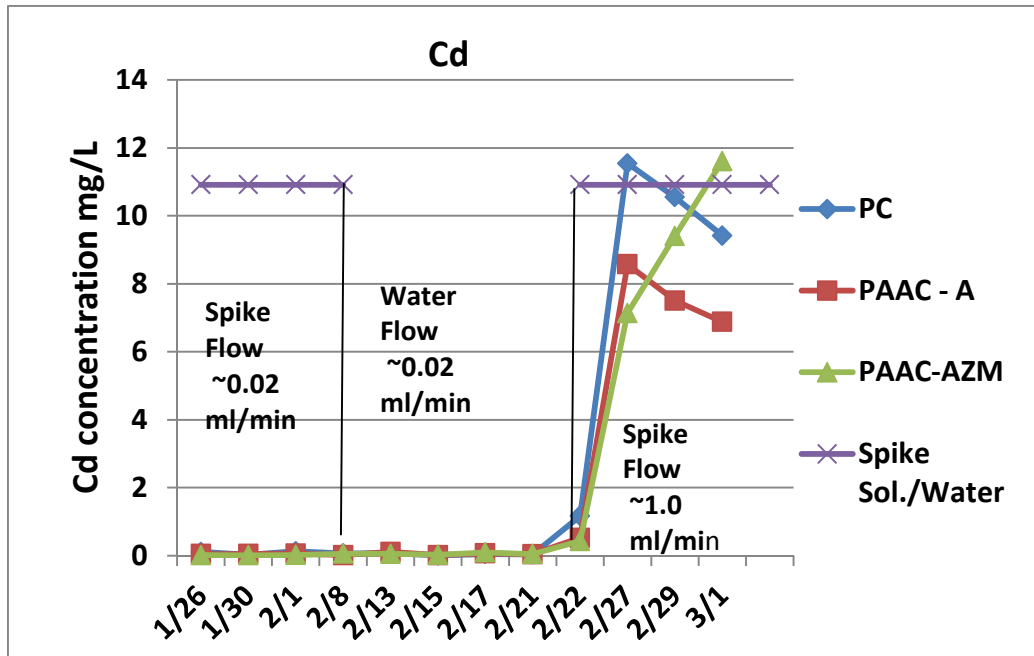
After the desorption study, the columns were leached at a higher flow rate (1.0 ml/min) with a low pH (2.53) spike solution containing about 10 mg/l of all tested metals. Under these extreme conditions, concentrations of Cd, Co, Cr, Ni, Pb, and Zn in the leachates from the PC and PAAC-AZM columns increased to levels found in the spike solution (Figures 16, 17, 18, 20, 21, and 23). However, As, Cu, and Se concentrations remained about 20-30 percent lower than in the spike solution indicating significant removal of these metals (Figures 15, 19, and 22). Unlike the PC and PAAC-AZM columns, the PAAC-A column effectively removed (up to about 40 percent) all tested metals during the entire two-week high flow study (Figures 15 - 23). Results from the PAAC-A flow-through column suggest that PAAC-A constitutes a better capping material than PC (permeable concrete without amendments) because its metal removal capacity is greater – a factor that could be important over long periods of time or in situations where there is substantial movement of water through a cap.



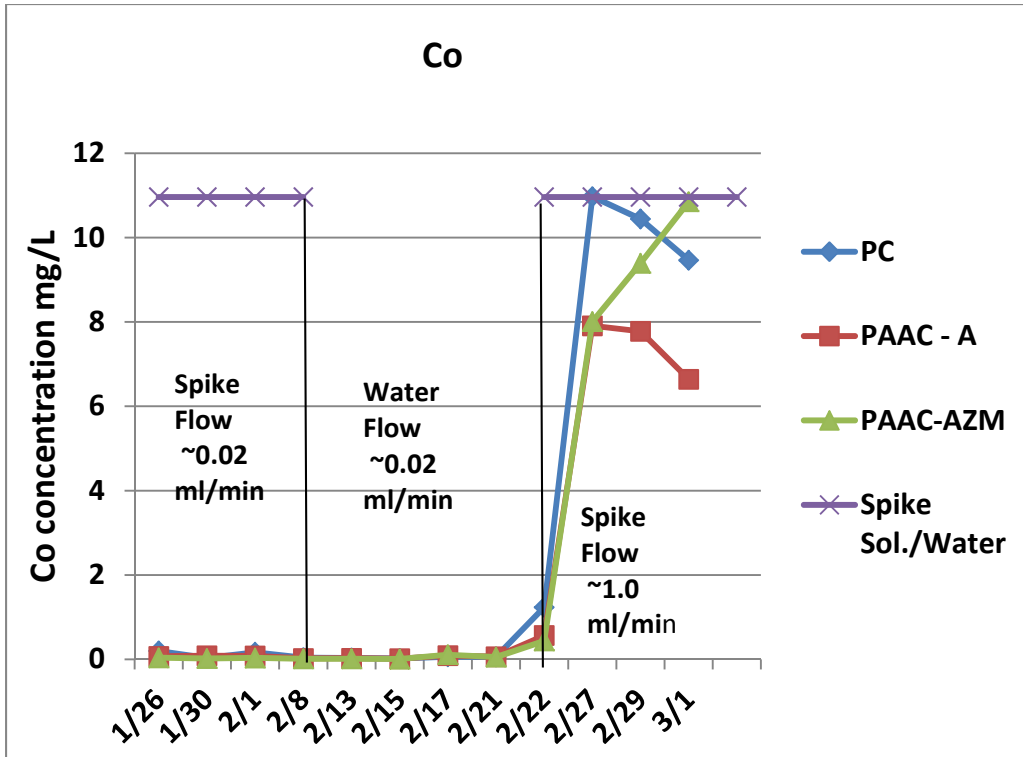
**Figure 14. Effect of PC and PAACs on pH values of the leachates; PAAC - Permeable Active Amendment Concrete; PAAC -A - PAAC with 20% apatite; PAAC - AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.**



**Figure 15.** As concentrations in leachates from the column studies; PAAC - Permeable Active Amendment Concrete; PAAC -A - PAAC with 20% apatite; PAAC - AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.

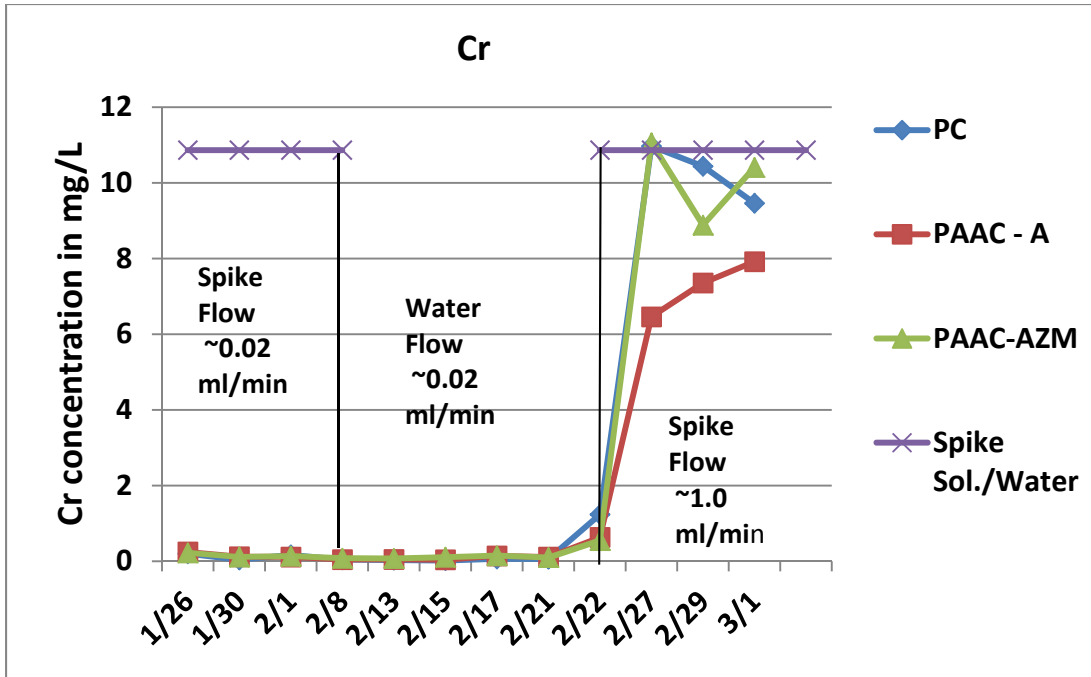


**Figure 16. Cd concentrations in leachates from the column studies; PAAC - Permeable Active Amendment Concrete; PAAC -A - PAAC with 20% apatite; PAAC - AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.**



**Figure 17. Co concentration in leachates from the column studies; PAAC - Permeable Active Amendment Concrete; PAAC -A - PAAC with 20% apatite; PAAC - AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.**





**Figure 18. Cr concentration in leachates from the column studies; PAAC - Permeable Active Amendment Concrete; PAAC -A - PAAC with 20% apatite; PAAC - AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.**

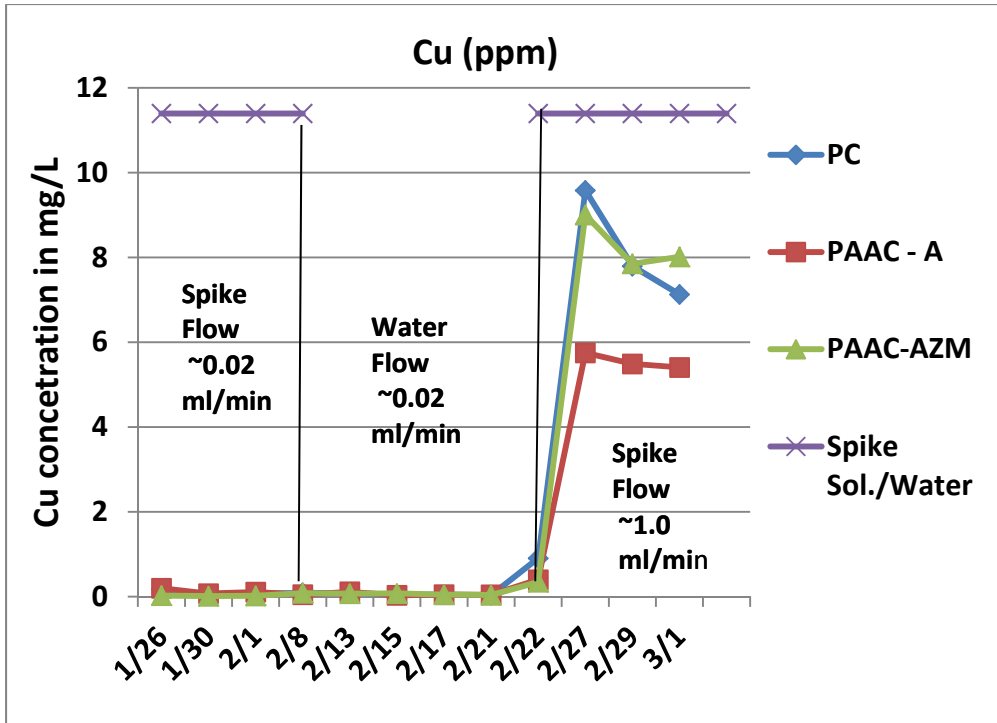


Figure 19. Cu concentration in leachates from the column studies; PAAC - Permeable Active Amendment Concrete; PAAC -A - PAAC with 20% apatite; PAAC - AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.

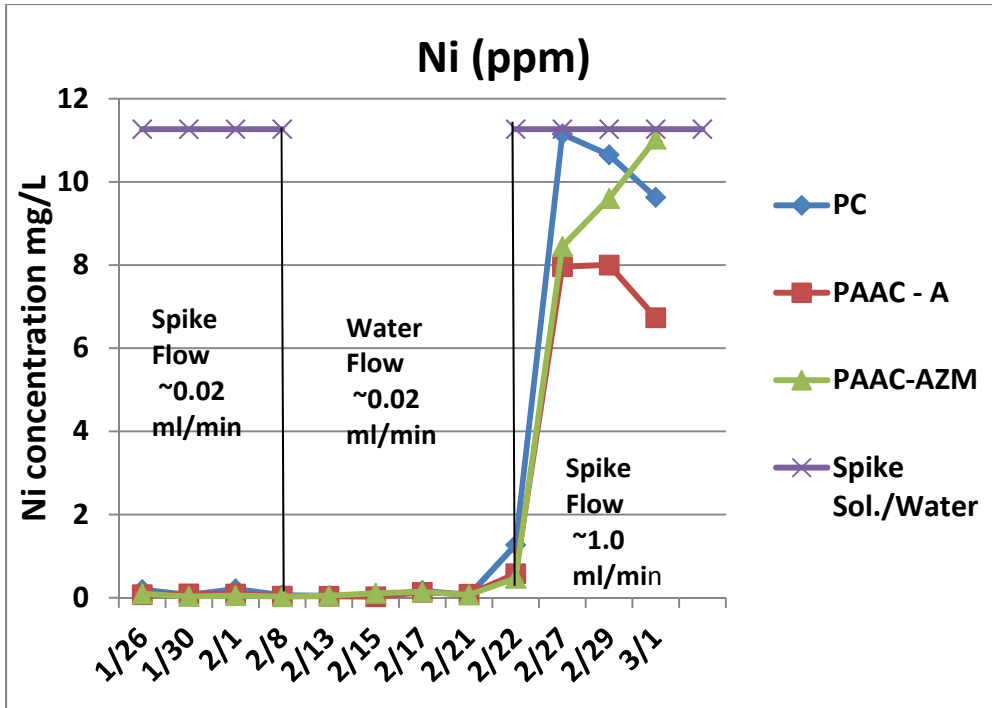


Figure 20. Ni concentration in leachates from the column studies; PAAC - Permeable Active Amendment Concrete; PAAC -A - PAAC with 20% apatite; PAAC - AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.

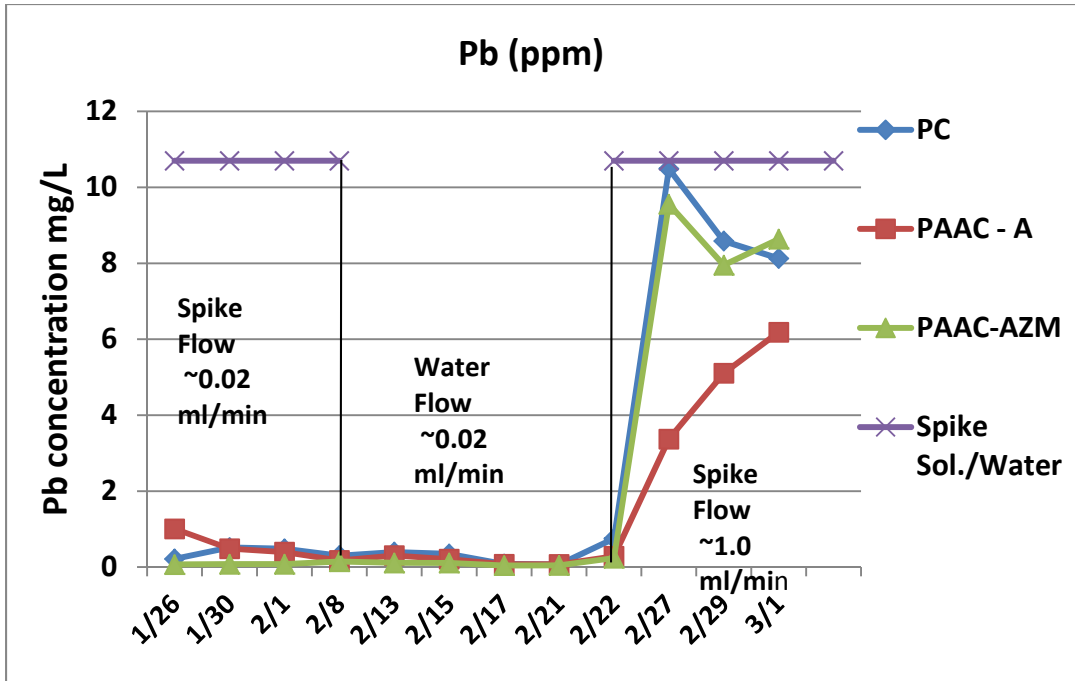
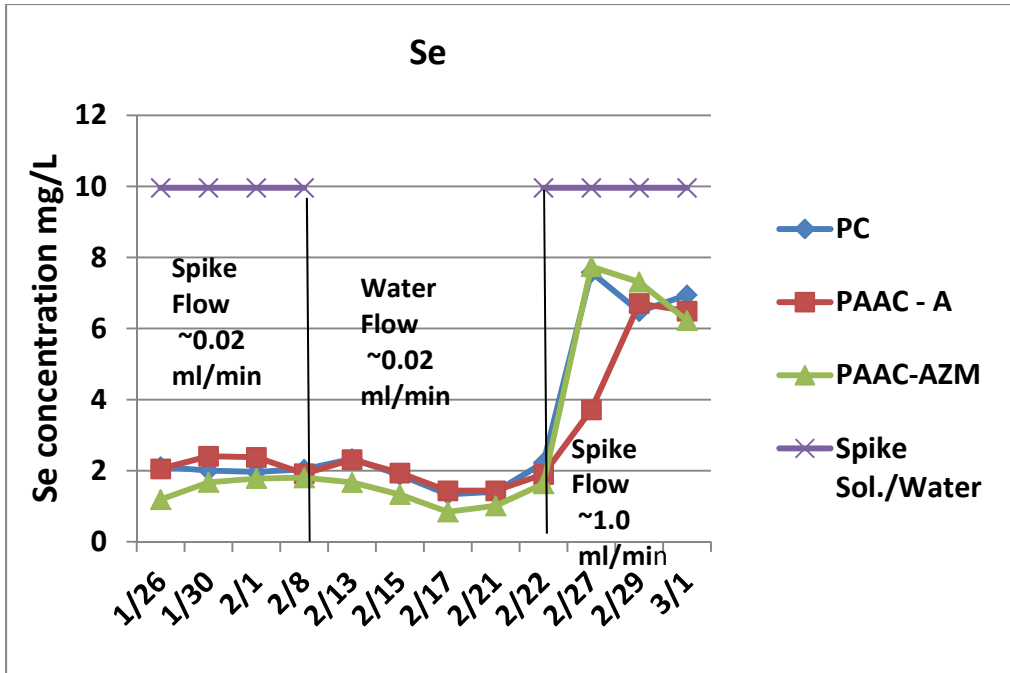


Figure 21. Pb concentration in leachates from the column studies; PAAC - Permeable Active Amendment Concrete; PAAC -A - PAAC with 20% apatite; PAAC - AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.



**Figure 22. Se concentration in leachates from the column studies; PAAC - Permeable Active Amendment Concrete; PAAC - A - PAAC with 20% apatite; PAAC - AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.**

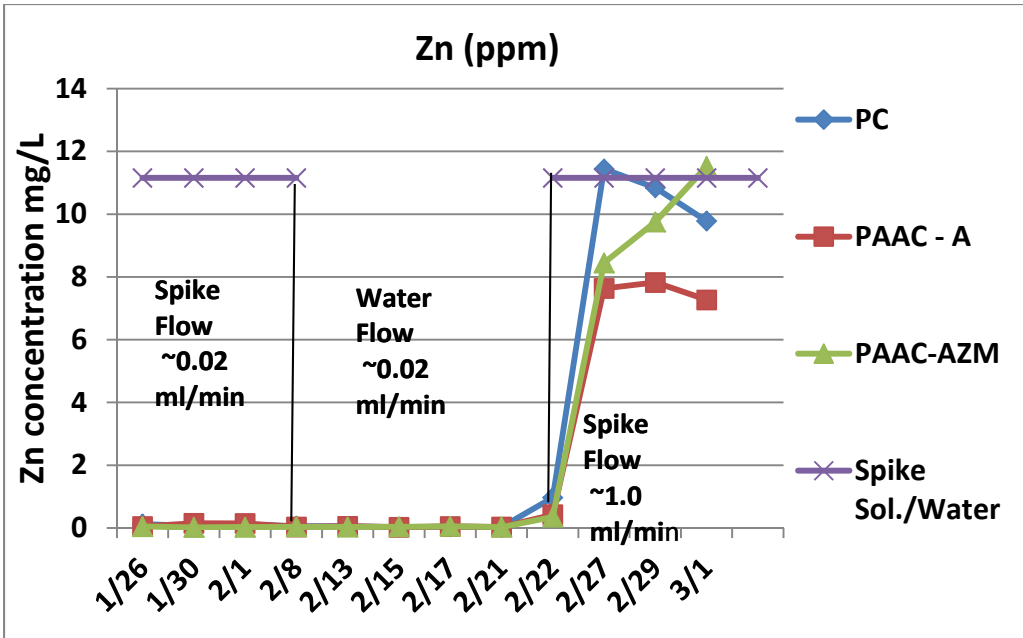
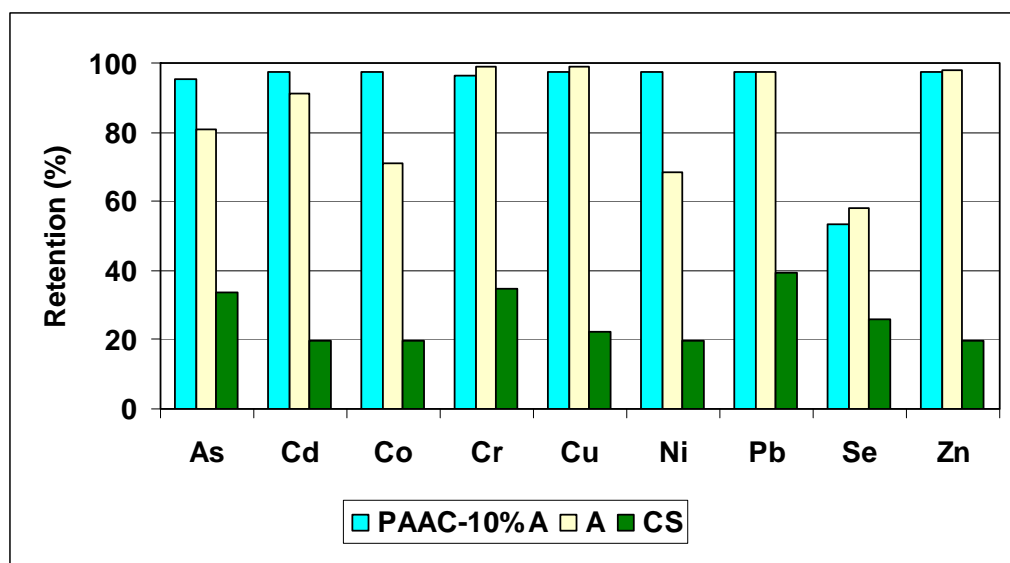


Figure 23. Zn concentration in leachates from the column studies; PAAC - Permeable Active Amendment Concrete; PAAC -A - PAAC with 20% apatite; PAAC - AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.

### TASK 3. EVALUATION OF PAAC FOR POTENTIAL ENVIRONMENTAL IMPACT

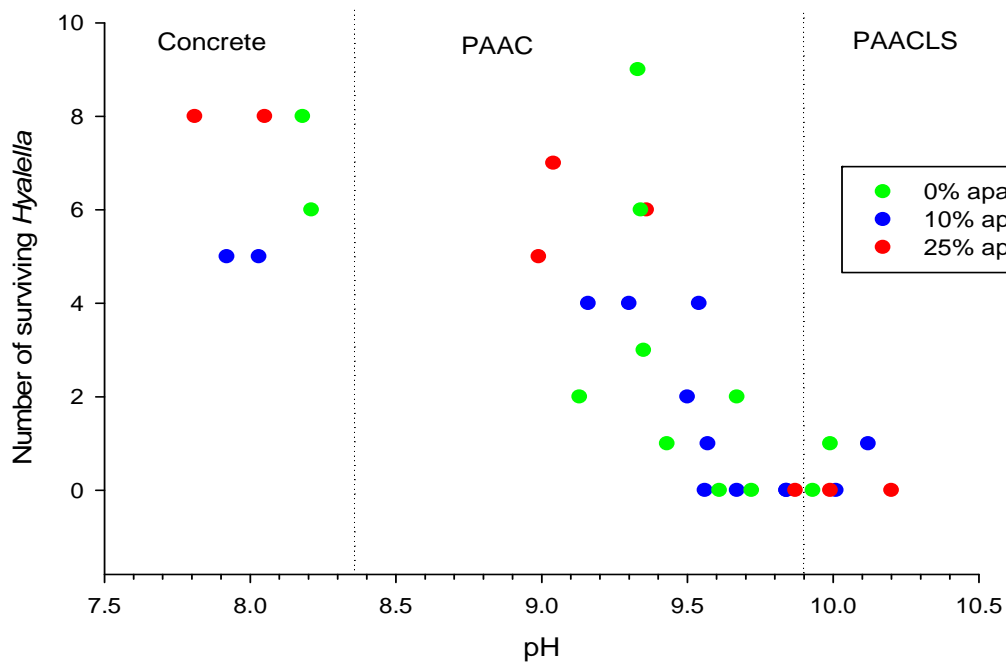
The PAAC with 10% North Carolina apatite was evaluated for potential remobilization of contaminants based on Toxicity Characteristic Leaching Procedure (TCLP) desorption. This material retained 90% or more of most tested metals indicating little potential for remobilization of contaminants based on TCLP desorption data (Figure 24). These data suggest that PAAC with apatite should not produce harmful environmental impacts due to leaching of metals.



**Figure 24. Average retention of metals by PAAC with 10% apatite (A) and crushed stone (CS) based on Toxicity Characteristic Leaching Procedure (TCLP) desorption data.**

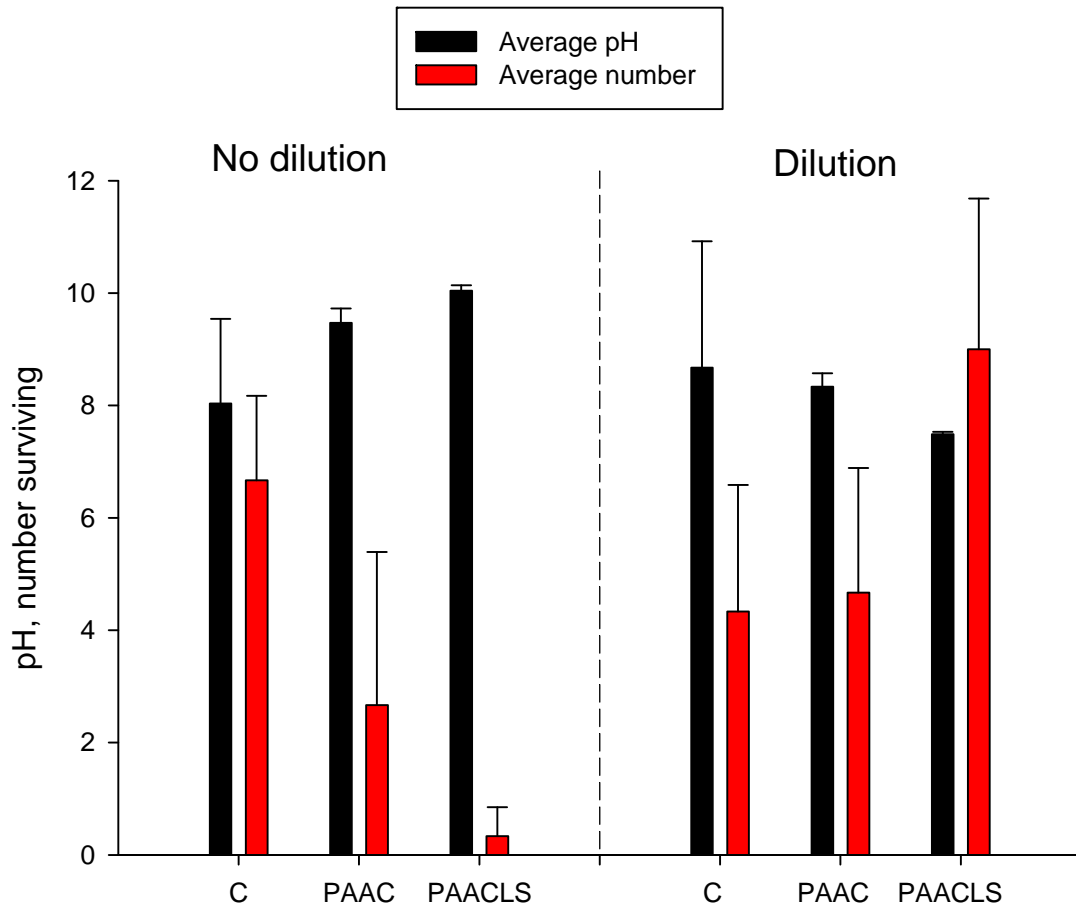
Static bioassays employing *Hyalella azteca* as the test organism were conducted to assess the potential toxicities of PAAC formulations described in Tables 1 and 2. There was substantial mortality of *Hyalella* in some PAAC formulations as a likely result of high pH (Figure 25). Mortality was greatest (nearly 100%) in beakers containing PAAC with limestone. Water column pH in these beakers often exceeded 10. Substantial mortality also occurred in other PAAC formulation in which the pH exceeded approximately 9.2 or 9.3. Survival was consistently greater at pHs below about 9.0. The pHs were highest in beakers containing PAAC with limestone and lowest in beakers containing concrete, although all pHs were well above neutral as a likely result of exposure of the water to the cement in the concrete. Lower pH in the beakers with conventional concrete may be the result of lower substrate surface area compared with PAAC. The pH values were unrelated to the amount of apatite included in the PAAC (Figure 25).

The high pHs observed in water within the test beakers containing PAAC would be unlikely in the field where dilution is greater and flushing occurs as a result of water movements. To simulate field conditions more realistically, a second series of experiments was conducted with a greater amount of water relative to concrete (1000 ml rather than 200 ml). Greater dilution resulted in a reduction of the pH in beakers containing PAAC and PAAC with limestone to an average of 8.3 and 7.5, respectively (Figure 26). Survival was much greater than in the preceding tests in which only 200 ml of water was used. The greatest improvement was associated with PAAC with limestone, where average survival increased from near zero to about 90% (Figure 26).



**Figure 25. Relationship between pH and number of surviving *Hyalella azteca* (out of 10) in static bioassay chambers containing concrete, pervious active amendment concrete (PAAC) and PAAC with limestone (PAACLs).**





**Figure 26. Average (standard deviation) pH and number of surviving *Hyalella azteca* (out of 10) in static bioassay chambers containing concrete (C), pervious active amendment concrete (PAAC), and PAAC with limestone (PAACLS). No dilution indicates test chambers containing 200 ml of water; dilution indicates test chambers containing 1000 ml of water.**

#### TASK 4. ASSESSMENT OF THE HYDRAULIC, PHYSICAL, AND STRUCTURAL PROPERTIES OF PAAC

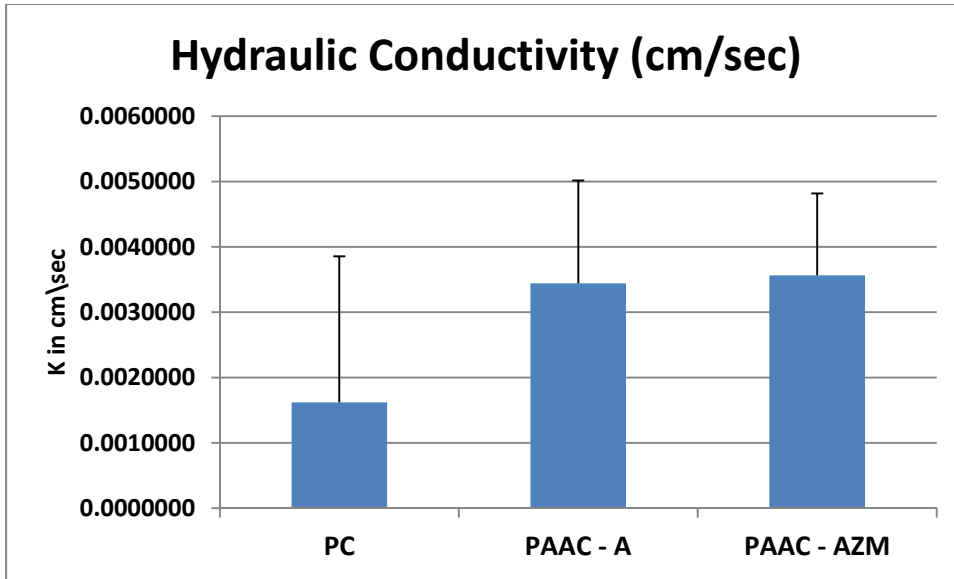
The hydraulic and physical properties of PC and two formulations of PAAC were measured using industry standard methods. The results from these measurements are presented in Table 18 and 19, Figures 27 and 28, and Attachment 1. For PC, the dry bulk density ranged from 1.378 to 1.435 g/cm<sup>3</sup>, porosity ranged from 0.452 to 0.475 cm<sup>3</sup>/cm<sup>3</sup>, and the saturated hydraulic conductivity ranged from 3.85E-04 to 4.97E-03 cm/sec. For PAAC-A, the dry bulk density ranged from 1.346 to 1.437 g/cm<sup>3</sup>, porosity ranged from 0.458 to 0.494 cm<sup>3</sup>/cm<sup>3</sup>, and the saturated hydraulic conductivity ranged from 1.11E-03 to 4.57E-03 cm/sec. For PAAC-AZM, the dry bulk density ranged from 1.145 to 1.230 g/cm<sup>3</sup>, porosity ranged from 0.508 to 0.552 cm<sup>3</sup>/cm<sup>3</sup>, and the saturated hydraulic conductivity ranged from 1.69E-03 to 4.30E-03 cm/sec. All three materials exhibited high porosity and hydraulic conductivity values compared to ordinary concrete, and the observed property ranges are consistent with typical permeable concrete. The two PAAC formulations tested exhibited higher porosity and hydraulic conductivity than the PC with the PAAC-AZM formulation having the highest property values. The substantial porosity and high hydraulic conductivity of the PAAC formulations make the PAAC ideal for flow through treatment of waters contaminated with heavy metals.

**Table 18. Physical properties of PAAC; PAAC-A - PAAC with 20% apatite; PAAC – AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.**

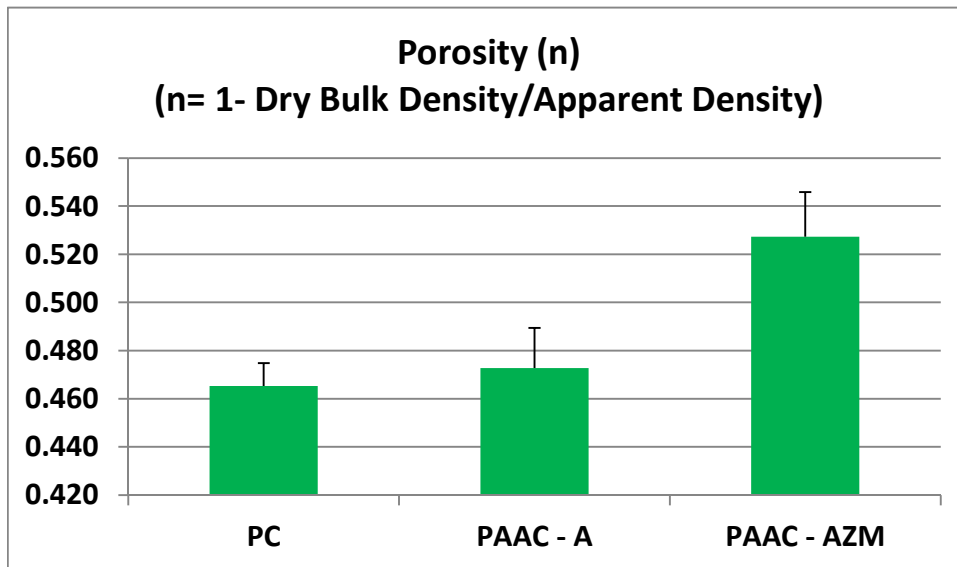
Sample ID	Treatment Name	Dry Bulk Density (g/cm <sup>3</sup> )	Porosity (cm <sup>3</sup> /cm <sup>3</sup> )	Hydraulic Conductivity (cm/sec)
PAC001	PC	1.435	0.452	3.85E-04
PAC002	PC	1.387	0.466	4.97E-04
PAC003	PC	1.378	0.475	6.25E-04
PAC004	PC	1.406	0.468	4.97E-03
PAC005	PAAC - A	1.346	0.494	4.03E-03
PAC006	PAAC - A	1.437	0.458	4.06E-03
PAC007	PAAC - A	1.427	0.461	1.11E-03
PAC008	PAAC - A	1.384	0.478	4.57E-03
PAC009	PAAC - AZM	1.197	0.529	4.18E-03
PAC010	PAAC - AZM	1.145	0.552	1.69E-03
PAC011	PAAC - AZM	1.230	0.508	4.30E-03
PAC012	PAAC - AZM	1.213	0.520	4.09E-03

**Table 19. Average physical properties of PAAC; PC - permeable concrete; PAAC-A - PAAC with 20% apatite; and PAAC – AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM).**

Treatment Name	Dry Bulk Density (g/cm <sup>3</sup> )		Porosity (cm <sup>3</sup> /cm <sup>3</sup> )		Hydraulic Conductivity (cm/sec)	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PC	1.402	0.025	0.465	0.010	1.62E-03	2.24E-03
PAAC - A	1.398	0.042	0.473	0.017	3.44E-03	1.57E-03
PAAC - AZM	1.196	0.037	0.527	0.019	3.57E-03	1.25E-03



**Figure 27. Average hydraulic conductivity of permeable active amendment concrete (PAAC); PAAC-A - PAAC with 20% apatite; PAAC – AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.**



**Figure 28. Average porosity of permeable active amendment concrete (PAAC); PAAC-A - PAAC with 20% apatite; PAAC – AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.**

## SUMMARY

This project developed a permeable active amendment concrete (PAAC) consisting of conventional materials including sand, gravel, and cement plus chemically active amendments such as apatite, limestone, organoclays, and zeolite. PAAC has the potential to produce a barrier that combines high structural integrity with the ability to stabilize a variety of contaminants such as heavy metals. This project identified several types of PAAC, but two types of PAAC: 1) PAAC with a single amendment [e.g., PAAC with 20% apatite (PAAC-A)]; and 2) PAAC with a mixture of amendments [e.g., 10% apatite, 5% zeolite and 5% organoclay (MRM) (PAAC-AZM)] were tested intensively for the removal and retention of contaminants under a range of environmental conditions and applications.

A sediment cap composed of PAAC provides a more permanent and effective solution to sediment contamination than most other remedial treatments because it can (1) sequester contaminants that are released from sediments by diffusion or advective transport, (2) resist erosion by water currents and waves, and (3) prevent physical disturbances caused by burrowing marine organisms. PAAC has the potential to produce active caps that prevent the migration of sediment contaminants by diffusion, advection, bulk sediment dispersal, and bioturbation in a variety of benthic environments including sloping shorelines and environments subject to dynamic forces. Existing capping technologies lack these capabilities.

PAAC can also be used for other purposes besides the construction of sediment caps. The ability of PAAC to remove contaminants from water that passes through the concrete matrix creates the potential to build structures such as retaining walls and seepage basins that purify water while permitting its passage. This can result in the economical and effective treatment of pollutants with minimal expenditure of energy and construction costs. Furthermore, PAAC can be used to quickly create simple, economical, and versatile filters that can remove a variety of pollutants from contaminated water at disaster sites and temporary encampments such as refugee centers and military field camps. This can be accomplished by constructing an enclosure such as a holding pond or trench, filling it with PAAC, and pumping water through the enclosure.

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**Attachment 1. Physical properties of PAAC; PAAC-A - PAAC with 20% apatite; PAAC – AZM - PAAC with a mixture of 10% apatite, 5% zeolite and 5% organoclay (MRM); and PC - permeable concrete.**



## Density, Absorption, Voids in Hardened Concrete

ASTM C 642-06

Project No: 6155-08-0031.29  
 Project Name: Twelve Permeable Concrete Mold Samples  
 Sample No: PAC001  
 Lab No: 11375

Tested by: EH  
 Test Date: 2/6/2012  
 Reviewed by: JW  
 Review Date: 2/14/2012

Date/Time	Oven Dry Mass (grams)	Difference in Mass (%)
2/7/2012	909.90	
2/8/2012	909.00	0.1

Date/Time	SD Mass after 48 hour Soak (grams)	Difference in Mass (%)
2/9/2012	978.10	
2/13/2012	982.80	0.48

\* after removing fragments

Oven Dry Mass, A (grams)	SD Mass after 48 hour Soak, B (grams)	SD Mass after 5 hour Boil, C (grams)	Apparent Mass in Water, D (grams)	Volume of Sample, E (Calculated from Dimension Measurements) (in <sup>3</sup> )
909.00	982.80	973.7	562.10	38.63

Absorption After Immersion, %, [(B-A)/A]*100	8.1
Absorption After Immersion & Boiling, %, [(C-A)/A]*100	7.1
Bulk Density, Dry, [A/(C-D)]* ρ, pcf	137.81
Bulk Density after Immersion, [B/(C-D)]* ρ, pcf	149.00
Bulk Density after Immersion & Boiling, [C/(C-D)]* ρ, pcf	147.62
Apparent Density, [A/(A-D)]* ρ, pcf	163.51
Volume of Permeable Voids, %, (C-A)/(C-D)*100	15.7
Bulk Density, Dry (Based on Volume) A/E, pcf	89.6
Porosity, n = 1-(Dry Bulk Density)/(Apparent Density)	0.452

ρ = Density of water



**Density, Absorption, Voids in Hardened Concrete**  
ASTM C 642-06

Project No: 6155-08-0031.29  
 Project Name: Twelve Permeable Concrete Mold Samples  
 Sample No: PAC002  
 Lab No: 11376

Tested by: EH  
 Test Date: 2/6/2012  
 Reviewed by: JW  
 Review Date: 2/14/2012

Date/Time	Oven Dry Mass (grams)	Difference in Mass (%)
2/7/2012	909.50	
2/8/2012	908.60	0.1

Date/Time	SD Mass after 48 hour Soak (grams)	Difference in Mass (%)
2/9/2012	982.10	
2/13/2012	986.00	0.40

\* after removing fragments

Oven Dry Mass, A (grams)	SD Mass after 48 hour Soak, B (grams)	SD Mass after 5 hour Boil, C (grams)	Apparent Mass in Water, D (grams)	Volume of Sample, E (Calculated from Dimension Measurements) (in <sup>3</sup> )
908.60	986.00	978.5	559.20	39.93

Absorption After Immersion, %, [(B-A)/A]*100	8.5
Absorption After Immersion & Boiling, %, [(C-A)/A]*100	7.7
Bulk Density, Dry, [A/(C-D)]* ρ, pcf	135.22
Bulk Density after Immersion, [B/(C-D)]* ρ, pcf	146.74
Bulk Density after Immersion & Boiling, [C/(C-D)]* ρ, pcf	145.62
Apparent Density, [A/(A-D)]* ρ, pcf	162.27
Volume of Permeable Voids, %, (C-A)/(C-D)*100	16.7
Bulk Density, Dry (Based on Volume) A/E, pcf	86.6
Porosity, n = 1-(Dry Bulk Density)/(Apparent Density)	0.466

ρ = Density of water



## Density, Absorption, Voids in Hardened Concrete

ASTM C 642-06

Project No: 6155-08-0031.29  
 Project Name: Twelve Permeable Concrete Mold Samples  
 Sample No: PAC003  
 Lab No: 11377

Tested by: EH  
 Test Date: 2/13/2012  
 Reviewed by: JW  
 Review Date: 2/20/2012

Date/Time	Oven Dry Mass (grams)	Difference in Mass (%)
2/13/2012	896.80	
2/14/2012	896.78	0.0

Date/Time	SD Mass after 48 hour Soak (grams)	Difference in Mass (%)
2/15/2012	967.80	
2/16/2012	970.80	0.31

\* after removing fragments

Oven Dry Mass, A (grams)	SD Mass after 48 hour Soak, B (grams)	SD Mass after 5 hour Boil, C (grams)	Apparent Mass in Water, D (grams)	Volume of Sample, E (Calculated from Dimension Measurements) (in <sup>3</sup> )
896.78	970.80	969.9	554.80	39.71

Absorption After Immersion, %, [(B-A)/A]*100	8.3
Absorption After Immersion & Boiling, %, [(C-A)/A]*100	8.2
Bulk Density, Dry, [A/(C-D)]* ρ, pcf	134.81
Bulk Density after Immersion, [B/(C-D)]* ρ, pcf	145.94
Bulk Density after Immersion & Boiling, [C/(C-D)]* ρ, pcf	145.80
Apparent Density, [A/(A-D)]* ρ, pcf	163.63
Volume of Permeable Voids, %, (C-A)/(C-D)*100	17.6
Bulk Density, Dry (Based on Volume) A/E, pcf	86.0
Porosity, n = 1-(Dry Bulk Density)/(Apparent Density)	0.475

ρ = Density of water



## Density, Absorption, Voids in Hardened Concrete

ASTM C 642-06

Project No: 6155-08-0031.29  
 Project Name: Twelve Permeable Concrete Mold Samples  
 Sample No: PAC004  
 Lab No: 11378

Tested by: EH  
 Test Date: 2/13/2012  
 Reviewed by: JW  
 Review Date: 2/20/2012

Date/Time	Oven Dry Mass (grams)	Difference in Mass (%)
2/13/2012	944.70	
2/14/2012	944.20	0.1

Date/Time	SD Mass after 48 hour Soak (grams)	Difference in Mass (%)
2/15/2012	1028.00	
2/16/2012	1026.80	-0.12

\* after removing fragments

Oven Dry Mass, A (grams)	SD Mass after 48 hour Soak, B (grams)	SD Mass after 5 hour Boil, C (grams)	Apparent Mass in Water, D (grams)	Volume of Sample, E (Calculated from Dimension Measurements) (in <sup>3</sup> )
944.20	1026.80	1025.00	587.30	40.93

Absorption After Immersion, %, [(B-A)/A]*100	8.7
Absorption After Immersion & Boiling, %, [(C-A)/A]*100	8.6
Bulk Density, Dry, [A/(C-D)]* ρ, pcf	134.61
Bulk Density after Immersion, [B/(C-D)]* ρ, pcf	146.38
Bulk Density after Immersion & Boiling, [C/(C-D)]* ρ, pcf	146.13
Apparent Density, [A/(A-D)]* ρ, pcf	165.08
Volume of Permeable Voids, %, (C-A)/(C-D)*100	18.5
Bulk Density, Dry (Based on Volume) A/E, pcf	87.8
Porosity, n = 1-(Dry Bulk Density)/(Apparent Density)	0.468

ρ = Density of water



**Density, Absorption, Voids in Hardened Concrete**  
ASTM C 642-06

Project No: 6155-08-0031.29  
 Project Name: Twelve Permeable Concrete Mold Samples  
 Sample No: PAC005  
 Lab No: 11379

Tested by: EH  
 Test Date: 2/13/2012  
 Reviewed by: JW  
 Review Date: 2/20/2012

Date/Time	Oven Dry Mass (grams)	Difference in Mass (%)
2/13/2012	855.54	
2/14/2012	854.71	0.1

Date/Time	SD Mass after 48 hour Soak (grams)	Difference in Mass (%)
2/15/2012	927.50	
2/16/2012	929.50	0.22

\* after removing fragments

Oven Dry Mass, A (grams)	SD Mass after 48 hour Soak, B (grams)	SD Mass after 5 hour Boil, C (grams)	Apparent Mass in Water, D (grams)	Volume of Sample, E (Calculated from Dimension Measurements) (in <sup>3</sup> )
854.71	929.50	928.70	533.20	38.73

Absorption After Immersion, %, [(B-A)/A]*100	8.8
Absorption After Immersion & Boiling, %, [(C-A)/A]*100	8.7
Bulk Density, Dry, [A/(C-D)]* ρ, pcf	134.85
Bulk Density after Immersion, [B/(C-D)]* ρ, pcf	146.65
Bulk Density after Immersion & Boiling, [C/(C-D)]* ρ, pcf	146.53
Apparent Density, [A/(A-D)]* ρ, pcf	165.89
Volume of Permeable Voids, %, (C-A)/(C-D)*100	18.7
Bulk Density, Dry (Based on Volume) A/E, pcf	84.0
Porosity, n = 1-(Dry Bulk Density)/(Apparent Density)	0.494

ρ = Density of water



## Density, Absorption, Voids in Hardened Concrete

ASTM C 642-06

Project No: 6155-08-0031.29  
 Project Name: Twelve Permeable Concrete Mold Samples  
 Sample No: PAC006  
 Lab No: 11380

Tested by: EH  
 Test Date: 2/16/2012  
 Reviewed by: JW  
 Review Date: 2/24/2012

Date/Time	Oven Dry Mass (grams)	Difference in Mass (%)
2/16/2012	921.50	
2/20/2012	919.80	0.2

Date/Time	SD Mass after 48 hour Soak (grams)	Difference in Mass (%)
2/21/2012	997.70	
2/22/2012	999.80	0.21

\* after removing fragments

Oven Dry Mass, A (grams)	SD Mass after 48 hour Soak, B (grams)	SD Mass after 5 hour Boil, C (grams)	Apparent Mass in Water, D (grams)	Volume of Sample, E (Calculated from Dimension Measurements) (in <sup>3</sup> )
919.80	999.80	995.80	573.10	39.04

Absorption After Immersion, %, [(B-A)/A]*100	8.7
Absorption After Immersion & Boiling, %, [(C-A)/A]*100	8.3
Bulk Density, Dry, [A/(C-D)]* ρ, pcf	135.78
Bulk Density after Immersion, [B/(C-D)]* ρ, pcf	147.59
Bulk Density after Immersion & Boiling, [C/(C-D)]* ρ, pcf	147.00
Apparent Density, [A/(A-D)]* ρ, pcf	165.55
Volume of Permeable Voids, %, (C-A)/(C-D)*100	18.0
Bulk Density, Dry (Based on Volume) A/E, pcf	89.7
Porosity, n = 1-(Dry Bulk Density)/(Apparent Density)	0.458

ρ = Density of water



**Density, Absorption, Voids in Hardened Concrete**  
ASTM C 642-06

Project No: 6155-08-0031.29  
 Project Name: Twelve Permeable Concrete Mold Samples  
 Sample No: PAC007  
 Lab No: 11381

Tested by: EH  
 Test Date: 2/16/2012  
 Reviewed by: JW  
 Review Date: 2/24/2012

Date/Time	Oven Dry Mass (grams)	Difference in Mass (%)
2/16/2012	898.00	
2/20/2012	896.10	0.2

Date/Time	SD Mass after 48 hour Soak (grams)	Difference in Mass (%)
2/21/2012	973.40	
2/22/2012	978.70	0.54

\* after removing fragments

Oven Dry Mass, A (grams)	SD Mass after 48 hour Soak, B (grams)	SD Mass after 5 hour Boil, C (grams)	Apparent Mass in Water, D (grams)	Volume of Sample, E (Calculated from Dimension Measurements) (in <sup>3</sup> )
896.10	978.70	971.30	557.90	38.28

Absorption After Immersion, %, [(B-A)/A]*100	9.2
Absorption After Immersion & Boiling, %, [(C-A)/A]*100	8.4
Bulk Density, Dry, [A/(C-D)]* ρ, pcf	135.26
Bulk Density after Immersion, [B/(C-D)]* ρ, pcf	147.73
Bulk Density after Immersion & Boiling, [C/(C-D)]* ρ, pcf	146.61
Apparent Density, [A/(A-D)]* ρ, pcf	165.34
Volume of Permeable Voids, %, (C-A)/(C-D)*100	18.2
Bulk Density, Dry (Based on Volume) A/E, pcf	89.1
Porosity, n = 1-(Dry Bulk Density)/(Apparent Density)	0.461

ρ = Density of water





**Density, Absorption, Voids in Hardened Concrete**  
ASTM C 642-06

Project No: 6155-06-0031.29  
 Project Name: Twelve Permeable Concrete Mold Samples  
 Sample No: PAC008  
 Lab No: 11382

Tested by: EH  
 Test Date: 2/16/2012  
 Reviewed by: JW  
 Review Date: 2/24/2012

Date/Time	Oven Dry Mass (grams)	Difference in Mass (%)
2/16/2012	867.90	
2/20/2012	866.00	0.2

Date/Time	SD Mass after 48 hour Soak (grams)	Difference in Mass (%)
2/21/2012	938.80	
2/22/2012	937.10	-0.18

\* after removing fragments

Oven Dry Mass, A (grams)	SD Mass after 48 hour Soak, B (grams)	SD Mass after 5 hour Boil, C (grams)	Apparent Mass in Water, D (grams)	Volume of Sample, E (Calculated from Dimension Measurements) (in <sup>3</sup> )
866.00	937.10	937.00	539.50	38.16

Absorption After Immersion, %, [(B-A)/A]*100	8.2
Absorption After Immersion & Boiling, %, [(C-A)/A]*100	8.2
Bulk Density, Dry, [A/(C-D)]* ρ, pcf	135.95
Bulk Density after Immersion, [B/(C-D)]* ρ, pcf	147.11
Bulk Density after Immersion & Boiling, [C/(C-D)]* ρ, pcf	147.09
Apparent Density, [A/(A-D)]* ρ, pcf	165.51
Volume of Permeable Voids, %, (C-A)/(C-D)*100	17.9
Bulk Density, Dry (Based on Volume) A/E, pcf	86.4
Porosity, n = 1-(Dry Bulk Density)/(Apparent Density)	0.478

ρ = Density of water



**Density, Absorption, Voids in Hardened Concrete**  
ASTM C 642-06

Project No: 6155-08-0031.29  
 Project Name: Twelve Permeable Concrete Mold Samples  
 Sample No: PAC009  
 Lab No: 11383

Tested by: EH  
 Test Date: 2/20/2012  
 Reviewed by: JW  
 Review Date: 2/28/2012

Date/Time	Oven Dry Mass (grams)	Difference in Mass (%)
2/20/2012	746.40	
2/21/2012	746.00	0.1

Date/Time	SD Mass after 48 hour Soak (grams)	Difference in Mass (%)
2/22/2012	841.90	
2/27/2012	839.90	-0.24

Oven Dry Mass, A (grams)	SD Mass after 48 hour Soak, B (grams)	SD Mass after 5 hour Boil, C (grams)	Apparent Mass in Water, D (grams)	Volume of Sample, E (Calculated from Dimension Measurements) (in <sup>3</sup> )
746.00	839.90	832.50	452.90	37.99

Absorption After Immersion, %, [(B-A)/A]*100	12.6
Absorption After Immersion & Boiling, %, [(C-A)/A]*100	11.6
Bulk Density, Dry, [A/(C-D)]* ρ, pcf	122.63
Bulk Density after Immersion, [B/(C-D)]* ρ, pcf	138.07
Bulk Density after Immersion & Boiling, [C/(C-D)]* ρ, pcf	136.85
Apparent Density, [A/(A-D)]* ρ, pcf	158.82
Volume of Permeable Voids, %, (C-A)/(C-D)*100	22.8
Bulk Density, Dry (Based on Volume) A/E, pcf	74.7
Porosity, n = 1-(Dry Bulk Density)/(Apparent Density)	0.529

ρ = Density of water



**Density, Absorption, Voids in Hardened Concrete**  
ASTM C 642-06

Project No: 6155-08-0031.29  
 Project Name: Twelve Permeable Concrete Mold Samples  
 Sample No: PAC010  
 Lab No: 11384

Tested by: EH  
 Test Date: 2/20/2012  
 Reviewed by: JW  
 Review Date: 2/28/2012

Date/Time	Oven Dry Mass (grams)	Difference in Mass (%)
2/20/2012	698.80	
2/21/2012	698.40	0.1

Date/Time	SD Mass after 48 hour Soak (grams)	Difference in Mass (%)
2/22/2012	780.70	
2/27/2012	779.90	-0.10

Oven Dry Mass, A (grams)	SD Mass after 48 hour Soak, B (grams)	SD Mass after 5 hour Boil, C (grams)	Apparent Mass in Water, D (grams)	Volume of Sample, E (Calculated from Dimension Measurements) (in <sup>3</sup> )
698.40	779.90	746.50	425.10	37.20

Absorption After Immersion, %, [(B-A)/A]*100	11.7
Absorption After Immersion & Boiling, %, [(C-A)/A]*100	6.9
Bulk Density, Dry, [A/(C-D)]* ρ, pcf	135.59
Bulk Density after Immersion, [B/(C-D)]* ρ, pcf	151.42
Bulk Density after Immersion & Boiling, [C/(C-D)]* ρ, pcf	144.93
Apparent Density, [A/(A-D)]* ρ, pcf	159.46
Volume of Permeable Voids, %, (C-A)/(C-D)*100	15.0
Bulk Density, Dry (Based on Volume) A/E, pcf	71.5
Porosity, n = 1-(Dry Bulk Density)/(Apparent Density)	0.552

ρ = Density of water



**Density, Absorption, Voids in Hardened Concrete**  
ASTM C 642-06

Project No: 6155-08-0031.29  
 Project Name: Twelve Permeable Concrete Mold Samples  
 Sample No: PAC011  
 Lab No: 11385

Tested by: EH  
 Test Date: 2/20/20112  
 Reviewed by: JW  
 Review Date: 2/28/2012

Date/Time	Oven Dry Mass (grams)	Difference in Mass (%)
2/20/2012	751.30	
2/21/2012	750.80	0.1

Date/Time	SD Mass after 48 hour Soak (grams)	Difference in Mass (%)
2/22/2012	842.40	
2/23/2012	833.60	-1.06

Oven Dry Mass, A (grams)	SD Mass after 48 hour Soak, B (grams)	SD Mass after 5 hour Boil, C (grams)	Apparent Mass in Water, D (grams)	Volume of Sample, E (Calculated from Dimension Measurements) (in <sup>3</sup> )
750.80	833.60	836.10	450.50	37.20

Absorption After Immersion, %, [(B-A)/A]*100	11.0
Absorption After Immersion & Boiling, %, [(C-A)/A]*100	11.4
Bulk Density, Dry, [A/(C-D)]* ρ, pcf	121.50
Bulk Density after Immersion, [B/(C-D)]* ρ, pcf	134.90
Bulk Density after Immersion & Boiling, [C/(C-D)]* ρ, pcf	135.30
Apparent Density, [A/(A-D)]* ρ, pcf	156.01
Volume of Permeable Voids, %, (C-A)/(C-D)*100	22.1
Bulk Density, Dry (Based on Volume) A/E, pcf	76.8
Porosity, n = 1-(Dry Bulk Density)/(Apparent Density)	0.508

ρ = Density of water



**Density, Absorption, Voids in Hardened Concrete**  
ASTM C 642-06

Project No: 6155-08-0031.29  
 Project Name: Twelve Permeable Concrete Mold Samples  
 Sample No: PAC012  
 Lab No: 11386

Tested by: EH  
 Test Date: 2/20/2012  
 Reviewed by: JW  
 Review Date: 2/28/2012

Date/Time	Oven Dry Mass (grams)	Difference in Mass (%)
2/21/2012	776.90	
2/22/2012	776.90	0.0

Date/Time	SD Mass after 48 hour Soak (grams)	Difference in Mass (%)
2/23/2012	880.20	
2/27/2012	877.90	-0.26

Oven Dry Mass, A (grams)	SD Mass after 48 hour Soak, B (grams)	SD Mass after 5 hour Boil, C (grams)	Apparent Mass in Water, D (grams)	Volume of Sample, E (Calculated from Dimension Measurements) (in <sup>3</sup> )
776.90	877.90	874.80	469.70	39.08

Absorption After Immersion, %, [(B-A)/A]*100	13.0
Absorption After Immersion & Boiling, %, [(C-A)/A]*100	12.6
Bulk Density, Dry, [A/(C-D)]* ρ, pcf	119.67
Bulk Density after Immersion, [B/(C-D)]* ρ, pcf	135.23
Bulk Density after Immersion & Boiling, [C/(C-D)]* ρ, pcf	134.75
Apparent Density, [A/(A-D)]* ρ, pcf	157.81
Volume of Permeable Voids, %, (C-A)/(C-D)*100	24.2
Bulk Density, Dry (Based on Volume) A/E, pcf	75.7
Porosity, n = 1-(Dry Bulk Density)/(Apparent Density)	0.520

ρ = Density of water



**HYDRAULIC CONDUCTIVITY**

Project No. *6155-08-0031.29* Tested By *JW*  
 Project Name *Twelve Permeable concrete Mold S* Test Date *1/31/2012*  
 Boring No. *PAC001* Reviewed By  
 Sample No. *PAC001* Review Date  
 Sample Depth *N/A* Lab No. *11375*  
 Sample Description *Concrete Core 405 No Amendment*

*ASTM D5084-03 - (Method C Falling Head Rising Tail)*

Sample Type:	Core
Sample Orientation:	Vertical
Initial Water Content, %:	5.1
Wet Unit Weight, pcf:	94.3
Dry Unit Weight, pcf:	89.7
Compaction, %:	N/A
<b>Hydraulic Conductivity, cm/sec. @20 °C</b>	<b>3.8E-04</b>

Remarks: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

**PERMEABILITY TEST  
(ASTM D5084 - 03) (Method C, Increasing Tailwater Level)**



Project Number 6155-08-0031.29      Tested By JW  
 Project Name Twelve Permeable concrete Mold Samples      Test Date 01/31/12  
 Boring No. PAC001      Reviewed By  
 Sample No. PAC001      Review Date  
 Sample Depth N/A      Lab No. 11375  
 Sample Description Concrete Core 405 No Amendment

Initial Sample Data			Final Sample Data		
Length, in	Diameter, in		Pan No.	N/A	
Location 1	5.525	Location 1	2.938	Wet Soil+Pan, g	986.32
Location 2	5.800	Location 2	2.924	Dry Soil + Pan, g	909.00
Location 3	5.738	Location 3	2.960	Pan Weight, g	0.00
Average	5.688	Average	2.941	Moisture Content, %	8.5
Volume, in <sup>3</sup>	38.63	Wet Soil + Tare, g	955.54	Dry Unit Weight, pcf	92.1
SG Measured	2.62	Tare Weight, g	0.00	Saturation, %	28.7
Soil Sample Wt., g	955.54	Dry Soil + Tare, g	909.00	Diameter, in.	N/A
Dry UW, pcf	89.7	Moisture Content, %	5.1	Length, in.	N/A
Saturation, %	16.3			Volume, in <sup>3</sup>	N/A

Consolidation	
Chamber Pressure, psi	49.6
Back Pressure, psi	44.6
Confining Pressure, psi	5
Initial Burette Reading	32.3
Final Burette Reading	15.8
Volume Change, cc	16.5
Permeant used	Water

Time (sec)	H <sub>a</sub> (cm)	H <sub>i</sub> (cm)	H <sub>b</sub> (cm)	H <sub>2</sub> (cm)	Temp (°C)	Initial Hydraulic Gradient	Final Hydraulic Gradient	k cm/sec at 20 °C
20	51.0	90.0	62.3	83.6	21.3	2.7	1.5	7.98E-04
20	48.1	94.4	57.3	85.3	21.3	3.2	1.9	6.63E-04
10	62.0	94.5	64.0	93.0	21.3	2.2	2.0	3.01E-04
20	59.0	93.2	62.5	91.8	21.3	2.4	2.0	2.04E-04
60	62.5	94.0	68.8	85.3	21.3	2.2	1.1	2.84E-04
35	59.5	94.0	62.0	91.0	21.3	2.4	2.0	1.31E-04

No. of Trials	Sample Type	Max. Density (pcf)	Compaction %	Sample Orientation
6	Core	N/A	N/A	Vertical

Avg. k at 20 °C      3.85E-04 cm/sec

a = area of burette in cm<sup>2</sup>      H<sub>b</sub> = final inlet head in cm      a = 0.16 cm<sup>2</sup>      Remarks:  
 L = length of sample in cm      H<sub>1</sub> = initial outlet head in cm      A = 43.82 cm<sup>2</sup>  
 A = area of sample in cm<sup>2</sup>      t = time in seconds      L = 14.45 cm



**HYDRAULIC CONDUCTIVITY**

Project No. *6155-08-0031.29* Tested By *JW*  
 Project Name *Twelve Permeable concrete Mold S* Test Date *1/31/2012*  
 Boring No. *PAC002* Reviewed By  
 Sample No. *PAC002* Review Date  
 Sample Depth *N/A* Lab No. *11376*  
 Sample Description *Concrete Core 405 No Amendment*

**ASTM D5084-03 - (Method C Falling Head RisingTail)**

Sample Type:	<i>UD</i>
Sample Orientation:	<i>Vertical</i>
Initial Water Content, %:	<i>5.5</i>
Wet Unit Weight, pcf:	<i>91.5</i>
Dry Unit Weight, pcf:	<i>86.7</i>
Compaction, %:	<i>N/A</i>
Hydraulic Conductivity, cm/sec. @20 °C	<i>5.0E-04</i>

Remarks: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_



**PERMEABILITY TEST  
(ASTM D5084 - 03) (Method C, Increasing Tailwater Level)**



Project Number 6155-08-0031.29 Tested By JW  
 Project Name Twelve Permeable concrete Mold Samples Test Date 01/31/12  
 Boring No. PAC002 Reviewed By  
 Sample No. PAC002 Review Date  
 Sample Depth N/A Lab No. 11376  
 Sample Description Concrete Core 405 No Amendment

Initial Sample Data			Final Sample Data		
Length, in	Diameter, in		Pan No.	N/A	
Location 1	5.698	Location 1	2.971	Wet Soil+Pan, g	985.93
Location 2	5.769	Location 2	2.947	Dry Soil + Pan, g	908.60
Location 3	5.886	Location 3	2.976	Pan Weight, g	0.00
Average	5.784	Average	2.965	Moisture Content, %	8.5
Volume, in <sup>3</sup>	39.93	Wet Soil + Tare, g	958.61	Dry Unit Weight, pcf	89.8
SG Measured	2.6	Tare Weight, g	0.00	Saturation, %	27.4
Soil Sample Wt., g	958.61	Dry Soil + Tare, g	908.60	Diameter, in.	N/A
Dry UW, pcf	86.7	Moisture Content, %	5.5	Length, in.	N/A
Saturation, %	16.4			Volume, in <sup>3</sup>	N/A

Consolidation

Chamber Pressure, psi	49.7
Back Pressure, psi	39.7
Confining Pressure, psi	10
Initial Burette Reading	35.0
Final Burette Reading	12.8
Volume Change, cc	22.2

Permeant used Water

Time (sec)	H <sub>a</sub> (cm)	H <sub>1</sub> (cm)	H <sub>b</sub> (cm)	H <sub>2</sub> (cm)	Temp (°C)	Initial Hydraulic Gradient		Final Hydraulic Gradient		k cm/sec at 20 °C
						Gradient	Temp	Gradient	Temp	
20	40.5	99.1	49.5	90.0	22.7	4.0	2.8	4.87E-04	22.7	4.57E-04
20	51.5	102.2	59.2	92.7	20.8	3.5	2.3	5.47E-04	20.8	5.36E-04
20	38.9	92.7	48.6	84.9	20.8	3.7	2.5	5.19E-04	20.8	5.09E-04
40	48.6	84.5	57.8	75.2	20.8	2.4	1.2	4.78E-04	20.8	4.69E-04
60	45.2	92.5	61.8	75.3	20.8	3.2	0.9	5.52E-04	20.8	5.41E-04
60	49.9	86.8	63.9	74.7	20.8	2.5	0.7	5.40E-04	20.8	5.30E-04
15	54.1	84.5	57.7	81.3	20.8	2.1	1.6	4.45E-04	20.8	4.37E-04

No. of Trials	Sample Type	Max. Density (pcf)	Compaction %	Sample Orientation
7	UID	N/A	N/A	Vertical

Avg. k at 20 °C **4.97E-04** cm/sec

a = area of burette in cm<sup>2</sup>      H<sub>a</sub> = initial inlet head in cm      a = 0.16 cm<sup>2</sup>      Remarks:  
 L = length of sample in cm      H<sub>1</sub> = initial outlet head in cm      A = 44.54 cm<sup>2</sup>  
 A = area of sample in cm<sup>2</sup>      t = time in seconds      L = 14.69 cm



**HYDRAULIC CONDUCTIVITY**

Project No. *6155-08-0031.29* Tested By *JW*  
 Project Name *Twelve Permeable concrete Mold S* Test Date *2/5/2012*  
 Boring No. *PAC003* Reviewed By  
 Sample No. *PAC003* Review Date  
 Sample Depth *N/A* Lab No. *11377*  
 Sample Description *Concrete Core 405 No Amendment*

***ASTM D5084-03 - (Method C Falling Head Rising Tail)***

Sample Type:	<i>UD</i>
Sample Orientation:	<i>Vertical</i>
Initial Water Content, %:	<i>5.2</i>
Wet Unit Weight, pcf:	<i>90.8</i>
Dry Unit Weight, pcf:	<i>86.4</i>
Compaction, %:	<i>N/A</i>
<b>Hydraulic Conductivity, cm/sec. @20 °C</b>	<b><i>6.2E-04</i></b>

Remarks: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

**PERMEABILITY TEST  
(ASTM D5084 - 03) (Method C, Increasing Tailwater Level)**



Project Number 6155-08-0031.29 Tested By JW  
 Project Name Twelve Permeable concrete Mold Samples Test Date 02/05/12  
 Boring No. PAC003 Reviewed By  
 Sample No. PAC003 Review Date  
 Sample Depth N/A Lab No. 11377  
 Sample Description Concrete Core 405 No Amendment

Initial Sample Data			Final Sample Data		
Length, in	Diameter, in		Pan No.	N/A	
Location 1	5.672	Location 1	2.959	Wet Soil+Pan, g	974.46
Location 2	5.748	Location 2	2.963	Dry Soil + Pan, g	896.78
Location 3	5.836	Location 3	2.972	Pan Weight, g	0.00
Average	5.752	Average	2.965	Moisture Content, %	8.7
Volume, in <sup>3</sup>	39.71	Wet Soil + Tare, g	946.48	Dry Unit Weight, pcf	89.9
SG Measured	2.62	Tare Weight, g	0.00	Saturation, %	27.7
Soil Sample Wt., g	946.48	Dry Soil + Tare, g	900.00	Diameter, in.	N/A
Dry UW, pcf	86.4	Moisture Content, %	5.2	Length, in.	N/A
Saturation, %	15.2			Volume, in <sup>3</sup>	N/A

Consolidation	
Chamber Pressure, psi	54.6
Back Pressure, psi	49.6
Confining Pressure, psi	5
Initial Burette Reading	32.8
Final Burette Reading	7.0
Volume Change, cc	25.8

Permeant used Water

Time (sec)	H <sub>a</sub> (cm)	H <sub>1</sub> (cm)	H <sub>0</sub> (cm)	H <sub>2</sub> (cm)	Temp (°C)	Initial Hydraulic Gradient		Final Hydraulic Gradient		k cm/sec at 20 °C
						Gradient	Gradient	Gradient	Gradient	
15	17.0	97.7	29.4	86.7	21.2	5.5	3.9	5.99E-04	5.82E-04	5.82E-04
30	17.0	97.7	35.3	82.0	21.2	5.5	3.2	4.79E-04	4.65E-04	4.65E-04
45	17.0	97.7	38.5	79.8	21.2	5.5	2.8	3.91E-04	3.80E-04	3.80E-04
60	17.0	97.7	40.2	78.4	21.2	5.5	2.6	3.27E-04	3.18E-04	3.18E-04
15	16.3	93.1	33.5	78.5	21.2	5.3	3.1	9.35E-04	9.09E-04	9.09E-04
30	16.3	93.1	40.5	68.5	21.2	5.3	1.9	8.83E-04	8.58E-04	8.58E-04
15	21.0	81.6	33.2	69.7	21.2	4.1	2.5	8.87E-04	8.62E-04	8.62E-04

No. of Trials	Sample Type	Max. Density (pcf)	Compaction %	Sample Orientation
7	UD	N/A	N/A	Vertical

Avg. k at 20 °C **6.25E-04** cm/sec

a = area of burette in cm<sup>2</sup> H<sub>0</sub> = initial inlet head in cm  
 L = length of sample in cm H<sub>1</sub> = initial outlet head in cm  
 A = area of sample in cm<sup>2</sup> t = time in seconds  
 a = 0.16 cm<sup>2</sup>  
 A = 44.54 cm<sup>2</sup>  
 L = 14.61 cm

Remarks:



**HYDRAULIC CONDUCTIVITY**

Project No. *6155-08-0031.29* Tested By *JW*  
 Project Name *Twelve Permeable concrete Mold S* Test Date *2/5/2012*  
 Boring No. *PAC004* Reviewed By  
 Sample No. *PAC004* Review Date  
 Sample Depth *N/A* Lab No. *11378*  
 Sample Description *Concrete Core 405 No Amendment*

***ASTM D5084-03 - (Method C Falling Head Rising Tail)***

Sample Type:	<i>UD</i>
Sample Orientation:	<i>Vertical</i>
Initial Water Content, %:	<i>7.7</i>
Wet Unit Weight, pcf:	<i>94.7</i>
Dry Unit Weight, pcf:	<i>87.9</i>
Compaction, %:	<i>N/A</i>
<b>Hydraulic Conductivity, cm/sec. @20 °C</b>	<b><i>5.0E-03</i></b>

Remarks: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

**PERMEABILITY TEST  
(ASTM D5084 - 03) (Method C, Increasing Tailwater Level)**



Project Number 6155-08-0031.29 Tested By JW  
 Project Name Twelve Permeable concrete Mold Samples Test Date 02/05/12  
 Boring No. PAC004 Reviewed By  
 Sample No. PAC004 Review Date  
 Sample Depth N/A Lab No. 11378  
 Sample Description Concrete Core 405 No Amendment

Initial Sample Data			Final Sample Data		
Length, in	Diameter, in		Pan No.	N/A	
Location 1	5.939	Location 1	3.005	Wet Soil+Pan, g	1037.78
Location 2	5.786	Location 2	3.003	Dry Soil + Pan, g	944.20
Location 3	5.750	Location 3	2.965	Pan Weight, g	0.00
Average	5.825	Average	2.991	Moisture Content, %	9.9
Volume, in <sup>3</sup>	40.93	Wet Soil + Tare, g	1016.91	Dry Unit Weight, pcf	90.8
SG Measured	2.65	Tare Weight, g	0.00	Saturation, %	32.0
Soil Sample Wt., g	1016.91	Dry Soil + Tare, g	944.20	Diameter, in.	N/A
Dry UW, pcf	87.9	Moisture Content, %	7.7	Length, in.	N/A
Saturation, %	23.2			Volume, in <sup>3</sup>	N/A

Consolidation

Chamber Pressure, psi	49.6
Back Pressure, psi	44.6
Confining Pressure, psi	5
Initial Burette Reading	33.3
Final Burette Reading	11.7
Volume Change, cc	21.6

Permeant used Water

Time (sec)	H <sub>a</sub> (cm)	H <sub>1</sub> (cm)	H <sub>b</sub> (cm)	H <sub>2</sub> (cm)	Temp (°C)	Initial Hydraulic Gradient		Final Hydraulic Gradient		k cm/sec at 20 °C
						Gradient	Temp (°C)	Gradient	Temp (°C)	
5	35.7	94.5	52.5	71.4	21.2	4.0	1.3	5.93E-03	21.2	5.76E-03
5	23.9	71.0	39.7	57.8	21.2	3.2	1.2	4.99E-03	21.2	4.85E-03
5	18.0	64.2	34.1	51.5	21.2	3.1	1.2	5.10E-03	21.2	4.95E-03
5	34.0	87.9	52.6	72.5	21.2	3.6	1.3	5.20E-03	21.2	5.06E-03
5	32.5	71.6	46.0	61.7	21.2	2.6	1.1	4.77E-03	21.2	4.63E-03
5	20.5	59.8	34.1	49.4	21.2	2.7	1.0	4.93E-03	21.2	4.79E-03
5	22.5	70.8	38.3	57.3	21.2	3.3	1.3	4.87E-03	21.2	4.73E-03

No. of Trials	Sample Type	Max. Density (pcf)	Compaction %	Sample Orientation
7	UD	N/A	N/A	Vertical

Avg. k at 20 °C **4.97E-03 cm/sec**

a = area of burette in cm<sup>2</sup>    H<sub>a</sub> = initial inlet head in cm    a = 0.16 cm<sup>2</sup>    Remarks:  
 L = length of sample in cm    H<sub>1</sub> = initial outlet head in cm    A = 45.33 cm<sup>2</sup>  
 A = area of sample in cm<sup>2</sup>    t = time in seconds    L = 14.80 cm



**HYDRAULIC CONDUCTIVITY**

Project No.	<i>6155-08-0031.29</i>	Tested By	<i>JW</i>
Project Name	<i>Twelve Permeable concrete Mold S</i>	Test Date	<i>2/5/2012</i>
Boring No.	<i>PAC005</i>	Reviewed By	
Sample No.	<i>PAC005</i>	Review Date	
Sample Depth	<i>N/A</i>	Lab No.	<i>11379</i>
Sample Description <i>Concrete Core 20% APA Extra 403</i>			

*ASTM D5084-03 - (Method C Falling Head Rising Tail)*

Sample Type:	<i>UD</i>
Sample Orientation:	<i>Vertical</i>
Initial Water Content, %:	<i>5.5</i>
Wet Unit Weight, pcf:	<i>88.7</i>
Dry Unit Weight, pcf:	<i>84.1</i>
Compaction, %:	<i>N/A</i>
<b>Hydraulic Conductivity, cm/sec. @20 °C</b>	<b><i>4.0E-03</i></b>

Remarks: \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

**PERMEABILITY TEST  
(ASTM D5084 - 03) (Method C, Increasing Tailwater Level)**

Project Number 6155-08-0031.29      Tested By JW  
 Project Name Twelve Permeable concrete Mold Samples      Test Date 02/05/12  
 Boring No. PAC005      Reviewed By  
 Sample No. PAC005      Review Date  
 Sample Depth N/A      Lab No. 11379  
 Sample Description Concrete Core 20% APA Extra 403



Initial Sample Data			Final Sample Data	
Length, in	Diameter, in		Pan No.	N/A
Location 1	5.727	Location 1	2.905	Wet Soil+Pan, g
Location 2	5.791	Location 2	2.896	Dry Soil + Pan, g
Location 3	5.843	Location 3	2.956	Pan Weight, g
Average	5.787	Average	2.919	Moisture Content, %
Volume, in <sup>3</sup>	38.73	Wet Soil + Tare, g	901.78	Dry Unit Weight, pcf
SG Measured	2.66	Tare Weight, g	0.00	Saturation, %
Soil Sample Wt., g	901.78	Dry Soil + Tare, g	854.71	Diameter, in.
Dry UW, pcf	84.1	Moisture Content, %	5.5	Length, in.
Saturation, %	15.0			Volume, in <sup>3</sup>

Consolidation	
Chamber Pressure, psi	54.6
Back Pressure, psi	49.6
Confining Pressure, psi	5
Initial Burette Reading	32.8
Final Burette Reading	14.4
Volume Change, cc	18.4
Permeant used	Water

Time (sec)	H <sub>a</sub> (cm)	H <sub>1</sub> (cm)	H <sub>2</sub> (cm)	H <sub>3</sub> (cm)	Temp (°C)	Initial Hydraulic Gradient	Final Hydraulic Gradient	k cm/sec at 20 °C
5	35.1	98.8	87.2	49.5	21.3	4.3	2.6	2.77E-03
5	28.4	87.2	77.0	39.6	21.3	4.0	2.5	2.46E-03
5	26.6	85.0	77.1	39.0	21.3	4.0	2.6	2.33E-03
5	24.7	81.0	71.5	36.5	21.3	3.8	2.4	2.59E-03
5	24.0	83.5	66.5	42.3	21.3	4.0	1.6	4.90E-03
6	28.2	82.9	62.0	51.0	21.3	3.7	0.7	7.28E-03
5	29.1	85.0	65.3	49.0	21.3	3.8	1.1	6.71E-03

No. of Trials	Sample Type	Max. Density (pcf)	Compaction %	Sample Orientation
7	UD	N/A	N/A	Vertical

Avg. k at 20 °C      4.03E-03 cm/sec

a = area of burette in cm<sup>2</sup>      H<sub>a</sub> = initial inlet head in cm      a = 0.16 cm<sup>2</sup>  
 L = length of sample in cm      H<sub>1</sub> = initial outlet head in cm      A = 43.17 cm<sup>2</sup>  
 A = area of sample in cm<sup>2</sup>      t = time in seconds      L = 14.70 cm



**HYDRAULIC CONDUCTIVITY**

Project No. *6155-08-0031.29* Tested By *JW*  
 Project Name *Twelve Permeable concrete Mold S* Test Date *2/10/2012*  
 Boring No. *PAC006* Reviewed By  
 Sample No. *PAC006* Review Date  
 Sample Depth *N/A* Lab No. *11380*  
 Sample Description *Concrete Core 20% APA Extra 403*

***ASTM D5084-03 - (Method C Falling Head Rising Tail)***

Sample Type:	<i>UD</i>
Sample Orientation:	<i>Vertical</i>
Initial Water Content, %:	<i>5.6</i>
Wet Unit Weight, pcf:	<i>94.8</i>
Dry Unit Weight, pcf:	<i>89.8</i>
Compaction, %:	<i>N/A</i>
<b>Hydraulic Conductivity, cm/sec. @20 °C</b>	<b><i>4.1E-03</i></b>

Remarks: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_



**PERMEABILITY TEST  
(ASTM D5084 - 03) (Method C, Increasing Tailwater Level)**



Project Number 6155-08-0031.29 Tested By JW  
 Project Name Twelve Permeable concrete Mold Samples Test Date 02/10/12  
 Boring No. PAC006 Reviewed By  
 Sample No. PAC006 Review Date  
 Sample Depth N/A Lab No. 11380  
 Sample Description Concrete Core 20% APA Extra 403

Initial Sample Data			Final Sample Data		
Length, in	Diameter, in		Pan No.	N/A	
Location 1	5.775	Location 1	2.953	Wet Soil+Pan, g	1007.67
Location 2	5.758	Location 2	2.972	Dry Soil + Pan, g	919.80
Location 3	5.655	Location 3	2.912	Pan Weight, g	0.00
Average	5.729	Average	2.946	Moisture Content, %	9.6
Volume, in <sup>3</sup>	39.04	Wet Soil + Tare, g	971.10	Dry Unit Weight, pcf	93.3
SG Measured	2.65	Tare Weight, g	0.00	Saturation, %	32.8
Soil Sample Wt., g	971.1	Dry Soil + Tare, g	919.80	Diameter, in.	N/A
Dry UW, pcf	89.8	Moisture Content, %	5.6	Length, in.	N/A
Saturation, %	17.5			Volume, in <sup>3</sup>	N/A

Consolidation	
Chamber Pressure, psi	39.6
Back Pressure, psi	34.6
Confining Pressure, psi	5
Initial Burette Reading	35.2
Final Burette Reading	10.8
Volume Change, cc	24.4
Permeant used	Water

Time (sec)	H <sub>a</sub> (cm)	H <sub>1</sub> (cm)	H <sub>b</sub> (cm)	H <sub>2</sub> (cm)	Temp (°C)	Initial Hydraulic Gradient		Final Hydraulic Gradient		k cm/sec at 20 °C
						Gradient	Temp (°C)	Gradient	Temp (°C)	
5	60.0	102.8	73.4	91.5	21.1	2.9	1.2	4.56E-03	4.44E-03	4.44E-03
5	60.5	103.0	73.2	92.5	21.1	2.9	1.3	4.18E-03	4.07E-03	4.07E-03
5	60.3	103.1	73.2	92.5	21.1	2.9	1.3	4.22E-03	4.11E-03	4.11E-03
5	60.3	102.0	72.9	91.5	21.1	2.9	1.3	4.28E-03	4.16E-03	4.16E-03
5	60.2	101.8	72.8	91.4	21.1	2.9	1.3	4.26E-03	4.15E-03	4.15E-03
6	60.1	104.8	73.4	93.8	21.1	3.1	1.4	3.46E-03	3.37E-03	3.37E-03
5	58.5	100.5	71.1	90.0	21.1	2.9	1.3	4.23E-03	4.12E-03	4.12E-03

No. of Trials	Sample Type	Max. Density (pcf)	Compaction %	Sample Orientation
7	UD	N/A	N/A	Vertical

Avg. k at 20 °C **4.06E-03** cm/sec

a = area of burette in cm<sup>2</sup>      H<sub>b</sub> = final inlet head in cm      a = 0.16 cm<sup>2</sup>      Remarks:  
 L = length of sample in cm      H<sub>1</sub> = initial outlet head in cm      A = 43.97 cm<sup>2</sup>  
 A = area of sample in cm<sup>2</sup>      t = time in seconds      L = 14.55 cm



**HYDRAULIC CONDUCTIVITY**

Project No.	<i>6155-08-0031.29</i>	Tested By	<i>JW</i>
Project Name	<i>Twelve Permeable concrete Mold S</i>	Test Date	<i>2/10/2012</i>
Boring No.	<i>PAC007</i>	Reviewed By	
Sample No.	<i>PAC007</i>	Review Date	
Sample Depth	<i>N/A</i>	Lab No.	<i>11381</i>
Sample Description <i>Concrete Core 20% APA Extra 403</i>			

*ASTM D5084-03 - (Method C Falling Head RisingTail)*

Sample Type:	<i>UD</i>
Sample Orientation:	<i>Vertical</i>
Initial Water Content, %:	<i>5.3</i>
Wet Unit Weight, pcf:	<i>93.9</i>
Dry Unit Weight, pcf:	<i>89.2</i>
Compaction, %:	<i>N/A</i>
<b>Hydraulic Conductivity, cm/sec. @20 °C</b>	<b><i>1.1E-03</i></b>

Remarks: \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

**PERMEABILITY TEST  
(ASTM D5084 - 03) (Method C, Increasing Tailwater Level)**



Project Number 6155-08-0031.29      Tested By JW  
 Project Name Twelve Permeable concrete Mold Samples      Test Date 02/10/12  
 Boring No. PAC007      Reviewed By  
 Sample No. PAC007      Review Date  
 Sample Depth N/A      Lab No. 11381  
 Sample Description Concrete Core 20% APA Extra 403

Initial Sample Data			Final Sample Data		
Length, in	Diameter, in		Pan No.	N/A	
Location 1	5.696	Location 1	2.893	Wet Soil+Pan, g	982.57
Location 2	5.786	Location 2	2.912	Dry Soil + Pan, g	896.10
Location 3	5.770	Location 3	2.929	Pan Weight, g	0.00
Average	5.751	Average	2.911	Moisture Content, %	9.6
Volume, in <sup>3</sup>	38.28	Wet Soil + Tare, g	943.79	Dry Unit Weight, pcf	92.4
SG Measured	2.65	Tare Weight, g	0.00	Saturation, %	32.4
Soil Sample Wt., g	943.79	Dry Soil + Tare, g	896.10	Diameter, in.	N/A
Dry UW, pcf	89.2	Moisture Content, %	5.3	Length, in.	N/A
Saturation, %	16.5			Volume, in <sup>3</sup>	N/A

Consolidation	
Chamber Pressure, psi	39.6
Back Pressure, psi	34.6
Confining Pressure, psi	5
Initial Burette Reading	35.2
Final Burette Reading	13.5
Volume Change, cc	21.7
Permeant used	Water

Time (sec)	H <sub>a</sub> (cm)	H <sub>1</sub> (cm)	H <sub>2</sub> (cm)	H <sub>b</sub> (cm)	Temp (°C)	Initial Hydraulic Gradient		Final Hydraulic Gradient		k cm/sec at 20 °C
						Gradient	Temp (°C)	Gradient	Temp (°C)	
5	62.0	102.0	97.9	66.7	21.0	2.7	2.1	1.35E-03	21.0	1.32E-03
10	62.0	102.0	94.9	70.3	21.0	2.7	1.7	1.32E-03	21.0	1.29E-03
5	60.0	100.6	96.9	64.2	21.0	2.8	2.2	1.18E-03	21.0	1.15E-03
10	60.0	100.6	94.2	67.6	21.0	2.8	1.8	1.15E-03	21.0	1.12E-03
5	58.6	100.0	96.7	62.4	21.0	2.8	2.3	1.02E-03	21.0	1.00E-03
10	58.6	100.0	94.2	65.3	21.0	2.8	2.0	9.78E-04	21.0	9.55E-04
15	58.6	100.0	92.3	67.6	21.0	2.8	1.7	9.37E-04	21.0	9.15E-04

No. of Trials	Sample Type	Max. Density (pcf)	Compaction %	Sample Orientation
7	UD	N/A	N/A	Vertical

Avg. k at 20 °C      1.11E-03 cm/sec

a = area of burette in cm<sup>2</sup>      H<sub>a</sub> = initial inlet head in cm      H<sub>b</sub> = final inlet head in cm      a = 0.16 cm<sup>2</sup>  
 L = length of sample in cm      H<sub>1</sub> = initial outlet head in cm      H<sub>2</sub> = final outlet head in cm      A = 42.95 cm<sup>2</sup>  
 A = area of sample in cm<sup>2</sup>      t = time in seconds      L = 14.61 cm



**HYDRAULIC CONDUCTIVITY**

Project No. *6155-08-0031.29* Tested By *JW*  
 Project Name *Twelve Permeable concrete Mold S* Test Date *2/10/2012*  
 Boring No. *PAC008* Reviewed By  
 Sample No. *PAC008* Review Date  
 Sample Depth *N/A* Lab No. *11382*  
 Sample Description *Concrete Core 20% APA Extra 403*

***ASTM D5084-03 - (Method C Falling Head Rising Tail)***

Sample Type:	<i>UD</i>
Sample Orientation:	<i>Vertical</i>
Initial Water Content, %:	<i>5.2</i>
Wet Unit Weight, pcf:	<i>91.0</i>
Dry Unit Weight, pcf:	<i>86.5</i>
Compaction, %:	<i>N/A</i>
<b>Hydraulic Conductivity, cm/sec. @20 °C</b>	<b><i>4.6E-03</i></b>

Remarks: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

**PERMEABILITY TEST  
(ASTM D5084 - 03) (Method C, Increasing Tailwater Level)**



Project Number 6155-08-0031.29 Tested By JW  
 Project Name Twelve Permeable concrete Mold Samples Test Date 02/10/12  
 Boring No. PAC008 Reviewed By  
 Sample No. PAC008 Review Date  
 Sample Depth N/A Lab No. 11382  
 Sample Description Concrete Core 20% APA Extra 403

Initial Sample Data			Final Sample Data		
Length, in	Diameter, in		Pan No.	N/A	
Location 1	5.590	Location 1	2.985	Wet Soil+Pan, g	946.37
Location 2	5.640	Location 2	2.928	Dry Soil + Pan, g	866.00
Location 3	5.533	Location 3	2.933	Pan Weight, g	0.00
Average	5.588	Average	2.949	Moisture Content, %	9.3
Volume, in <sup>3</sup>	38.16	Wet Soil + Tare, g	911.30	Dry Unit Weight, pcf	90.1
SG Measured	2.65	Tare Weight, g	0.00	Saturation, %	29.4
Soil Sample Wt., g	911.3	Dry Soil + Tare, g	866.00	Diameter, in.	N/A
Dry UW, pcf	86.5	Moisture Content, %	5.2	Length, in.	N/A
Saturation, %	15.2			Volume, in <sup>3</sup>	N/A

**Consolidation**

Chamber Pressure, psi	39.0
Back Pressure, psi	34.0
Confining Pressure, psi	5
Initial Burette Reading	35.2
Final Burette Reading	10.2
Volume Change, cc	25.0

Permeant used: Water

Time (sec)	H <sub>0</sub> (cm)	H <sub>1</sub> (cm)	H <sub>0</sub> (cm)	H <sub>2</sub> (cm)	Temp (°C)	Initial Hydraulic Gradient	Final Hydraulic Gradient	k cm/sec at 20 °C
5	55.0	92.9	67.0	83.2	21.1	2.7	1.1	4.38E-03
5	49.6	86.0	61.7	76.5	21.1	2.6	1.0	4.64E-03
5	50.5	89.7	63.0	78.8	21.1	2.8	1.1	4.68E-03
5	50.0	88.0	62.5	77.3	21.1	2.7	1.0	4.86E-03
5	41.0	77.2	52.6	67.1	21.1	2.6	1.0	4.72E-03
5	52.5	90.7	64.9	80.0	21.1	2.7	1.1	4.78E-03
5	54.6	89.5	66.0	79.8	21.1	2.5	1.0	4.78E-03

No. of Trials	Sample Type	Max. Density (pcf)	Compaction %	Sample Orientation
7	UD	N/A	N/A	Vertical

**Avg. k at 20 °C 4.57E-03 cm/sec**

a = area of burette in cm<sup>2</sup>      H<sub>0</sub> = initial inlet head in cm      a = 0.16 cm<sup>2</sup>      Remarks:  
 L = length of sample in cm      H<sub>1</sub> = initial outlet head in cm      A = 44.06 cm<sup>2</sup>  
 A = area of sample in cm<sup>2</sup>      t = time in seconds      L = 14.19 cm



**HYDRAULIC CONDUCTIVITY**

Project No.	<i>6155-08-0031.29</i>	Tested By	<i>JW</i>
Project Name	<i>Twelve Permeable concrete Mold S</i>	Test Date	<i>2/15/2012</i>
Boring No.	<i>PAC009</i>	Reviewed By	
Sample No.	<i>PAC009</i>	Review Date	
Sample Depth	<i>N/A</i>	Lab No.	<i>11383</i>
Sample Description <i>Concrete Core 10% Apatite 5% Zealite 5% MRM 404</i>			

*ASTM D5084-03 - (Method C Falling Head RisingTail)*

Sample Type:	<i>UD</i>
Sample Orientation:	<i>Vertical</i>
Initial Water Content, %:	<i>8.0</i>
Wet Unit Weight, pcf:	<i>80.8</i>
Dry Unit Weight, pcf:	<i>74.8</i>
Compaction, %:	<i>N/A</i>
<b>Hydraulic Conductivity, cm/sec. @20 °C</b>	<b><i>4.2E-03</i></b>

Remarks: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

**PERMEABILITY TEST  
(ASTM D5084 - 03) (Method C, Increasing Tailwater Level)**



Project Number 6155-08-0031.29 Tested By JW  
 Project Name Twelve Permeable concrete Mold Samples Test Date 02/15/12  
 Boring No. PAC009 Reviewed By  
 Sample No. PAC009 Review Date  
 Sample Depth N/A Lab No. 11383  
 Sample Description Concrete Core 10% Apatite 5% Zealite 5% MRM 404

Initial Sample Data		Final Sample Data	
Length, in	Diameter, in	Pan No.	N/A
Location 1 5.369	Location 1 2.952	Wet Soil+Pan, g	871.44
Location 2 5.778	Location 2 2.966	Dry Soil + Pan, g	746.00
Location 3 5.324	Location 3 2.987	Pan Weight, g	0.00
Average 5.490	Average 2.968	Moisture Content, %	16.8
Volume, in <sup>3</sup> 37.99	Wet Soil + Tare, g 805.89	Dry Unit Weight, pcf	78.1
SG Measured 2.55	Tare Weight, g 0.00	Saturation, %	41.4
Soil Sample Wt., g 805.89	Dry Soil + Tare, g 746.00	Diameter, in.	N/A
Dry UW, pcf 74.8	Moisture Content, % 8.0	Length, in.	N/A
Saturation, % 18.2		Volume, in <sup>3</sup>	N/A

Consolidation	
Chamber Pressure, psi	39.4
Back Pressure, psi	34.4
Confining Pressure, psi	5
Initial Burette Reading	35.2
Final Burette Reading	8.7
Volume Change, cc	26.5
Permeant used	Water

Time (sec)	H <sub>a</sub> (cm)	H <sub>i</sub> (cm)	H <sub>b</sub> (cm)	H <sub>2</sub> (cm)	Temp (°C)	Initial Hydraulic Gradient	Final Hydraulic Gradient	k cm/sec at 20 °C
5	53.5	95.8	66.9	84.9	21.6	3.0	1.3	4.27E-03
5	52.3	95.0	66.1	83.9	21.6	3.1	1.3	4.37E-03
5	52.5	95.7	66.2	84.6	21.6	3.1	1.3	4.27E-03
5	51.6	94.5	65.3	83.6	21.6	3.1	1.3	4.26E-03
5	48.7	89.0	61.9	78.6	21.6	2.9	1.2	4.40E-03
5	53.5	91.3	65.7	81.3	21.6	2.7	1.1	4.42E-03
5	52.5	94.0	66.0	83.2	21.6	3.0	1.2	4.40E-03

No. of Trials	Sample Type	Max. Density (pcf)	Compaction %	Sample Orientation
7	UID	N/A	N/A	Vertical

Avg. k at 20 °C **4.18E-03 cm/sec**

a = area of burette in cm<sup>2</sup>      H<sub>a</sub> = initial inlet head in cm      a = 0.16 cm<sup>2</sup>  
 L = length of sample in cm      H<sub>i</sub> = initial outlet head in cm      A = 44.65 cm<sup>2</sup>  
 A = area of sample in cm<sup>2</sup>      t = time in seconds      L = 13.95 cm

Remarks:



**HYDRAULIC CONDUCTIVITY**

Project No. *6155-08-0031.29* Tested By *JW*  
 Project Name *Twelve Permeable concrete Mold S* Test Date *2/15/2012*  
 Boring No. *PAC010* Reviewed By  
 Sample No. *PAC010* Review Date  
 Sample Depth *N/A* Lab No. *11384*  
 Sample Description *Concrete Core 10% Apatite 5% Zealite 5% MRM 404*

*ASTM D5084-03 - (Method C Falling Head RisingTail)*

Sample Type:	<i>UD</i>
Sample Orientation:	<i>Vertical</i>
Initial Water Content, %:	<i>6.9</i>
Wet Unit Weight, pcf:	<i>76.5</i>
Dry Unit Weight, pcf:	<i>71.5</i>
Compaction, %:	<i>N/A</i>
<b>Hydraulic Conductivity, cm/sec. @20 °C</b>	<b><i>1.7E-03</i></b>

Remarks: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_



**PERMEABILITY TEST  
(ASTM D5084 - 03) (Method C, Increasing Tailwater Level)**



Project Number 6155-08-0031.29 Tested By JW  
 Project Name Twelve Permeable concrete Mold Samples Test Date 02/15/12  
 Boring No. PAC010 Reviewed By  
 Sample No. PAC010 Review Date  
 Sample Depth N/A Lab No. 11384  
 Sample Description Concrete Core 10% Apatite 5% Zealite 5% MRM 404

Initial Sample Data			Final Sample Data		
Length, in	Diameter, in		Pan No.		N/A
Location 1	5.564	Location 1	2.891	Wet Soil+Pan, g	819.82
Location 2	5.338	Location 2	2.985	Dry Soil + Pan, g	698.40
Location 3	5.358	Location 3	2.992	Pan Weight, g	0.00
Average	5.420	Average	2.956	Moisture Content, %	17.4
Volume, in <sup>3</sup>	37.20	Wet Soil + Tare, g	746.43	Dry Unit Weight, pcf	74.6
S.G. Measured	2.56	Tare Weight, g	0.00	Saturation, %	39.0
Soil Sample Wt., g	746.43	Dry Soil + Tare, g	698.40	Diameter, in.	N/A
Dry UW, pcf	71.5	Moisture Content, %	6.9	Length, in.	N/A
Saturation, %	14.3			Volume, in <sup>3</sup>	N/A

Consolidation

Chamber Pressure, psi	34.2
Back Pressure, psi	29.2
Confining Pressure, psi	5
Initial Burette Reading	35.2
Final Burette Reading	9.9
Volume Change, cc	25.3

Permeant used: Water

Time (sec)	H <sub>a</sub> (cm)	H <sub>1</sub> (cm)	H <sub>b</sub> (cm)	H <sub>2</sub> (cm)	Temp (°C)	Initial Hydraulic Gradient		Final Hydraulic Gradient		k cm/sec at 20 °C
						Initial Hydraulic Gradient	Temp (°C)	Final Hydraulic Gradient	k cm/sec at 20 °C	
5	50.5	93.8	58.2	87.2	21.7	3.1	2.1	1.99E-03	1.91E-03	
10	50.5	93.8	63.1	83.1	21.7	3.1	1.5	1.92E-03	1.84E-03	
10	55.7	98.8	67.0	89.3	21.7	3.1	1.6	1.64E-03	1.57E-03	
5	54.1	98.4	61.0	92.6	21.7	3.2	2.3	1.68E-03	1.61E-03	
10	54.1	98.4	66.1	88.3	21.7	3.2	1.6	1.72E-03	1.65E-03	
5	52.6	97.5	59.8	91.5	21.7	3.3	2.3	1.73E-03	1.66E-03	
10	52.6	97.5	64.5	87.5	21.7	3.3	1.7	1.66E-03	1.60E-03	

No. of Trials	Sample Type	Max. Density (pcf)	Compaction %	Sample Orientation
7	UD	N/A	N/A	Vertical

Avg. k at 20 °C: 1.69E-03 cm/sec

a = area of burette in cm<sup>2</sup>      H<sub>a</sub> = initial inlet head in cm      H<sub>b</sub> = final inlet head in cm      a = 0.16 cm<sup>2</sup>  
 L = length of sample in cm      H<sub>1</sub> = initial outlet head in cm      H<sub>2</sub> = final outlet head in cm      A = 44.28 cm<sup>2</sup>  
 A = area of sample in cm<sup>2</sup>      t = time in seconds      L = 13.77 cm

Remarks:



**HYDRAULIC CONDUCTIVITY**

Project No. *6155-08-0031.29* Tested By *JW*  
 Project Name *Twelve Permeable concrete Mold S* Test Date *2/15/2012*  
 Boring No. *PAC011* Reviewed By  
 Sample No. *PAC011* Review Date  
 Sample Depth *N/A* Lab No. *11385*  
 Sample Description *Concrete Core 10% Apatite 5% Zealite 5% MRM 404*

*ASTM D5084-03 - (Method C Falling Head Rising Tail)*

Sample Type:	<i>UD</i>
Sample Orientation:	<i>Vertical</i>
Initial Water Content, %:	<i>6.7</i>
Wet Unit Weight, pcf:	<i>82.0</i>
Dry Unit Weight, pcf:	<i>76.9</i>
Compaction, %:	<i>N/A</i>
<b>Hydraulic Conductivity, cm/sec. @20 °C</b>	<b><i>4.3E-03</i></b>

Remarks: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

**PERMEABILITY TEST  
(ASTM D5084 - 03) (Method C, Increasing Tailwater Level)**



Project Number 6155-08-0031.29      Tested By JW  
 Project Name Twelve Permeable concrete Mold Samples      Test Date 02/15/12  
 Boring No. PAC011      Reviewed By  
 Sample No. PAC011      Review Date  
 Sample Depth N/A      Lab No. 11385  
 Sample Description Concrete Core 10% Apatite 5% Zealite 5% MRM 404

Initial Sample Data			Final Sample Data		
Length, in	Diameter, in		Pan No.		N/A
Location 1	5.589	Location 1	2.987	Wet Soil+Pan, g	894.05
Location 2	5.251	Location 2	2.978	Dry Soil + Pan, g	750.80
Location 3	5.140	Location 3	2.981	Pan Weight, g	0.00
Average	5.327	Average	2.982	Moisture Content, %	19.1
Volume, in <sup>3</sup>	37.20	Wet Soil + Tare, g	800.82	Dry Unit Weight, pcf	79.8
SG Measured	2.5	Tare Weight, g	0.00	Saturation, %	50.0
Soil Sample Wt., g	800.82	Dry Soil + Tare, g	750.80	Diameter, in.	N/A
Dry UW, pcf	76.9	Moisture Content, %	6.7	Length, in.	N/A
Saturation, %	16.2			Volume, in <sup>3</sup>	N/A

**Consolidation**  
 Chamber Pressure, psi 44.4  
 Back Pressure, psi 39.4  
 Confining Pressure, psi 5  
 Initial Burette Reading 35.2  
 Final Burette Reading 13.0  
 Volume Change, cc 22.2  
 Permeant used Water

Time (sec)	H <sub>a</sub> (cm)	H <sub>1</sub> (cm)	H <sub>6</sub> (cm)	H <sub>2</sub> (cm)	Temp (°C)	Initial Hydraulic Gradient	Final Hydraulic Gradient	k cm/sec at 20 °C
5	58.0	93.4	69.6	83.4	21.7	2.6	1.0	4.53E-03
5	52.0	90.5	64.6	79.4	21.7	2.8	1.1	4.59E-03
5	53.1	90.4	65.3	79.9	21.7	2.8	1.1	4.51E-03
5	48.3	80.3	59.0	71.2	21.7	2.4	0.9	4.63E-03
5	53.0	90.4	65.0	79.9	21.7	2.8	1.1	4.42E-03
5	52.6	91.0	65.0	80.2	21.7	2.8	1.1	4.45E-03
5	46.1	88.5	59.5	77.0	21.7	3.1	1.3	4.25E-03

No. of Trials	Sample Type	Max. Density (pcf)	Compaction %	Sample Orientation
7	UD	N/A	N/A	Vertical

Avg. k at 20 °C **4.30E-03 cm/sec**

a = area of burette in cm<sup>2</sup>      H<sub>6</sub> = initial inlet head in cm      a = 0.16 cm<sup>2</sup>  
 L = length of sample in cm      H<sub>1</sub> = initial outlet head in cm      A = 45.06 cm<sup>2</sup>  
 A = area of sample in cm<sup>2</sup>      t = time in seconds      L = 13.53 cm

Remarks:  
 \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_



**HYDRAULIC CONDUCTIVITY**

Project No. *6155-08-0031.29* Tested By *JW*  
 Project Name *Twelve Permeable concrete Mold S* Test Date *2/17/2012*  
 Boring No. *PAC012* Reviewed By  
 Sample No. *PAC012* Review Date  
 Sample Depth *N/A* Lab No. *11386*  
 Sample Description *Concrete Core 10% Apatite 5% Zealite 5% MRM 404*

*ASTM D5084-03 - (Method C Falling Head Rising Tail)*

Sample Type:	<i>UD</i>
Sample Orientation:	<i>Vertical</i>
Initial Water Content, %:	<i>8.5</i>
Wet Unit Weight, pcf:	<i>82.2</i>
Dry Unit Weight, pcf:	<i>75.8</i>
Compaction, %:	<i>N/A</i>
<b>Hydraulic Conductivity, cm/sec. @20 °C</b>	<b><i>4.1E-03</i></b>

Remarks: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

**PERMEABILITY TEST  
(ASTM D5084 - 03) (Method C, Increasing Tailwater Level)**



Project Number 6155-08-0031.29  
 Project Name Twelve Permeable concrete Mold Samples  
 Boring No. PAC012  
 Sample No. PAC012  
 Sample Depth N/A  
 Sample Description Concrete Core 10% Apatite 5% Zealite 5% MIRM 404

Tested By JW  
 Test Date 02/17/12  
 Reviewed By  
 Review Date  
 Lab No. 11386

Initial Sample Data			Final Sample Data		
Length, in	Diameter, in		Pan No.	N/A	
Location 1	5.487	Location 1	2.960	Wet Soil+Pan, g	909.40
Location 2	5.556	Location 2	2.998	Dry Soil + Pan, g	776.90
Location 3	5.682	Location 3	3.004	Pan Weight, g	0.00
Average	5.575	Average	2.987	Moisture Content, %	17.1
Volume, in <sup>3</sup>	39.08	Wet Soil + Tare, g	843.09	Dry Unit Weight, pcf	77.8
SG Measured	2.53	Tare Weight, g	0.00	Saturation, %	41.9
Soil Sample Wt., g	843.09	Dry Soil + Tare, g	776.90	Diameter, in.	N/A
Dry UW, pcf	75.8	Moisture Content, %	8.5	Length, in.	N/A
Saturation, %	19.9			Volume, in <sup>3</sup>	N/A

**Consolidation**

Chamber Pressure, psi	39.2
Back Pressure, psi	34.2
Confining Pressure, psi	5
Initial Burette Reading	17.6
Final Burette Reading	1.1
Volume Change, cc	16.5
Permeant used	Water

Time (sec)	H <sub>a</sub> (cm)	H <sub>1</sub> (cm)	H <sub>6</sub> (cm)	H <sub>2</sub> (cm)	Temp (°C)	Initial Hydraulic Gradient	Final Hydraulic Gradient	k cm/sec at 20 °C
5	55.6	100.3	70.6	87.9	21.7	3.2	1.2	4.76E-03
5	49.6	101.3	66.3	87.7	21.7	3.7	1.5	4.42E-03
5	49.8	101.1	65.9	87.9	21.7	3.6	1.6	4.24E-03
5	48.1	99.6	64.7	86.3	21.7	3.6	1.5	4.35E-03
5	49.6	99.0	65.3	86.5	21.7	3.5	1.5	4.24E-03
6	49.9	100.2	65.9	87.2	21.7	3.6	1.5	3.59E-03
5	49.5	100.0	65.5	87.1	21.7	3.6	1.5	4.26E-03

No. of Trials	Sample Type	Max. Density (pcf)	Compaction %	Sample Orientation
7	UD	N/A	N/A	Vertical

**Avg. k at 20 °C**      **4.09E-03 cm/sec**

a = area of burette in cm<sup>2</sup>      H<sub>6</sub> = initial inlet head in cm      a = 0.16 cm<sup>2</sup>      Remarks:  
 L = length of sample in cm      H<sub>1</sub> = initial outlet head in cm      A = 45.22 cm<sup>2</sup>  
 A = area of sample in cm<sup>2</sup>      t = time in seconds      L = 14.16 cm