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Evaluating The Use Of Recycled Concrete Aggregate In French Drain Applications

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EVALUATING THE USE OF RECYCLED CONCRETE AGGREGATE
IN FRENCH DRAIN APPLICATIONS

by

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B.S. University of Central Florida, 2011

A thesis submitted in partial fulfillment of the requirements
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ABSTRACT

Recycled concrete aggregate (RCA) is often used as a replacement of virgin aggregate in road foundations (base course), embankments, hot-mix asphalt, and Portland cement concrete. However, the use of RCA in exfiltration drainage systems, such as French drains, is currently prohibited in many states of the U.S. The French drain system collects water runoff from the road pavement and transfers to slotted pipes underground and then filters through coarse aggregate and geotextile. The primary concerns with using RCA as a drainage media are the fines content and the precipitation of calcium carbonate to cause a reducing in filter fabric permittivity. Additional concerns include the potential for rehydration of RCA fines.

The performance of RCA as drainage material has not been evaluated by many researchers and the limited information limits its use. A literature review has been conducted on the available information related to RCA as drainage material. A survey was issued to the Departments of Transportation across the nation in regards to using RCA particularly in French drains. Some state highway agencies have reported the use of RCA as base course; however, no state reports the use of RCA in exfiltration drainage systems. This thesis describes the investigations on the performance of RCA as backfill material in French drains.

RCA was tested for its physical properties including, specific gravity, unit weight, percent voids, absorption, and abrasion resistance. RCA cleaning/washing methods were also applied to evaluate the fines removal processes. The potential for RCA rehydration was

evaluated by means of heat of hydration, pH, compressive strength, and setting time. The permeability of RCA was tested using the No. 4 gradation. Long term permeability testing was conducted to evaluate the tendency for geotextile clogging from RCA fines. Calcium carbonate precipitation was also evaluated and a procedure to accelerate the precipitation process was developed.

The results show that RCA has a high abrasion value, that is, it is very susceptible to break down from abrasion during aggregate handling such as transportation, stockpiling, or placing. The most effective cleaning method was found to be pressure washing with agitation. RCA has not demonstrated the tendency to rehydrate and harden when mixed with water. The permeability test results show that the No. 4 gradation does not restrict the flow of water; the flow rate is highly dependent on the hydraulic system itself, however excessive fines can cause large reductions in permeability over time. It has been determined that No. 4 gradation of RCA can provide a suitable drainage media providing the RCA is properly treated before its use.

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CHAPTER 1: INTRODUCTION

1.1 Problem Statement

On November 10, 2010, the Florida Department of Transportation (FDOT) modified Section 901 of its Standard Specifications for Road and Bridge Construction by issuing a Materials Bulletin/Construction Memorandum (MB/CM) allowing the use of recycled concrete aggregate (RCA) from sources other than FDOT projects. The MB/CM document has been incorporated into the Department's January 2012 Specification Workbook. Prior to the above changes, FDOT only allowed RCA from a project source which was produced and placed in accordance with applicable Specifications, that is, at the time of the source's construction. The allowable uses were in nonstructural concrete applications or hot bituminous mixtures. With the current changes, FDOT added clean-debris recycling facilities as suppliers of RCA for coarse aggregate. Uses include pipe backfill under wet conditions, underdrain aggregate, or concrete meeting the requirements of Section 347. RCA for hot bituminous mixtures must still originate from a source which was produced and placed in accordance with applicable Specifications.

However, the use of RCA in French drains has yet to receive approval. French drain systems collect water from the roadway and transfer the water into slotted pipes underground. The water then filters through coarse aggregate and passes through a permeable filter fabric.

When RCA is used in French drain systems, therefore, the presence of fine particles in the aggregate has the potential to clog the filter fabric rendering it inoperable, or significantly reducing its performance efficiency. The fines from RCA may pose an additional risk if they re-cement in the pores of the filter fabric.

1.2 Project Description

In an effort to either support or oppose the use of RCA in French drains in FDOT standard specifications, this project has been issued by the FDOT. This project will evaluate the properties, effects, and consequences of using RCA as an exfiltration drain material. The experimental study and examination of RCA was developed to objectively study the use RCA.

1.2.1 Research Objectives

The main objectives of this thesis are to study the effects of using RCA in French drains. The following objectives have been proposed:

- Determine the current standards and practices of using RCA in French drains;

- Develop a laboratory testing procedure to evaluate various fines removal methods;

- Evaluate the potential of rehydration for RCA;

- Determine the effect of RCA fines on the overall permeability performance, and

- Develop an experimental design to evaluate clogging of geotextile.

1.2.2 Research Methodology

Publications of RCA have been reviewed and an experimental design has been developed to identify and evaluate the issues associated with RCA as a drainage material. A survey was issued to the nations Departments of Transportation regarding their experience with RCA and its uses in each state. Methods to remove RCA fines were developed to simulate in-field aggregate washing techniques. The potential for RCA rehydration was evaluated by the use of compressive strength, pH, heat of hydration, and time of setting tests. Permeability testing on RCA was conducted under varied testing conditions, such as, percent fines addition, hydraulic gradient, and tubing and permeameter sizes. In addition, a long-term permeability was monitored to measure the clogging buildup due to RCA fines and calcite precipitation.

1.2.3 Research Scope

Based on the results from the project investigations, a recommendation will be made as to whether RCA should or should not be used in French drains or what restrictions may be applied to its use.

1.3 Organization of Thesis

The chapters of this thesis are organized and described as follows:

- Chapter 2: This chapter reviews literature of RCA regarding: 1) the production, 2) properties, 3) the uses, 4) Aggregate washing and cleaning methods, 5) the problems associated with using RCA including excess fines, rehydration, and clogging potential, and 6) a review of the survey results from state highway officials.

- Chapter 3: Physical characteristics, including 1) physical properties of RCA, 2) evaluating aggregate handling process, and 3) RCA washing methods are described and discussed.

- Chapter 4: Rehydration of RCA was evaluated through the compressive strength, pH, heat of hydration, setting time, and petrographic analyses.

- Chapter 5: Extensive permeability testing was conducted including various size permeameters and tubes.

- Chapter 6: Clogging tests were performed to examine the effect of percent fines addition. Calcium carbonate precipitation potential is studied and discussed.

- Chapter 7: This chapter includes a summary of the project and results and the conclusion is presented.

CHAPTER 2: LITERATURE REVIEW

2.1 RCA Production

RCA can be defined as a material that consists of about 60 to 75 percent high quality, well-graded aggregates bonded by a hardened mortar. RCAs also included about 10 to 30 percent sub-base soil materials and asphalt material from either the shoulder or composite pavement (Kuo et al, 2001). As a result of the reclamation process, when the recovered concrete material is picked up, usually by a backhoe machine, soils or other base/subbase material are attached to the RCA such that the mixture of RCA typically includes concrete, soil, small amounts of asphalt, and other debris. Once the concrete has been demolished, the rubble is hauled to a facility for stockpiling and processing. However, for some large demolition projects, the crushed concrete can be processed on site with a mobile crushing plant, which also screens and removes metal debris.

RCA can be obtained from obsolete concrete structures including, buildings, roads, or runways. Other structures such as Portland cement concrete curb, sidewalk and driveway which may typically be reinforced and should go through a screening process which uses magnetic separators to extract the ferrous material. Some reinforcement such as welded mesh, however, are much more difficult to separate, in such cases the final RCA product may contain some metal debris.

There are two main types of crushing devices that recycling plants utilize; compression crushers and impact crushers (Figure 1). Common compression crushers used are the cone, and jaw crushers, where two common impact crushers used are impact and horizontal crushers. Recycling plants may use one or two crushers during the production process. The primary crusher is used for larger pieces, in which the resulting aggregates go through a screening process and then onto the secondary crusher, where the RCA is broken down into the desired size. In North America, 61% of recyclers use jaw crushers for the primary crushing, and 43% use cone crushers for secondary crushing (Environmental Council of Concrete Organizations, 1999). And as a result from these processes, the original concrete will yield about 75% course aggregate, and 25% of fines (Environmental Council of Concrete Organizations, 1999). An outline of a typical RCA production process is shown in Figure 2 2.
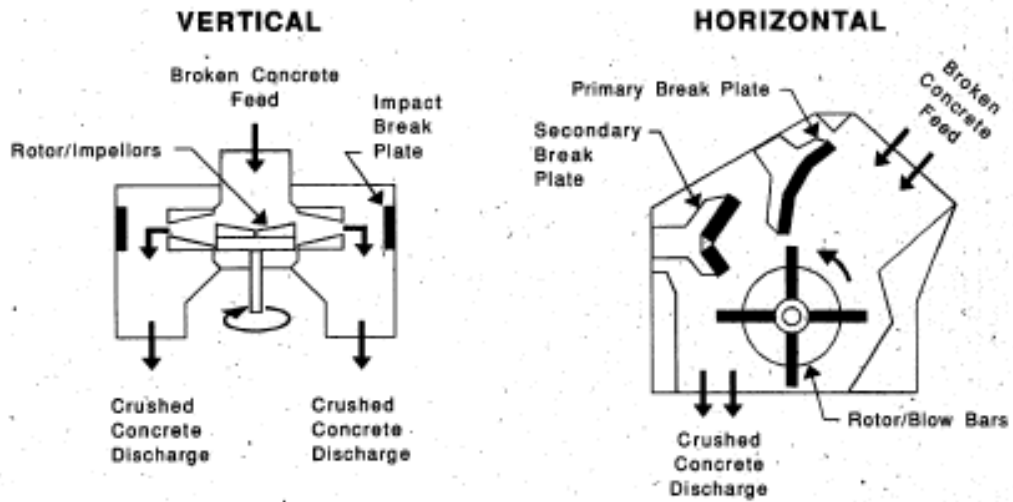
Figure 1. Compression and Impact Crushers (Environmental Council of Concrete Organizations, 1999)
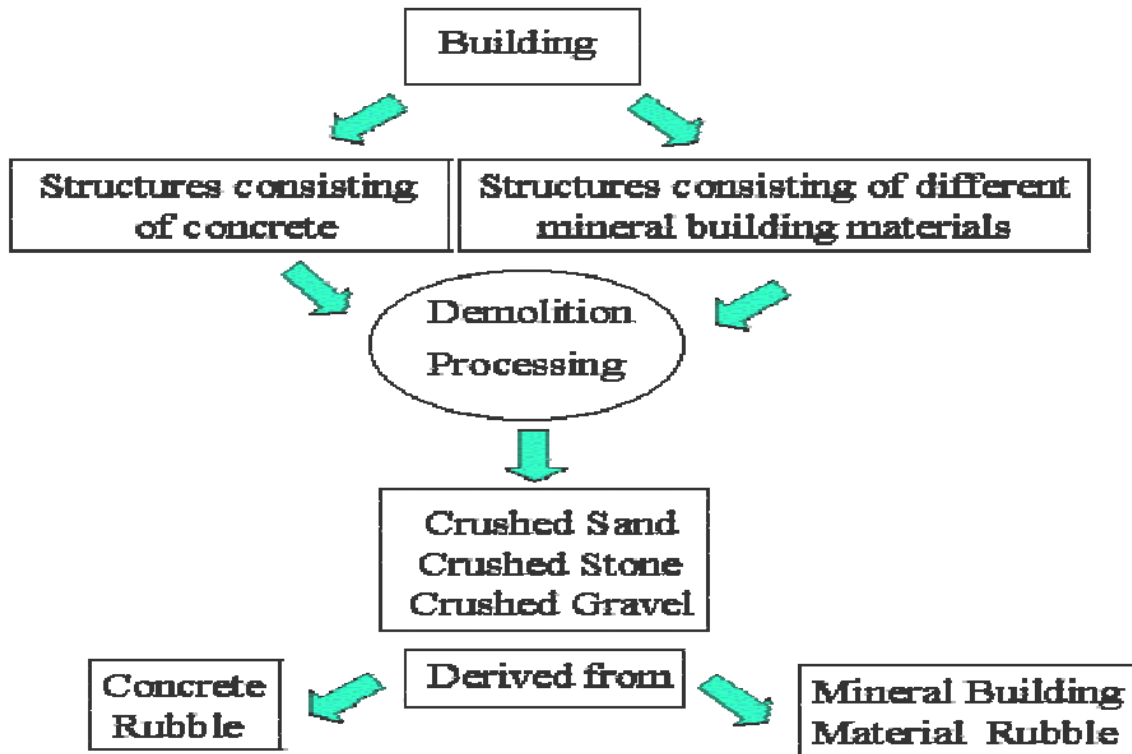
Figure 2. RCA Production Process (Kuo, 2001)

2.2 RCA Properties

2.2.1 Physical Properties

The properties of RCA differ greatly from those of virgin aggregates primarily due to the existence of mortar attached to the aggregate. The original coarse aggregate type contributes to the amount of mortar content in that, smooth rounded coarse aggregates tend to break apart at the aggregate-mortar interface during the crushing processes. A Canadian study on RCA (Fathifazl,

2008) reported the mortar content of RCA can be as high as 41 percent by volume depending on the original concrete mix proportions and crushing operations.

The specific gravity of RCA is highly dependent on the mortar content. The increased amount of mortar leads to lower specific gravity of the RCA. A study (Vancura et al., 2010) indicated that absorption capacities of RCA are consistently higher than virgin aggregate due to the inclusion of the old mortar. These absorption values can range from 2 to 10% in some extreme cases, depending on the absorption capacity of original aggregate, concrete mix proportions, and crushing operations (Hiller et al., 1999). It was reported that RCA concrete had a reduced level of freeze-thaw resistance due to the high absorption of the RCA (Salem and Burdette, 1998).

The gradation of the RCA should also be considered, as the amount of fines in the aggregate can contribute to the clogging potential of the drainage system (Hiller et al, 2011). In addition, RCA particles at the finer end of a gradation specification may meet the standard, but will result in a concrete with a high water demand from the aggregates due to the hydrated cement paste. If these aggregates are used as a filler material in drainage systems, finer particles will lead to a reduction in draining capacity and longer saturation time. As a result, less support and poorer pavement performance will occur.

The crushing process to generate RCA exposes unhydrated fines, which can lead to cementation when exposed to water or particularly humid conditions, thus changing the physical properties of the RCA (Hiller et al, 2011). On the contrary to how most virgin aggregates perform, RCAs typically fail the sulfate soundness test (ASTM-C88 2008) using sodium sulfate, but tended to perform well using magnesium sulfate in a limited study (Snyder et al. 1996).

2.2.2 Chemical Properties

The reduction of geotextile permittivity has been an associated issue for the use of RCA as a base course in pavement systems. This is typically because of the accumulation of calcium carbonate precipitation, depositing onto the geotextiles of subsurface drainage systems (MnDOT, 1983). Some research has shown through laboratory studies that RCA has the potential to produce a substantial amount of calcium carbonate, whereas virgin aggregates do not share the same tendency (Muethel, 1980; Tamirisa, 1993). Therefore, it is essential to develop an understanding of the chemical process of calcium carbonate precipitation from RCA, as it is a critical issue for RCA as it relates to the potential to cause geotextile clogging and to determine possible mitigation techniques.

The background for understanding the precipitation of calcium carbonate can be found in the processes of precipitations in limestone carvers. Limestone, water, and the atmosphere are factors for the precipitation of calcite, similarly, the chemical reactions can also be observed with

concrete. When concrete is exposed to moisture and carbon dioxide (CO_2), the calcium hydroxide ($Ca(OH)_2$, or Portlandite) is readily dissolved, causing a pH effluent containing calcium and hydroxide ions.

Figure 3. Photo of Calcium Carbonate (calcite)

2.3 Uses of RCA

2.3.1 Base Layer

RCA products have been used as replacements for virgin aggregate in pavement foundation and other applications since the early 1980s (Snyder and Bruinsma, 1995). The use of RCA can be in several areas, such as soil stabilization, subbase and base courses, and as aggregate for hot-mix asphalt (HMA) or Portland cement concrete (PCC). In a national survey administered by Rutgers University (Bennert and Maher, 2008), a research team gathered

information on which state departments use RCA in pavement base or subbase layers. A total of 25 states and 1 Canadian province responded. The survey covered questions regarding RCA as a pavement material, specifications or practices for permeability levels, material blending practices, use of filter fabric, problems encountered with use of RCA or permeability, and issues with alkali silica reactivity aggregates. Twelve of the states that responded use RCA for both base and subbase, while several others indicate they use RCA for base only and five reported they do not use RCA. 71% of the responses indicate that RCA alone is used as a pavement layer, while 29% state that the use of RCA blended with other materials is used. Of the organizations that report using RCA alone in pavement layers, 50% of them use a gradation to specify material properties, while the other 50% use other criteria, and some in combination with gradation.

In a study by Chini and Kuo (Chini and Kuo, 1998) the aggregate properties that most influence the functionality of pavement base courses were determined. These properties are listed as, aggregate stability, particle size distribution, permeability, plastic index, limerock bearing ratio, particle shape, soundness, sodium sulfate test, abrasion test, and compaction. The effects of RCA in pavement drainage have been studied by Snyder and Bruinsma (Snyder and Bruinsma, 1996) and discovered that all recycled aggregates produced some amount of precipitate, which could be related to the amount of exposed cement paste. There were substantial amounts of non-carbonate residue buildup found around the pavement drainage system; it was found that washing the aggregate before use in the pavement can reduce the

accumulation of fines. The accumulation of these fines also caused permeability issues with drainage and geotextiles.

2.3.2 Exfiltration Trench and Drainfield

There have been minimal sources reporting on the use of RCA in exfiltration systems; however, several counties in Florida (Duval and Volusia) were given permission to use RCA as media in waste-water treatment drainfields (Sherman et al., 1994). While neither county had evaluated the performance of the RCA, state environmental specialists conducted an evaluation of the RCA product and its reliability over the use of conventional aggregate (limestone).

Exfiltration trench systems are similar to French drain systems (Figure 4) in that they are both subsurface structures including a perforated pipe, filter material (coarse aggregate), fine drainage materials (sand and pea gravel), and filter fabric. Exfiltration trenches are most commonly associated with storm water control and treatment. Some drainage fields consists of a series of exfiltration trenches used in conjunction with septic tanks where the effluent from septic tanks are distributed through a drainfield and the water exists the perforated pipes and filters through the aggregate, then the treated water is allowed to percolate into the native soil. Exfiltration trenches are especially useful when there is limited land area to devote to storm water management (St. Johns River Management District, 2010).
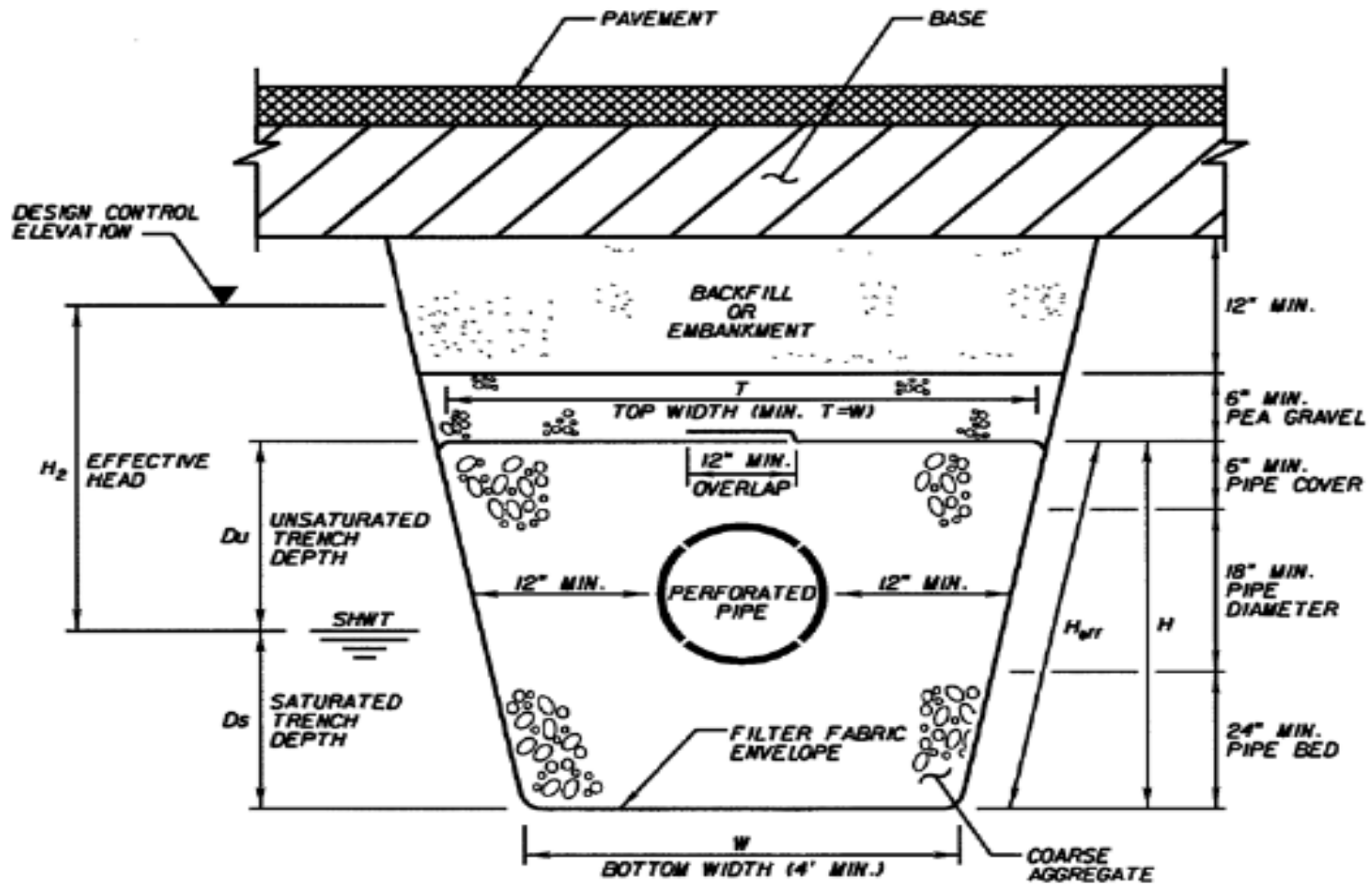
Figure 4. Cross Section of an Exfiltration Trench (FDOT Drainage Handbook Exfiltration Systems, 2012)

Exfiltration trenches are also used to control storm water surface runoff from roadways. Exfiltration trenches can be constructed to capture the first flush of surface runoff which would contain the most pollutants and treat the water and allow it to exfiltrate into the soil, where most of the following volume can be diverted as it may not need such a treatment. This design is an off-line exfiltration system; however, an exfiltration trench can be designed as an on-line system. In the on-line system the entirety of the runoff volume passes through the perforated piping, and if there is runoff in excess of the treatment capacity of the system, then water carrying some pollutants is delivered to the receiving body. The installation of an exfiltration trench depends on the native soils permeability. The permeability of the soil should be able to handle 1×10^{-5}cfs/ft^2 per ft of head (FDOT Drainage Handbook Exfiltration Systems, 2012). The filter fabric should also be as permeable as or more so than the surrounding soil. The entire system should also be able to return to a 'dry' condition within a certain time period. The aggregate to be used in an exfiltration trench should be uniform-graded, natural or artificial and have less than 3% material passing the No. 200 sieve (FDOT Drainage Handbook Exfiltration Systems, 2012).

Sherman et al. (Sherman et al., 1994) investigated 45 drainfields for signs of failure based on the following criteria: 1) any system which had been expanded beyond the original installation, 2) any systems reported to have been replaced after displaying obvious signs of failure, as in, effluent surfacing, sewage backing up into household plumbing, and 3) any systems showing signs of impending failure, such as effluent ponding to or above the perforated pipe inlet. Furthermore, claims from one septic tank contractor states that the RCA aggregates

break down when exposed to septic tank effluent, and that the aggregates undergo cementation while in place due to the observation of large chunks of aggregate being extracted during repairs. The researchers investigated these claims and their results show that only 2 of the 45 systems examined classify as system failures. It is believed that the failed systems were due to the use of an unapproved No. 57 aggregate being used (Sherman et al., 1994). This gradation size is very popular for the use in concrete mix; however, its properties that make it suitable for concrete mix also make it unsuitable for the use in drainfields. The amount of fine particles from this aggregate are believed to be the cause of failure, as drainfields require aggregates with maximum porosity and few particles smaller than 0.187 in. Results showed that RCA apparently had all the required qualities for an effective media, including the ability to crush it to specification size, retaining good porosity and strong enough to not pack down after installation (Sherman et al., 1994). The authors conclude that as long as proper quality control is observed during the manufacturing that RCA equals or exceeds the standards of other approved materials.

2.4 Problems Associated with RCA as Drainage Material

2.4.1 Rehydration

Concrete typically includes a small percentage of unhydrated cement as the full cement hydration process is not typically achieved in the original concrete. This unhydrated cement may become a significant issue in fine RCA stockpiles as these aggregates can experience cementing through either direct water exposure or high humidity. Eliminating the use of fines from drained foundation layers should all but eliminate this concern as well. The stockpile experience from the

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Minnesota Department of Transportation (MnDOT) suggests that coarse and open-graded materials do not rehydrate in the short term (1 year of exposure) and should not do so in the long term because there are insufficient particle surfaces to bind the coarse particles (Snyder, 1995).

In a study by Katz (Katz, 2002), the properties of concrete were analyzed when it was made with recycled aggregate from partially hydrated old concrete. The report examines the effects of partially hydrated recycled aggregate when used in new concrete, and the properties of the new concrete made with it. When hardened cement was crushed to a fine grade, the amount of exposed unhydrated cement was. It was also determined that the amount of mortar that was still adhering to the natural aggregates in each size fraction was constant, regardless of crushing age. Absorption rates were much higher with recycled concretes with little effect from the crushing age. It was also found that the addition of RCA produced from 1 day old concrete was able to improve the properties of new concrete made with such RCA. However, the cementing potential of recycled aggregates quickly decreases with time to almost no cementing potential after 3 days. Recycled aggregates made from 1 day old concrete are weak, but possess some cementing potential, while aggregates made from 28 day old concrete is still stronger but without any cementing potential.

2.4.2 Clogging Potential in Drainage Systems

The clogging of a geotextile filter fabric is brought on by several means, the calcite precipitation and from the fine material produced from the RCA. The MnDOT has extensive experience with the use of RCA in conjunction with a geotextile filter fabric (Snyder, 1996). The

MnDOT obtained filter fabric samples in 1989 and 1993 from several project locations and tested for the loss of permittivity. It was found that the filter fabric has lost on average 50% permittivity in 4 years and 53% in 8 years. Samples from the top and bottom of the pipe exhibited less loss of permittivity, while the side wall samples showed the greatest loss in permittivity. This is due to the phenomenon that the bottom samples would have gathered less calcite precipitation since the bottom of the pipe is submerged for longer periods of time, thus being exposed to less of the carbon dioxide in the atmosphere than the top and side walls. It was also determined that about 17 to 84% of the permittivity loss was due to calcite precipitation, while the rest of the loss was due to non-carbonate material (fines). Calcite buildups were measured by soaking the sample in acid, which reacts with the calcite, therefore any leftover material is due to the non-carbonate material (Snyder, 1996).

Bruninsma et al. (Bruninsma et al., 1997) described a MnDOT study of the Lakeville test beds in 1989, where a series of test beds were constructed containing RCA and virgin aggregates. Each test bed contained a 0.015 ft/ft slope drain to move the rainwater to an edge drain system. The test beds with the RCA exhibited slightly higher pH values due to the recycled fines than with the beds with virgin aggregates. After 3 years, test samples of the filter fabric were obtained from the top and bottom of the wrapped edges drains for permittivity testing. Samples taken from both the beds with virgin aggregate, and RCA showed a loss in permittivity; however, the permittivity losses for the RCA test beds was determined to be mostly due to calcite precipitate (Bruninsma et al., 1997). Approximately 70% of the loss was due to calcite buildup while 30% from non-carbonate material (Bruninsma et al., 1997).

2.4.3 Environmental and Chemical Effects

RCAs typically exhibit levels of high alkalinity as attributed to the component of mortar (Kuo et al, 2001) and this frequently causes the RCA-water mixture to reach pH levels of higher than 11. A study (Steffes, 1999) evaluated the leachate from RCA from Iowa State in drainage applications and the loss of vegetation due to high pH levels and the precipitation of calcium carbonate were considered. Based on the other study (Snyder and Bruinsma, 1996), on the contrary, the effluent from the RCA possessed higher levels of pH for the first few years; however, there was not enough of a pH change to cause environmental issues, as the effluent would be diluted with the excess surface runoff.

It has been widely observed that effluent water exposed to RCA fines exhibit higher levels of pH, which is the primary environmental concern. Steffes (Steffes, 1999) evaluated three samples of RCA for pH levels of effluent. Sample 'A' contained 32 lbs of RCA fines in the bottom 2 in. of a container, and 60 lbs of RCA at a No. 12 gradation in the top 4 in. of the container. Sample 'B' contained 10 lbs of fines and 96 lbs of No. 12 gradation mixed together consisting of the total height of 6 in. And sample 'C' contained 95 lbs of No. 12 gradation only. The test procedure consisted of saturating the samples and collecting the effluent for testing, then waiting 7 days. This cycle is repeated for a year. The results show consistently high pH levels, initially at an average pH of 12.5 and decreased gradually over the first 30 weeks and stabilized at around 11.5 by the end of the year. However, the effluent from sample A had consistently been measured to be about 0.3 lower than effluent from samples B or C. The author believes that

this is caused by the active lime within the RCA fines being able to react with atmospheric CO_2 or being leached by the water faster than the other two samples. Furthermore, the author examined the field conditions of RCA being used in drainage applications and has concluded that high pH levels can exist many years after construction, and that the calcite precipitate can lead to clogging of wire mesh rodent guards at drain outlets. It was also found that the high pH levels kill and impede vegetation growth at the outlet and that the leading soil erosion can be hazardous to maintenance equipment and personnel.

The production of cement results in the emission of CO_2 by the calcination of limestone when it is burnt. However, hardened concrete has the ability to bind CO_2 by the amount that was initially emitted by the calcination of the limestone to create the cement (Engelsen et al., 2005). When concrete structures are demolished, and RCA is produced, there is an increase in the surface area and the material possesses the ability to uptake CO_2. Engelsen et al. (Engelsen et al., 2005) conducted an experiment to measure the CO_2 uptake capacity of RCA in Nordic countries. Concrete specimens were made in 0.039-in. cubes and aged for 90 days. Then, the samples were crushed and promptly packed in air-tight containers and the air was replaced with nitrogen gas to inhibit any further carbonation before testing. The testing of the RCA involved placing the RCA in air-tight testing chambers and maintaining the CO_2 content at 35,000ppm. Once the CO_2 level decreased to 3,500ppm, the chamber was then refilled back to the 35,000ppm. Depending on the water to cement ratio of the original concrete mix design, the CO_2 uptake can be as high as 89% of the original CO_2 produced during calcination.

2.5 Aggregate Washing

Aggregate washing is a process to remove the deleterious materials such as fines, clays, or loose debris. It is important to treat or remove fine materials from aggregate as it may lead to a reduction in drainage performance. Aggregate washing plants utilize large scale cleaning machines like the log washer, barrel washer, and vibrating wet screens and coarse aggregate scrubbers (Figures 5 and 6). The actual mechanism that separates fine material from the aggregate occurs as suspension, abrasion, or pressurized water. Some cleaning machines will utilize a combination of these effects, such as the vibrating wet screen to abrade aggregates and use water jets in a final stage of cleaning to remove any last remaining debris. A main advantage to the wet screening process is that the aggregate can be cleaned as well as graded into specified size fractions. Water suspension and water jets are useful for removing loose debris; however, for adhered fines similar to what one may find with recycled concrete aggregate, abrasion may be required to remove most of the fines (Dull, 1914).

Figure 5. Aggregate Log Washer (Trio Engineered Products Inc., 2011)
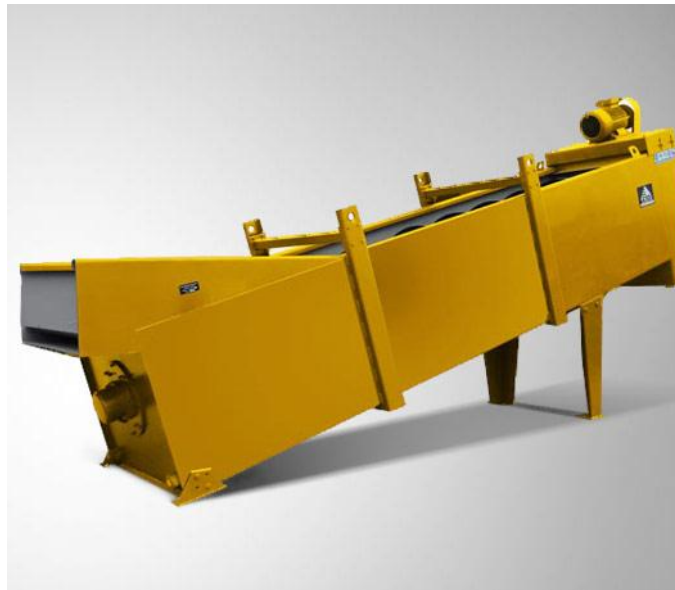
Figure 6. Coarse Aggregate Scrubber (Trio Engineered Products Inc., 2011)

2.6 Survey on Practices and Policies

A survey on the use of RCA was issued to multiple state DOTs regarding their specifications and experiences with RCAs. The agencies were asked whether they use RCA in drainage applications or have specifications regarding RCA in drainage applications. Of the states that responded all reported that they have no current standard practices for the use of RCA in French drains. However, some states, including Alabama, North Dakota, Washington, Mississippi, and New York State allow the use of RCA in road base/subbase construction. Several agencies showed strong interests in this research and are working toward the allowance of RCA in drainage applications. The survey responses are shown in Table 1. The survey questions are as follows:

1. Does your state DOT use RCA in Exfiltration trench?

2. Does your state DOT have a specification for the RCA used in Exfiltration trench?

3. Has your state DOT experienced any problem (i.e. poor drainage performance, environmental issue, etc.) by using the RCA in drainage systems?

Table 1: Survey responses from various state departments

State	Question 1	Question 2	Question 3	Note
Alabama	No	Not specifically.	N/A	We do allow reclaimed concrete aggregates in embankments and as base material after rubblization but have not seen a request for use as a drainage medium.
New Jersey	No	No	No	In NJ, we have concerns regarding the pH of water flowing through RCA so we have not used it in drainage systems. Most of the RCA that we have also has a high percentage of fines - 10% or more. This material is pretty much impermeable. A different gradation of RCA may be drainable but we don't have anyone who wants to make a different gradation.
Indiana	No	No	Yes, but not in this specific application.	We have used RCA as a subbase material beneath concrete pavement and experienced clogging of the X drain system. This was due to the much higher percentage of minus #200 sieve material in the RCA than we have in virgin aggregate and possibly un-hydrated cement in the RCA. Also, we have had leachate issues in other applications. We currently allow RCA in subgrade treatments and have a research project ongoing to study using RCA in concrete at varying percentages.
Oklahoma		No	No	Our specifications do not specifically address the use of RCA in this application. Technically it could be used if it met the specifications. To our knowledge RCA has not been used in this application.

Table 1 (Continued): Survey responses from various state departments

State	Question 1	Question 2	Question 3	Note
Georgia	No	No	No	
North Dakota	No	No	N/A	We have used it as a drainable base layer (cement stabilized) without any problems.
Connecticut	No	No	No	
Washington	No	N/A	N/A.	We have used RCA for base and subbase effectively and have a study underway to look at using it back in PCC.
Ontario Ministry of Transportation	No.	No	N/A	We use reclaimed concrete aggregate only in granular base/subbase
Arizona	No	No	No	
Montana	No	No	N/A	
Nebraska	No.	No	N/A	We allow use of crushed concrete, bituminous millings, or aggregate D (sand and gravel mix) in our typical 4" foundation course below PCC pavements. We require the use of crushed gravel or crushed rock for our granular subdrains (French drains). We typically do not wrap our granular drains with fabric unless we are also installing perforated pipe longitudinal drains. See attached special provision for granular subdrain gradation and detail.

Table 1 (Continued): Survey responses from various state departments

State	Question 1	Question 2	Question 3	Note
Texas	No	No	No	Our specifications do not prevent the use of RCA, but there are no know uses of RCA for this purpose. The specifications are written that would indirectly discourage use of RCA.
New Hampshire	No	No	No	
Ohio	No	No	No	Currently ODOT does not have formal established specifications for exfiltration trenchs as they are still experimental in use in ohio. Our latest testing uses natural sands with a cement or asphalt treated free draining system at the top. Your applications may not be quite the same. For pavement drainage we use 4 or 6 inch underdrains allowing only#8, #89 or #9 ACBF aggregate, gravel or limestone. We require the underdrain excavation to be filterfabric lined. We do not allow RCA in this application. OHIO has had problems with RCA environmental pH runoff and re-cementing of the product causing us pavement problems. Due to that we don't allow the use of RCA as aggregate roadbase, We have had tufa development in pavement drainage systems because of RCA used for undercuts for repair of poor pavement subbase. We also had laboratory research looking at RCA as a roadbase material that predicted tufa due to reaction between RCA and roadway runoff into the drainage.

Table 1 (Continued): Survey responses from various state departments

State	Question 1	Question 2	Question 3	Note
Mississippi	No	No	N/A	Mississippi DOT uses and/or allows crushed concrete as a substitute for crushed stone base and as a substitute for granular material used on shoulders.
Rohde Island	No	No	N/A	
RIDOT	No	No	N/A	
South Carolina	No	No	N/A	
Maine	No	No	N/A	
Kansas	No	No	N/A	Never approved for drainage application. RCA is not an approved material in Kentucky but I have attached old special note for your information. The only time I know of it being used the outwash clogged screens and killed vegetation. Pictures are attached. Other concerns would be clogging of fabric and corrosion of metal pipes (see the photos below).

Table 1 (Continued): Survey responses from various state departments

State	Question 1	Question 2	Question 3	Note
Utah	No	No	N/A	Our standard specification, 02056 Embankment, Borrow, and Backfill, under Section 2.1.A. states: Provide materials free of contamination from chemical or petroleum products for embankment and backfill placements. Materials may include recycled portland cement concrete. Do not include asphalt pavement materials. So you can see the material is allowed but it must meet the same specification as virgin materials. I have attached a copy of this specification for your information. We do not have a separate specification for French Drains, Exfiltration trench or RCA.
Louisiana	No	No	N/A	
New York State	Not yet	Not yet	N/A	Current NYSDOT specifications do not allow RCA as a drainage filter material. This is something that we plan to change in the future. We allow RCA as embankment, as subbase gravel, and as select fill at this time. We do use RCA in a large number of other applications and have had no specific concerns.

2.7 Case Studies for the Use of RCA in Minnesota

Trunk Highway 212, Near Glencoe

Edge drains were retrofitted along Trunk Highway (TH) 212 near Glencoe, Minnesota, in 1985 (Snyder, 1995). The pre-existing base included natural aggregates which were graded to a

dense-graded aggregate classification. After four years of service, samples of the longitudinal edge drain wrap were taken for permittivity testing. The average permittivity loss at the top of the pipe was 1.0/sec (dropping the fabric permittivity below the MnDOT Specification 3733 limit of 0.7/sec), while the average losses at the bottom was 0.5/sec. It was concluded that the buildups of noncarbonated material causes the permittivity losses. The provided data indicate that significant reductions in filter fabric permittivity can occur even without recycled concrete base materials. Thus, evaluations of the permittivity loss associated with recycled concrete aggregates should include a determination of the amount of loss due to the buildups of noncarbonate materials.

Trunk Highway 15, Near Hutchinson

A similar field study was conducted by MnDOT in 1991 (Snyder, 1995). Eight test sections were constructed along portions of TH15 from Hutchinson to Dassel, Minnesota. Each section is 400 ft long and 27 ft wide with edge drains at both sides of the pavement. Three out of eight sections used RCA in the pavement foundation. The remaining sections included no RCA. Muethel (Muethel, 1989) illustrated that precipitation accumulation in this study was much greater than that found in test beds in Lakeville. These differences were attributed to differences in water flow patterns and wetting and drying characteristics at the two sites.

The results of this study suggest that the use of RCA in untreated pavement bases may cause a decrease in drainage outflow when compared with using natural aggregates. However, this decrease can be minimized or eliminated by the use of open-graded materials, blending with

natural crushed rock or by use of unwrapped drainage pipes. RCAs in open-graded bases with unwrapped pipes exhibited greater outflows than the natural base and wrapped pipe section.

CHAPTER 3: PHYSICAL CHARACTERIZATION

3.1 Introduction

RCA was obtained from a local construction and demolition waste recycling facility in Orlando FL. Two 55 gallon drums of RCA were obtained and are shown in Figure 7. The material was advertised as the No. 4 gradation, however a gradation analysis test (ASTM D422) was performed (results shown in Figure 8) and the actual gradation has failed to comply with the No. 4 gradation.

Figure 7. RCA Being Obtained from an Orlando, Fl Recycling Facility
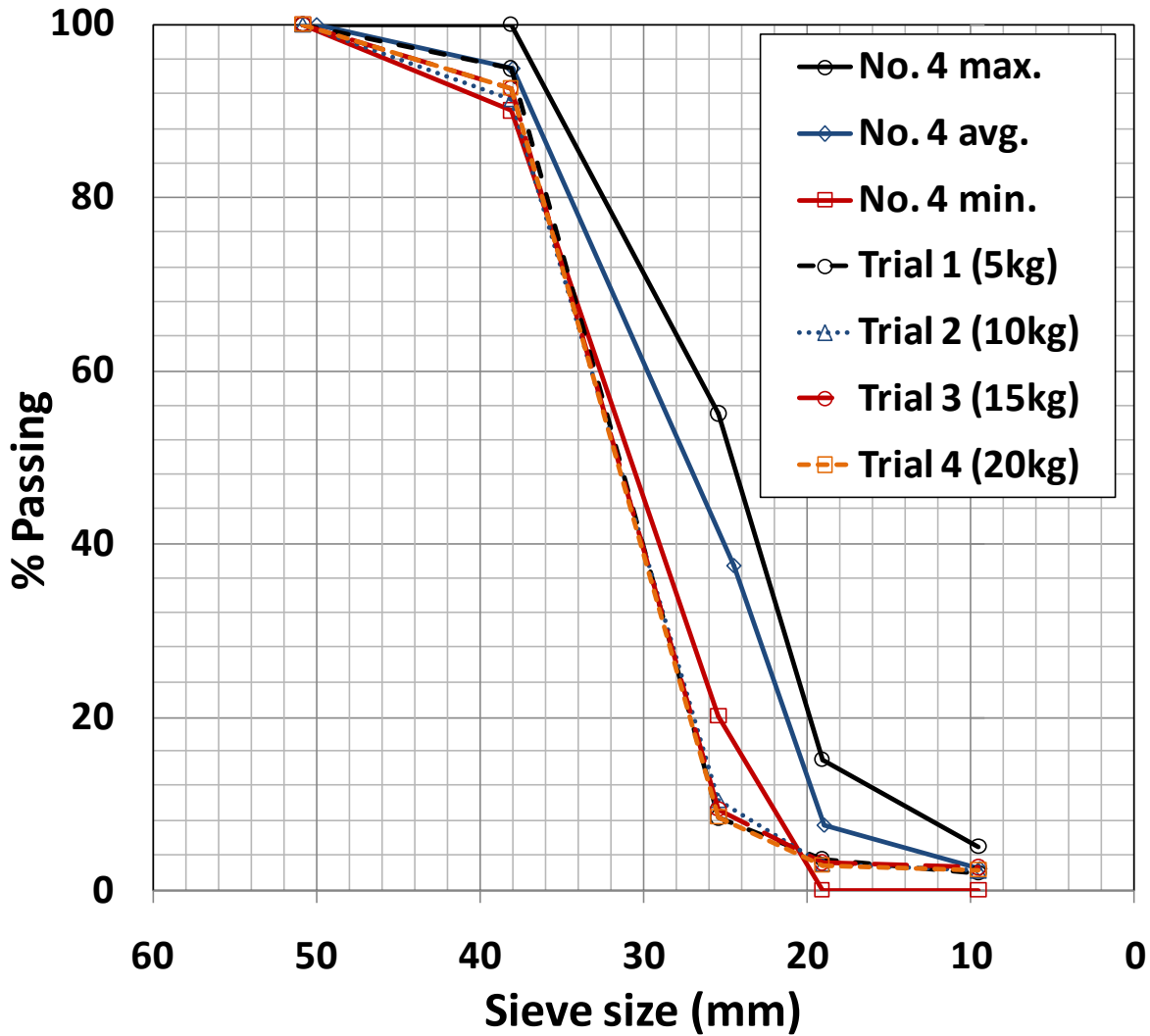
Figure 8. Gradation Analysis Results of RCA

Up to 20 kg of RCA was tested using the TS-1 Gilson Testing Screen and the 2, 1.5, 1, 3/4, and 3/8 in. sieves. Using this testing screen the RCA can be separated into different size fractions and recombined according to the No. 4 gradation. Samples were prepared using this process and a 10kg sample of each No. 4 gradation (max, avg, min) was prepared for aggregate handling, physical properties, and permeability testing. Other samples were also prepared with

the 'as received' (further referred to 'as is') RCA and no size proportioning was applied. A photo of the 'as is' RCA is shown in Figure 99. For comparison, the base course gradation is shown plotted with the No. 4 gradation on a log scale in Figure 10.

Figure 9. The 'as is' RCA
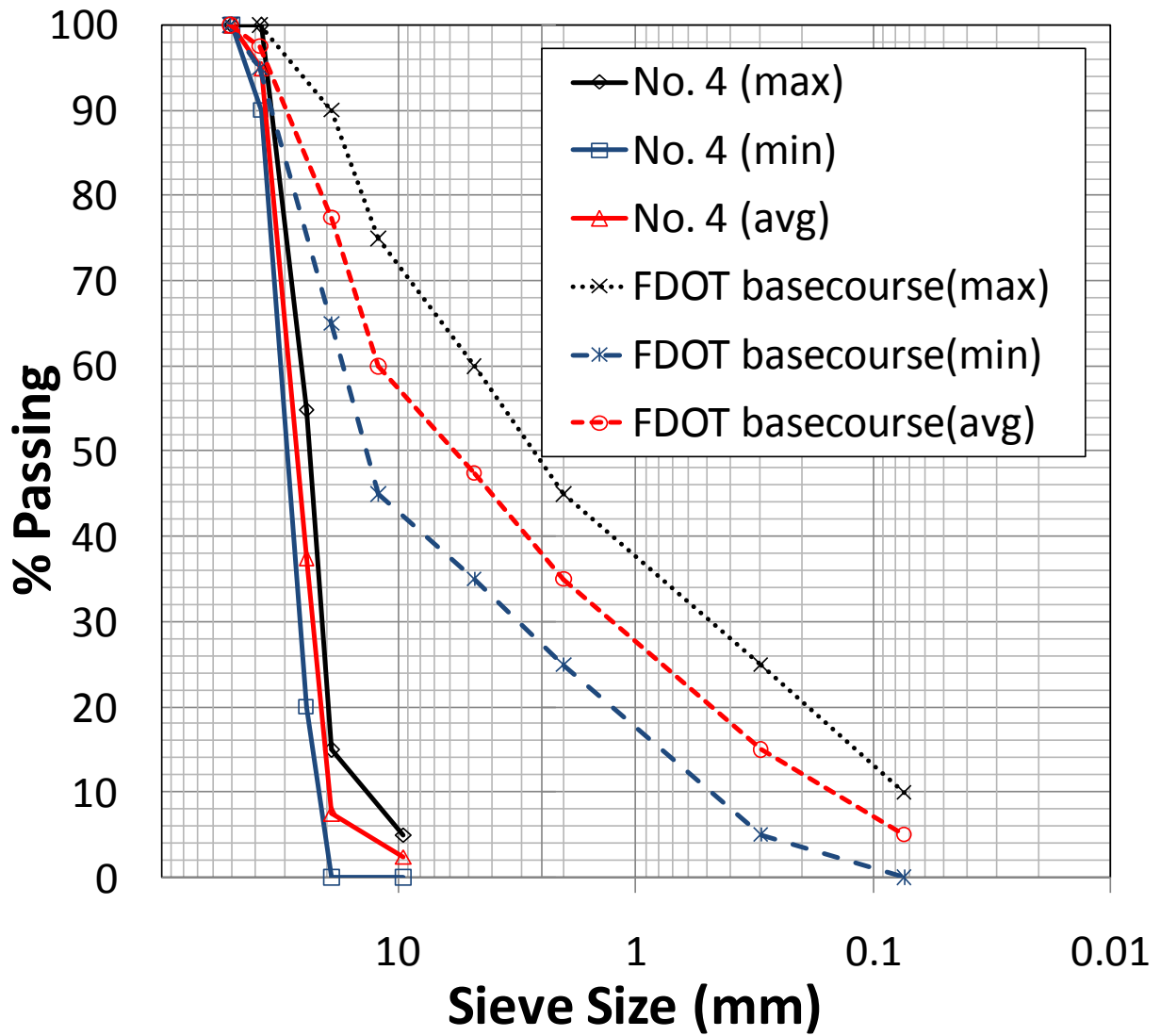
Figure 10. Gradation of Base Course Compared to No. 4 Aggregate on Log Scale

3.2 Physical Properties

3.2.1 Abrasion Resistance

The abrasion resistance of RCA was measured with the use of the HM-70A Los Angeles Abrasion Machine which was provided by the FDOT District 5 office. ASTM C535 provides the procedure for this test. According to the standard, grade 3 shall be used to best represent the No. 4 grade. Grade 3 includes 5000 g of material passing 1.5in. sieve but retained on 1in. sieve and 5000 g of material passing the 1in. sieve but retained on the 3/4 in. sieve. The gradation of grade 3 is shown in comparison to the No. 4 gradation in Figure 11. The material was placed into the L.A. abrasion machine along with the charge of 12 steel balls each with a diameter of about 1.84 in. and a combined weight of about 5000 g. The test procedure states that the sample is to be abraded in the L.A. abrasion machine for 1000 revolutions. The material is then removed and sieved over a No. 12 sieve (1.7 mm). The material passing the No. 12 sieve is discarded and the percent mass lost is reported as the original mass minus the final mass divided by the original mass.
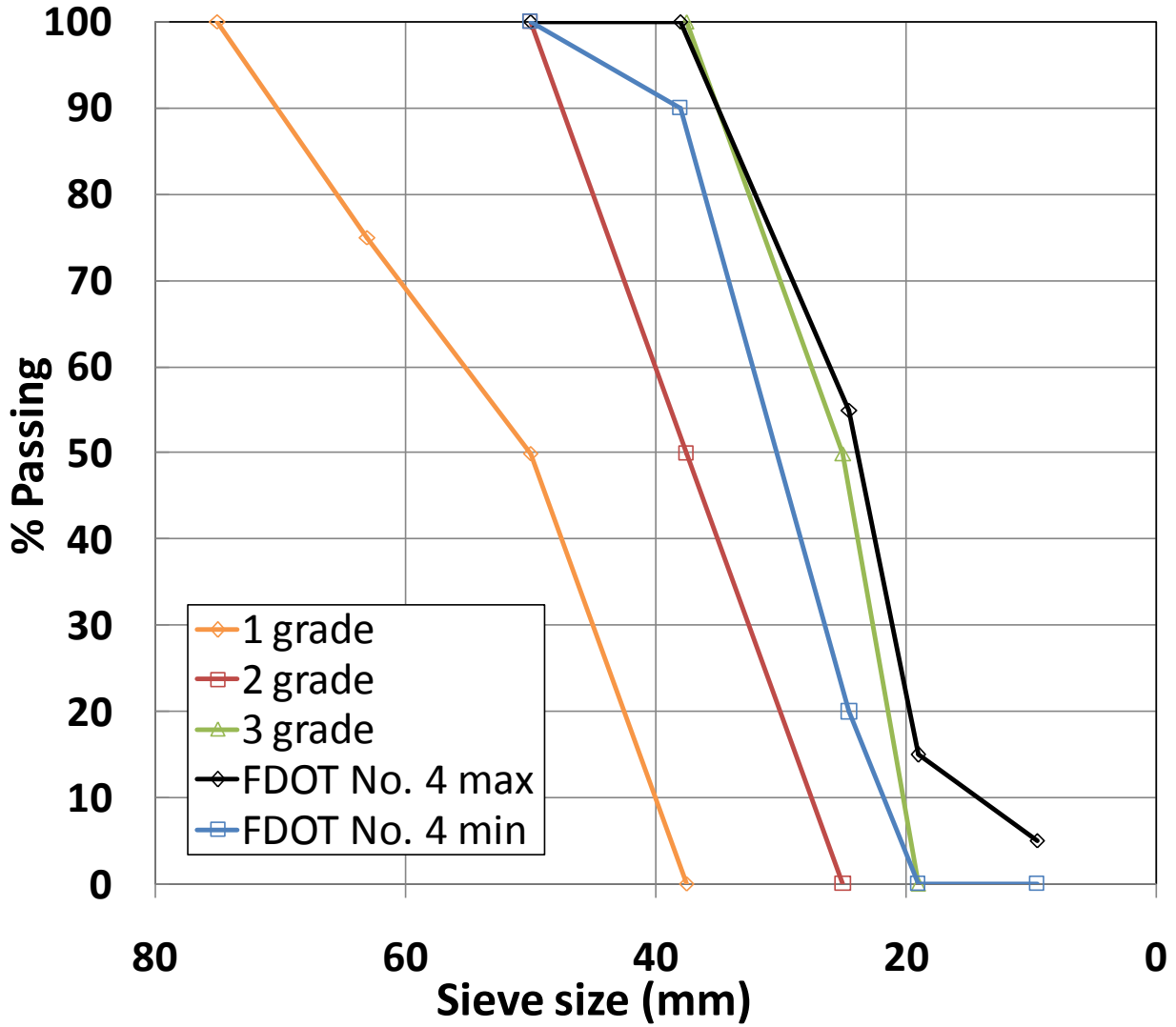
Figure 11. Grades Provided by ASTM C535

3.2.2 Specific Gravity and Absorption

The specific gravity and absorption of RCA was determined in accordance with ASTM C127. The specific gravity for No. 4minimum limit, maximum limit, and average was calculated

by measuring the submerged weight, saturated surface dry weight and oven dry weight of the RCA. The calculation for specific gravity is presented in equation 3.1.

$$G_S = \frac{A}{B-C}$$
(3.1)

Where

A = Oven dry weight (g),

B = Saturated surface dry weight (g), and

C = Submerged weight (g).

With these measurements, the absorption can also be calculated by equation (3.2)

$$Absorption(\%) = \frac{B-A}{A} \cdot 100$$
(3.2)

The RCA was submerged in water for 24 hours at room temperature, the aggregates were dried using a large absorbent cloth and the weight was measured as B. after the saturated surface dry measurement was recorded the RCA was placed into a wire basket and weighed while being submerged in water; using an analytical balance and string which was tied to the wire basket, the measurement was taken as C. After the submerged weight was recorded the RCA was placed in an oven at 110°C and dried to a constant mass and recorded the weight as A.

3.2.3 Unit Weight and Percent Voids

The unit weight and percent voids were measured as specified in ASTM C29. The bulk unit weight was determined by filling a rigid wall container in three layers with RCA. Each layer is rodded with 25 strokes from a tamping rod. The weight of the RCA was recorded and divided by the volume of the container and denoted as M. with the unit weight and specific gravity, the percent voids for each gradation can be calculated with Equation (3.3).

$$\% \, Voids = \frac{(G_s \cdot \gamma_w) - M}{G_s \cdot \gamma_w} \cdot 100 \qquad\qquad (3.3)$$

Where

G_s = Specific gravity,

γ_w = Unit weight of water (1g/cm^3), and

M = Unit weight of RCA (g/cm^3).

The specific gravity for RCA can vary depending on the source material, since RCA is a waste material it includes deleterious materials with different properties than crushed concrete. Absorption and unit weight can also vary depending on the debris content, while percent void space is related to particle size. Since the RCA crushing equipment can be used to crush concrete to a particular gradation, any deleterious materials in the RCA will be of similar size to the final product.

The specific gravity, unit weight, percent voids, L.A. abrasion value and absorption of RCA are shown in Table 2. There are slight variations of the physical properties between the No. 4 gradations. The void percent slightly increases with an increase is particle size, that is, the more open No. 4 gradation (minimum limit) has the highest measured voids while the closed grade No. 4 (maximum limit) has the least measured voids. The large void content allows for smaller overall dimensions for drain construction (Minnesota Pollution Control Agency, 2000). The L.A. abrasion value measured was 43.7%. This value is under the FDOT limit of 45%. However, this test indicates that RCA is very susceptible to degradation and the generation of fines during transporting, stockpiling or placing. In a study performed by Kuo (2001) similar results from RCA samples collected in 7 districts of the Florida Department of Transportation were found. Whereas Kahraman (2007) reports L.A. abrasion values for virgin aggregates (limestone) at 28.9% mass loss. A photo of RCA subjected to abrasion is provided in Figure 12.

Table 2. Physical Properties of RCA

	No. 4 gradation		
	Avg	Max	Min
Specific gravity	2.16	2.18	2.19
Unit wt. (g/cm^3)	1.21	1.25	1.22
voids (%)	43.9	42.6	44.3
L.A. abrasion value	43.70%		
Absorption (%)	6.43%		
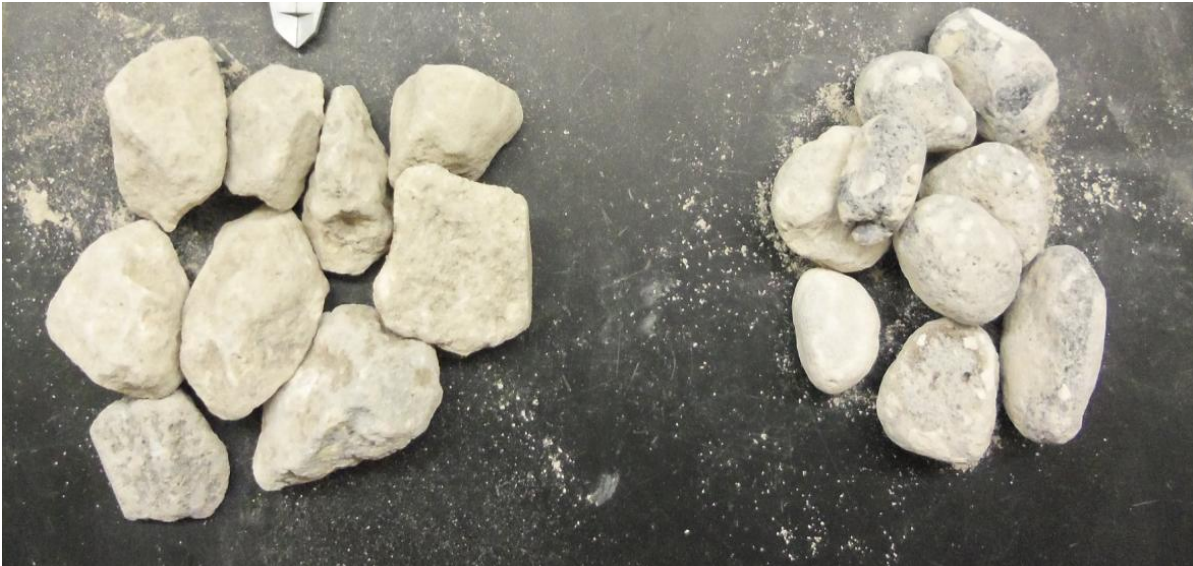
Figure 12. RCA Before (Left) and After (Right) L.A. Abrasion Test.

3.3 Aggregate Handling Process

Testing was conducted in an attempt to evaluate the handling process of RCA. Aggregates undergo degradation by stockpiling, transporting and placing at the site. To simulate the aggregate handling process the use of a Los Angeles abrasion machine (simulating vertical or crushing abrasion) and a Gilson TS-1 testing screen mechanical shaker (simulating the horizontal movements of aggregates). The L.A. abrasion machine was used first with just the RCA and the mechanical shaker was used second. The mechanical shaker can be used with just the bottom pan to provide an area where aggregates can be vibrated and can move freely. The RCA was placed in the L.A. abrasion machine and the mechanical shaker at various times to best simulate the effect of the handling process. The sample details are shown in Table 3.

Table 3. Sample Details for Aggregate Handling Simulation

Sample ID	L.A. Abrasion	Mech. Shaking
AHP1	10 Minutes	5 Minutes
AHP2	10 Minutes	10 Minutes
AHP3	10 Minutes	15 Minutes
AHP4	20 Minutes	5 Minutes
AHP5	20 Minutes	10 Minutes
AHP6	20 Minutes	15 Minutes

The results from the aggregate handling process are shown Figure 13, and 14. All six samples were combined according to the No. 4 average gradation (Figure 13) to serve as a starting point. After the appropriate times in the L.A. abrasion machine and the mechanical shaker the samples were tested again for gradation to see the effect of the simulation. The results shown in Figure 14, suggest that the vertical movement and crushing abrasion provided by the L.A. abrasion machine has a more substantial impact on the final gradation than the horizontal movements provided by the mechanical shaker. Samples, AHP1, AHP2, and AHP3 show that the final gradation is very similar, and that with 10 minutes in the L.A. abrasion machine controls the final gradation, while the 5, 10 and 15 minutes of the mechanical shaker have little to no effect. Samples AHP4, AHP5, and AHP6 show that 20 minutes in the L.A. abrasion machine will generate more fines than the samples with 10 L.A. abrasion, and the effect of the mechanical shaker shows slightly more variation. In general the degradation of RCA is highly dependent on the vertical and crushing movements than the horizontal movements.

Sample ID	L.A. Abrasion	Mech. Shaking
AHP1	10 Minutes	5 Minutes
AHP2	10 Minutes	10 Minutes
AHP3	10 Minutes	15 Minutes
AHP4	20 Minutes	5 Minutes
AHP5	20 Minutes	10 Minutes
AHP6	20 Minutes	15 Minutes
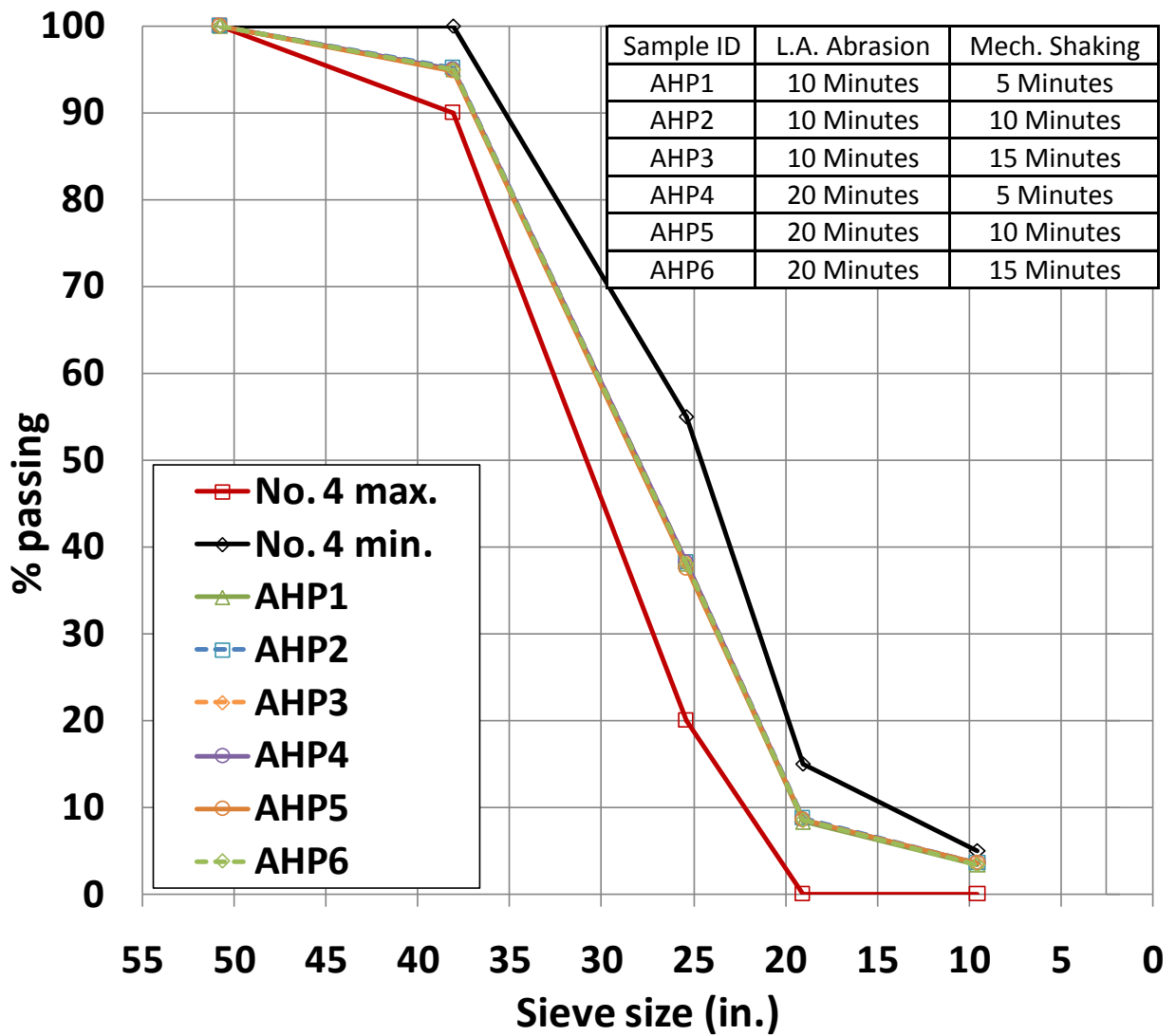
Figure 13. Initial Gradation of Aggregate Handling Process Test

Sample ID	L.A. Abrasion	Mech. Shaking
AHP1	10 Minutes	5 Minutes
AHP2	10 Minutes	10 Minutes
AHP3	10 Minutes	15 Minutes
AHP4	20 Minutes	5 Minutes
AHP5	20 Minutes	10 Minutes
AHP6	20 Minutes	15 Minutes
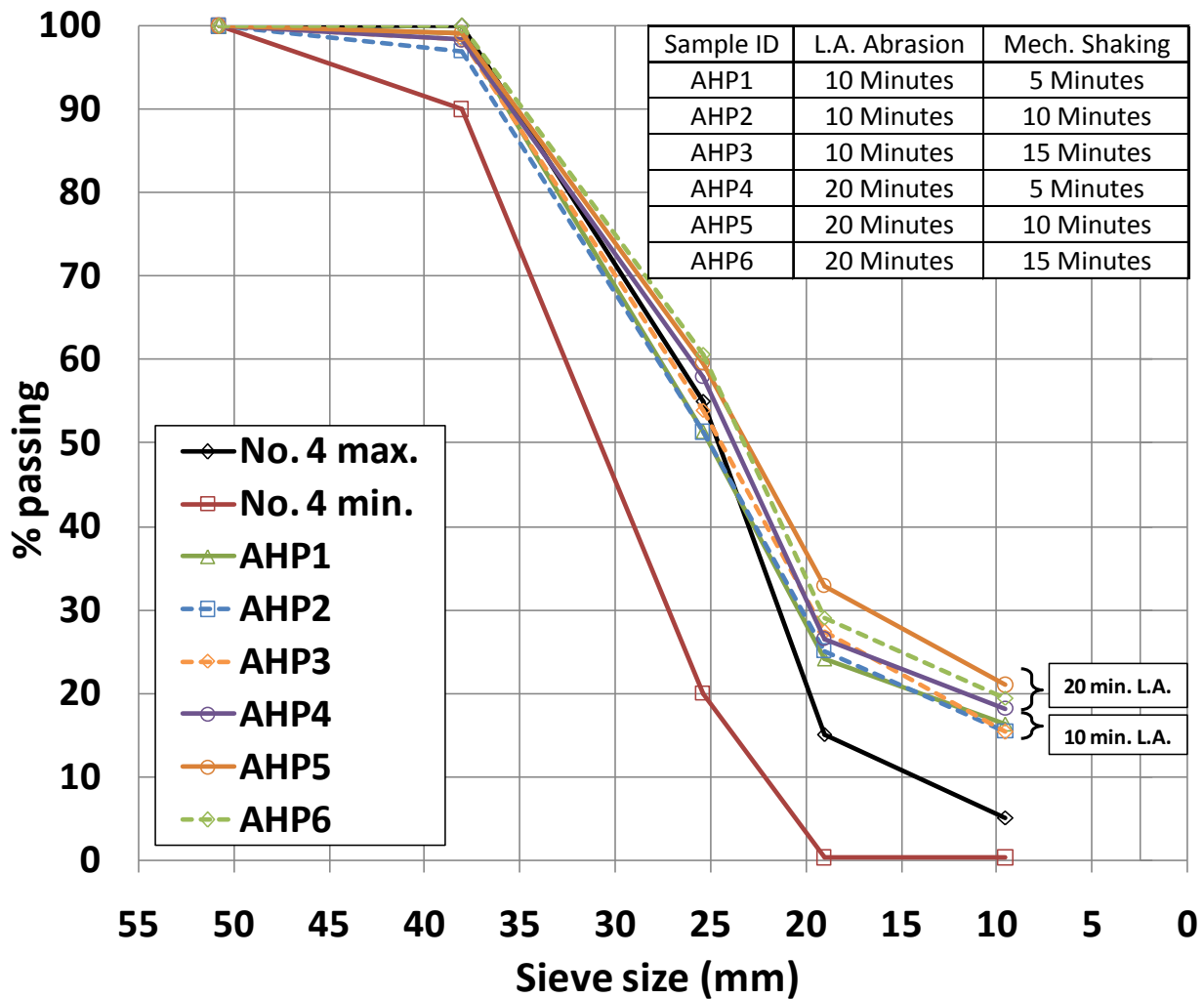
Figure 14. Final Gradations after Aggregate Handling Process Test

3.4 Washing Methods

An initial testing setup was developed to simulate the large scale aggregate washing processes. The testing setup included plastic bins to accommodate 10 kg of RCA. A total of 7 samples were prepared for testing. The sample information is listed in Table 4 and a photo of the

testing setup is show in Figure 15. Three different cleaning methods were evaluated, suspension only, in which the RCA is soaked in water for a given time and the water is drained out. Agitation was another method used for aggregate cleaning in which the RCA was soaked for the same times given in the suspension only samples, but the RCA is agitated by hand and abraded while the water is allowed to drain out. The pressure washing method was also tested by washing RCA for 2 minutes while the water can freely drain out. All samples were air dried for two days before a final gradation analysis was conducted.

Table 4. Samples for Aggregate Washing

| | | Method | |
	Suspension	Suspension + agitation	Pressure washing
time duration	1hr	1hr	
	4hr	4hr	2 min.
	24hr	24hr	

Figure 15. Aggregate Washing Setup

An additional aggregate washing test was conducted using an automated process. Similar to the first washing test, this test simulates aggregate suspension, agitation, and pressure washing. All samples were approximately 5kg, and the weight of the samples were weighed before and after washing to measure the mass lost. The sample information for this test set is shown in Table 5. The suspension test was performed using a wire mesh basket suspended in water. This setup was necessary to allow suspended particles to settle to the bottom of the water container and being completely separated from the bulk aggregate sample. The agitation and pressure washing test was conducted using an automated barrel mixer. Samples of RCA are placed in the mixer with approximately 9.8kg of water. The agitation test involved mixing the water and RCA for 5, 10 and 15 minutes, after which the RCA was oven dried and the weight was recorded. The pressure washing test was conducted in a similar manner to the agitation test, however the excess water was allowed to drain during the test, and a water nozzle was mounted and directed at the aggregate. The mounted water nozzle ensured that the treatment received by the RCA was consistent between each test. The testing setup for this series of washing treatments is shown in Figure 16.

Table 5. RCA Washing Samples for Mixer Setup

| | | Method | |
	Suspension	Suspension + agitation	Pressure washing
time duration	5min	5min	5min
	10min	10min	10min
	15min	15min	15min
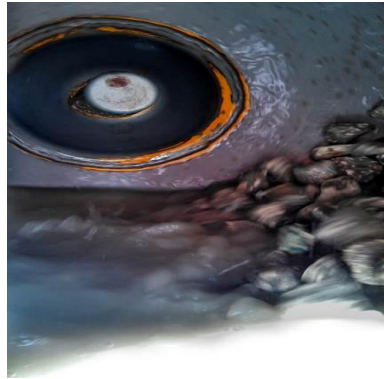
(a) Suspension   (b) Suspension + Agitation   (c) Pressure washing

Figure 16. Testing Setup for Automated Aggregate Washing

The results from the initial aggregate washing test are shown in Figure 17. It was assumed that all samples were equal. However performing a sieve analysis on the samples would in essence be separating all of the different size fractions, i.e. removing the fines from the sample. It would be ideal to know the exact gradation of the samples before performing a fines removal method; however the very act of the sieve analysis is separating the fines as well. If a sieve analysis was performed prior to washing, then the sample would have to be recombined in a way that is unlike the natural condition of the received RCA. Therefore this test is based on the assumption that all samples were equal in gradation, and only after the aggregate washing was a sieve analysis was performed. Should this assumption be valid, there appears to exist a trend between washing method and less fine material, that is, the pressure washing, suspension + agitation, and suspension only methods decrease in effectives respectively, independent of washing times. However these results were insufficient for determining the most effective aggregate washing procedure. For this reason an additional washing test was performed.

The results for the mixer setup washing test are shown in Figure 18. A Similar trend appears such that the most effective method for fines removal is pressure washing, suspension + agitation, and suspension only, respectively. The results from this washing test are more conclusive since the entire process was automated, and the trend is as what would be expected.
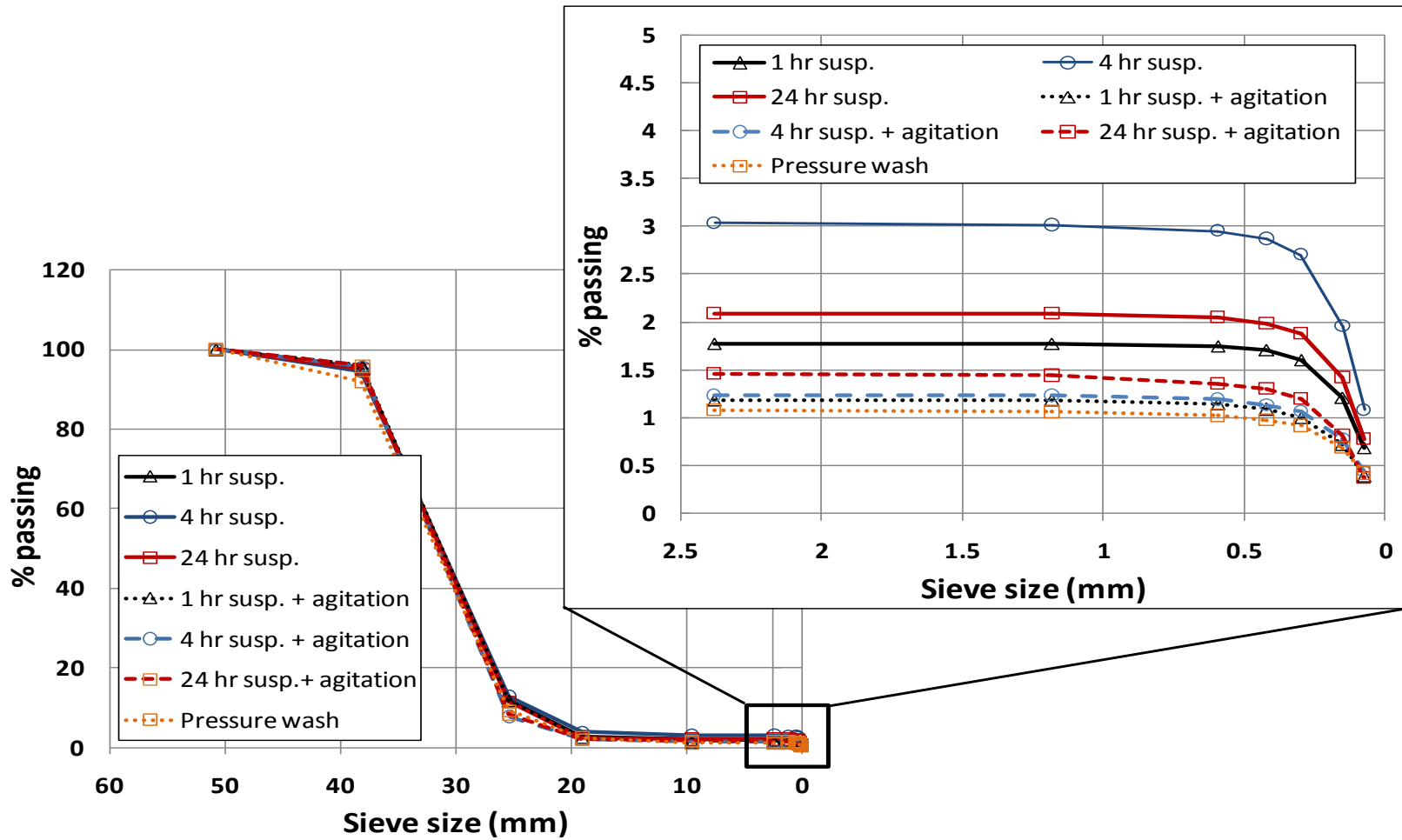
Figure 17. Results from Initial Aggregate Washing Test
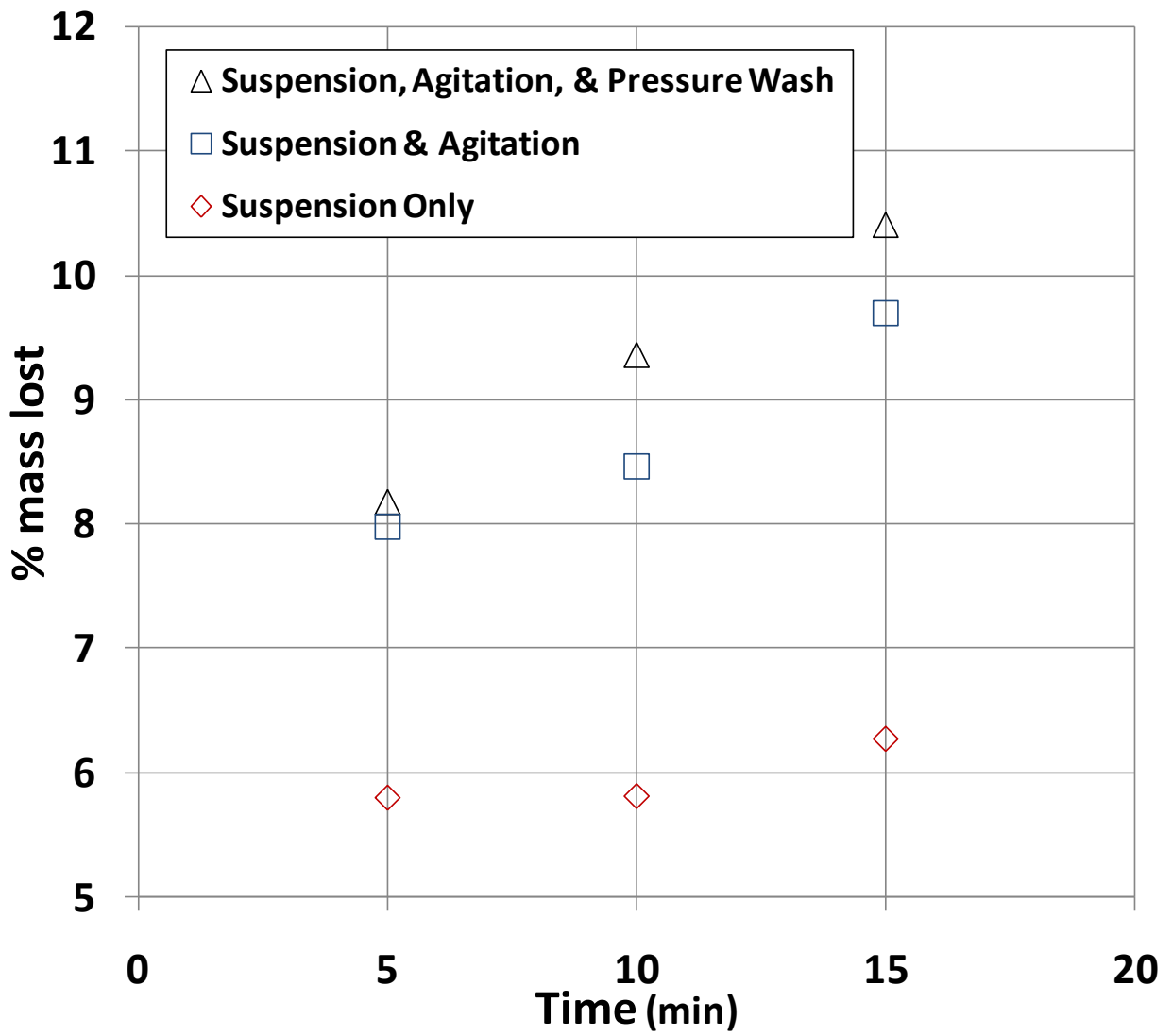
Figure 18. Results for Mixer Setup Aggregate Washing Test

3.5 Summary

RCA No. 4 aggregate was obtained and tested for its conformity to the gradation standards. It was found that the RCA did not meet the No. 4 specifications; therefore the No. 4 aggregate was created by combining the individual size fractions required. The physical properties of RCA were tested, and it was determined that RCA has a relatively high value of L.A. abrasion. This suggests that RCA is susceptible to degradation and fines generation. The aggregate handling process was evaluated and it was determined that the vertical/crushing motion provided by the L.A. abrasion machine was more influential in the final gradation than the shaking or horizontal movement provided by the mechanical shaker. Aggregate washing methods were tested using a manual agitation process set up, and also an automated setup. It was found that a combination of agitation and pressure washing was the most effective at removing fine material.

CHAPTER 4: EVALUATION OF REHYDRATION

4.1 Introduction

To determine whether rehydration of RCA occurs, several tests were conducted, including pH, compressive strength, hydration temperature, and time of setting tests. In addition, petrographic examinations, scanning electron microscopy (SEM), energy dispersive x-ray (EDX), and x-ray diffraction (XRD) were utilized. These tests are designed to maximize the possibility to observe rehydration of cement. In order to do this, RCA is ground using a ball mill to fine particles (passing the No. 200 sieve). This will ensure that if there exists a substantial amount of unhydrated cement fines, that the most will be exposed through this grinding process. The RCA fines are shown in Figure 19 and were used in all of the following tests to determine rehydration.

4.2 Compressive Strength and pH Test

Compressive strength tests were conducted based from the ASTM C39 procedure for concrete cylinders. Samples were prepared by grinding RCA and sieving with a No. 200 (75μm) sieve. The material passing the No. 200 sieve was collected and mixed with water with a water to cement ratio of 0.5. Control samples of virgin cement were also mixed with the same water to cement ratio. The sample information is listed in Table 6. Samples were cast into 2 in. diameter

and 4 in. in length cylinders. All samples were placed into a temperature and humidity controlled chamber with a wireless temperature and humidity sensor. The average temperature and humidity in the chamber were 95˚F and 99% relative humidity, respectively. Virgin Cement samples were unmolded after 3 days from casting, and were placed back into the environmental chamber.

Figure 19. Ground RCA Fines

Table 6.Sample Information for Compressive Strength and pH Tests.

Sample ID	Material	Tests performed	w/c ratio	Tested at day
A3	RCA	pH	0.5	3
A7	RCA	Comp. & pH	0.5	7
A14	RCA	pH	0.5	14
A28	RCA	Comp. & pH	0.5	28
C3	Virgin Cement	pH	0.5	3
C7	Virgin Cement	Comp. & pH	0.5	7
C14	Virgin Cement	pH	0.5	14
C28	Virgin Cement	Comp. & pH	0.5	28
A24hr	RCA	pH	0.5	<24 hours
C24hr	Virgin Cement	pH	0.5	<24 hours
A58	RCA	SEM, EDX, XRD	0.5	58

Compressive strength samples were tested at 7 and 28 days after casting, and pH samples were tested at 0 min, 15 min, 1 hr, 2 hr, 6 hr, 10 hr and 24 hr (A24hr and C24hr sample ID), and 3, 7, 14, and 28 days after casting. One cylinder each (A24hr and C24hr) was sufficient to gather pH data for the first 24 hours after casting. A universal testing machine (UTM) with 120 kip capacity was used to test the compressive strength of the C28 sample. However the RCA samples were too weak to use the UTM and be able to obtain accurate readings, therefore a lower capacity (10,000 lbs) Marshall testing frame was used for A7, A28 and C7 samples. The crushed samples were retained for pH testing.

The pH tests were conducted by reducing hardened sample segments to less than 75 μm and combined with an equal part of water. These samples were created by crushing and grinding the original samples until 30 g of material passing the No. 200 sieve was collected. The hardened cement was grinded by a mechanical grinder initially to a size of about 1/8 in. diameter size and then ground by hand using a mortar and pestle until particles passing the No. 200 sieve were obtained. The fine material was mixed for 2 minutes with 30 g of deionized water to achieve a 1 to 1 ratio of cement to water as described by the pH slurry method (ESDRED, 2005). The 1 to 1 ratio is necessary for the measurement of pH since the mixture should be of liquid consistency for an accurate reading with the pH meter. The pH meter used is an Oakton pHTestr 20 and the testing equipment is pictured in Figure 20.

Figure 20. pH Testing Setup

Compressive strength and pH testing has been conducted on RCA fines and virgin cement mixed with a water to cement ratio of 0.5. The results of the compressive strength tests are shown in Figure 21. The virgin cement samples (C7 and C28) increase in strength from about 10 MPa to 28 MPa, however the RCA samples (A7 and A28) resulted in considerably lower strengths at 0.1 and 0.4 MPa for 7 and 28 days respectively. It was observed that the RCA samples were very weak and must be handled carefully as the samples could be broken apart by hand or fall apart if submerged in water for several minutes. Clearly very little to no strength building has developed in RCA samples. The apparent strength of RCA is more likely due to cohesion after a decrease in water content (Dafalla, 2013). Comparatively, RCA posses only 1.6% the strength of virgin cement at 28 days. These results suggest that RCA does not tend to rehydrate under the presence of moisture. Photos of the failed specimens are shown in Figure 22. The fracture patterns for virgin cement exhibits type 3, columnar vertical cracking through both ends, with no well-formed cones, while the RCA sample appears to have bearing capacity failure which forms a cone shape shear failure surface (Das, 2006).
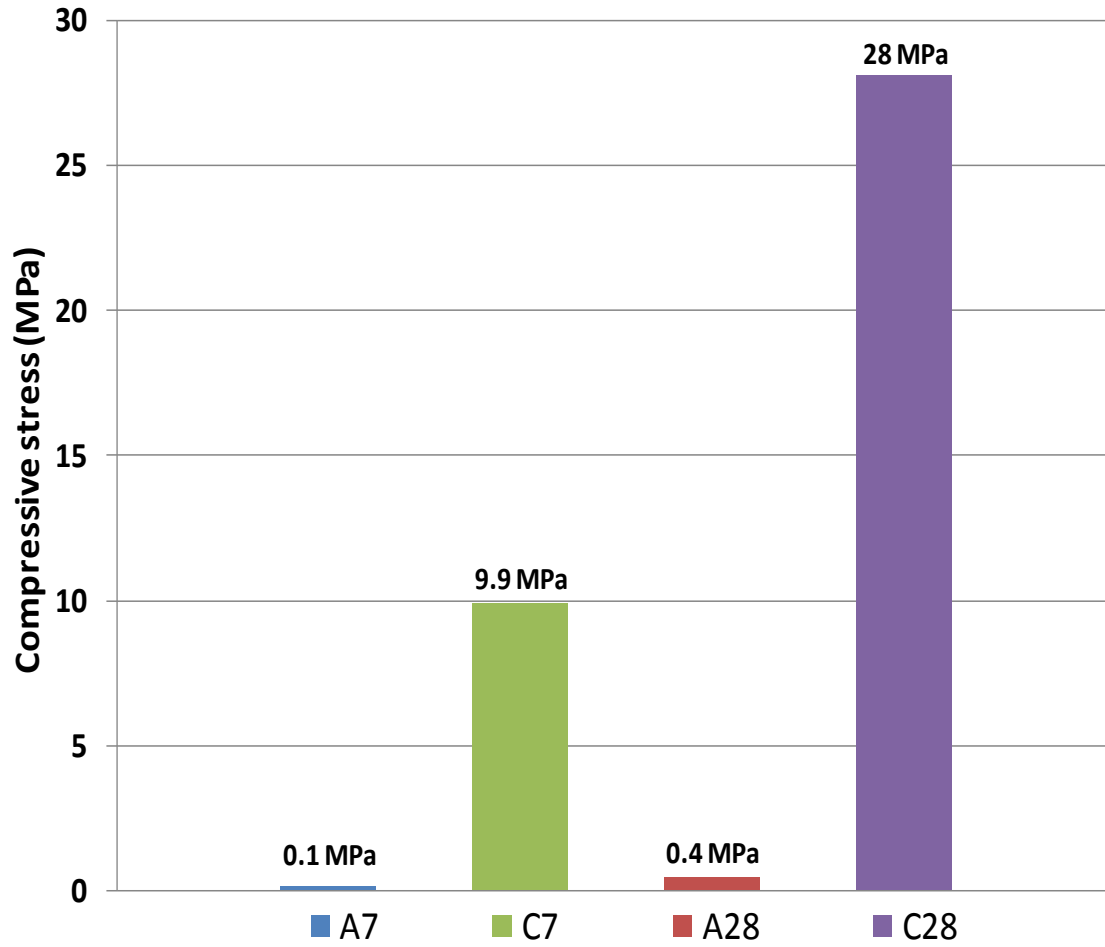
Figure 21. Compressive Strength Results for RCA (A7 and A28) and Virgin Cement (C7 and

C28)

(a)   (b)

Figure 22. Failed Samples of (a) Virgin Cement and (b) RCA

The results for the pH test are shown in Figure 23. Virgin cement had an initial pH of about 12.7 and increases steadily for the first 24 hours to about 13 and the rate of increase slows considerably and reaches a pH of 13.1 after 28 days. The initial increase of pH is likely due to the rapid dissolution of calcium, sodium and potassium hydroxides to produce an alkaline mixture. RCA samples had an initial pH of about 12.5 but quickly decreased to about 12.3 in the first 24 hours. After which the pH becomes relatively constant at about 12.1. The initially high

pH is likely due to the already present dissolved calcium, sodium and potassium hydroxides, and with time the precipitation of calcium carbonate may be evidenced by the decrease in pH (Steffes, 1999).
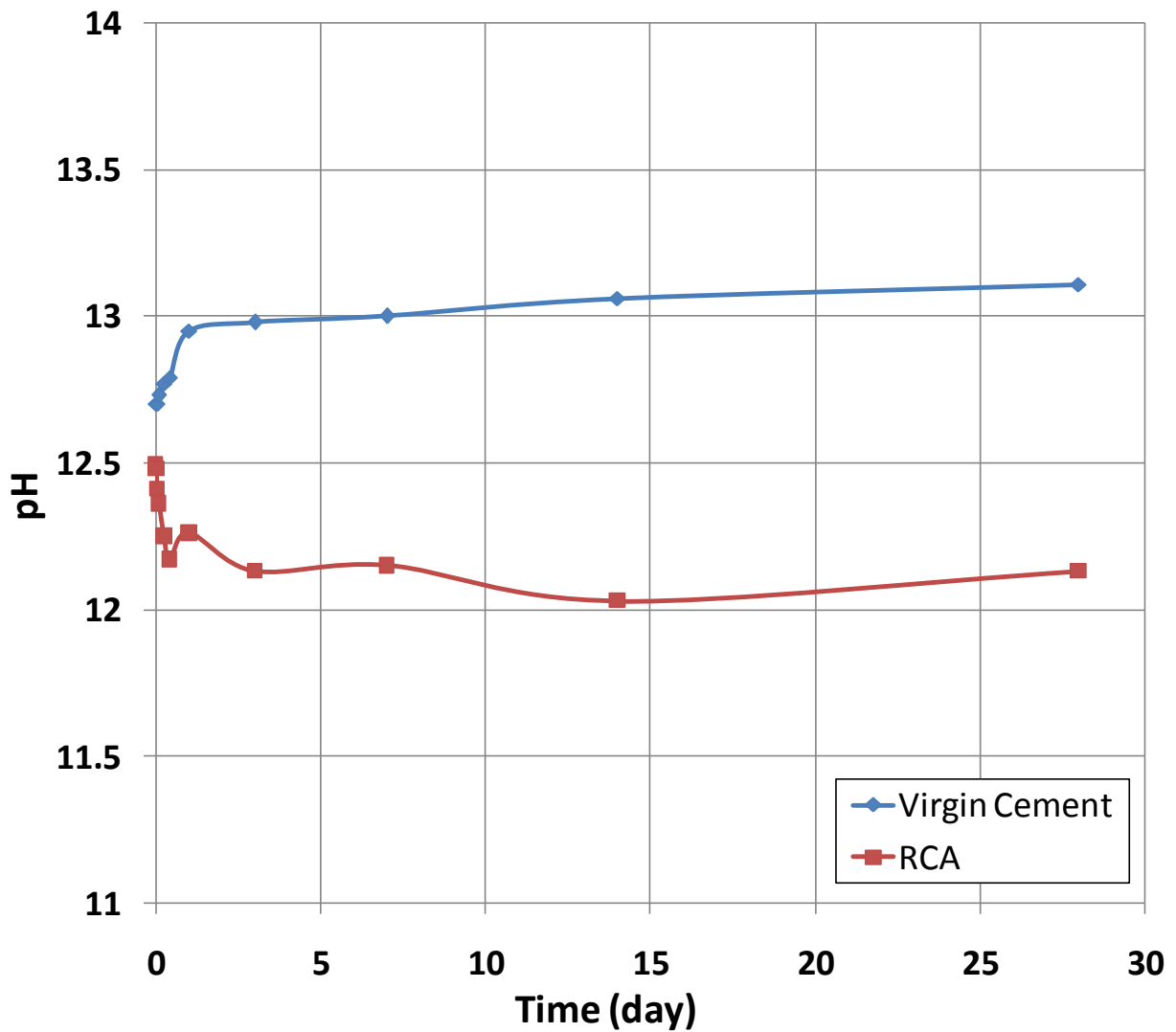
Figure 23. pH Testing Results for Virgin Cement and RCA

4.3 Heat of Hydration

A test to measure the heat generation from cement hydration was developed. In lieu of a calorimeter to measure heat generation, a thermocouple was used to measure temperature of RCA and of virgin cement during hydration. Temperature is an indication of the heat possessed by the samples and will be sufficient to compare the temperature of virgin cement and RA fines as signs of hydration. The sample information for this test is shown in Table 7.The thermocouple used a four-channel Omega HH309A data logger.

Table 7. Sample Information for Heat of Hydration

Sample ID	Material	Cylinder Size (DxL)	w/c
HH1	RCA	4 in. x 6 in.	0.5
HH2	Virgin Cement	4 in. x 6 in.	0.5

All the samples were prepared with a water to cement ratio of 0.5 and mixed by hand for 2 minutes. The samples were prepared and tested one at time. The sample molds were cylinder size (D x L) 4 in. x 6 in. however it is necessary to insulate the samples throughout the hydration stages. Therefore a 2 in. thick Styrofoam capping was used. The thickness of the Styrofoam capping limits the sample heights as seen in Table7. The molds were also placed in a water bath for additional insulation. Insulating the samples will ensure that if any heat generation occurs that the heat will stay within the sample for long enough for the detection by the thermocouple. A thermocouple probe was placed in the centroid of each sample, while another probe was placed in the water bath and a third probe recorded the air temperature in the testing room. The

testing setup for this experiment is shown in Figure 24. After each mixture was prepared and poured into the mold, the Styrofoam capping with the mounted thermocouple probe (see Figure 24b) was immediately placed into the top of the mold and the mold was then placed into the water bath. The thermocouple software began recording and took measurements every 15 seconds for 24 hours.
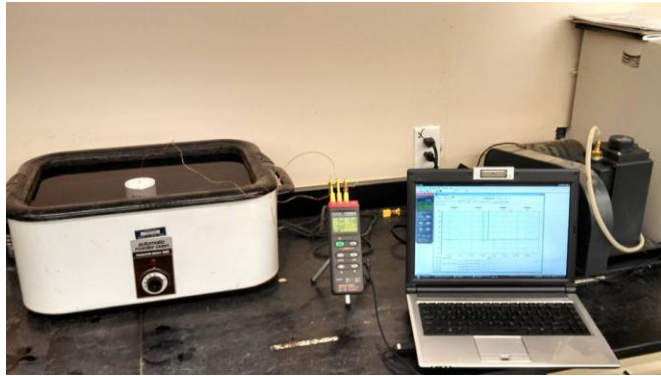
(a)

(b)

Figure 24. (a) Testing Setup for Heat of Hydration and (b) Probe Placement in Specimen

Testing to evaluate the formation of calcium silicate hydrate, the strength building component of hydrated cement, was performed by measuring temperature of RCA and virgin cement samples for 24 hours after mixing. Cement hardening occurs during the acceleration stage where peak heat generation occurs. The temperature variations for virgin cement hydration are well established (Mindess, 2003) and the different stages are clearly seen in Figure 25. However, the temperature variations of RCA are defined by the temperature of the environment, and no internal heat generation can be observed. The initial temperature of RCA is from the temperature of the mix water, after mixing the temperature steadily decreases and comes to equilibrium with the surround bath water, as shown in the Figure 25.
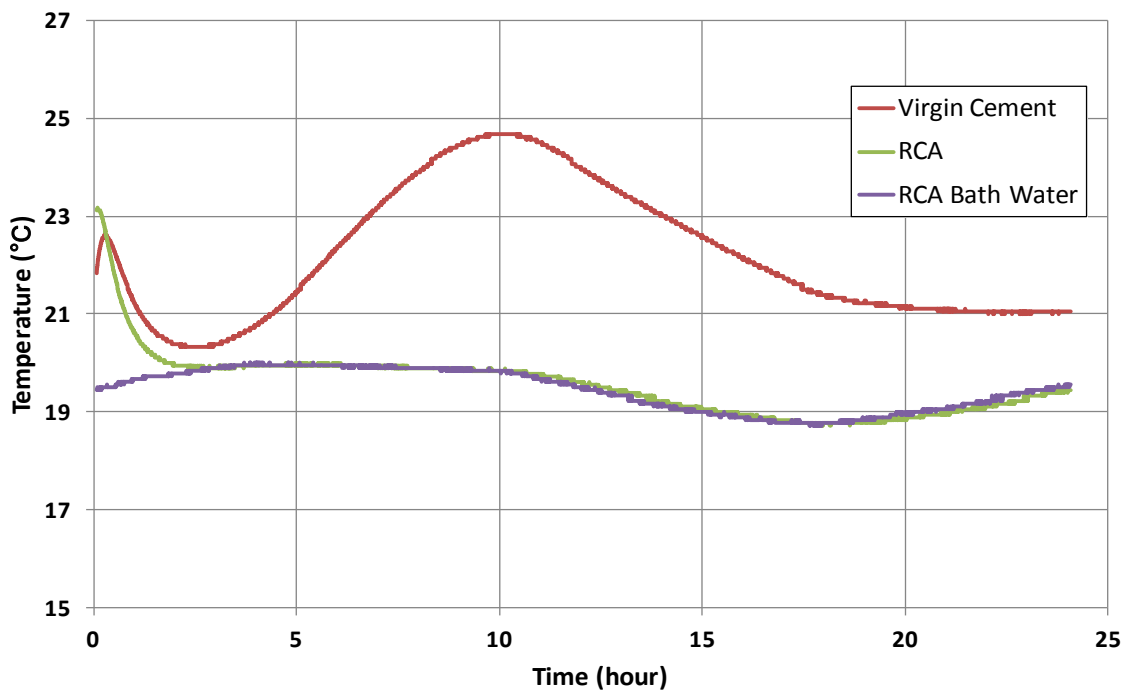
Figure 25. Measured Temperature of RCA and Virgin Cement Paste.

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Any increase in temperature of RCA that is observed is due to the temperature of the bath water which may vary throughout the 24 sampling period from the climate controls within the laboratory. The actual data measured was temperature and not heat. This test differs from ASTM C186 for the heat of hydration of hydraulic cement. Where the ASTM C186 utilizes a calorimeter to measure directly the heat generation, this test setup uses a thermocouple to measure the temperature as an indication of the heat generation. Since the purpose of this test is not to report the heat of hydration but to compare the heat generation by hydration between virgin cement and RCA fines, this test is suitable for determining the rehydration potential of RCA.

4.4 Time of Setting

The time of setting test was performed according to ASTM C191 (ASTM C191) using a Vicat needle. Samples were prepared according to Table 8. This test method is used to determine the initial set and final set of cement. Both virgin cement and RCA was tested for initial set and final set by this method. The testing device used is the Vicat apparatus (pictured in Figure 26). The test is performed by releasing a 300 g needle with 1 mm diameter into the sample. The initial set time is defined by the time required to achieve a penetration reading of less than 25 mm. the final set time is defined as the time required such that the 1 mm diameter needle does not make a fully circular indentation on the sample surface. This testing method can be useful in

the determination of any possible rehydration from RCA fines. If a set time is detected in the RCA sample, it can indicate that RCA has the potential for rehydration.

Table 8. Sample Information for Time of Setting

Sample ID	Material	w/c
TS1	RCA	0.5
TS2	Virgin Cement	0.5
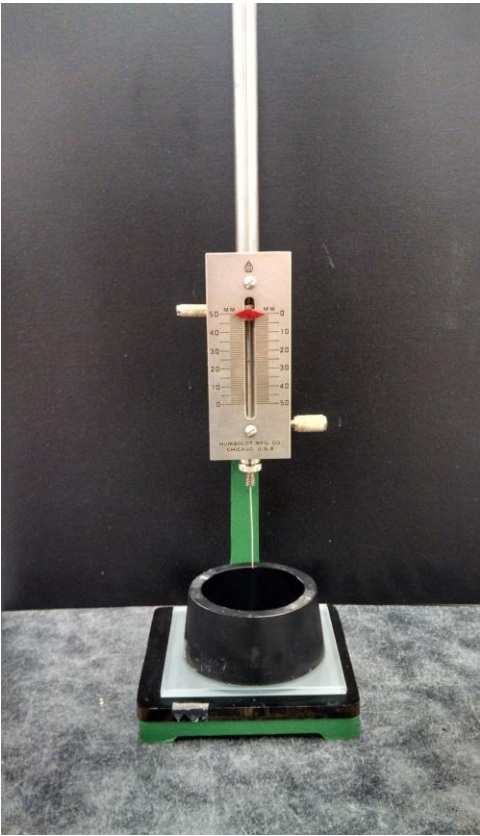
(a)   (b)

Figure 26. Vicat Apparatus View from (a) front, and (b) side

The time of setting test was conducted and the results are shown in Table 9. The results indicate that RCA was insufficient for enough strength gain to detect an initial or final set. The RCA sample test was terminated after 24 hours since no initial set was detected. Additionally, at the final measurement of RCA at 24 hours, the Vicat needle was able to penetrate the full depth of the sample.

Table 9. Time of Setting Test Results

Sample ID	Initial Set	Final Set
TS1	Not Detected	Not Detected
TS2	5 hr 23 min	9 hr 10 min

4.5 Petrographic Analyses

4.5.1 RCA Fines

EDX and XRD analyses (ASTM C295) were carried out in order to characterize the chemical compositions and crystallographic structure of RCA fines, respectively. The chemical compositions of RCA fines obtained from EDX are listed in Table 10. The major elements present within RCA fines are Ca, Si, and Al, as are the main chemical compositions of concrete (Mindess, 2003).The XRD spectrum analysis shown in Figure 27 indicates that the main mineral components of RCA fines are calcite ($CaCO_3$) and quartz (SiO_2). This observation confirms hat RCA is mainly composed of hydrated cement, sand, and limestone, which is consistent with the

EDX results. However, no evidence of the existence of portlandite ($Ca(OH)_2$), the byproduct of hydration, was found. This is appears to be attributed to: (1) a carbonation process (Song, 2011; Mindess, 2003; Mehta, 2006) that portlandite gradually transforms into calcite over time, and (2) a leaching out of portlandite due to its relatively high solubility (Mehta, 2006; Hewlett, 2004) especially when RCA was stored in open stockpiles in Florida with high temperature and relative humidity for a considerable amount of time. The absence of portlandite in RCA can also be found from other research works (Song, 2011; Poon, 2006).

Table 10. Chemical Compositions of RCA Fines

Element:	Test Values, % by weight
Carbon (C)	20.98
Oxygen (O)	37.43
Aluminum (Al)	3.67
Silicon (Si)	3.68
Calcium (Ca)	34.24
Total	100
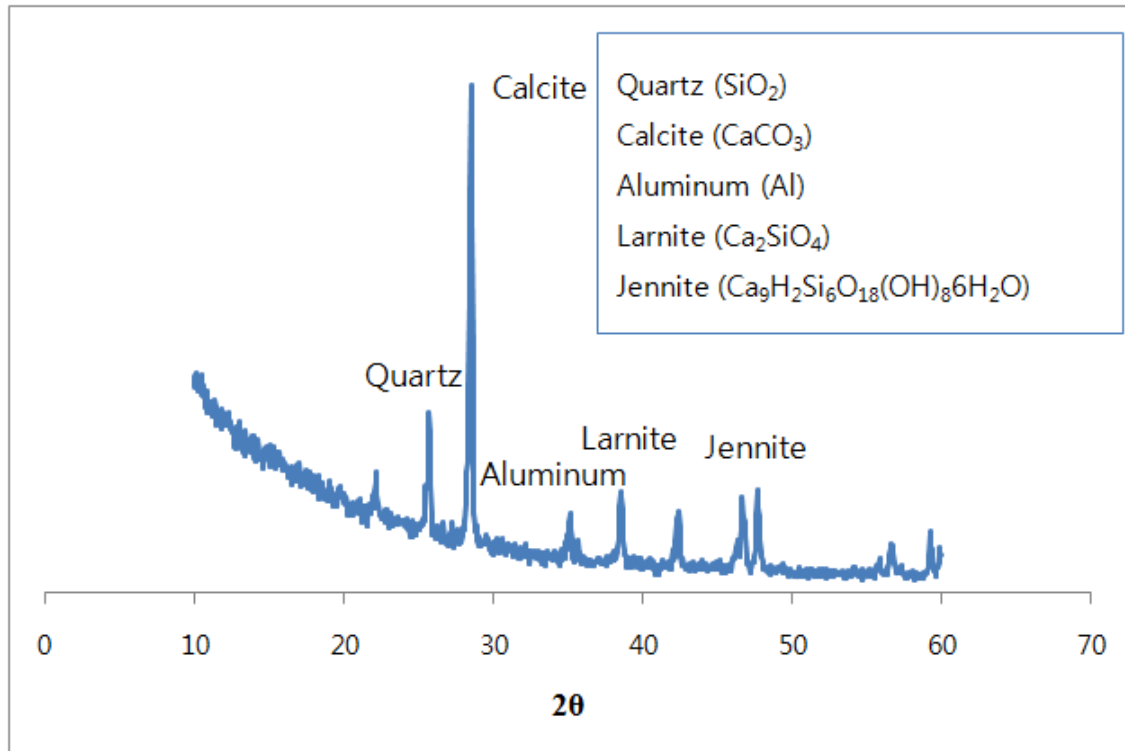
Figure 27. XRD Spectrum of RCA Fines

4.5.2 RCA Paste

SEM, EDX, and XRD was conducted 56 days after the casting sample A58, in order to evaluate the microstructural properties related to the possible re-cementation reactivity of RCA paste. Prior to the test, the RCA paste sample for the petrographic examinations was ground and kept in an oven at 105°C for 48 hours, in order to completely eliminate moisture within the paste. The JEOL JSM-6480 was used to obtain SEM and EDX analyses. SEM was used to detect the microscopic morphology, while EDX was employed to identify the chemical compositions of

RCA paste. XRD was carried out using the Rigaku D/MAX-II XRD with copper K-α radiation to observe the mineral components and crystallographic structure of RCA paste.

The microscopic morphology and corresponding chemical compositions of the RCA paste obtained from SEM and EDX are shown in Figure 28. The EDX data presented in the Figure are sourced from the locations selected in the SEM images (either red spot or rectangular box). A large number of pores are clearly observed from all SEM images, which may lead to intrinsic characteristics of high water absorption and low density of RCA paste. Similar to the previous EDX results from the RCA fines, the major elements present within RCA paste are Ca, Si, and Al, but with different ratios. Calculated Ca/Si ratios based on chemical compositions are also presented along with each SEM image. The Ca/Si ratio is directly related to the lime (CaO) concentration (Bergaya, 2011) and therefore, Ca/Si ratio is one of the main factors that characterizes the physical and chemical properties of C-S-H. C-S-H is formed by the hydration of alite (C_3S) and belite (C_2S) in Portland cement (Mindess, 2003; Mehta, 2006), and it has been reported that Ca/Si ratio of C-S-H generally falls in the range of 1.2 to 2.3 (Richardson, 1997), which decreases with time (Barnes, 2002).
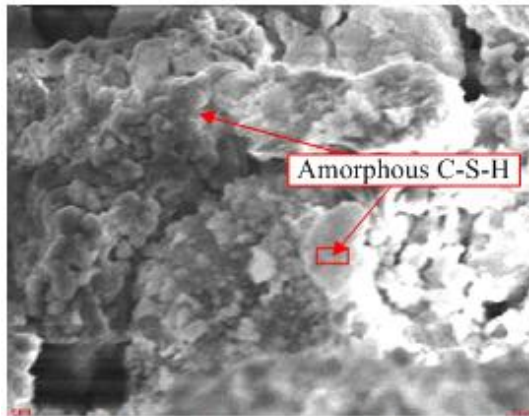
Element	Weight %	Atomic %
C	26.18	37.95
O	41.61	45.27
Al	3.15	2.03
Si	11.46	7.10
Ca	17.60	7.64
Total	100.00	99.99

(a) Amorphous region of C-S-H and its chemical compositions (Ca/Si ratio = 1.07)
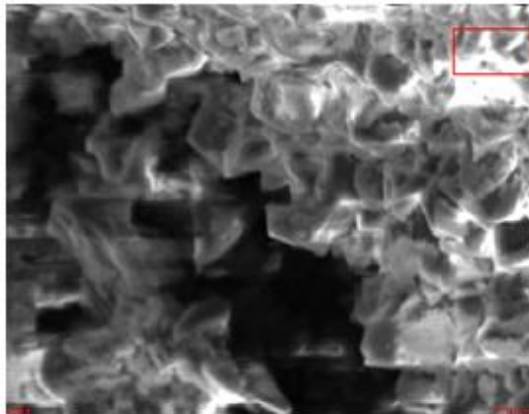
Element	Weight %	Atomic %
C	23.17	33.93
O	44.44	48.86
Al	8.58	5.59
Si	6.16	3.86
Ca	17.65	7.75
Total	100.00	99.99

(b) Jennite and its chemical compositions (Ca/Si ratio = 2.01)
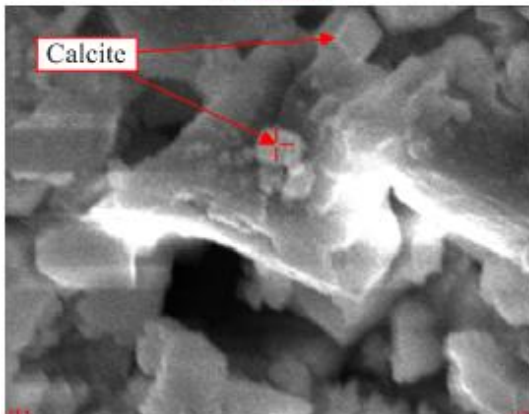
Element	Weight %	Atomic %
C	18.13	32.51
O	27.44	36.95
Al	2.37	1.89
Si	2.90	2.22
Ca	49.16	26.42
Total	100.00	99.99

(c) Calcite (rhombohedral crystal structure) and its chemical compositions (Ca/Si ratio =7.73)

Figure 28. Microscopic Morphology and Corresponding Chemical Compositions of RCA Paste

Except for the detection of calcite ($CaCO_3$) shown in Figure 28 (c), two different Ca/Si ratios of 1.1 and 2.0 were obtained from the microscopic analyses. Based on the morphology, corresponding chemical compositions, and calculated Ca/Si ratio, Figure 28 (a) is considered to be old C-S-H structure, which suggests that the RCA paste has been fully hydrated. The SEM image and EDX analysis shown in Figure 28 (b) appears to be old Jennite ($Ca_9H_2Si_6O_{18}(OH)_86H_2O$) as one analogue of C-S-H and its Ca/Si ratio of 2.0 agrees with other research studies on Jennite (Richardson, 1997; Taylor, 1986).Calcite with its distinctive rhombohedral structure was detected from the SEM image as seen in Figure 28 (c). The corresponding EDX data with a large amount of Ca and high Ca/Si ratio demonstrates the presence of Ca-rich environment, and also indicates that the hydration reaction of this RCA paste has been completed and the hydrated cement minerals have been carbonated over time. Similar results can be found from other research works (Subramani, 2008).

The XRD spectrum shown in Figure 29 indicates that the main components of RCA paste are calcite ($CaCO_3$) and Wollastanite ($CaSiO_3$), which agrees with the SEM and EDX analyses presented in Figure 28. It is important to note that no peaks of Portlandite ($Ca(OH)_2$), byproduct of hydration, were detected from this analysis, which indicate that there is little probability of re-cementation or pozzolanic reaction within the RCA paste.
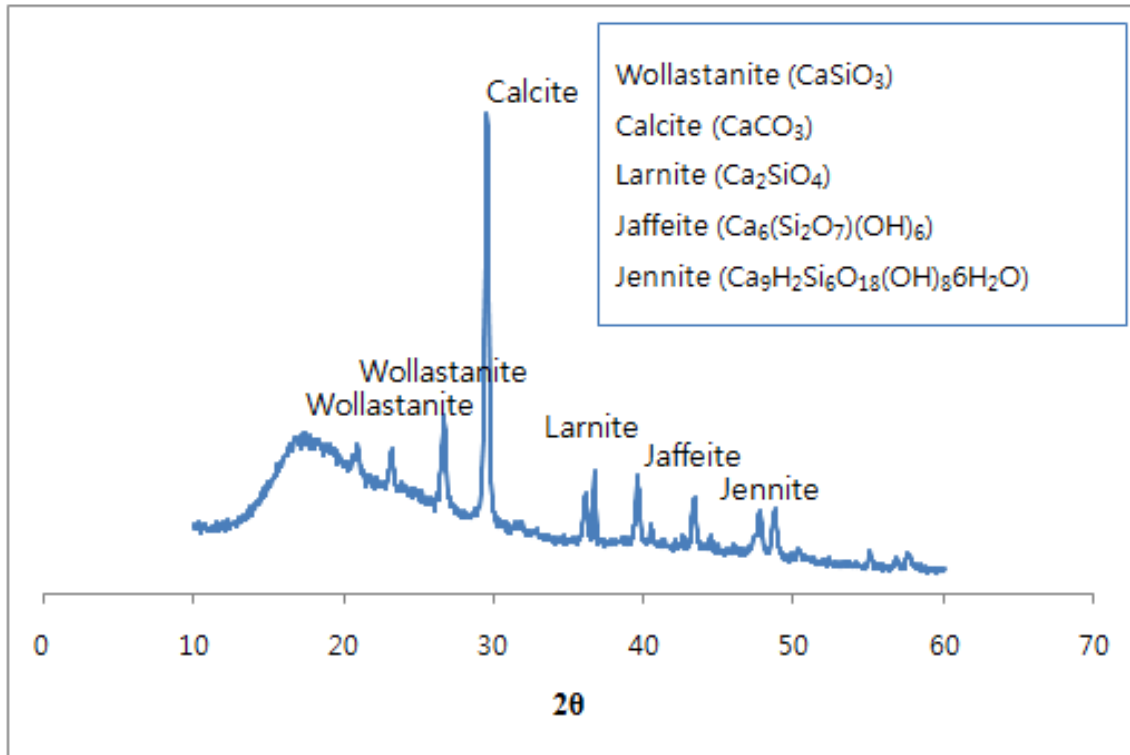
Figure 29. XRD Spectrum of RCA Paste.

4.6 Summary

The results from the rehydration evaluation tests suggest that RCA fines do not have the ability to rehydrate such that any bonds between particles can form. Compressive strength tests showed that RCA gains minimal strength from setting when compared to the samples of virgin cement. The hydration temperature test shows that throughout the 24 hour sampling period there was no internal heat generation from the RCA sample, suggesting that the hydration phase never

occurred. The time of setting by the Vicat needle test also showed that within 24 hours an initial set or final set could not be observed.

CHAPTER 5: PERMEABILITY OF RCA

5.1 Introduction

Permeability testing was conducted to evaluate the flow of water through the RCA No. 4 aggregate. It is necessary to understand the factors affecting the permeability of the No. 4 aggregate, including the effect of permeameter size, tube size, fines (passing the No. 200 sieve), and the addition of a geotextile. Permeability tests can be conducted by the falling head test, or the constant head test. Typically if a soil or material is expected to have a very low permeability such as clay, it would be necessary to perform a falling head permeability test. For larger size materials like sand or coarse aggregate, it is more appropriate to use a constant head permeability test. The purpose of permeability testing is to assess the materials ability to drain water. This is especially important for this project since the RCA No. 4 aggregate is to be used in a French drain system. Using the constant head peremeability test method, the optimum hydraulic system (permeameter and tube size) was determined and the effect of fines on permeability was examined.

5.2 Theoretical Background

The coefficient of permeability, denoted as k, is a property of soil as a constant value and it is described by Darcy's Law shown in equation (5.1).

$$v \propto k \cdot i \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (5.1)$$

Where

v = Flow velocity (cm/s),

k = Coefficient of Permeability (cm/s), and

i = Hydraulic gradient (cm/cm).

That is to say that, the flow velocity is proportional to the hydraulic gradient by the coefficient of permeability, k. This principal can be applied to different types of permeability tests (e.g. falling head, or constant head). The flow velocity in a constant head test can be calculated by equation 5.2 and the hydraulic gradient is defined in equation 5.3.

$$v = \frac{Q}{A \cdot t} \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (5.2)$$

Where

v = Flow velocity (cm/s),

Q = Volume of discharge collected in time, t (cm^3),|

A = Cross sectional area of the specimen (cm^2), and

t = Time to collect discharge, Q (s).

$$i = \frac{h}{L} \qquad\qquad (5.3)$$

Where

i = Hydraulic gradient (cm/cm),

L = Length of the specimen (cm), and

h = Head, difference in elevation of head tank and tailwater tank (cm).

From equations 5.2 and 5.3, the equation to use Darcy's Law in a constant head permeability test is can be formed and is shown in equation 5.4.

$$k = \frac{Q \cdot L}{A \cdot h \cdot t} \qquad\qquad (5.4)$$

Where

k = Coefficient of permeability (cm/s),

Q = Volume of discharge collected in time, t (cm^3),|

L = Length of the specimen (cm),

A = Cross sectional area of the specimen (cm^2),

h = Head, difference in elevation of head tank and tailwater tank (cm), and

t = Time to collect discharge, Q (s).

Aggregates to be used in French drain systems should be a sound, clean and open-graded material. The aggregate should have a high permeability to allow for the free passage of water; Haung (2004) reports permeability for open-graded aggregate as 49 cm/s, 13.4 cm/s, and 2.8 cm/s for aggregates ranging from 1.5-1 in., 3/4-3/8 in., and 0.18-0.09 in. respectively. Therefore it would be expected that the No. 4 aggregate to have a coefficient of permeability between 49 and 13 cm/s. However the effect from fines could cause reductions in permeability. Haung (2004) reports that the effect of fines can decrease the permeability of a coarse aggregate by up to 99% depending on the type of fines (e.g. silica, limestone, silt, clay, etc.) for 25% fines content.

5.3 Permeability Testing Setup

Permeability testing was conducted by means of the constant head permeability test (ASTM D2434). The testing setup consists of a permeameter, a constant head tank, a constant head tailwater tank and the testing specimen. The test setup used in this study is shown in Figure 30. Since the large voids in RCA No. 4 aggregate allow for much faster flows than say a more traditional soil specimen such as sand or clay, the falling-head permeability test setup should be avoided. As a result of high flow rates, it is necessary to collect and recycle the water. In addition, the permeability setup was designed to better simulate a continuous source of fines from surrounding soils in the field; thus, water flow through the RCA No.4 aggregate was re-circulated.

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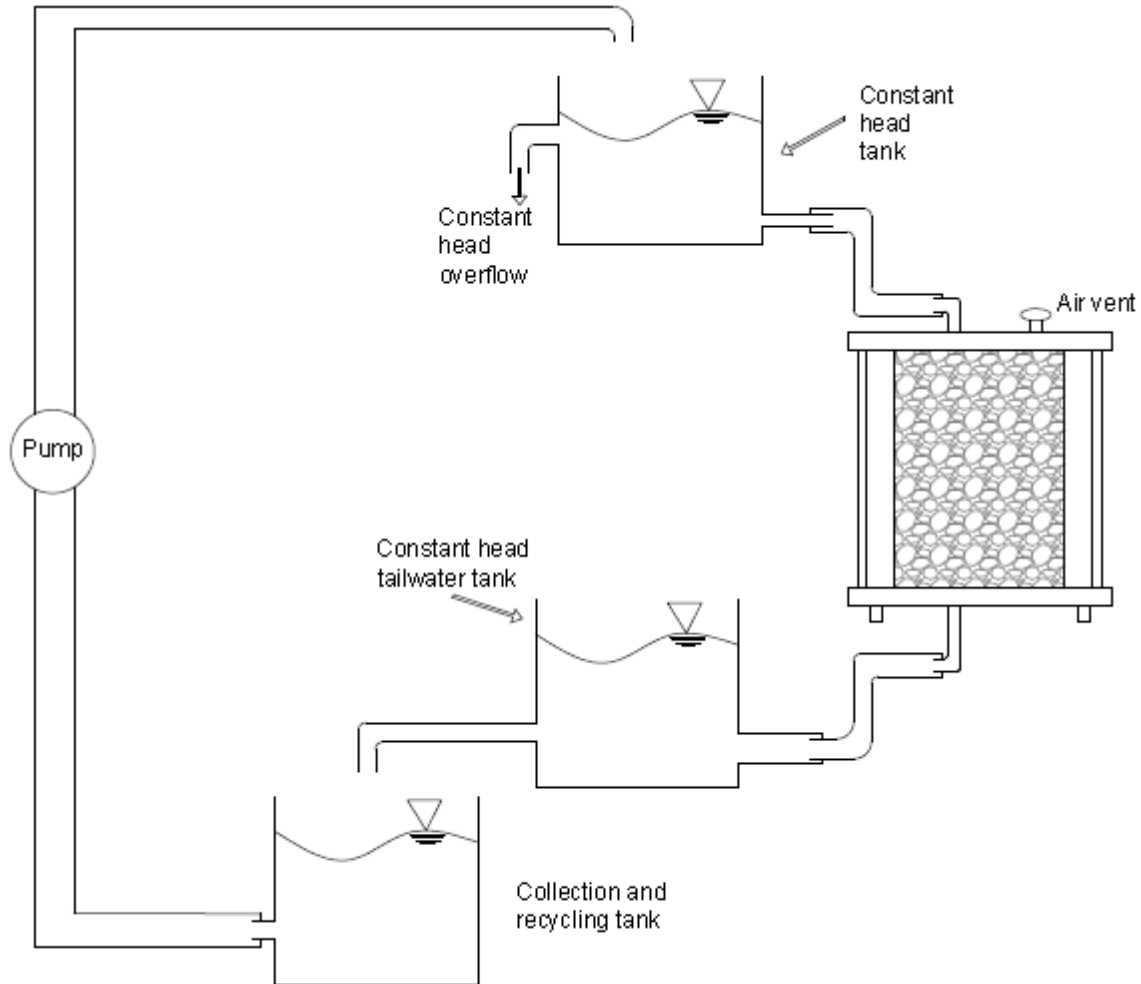
Figure 30. Constant Head Test Schematic

The hydraulic gradient is defined as the applied head divided by the length of the specimen, L; Darcy's Law states that the relationship between the flow velocity and the hydraulic gradient is proportional. However, this relationship is only valid when the flow regime is laminar and the soil is fully saturated (Das, 2006). The permeability tests were conducted

using a stationary constant head tank and a constant head tailwater tank placed on a hydraulic jack such that the tailwater tank can be raised and lowered to adjust the head. The measurement of flow was measured by using a container to collect the discharge from the tailwater tank and a timer was used to measure the amount of time for collection. The discharge was collected at six different values of head (approximately 3, 9, 14, 20, 24, and 30in.). Measurements of flow rates were recorded after steady state flow was achieved. To ensure the system was steady before a reading was taken, several tests were conducted to observe the time required for steady state flow. These tests were conducted by using the 9in.permeameter with the No. 4 average gradation and 1/2 in. and 1/4 in. tube sizes. Both cases resulted in the steady state flow after 1 minute and the 1/2in. tube showed a little more variation in the discharge than the 1/4 in. tube after 1 minute. It was observed that the system adjusts fairly quickly when changing from one head to another, by two minutes, the hydraulic system had completely stabilized, therefore during testing, two minutes are allowed from the time of changing the head to the time of taking a reading. The time to steady state flow results are shown in Figure 31.
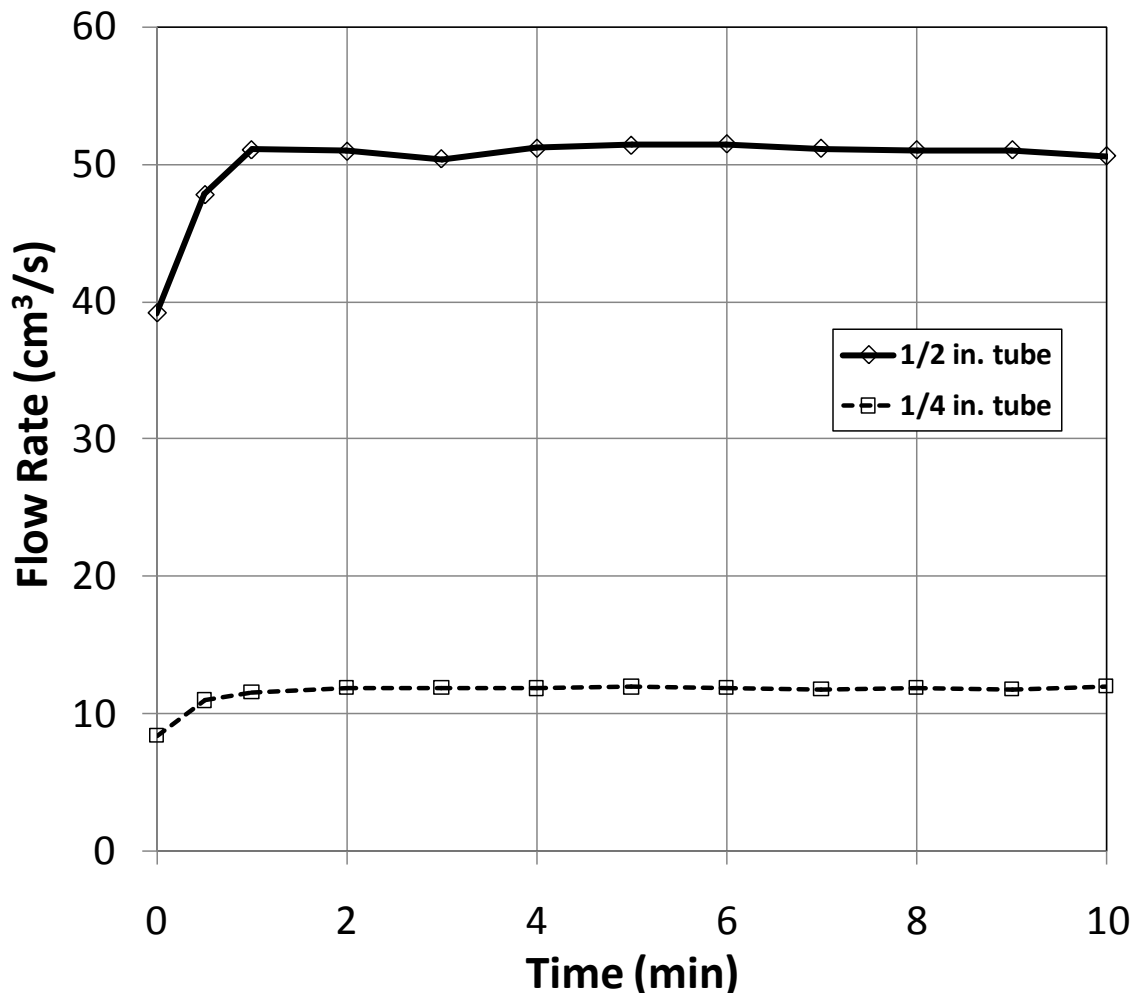
Figure 31. Time to Stability Using 9 in. Permeamter and No. 4 Average Gradation

The sample information for this test is listed in Table 11. Several different permeameter sizes were used and different connecting tube sizes (see Table11). Evaluating the effect of the permeameter and tube sizes, i.e. the hydraulic system, will differentiate whether flow rates are controlled by the RCA itself or by the hydraulic system. Figure 32 shows a photograph of the 9 in. and the 6 in permeameter used.

Figure 32. Photograph of the (a) 9 in. and (b) 6 in. Permeameter

For French drain applications the FDOT specifies several types of geotextiles to be used (State of Florida Department of Transportation, 2007). The specified geotextiles are used for filtration to retain the coarse aggregates but allow for the passage of water back into the groundwater. The main property of geotextiles which are most important to drainage applications is the apparent opening size (AOS). The AOS refers to the size of each opening in the geotextile

and is manufactured in sizes equivalent to U.S. standard sieve sizes. Depending on the percent of fines (passing the No. 200 sieve) the AOS required for French drains vary from No. 40 to No. 70 sizes. Since the percent of fines for the No. 4 gradation is less than 15% a geotextile of AOS equivalent to the No. 40 sieve (0.0165 in) was required by FDOT specifications. A woven geotextile with AOS equivalent to No. 40 sieve was purchased from US Fabrics Inc. to be used in permeability testing. The geotextile was secured into the bottom of the 6 and 9 in. permeameters. A section of geotextile was cut and fitted into the permeameters using acrylic silicon caulking to secure the geotextiles in place (Figure 34). The caulking provided a barrier such that the flowing water must pass through the geotextile and cannot by pass between the permeameter cell wall and geotextile. A photograph of the geotextile used can be seen in Figure 33.

Figure 33. Photograph of Geotextile

(a)

(b)

Figure 34. Geotextile Placement in Permeameter (a) Top View and (b) Side View

Table 11. Sample Information for Permeability Testing

Sample ID	Gradation	Permeameter size (in.)	Tube Size (in.)	Geotextile
P1	empty	6	3/4	yes
P2	empty	6	1/2	yes
P3	empty	6	1/4	yes
P4	empty	9	1/2	no
P5	empty	9	1/4	no
P6	empty	9	1/2	yes
P7	empty	9	1/4	yes
P8	'as is'	9	1/2	yes
P9	'as is'	9	1/4	yes
P10	No. 4 avg.	9	1/2	yes
P11	No. 4 avg.	9	1/4	yes
P12	No. 4 min.	9	1/2	yes
P13	No. 4 min.	9	1/4	yes
P14	No. 4 max.	9	1/2	yes
P15	No. 4 max.	9	1/4	yes

5.4 Design of Optimum Hydraulic System

The effect of the hydraulic system should be evaluated if aggregates have sufficient void space that the flow of water through the media is fast enough for a turbulent flow regime. In such a case the limiting factor on the flow can be the permeameter, and/or tube sizes (i.e. the hydraulic system) itself. If flow rates through the aggregate are detected that are close enough to the flow rates of the empty hydraulic system, then that material can have a higher flow capacity than what is measureable with the current hydraulic systems available. Therefore several tests were conducted without any RCA material and only different sized permeameters and tubes.

Figure 35 shows the flow rate with a 6 in. permeameter and 3/4, 1/2, and 1/4 in. tube sizes. It is clear to see that the tube size has a substantial impact on the flow. As would be expected, the highest flow rate is obtainable from the 3/4 in. tubing and the slowest flow results from the 1/4 in. tube. Similarly using a 9 in. permeameter the flow rates were measured with a 1/2 and 1/4 in. tube and the results are shown in Figure 36. As expected the flow rate is determined by the tube size. The variability in flow rates ranging with a head of 3 to 30 in. is greater with the larger tube sizes, therefore it is ideal to use the smaller tube size (1/4 in.) for testing since it results in less variability between the range of applied heads.

Sample ID	Gradation	Permeameter size (in.)	Tube Size (in.)	Geotextile
P1	empty	6	3/4	yes
P2	empty	6	1/2	yes
P3	empty	6	1/4	yes
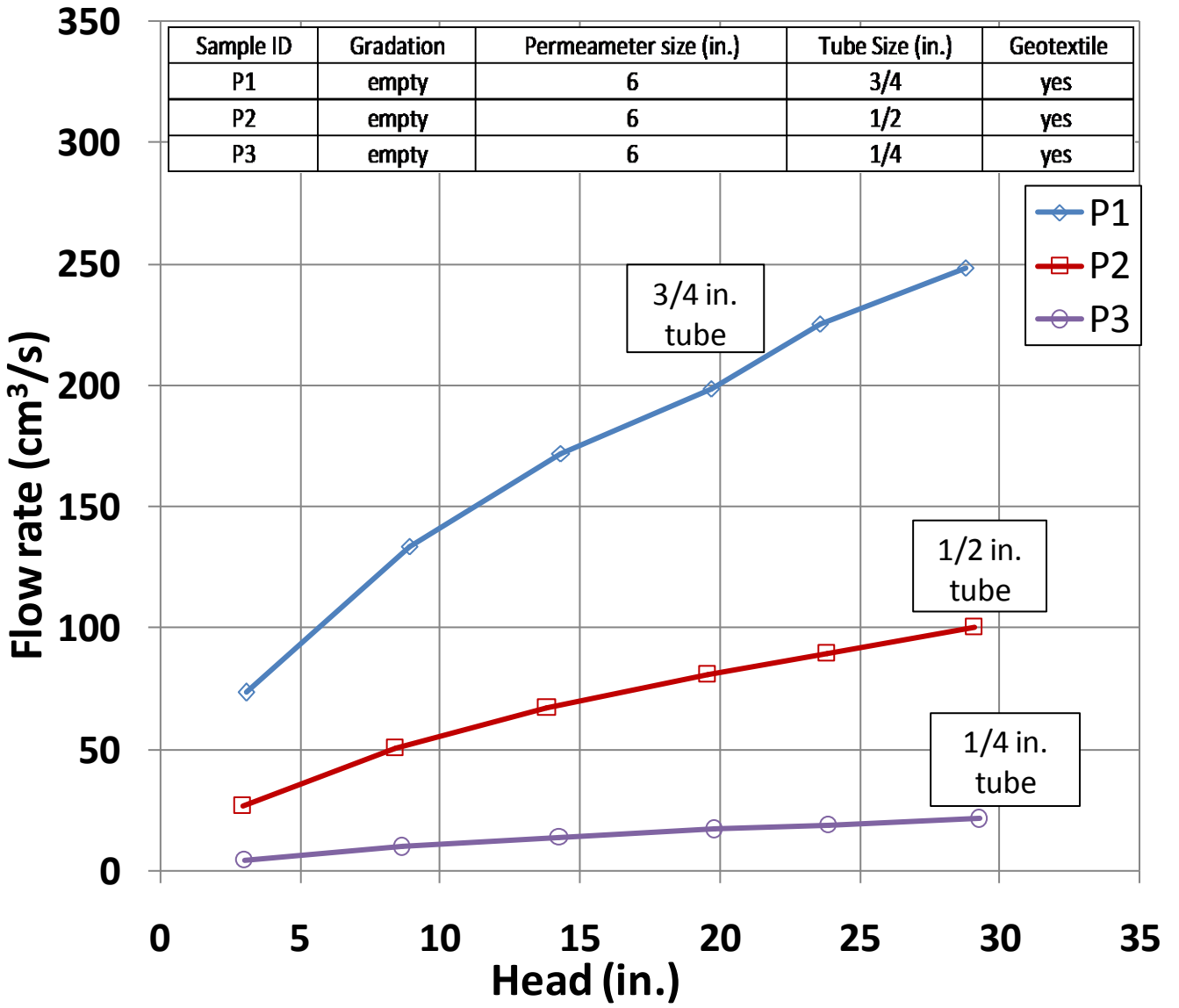
Figure 35. Influence of Tube Size on Flow Rate with 6 in. Permeameter

Sample ID	Gradation	Permeameter size (in.)	Tube Size (in.)	Geotextile
P6	empty	9	1/2	yes
P7	empty	9	1/4	yes
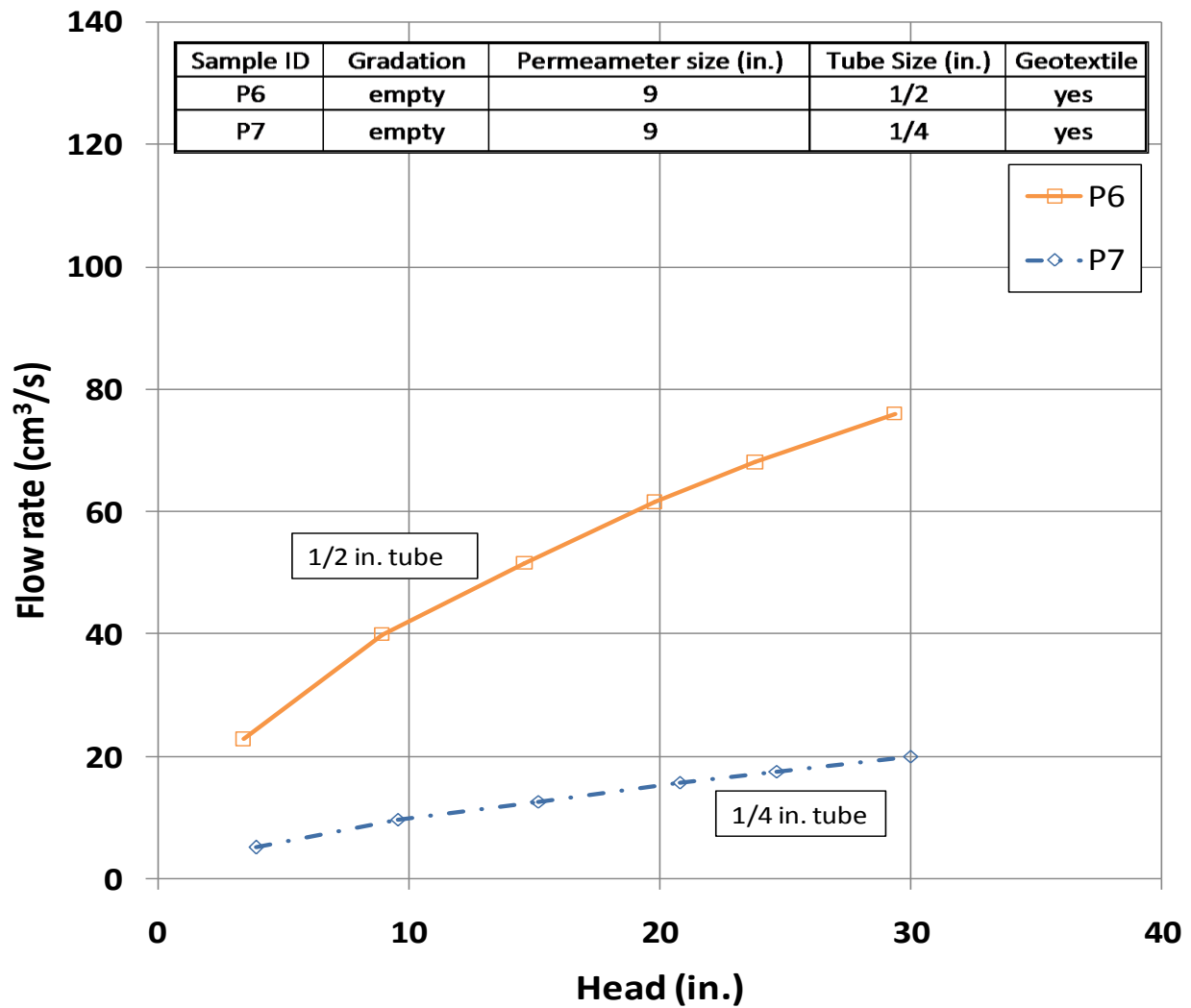
Figure 36. Influence of Tube Size on Flow Rate with 9 in. Permeameter

Figure 37 shows the results of testing performed to evaluate the effect of the permeameter size with the 1/2 and 1/4 in. tube sizes. The results show a clear separation between 6 and 9 in. permeameter sizes when using the 1/2 in. tube. However with the 1/4 in. tube the effect of the

permeameter size is negligible, and further supports the use of 1/4 in. tubing for the optimum hydraulic system.

Sample ID	Gradation	Permeameter size (in.)	Tube Size (in.)	Geotextile
P2	empty	6	1/2	yes
P3	empty	6	1/4	yes
P6	empty	9	1/2	yes
P7	empty	9	1/4	yes
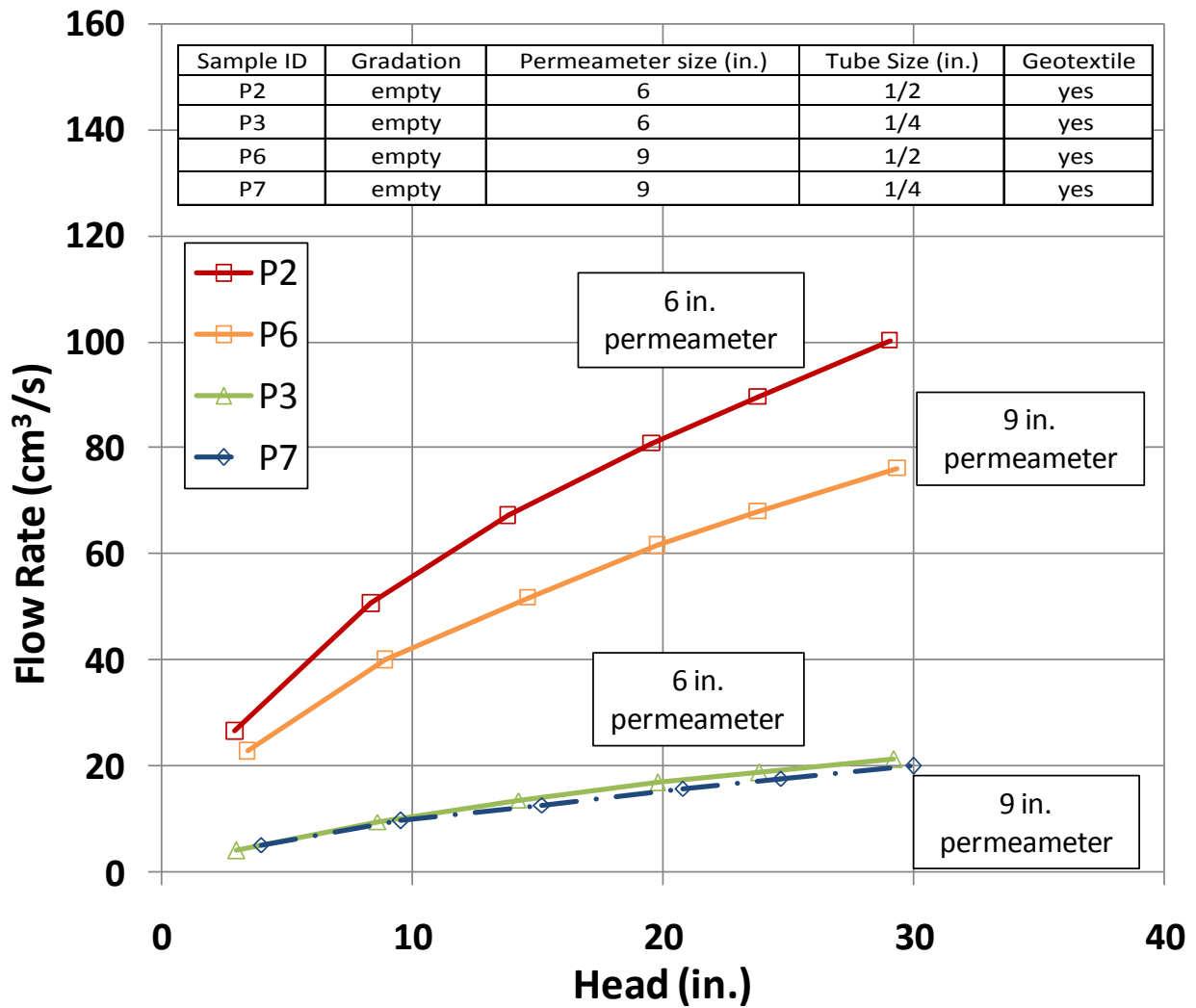
Figure 37. Effect of Permeameter Size with 1/2 and 1/4 in. Tube on Flow Rate

The effect of the geotextile is seen in Figure 38. The addition of the geotextile causes a small reduction in flow rate while using the 1/2 in. tube. However while using the 1/4 in. tube the effect of the geotextile is negligible. These results indicate that both the 6 and 9 in. permeameters may be used if the 1/4 in. tube is used.

Sample ID	Gradation	Permeameter size (in.)	Tube Size (in.)	Geotextile
P4	empty	9	1/2	no
P5	empty	9	1/4	no
P6	empty	9	1/2	yes
P7	empty	9	1/4	yes
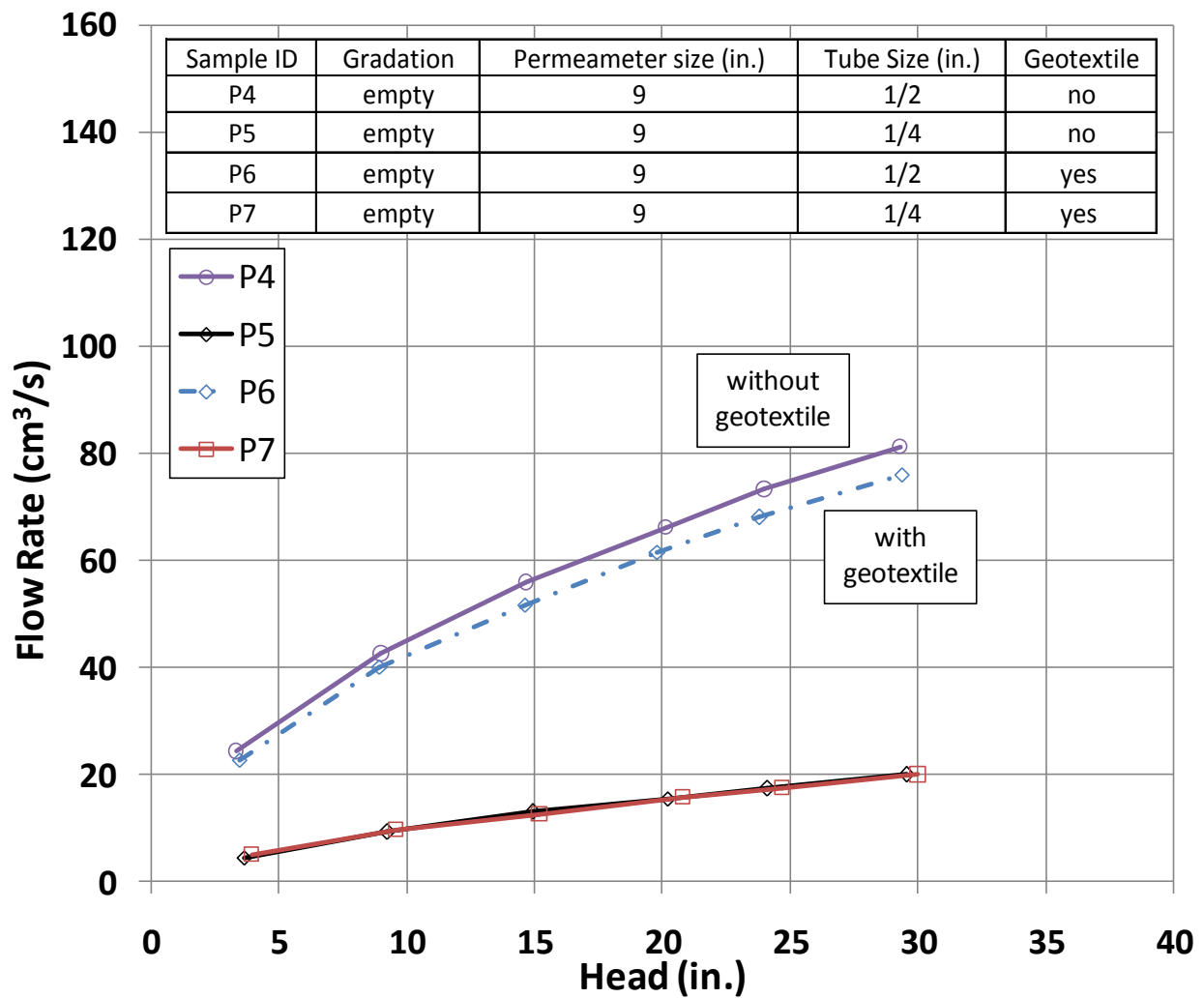
Figure 38. Effect of the Addition of Geotextile with 1/2 and 1/4 in. Tube Sizes on Flow Rate

5.5 Permeability vs. Flow Rate

The results so far have been reported as flow rate instead of the coefficient of permeability. Since the coefficient of permeability for soils is a constant term, there should be no variation with a change in applied head. Figures 39 and 40 show the results of sample P11 which are plotted by two different methods, the coefficient of permeability vs. hydraulic gradient, and flow rate vs. head. Clearly there is a variation of coefficient of permeability with a change in head. This indicates that the No. 4 aggregate does not follow Darcy's Law and it is inappropriate to report results as coefficient of permeability. However, results may be reported as flow rate when the control samples (empty permeameters) are presented. The flow rates of No. 4 aggregate can be compared to the flow rates of just the empty permeameter to determine whether the flow rates are controlled by the aggregate or the hydraulic system. Therefore the results of the permeability test will be reported as flow rate vs. head.

Sample ID	Gradation	Permeameter size (in.)	Tube Size (in.)	Geotextile
P11	No. 4 avg.	9	1/4	yes
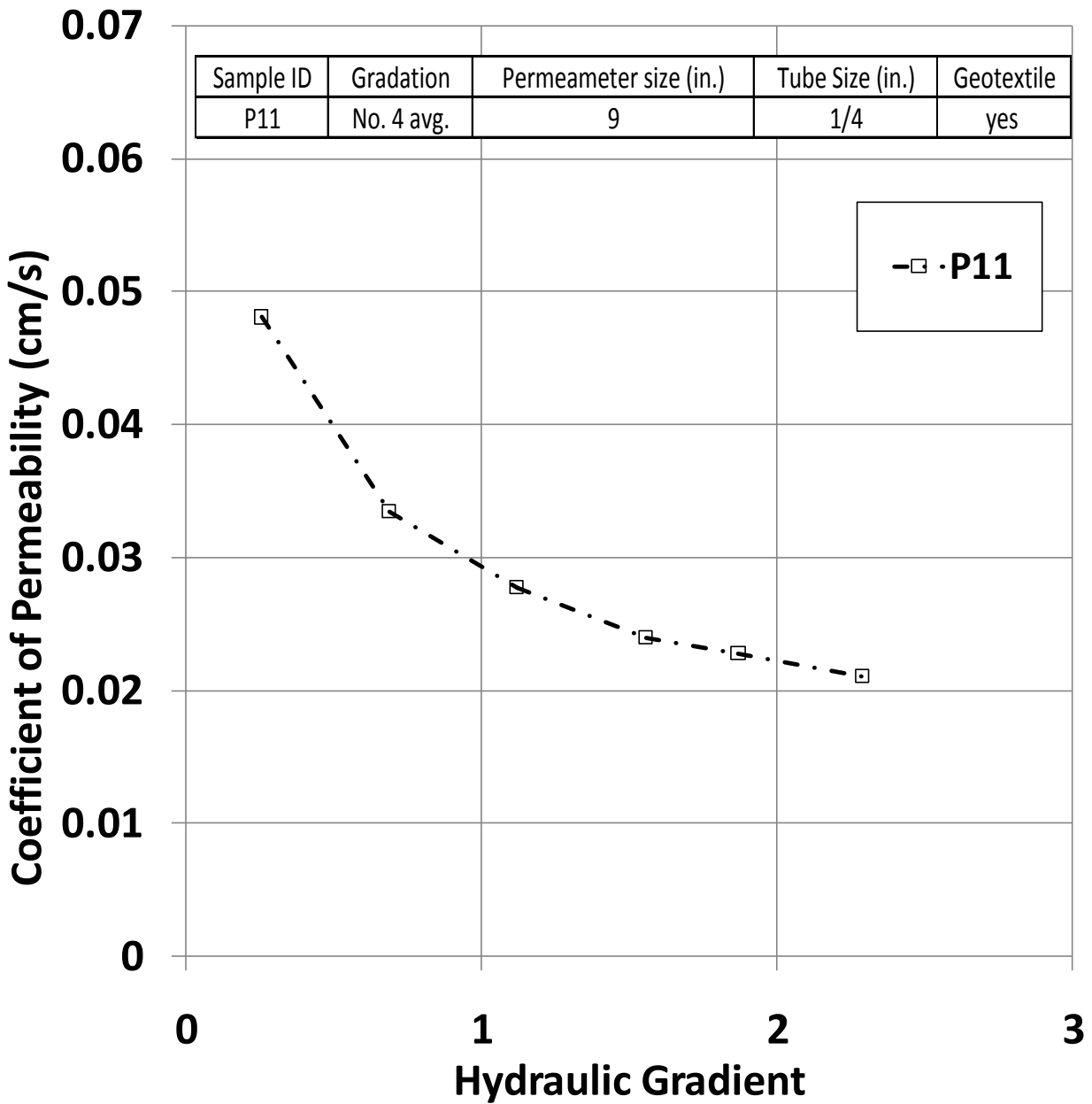
Figure 39. Results Plotted as Coefficient of Permeability vs. Hydraulic Gradient

Sample ID	Gradation	Permeameter size (in.)	Tube Size (in.)	Geotextile
P11	No. 4 avg.	9	1/4	yes
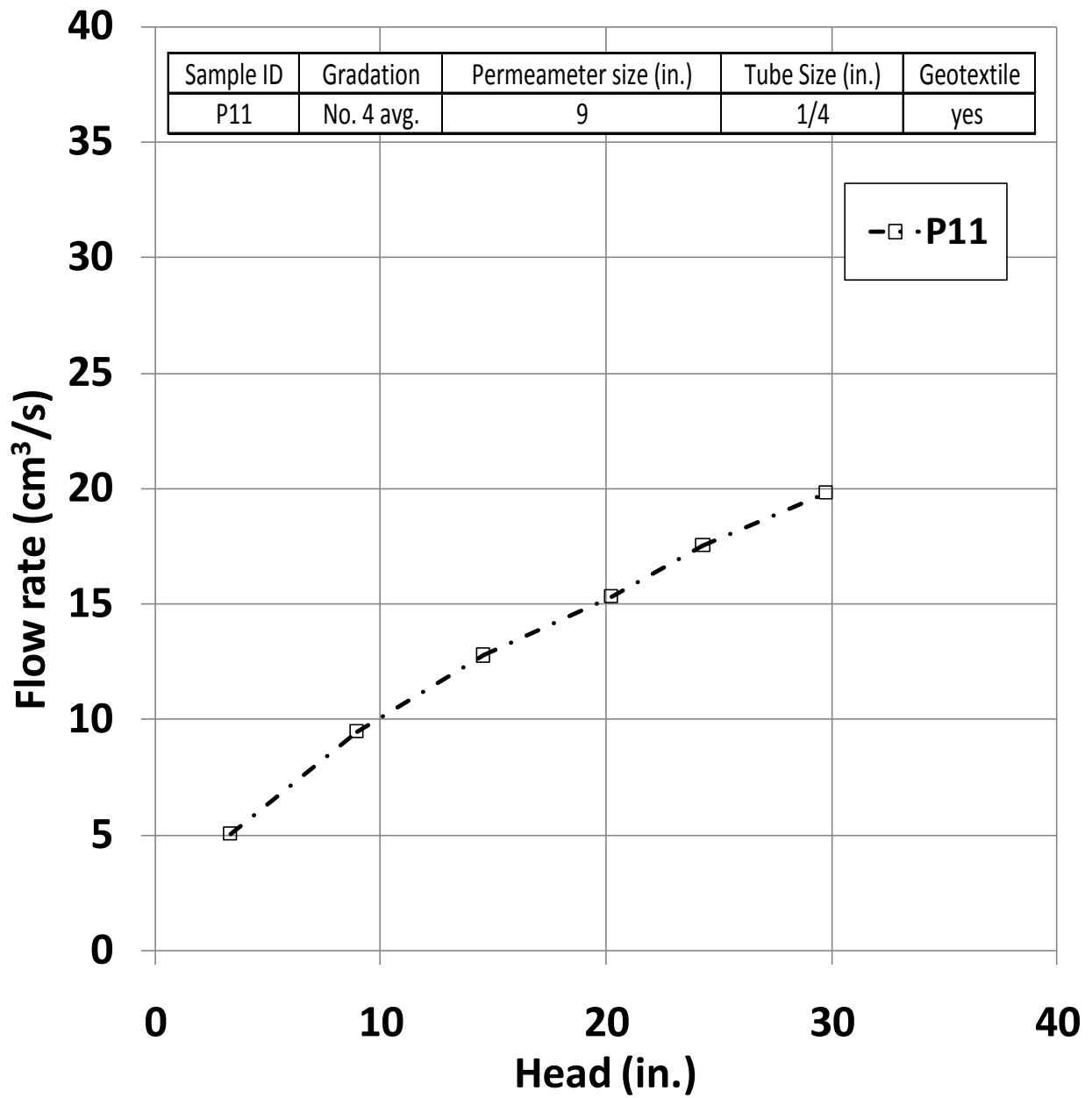
Figure 40. Results Plotted as Flow Rate vs. Head

5.6 Permeability of RCA

The results for RCA permeability testing are shown in Figure 41. The No 4 average, minimum, and maximum gradation as well as 'as is' gradation were tested and compared to results from the hydraulic system testing, i.e. the empty permeameter cells. Each sample was tested with the 1/2 in. and 1/4 in. tubing. The results show that all four of these gradations do not impose or restrict the flow of water by any means. Since the results show the same values for the empty permeameter tests, that is, the flow rates may possibly exceed what is possible for the permeameter sizes. The permeability was also measured with the addition (0, 2 and 4%) of fines. These percentages are based from FDOT standard specification section 901-1.2, which states that coarse aggregate may not have more than 1.75% fines at source, or 3.75% at point of use for L.A. abrasion values of 30 or greater. Since the percent fines is limited by the standards it will be beneficial to see the results if these standards were not in compliance. The results of this permeability test are shown in Figure 42.

Sample ID	Gradation	Permeameter size (in.)	Tube Size (in.)	Geotextile
P6	empty	9	1/2	yes
P7	empty	9	1/4	yes
P8	'as is'	9	1/2	yes
P9	'as is'	9	1/4	yes
P10	No. 4 avg.	9	1/2	yes
P11	No. 4 avg.	9	1/4	yes
P12	No. 4 min.	9	1/2	yes
P13	No. 4 min.	9	1/4	yes
P14	No. 4 max.	9	1/2	yes
P15	No. 4 max.	9	1/4	yes
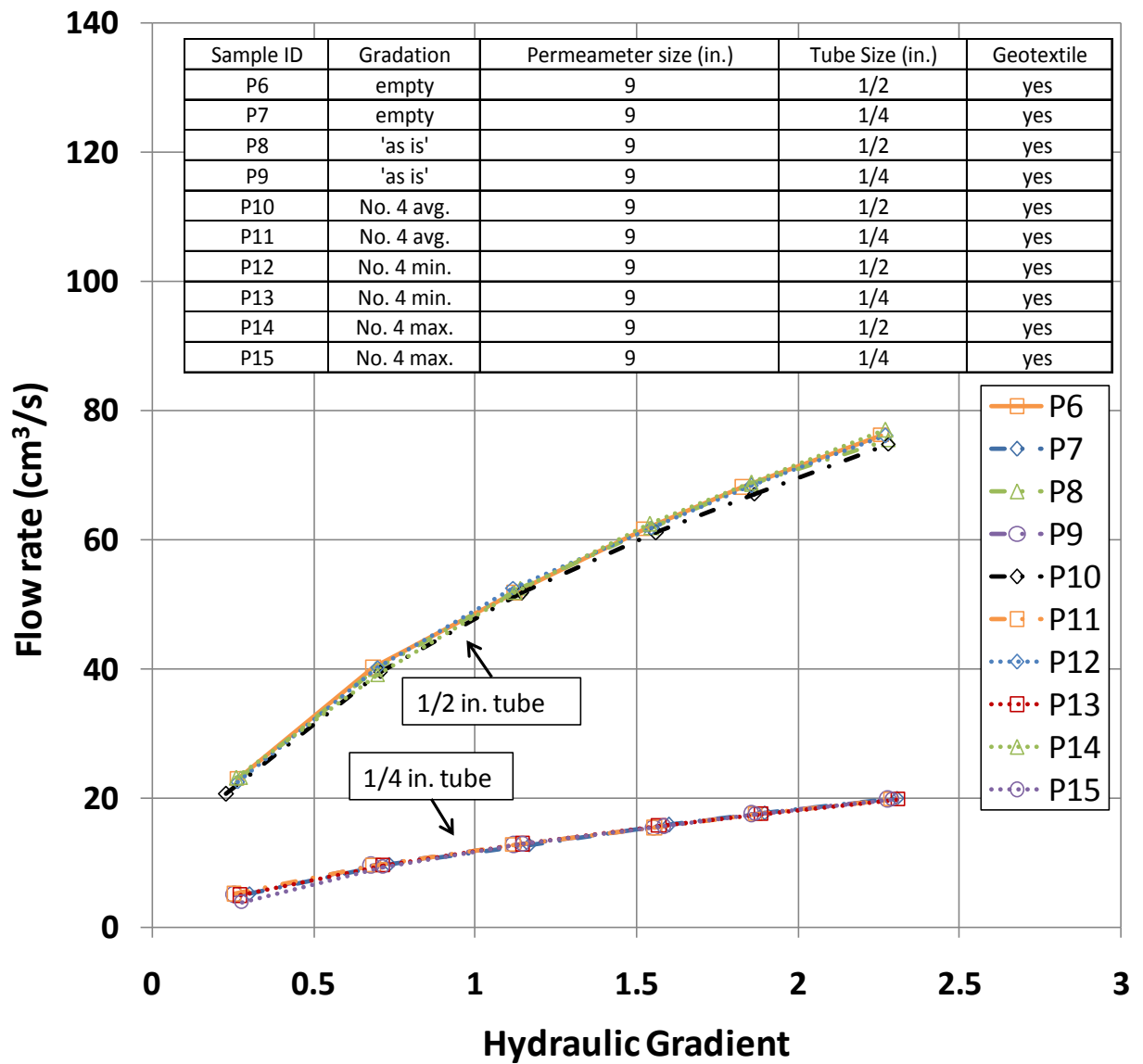
Figure 41. Results for Different RCA Gradations in the 9 in. Permeameter as Flow Rate
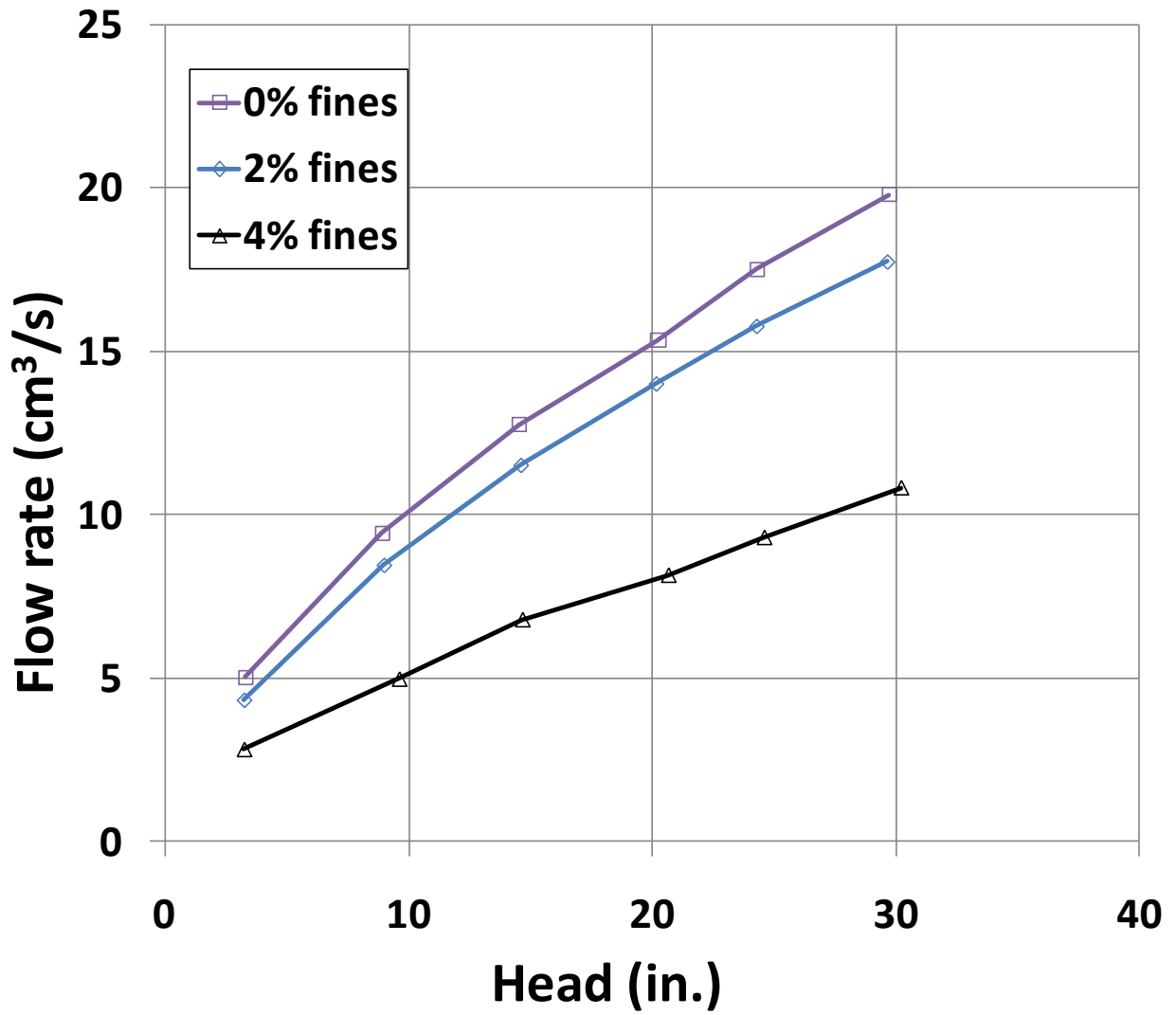
Figure 42. Flow Rate vs. Head with 0, 2, and 4 % Fines Addition

5.7 Summary

It was determined that that the optimum hydraulic system to use for permeability testing is with 1/4 in. tubing. This size tubing slows the flow rate and reduces turbulence within the permeameter cell and limits the flow variability. The results from these permeability tests confirms that the No. 4 aggregate does not in fact follow Darcy's Law similar to that of other studies (Mulqueen, 2005) and thus a single value of the coefficient of permeability shall not be reported. However, for this very reason, the No. 4 gradation would prove to be a useful drainage media since it does not restrict the flow of water. The effect of fines can be substantial for up to 4% fines. As expected an increasing amount of fines leads to a greater reduction in flow rate.

CHAPTER 6: CLOGGING EVALUATION OF RCA

6.1 Introduction

In cases with high amounts of fines, the flow of water may be slowed through the geotextile. Clogging tests were conducted to determine the long term effects of the flow of water through RCA. The effect of excess RCA fines (physical clogging) was conducted using RCA with 0, 2 and 4 % fines addition and flow rate was measured with respect to time. Calcite precipitation which occurs as a chemical reaction from RCA may also cause a reduction if the solid precipitates deposits onto the geotextile. An accelerated calcite precipitation method was developed to determine the potential of calcite production of RCA as well as the effect of RCA fines on the calcite formation. This chapter describes the physical and chemical evaluation of RCA clogging potential.

6.2 Causes of Drainage Clogging

The reduction of drainage capacity in French drain systems can be associated with the accumulation of fine material on the geotextile. In French drain systems the geotextile may vary from an AOS equivalent to the No. 40 sieve to the No. 70 sieve. The buildup of material on the geotextile may be from fine material, or from the precipitation of calcium carbonate which may also deposit on the geotextile.

6.2.1 Excess Fines (Physical Clogging)

Aggregates used in drainage layers and French drains should be sound, clean, and open-graded. Aggregates should have a high permeability to accommodate the free passage of water and be protected from clogging by means of a filter (Huang, 2004). It has long been recognized that proper gradation and density are critical to the permeability of granular materials. To obtain the desired permeability, the fine particles need be deleted; thus, the stability of the drainage layer may be reduced. The effect of fines can have a substantial impact on the permeability as seen in Figure 43.
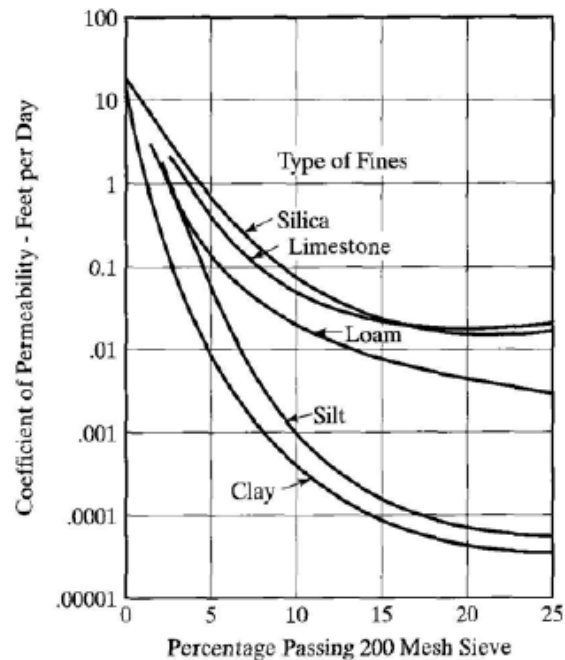
Figure 43. Effect of Different Types of Fines on Permeability of Coarse Aggregate (Haung, 2004)

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6.2.2 Calcite Precipitation (Chemical Clogging)

The precipitation of calcite depends on many variables; however, the scope of this project is to observe the maximum possible calcite that can be precipitated from a sample of RCA using an accelerated process. The precipitation of calcite reacts according to equations 6.1, 6.2 and 6.3 (Butler, 2013).

$$CO_2(g) \leftrightarrow CO_2(aq) \tag{6.1}$$

$$CO_2(aq) + H_2O \leftrightarrow H_2CO_3 \tag{6.2}$$

$$2HCO_3^- + Ca^{2+} \leftrightarrow CaCO_3 + H_2CO_3 \tag{6.3}$$

From equations 6.1, 6.2, and 6.3 it can be seen that the primary influence of calcium carbonate is the addition of CO_2. In natural systems of French drains the only source of CO_2 comes from the atmospher. However CO_2 only makes up about 0.039% (NOAA, 2013) and thus calcium carbonate precipitation in the environment may take up to a year to occur (Steffes, 1999). Calcium carbonate is precipitated when CO_2 is dissolved in water and promotes the dissolution of calcium ions. The now calcium-rich solution has to potential to precipitate calcite, only after the excess CO_2 is removed.

6.3 Physical Clogging Test

The effect of excess fines in RCA has been studied. These fines were generated by grinding RCA in a ball mill and sieve the material over the No. 200 sieve to collect the fine material. Samples have been prepared and the sample details are listed in Table 12. 0, 2 and 4% excess fines were chosen for fines addition to the clogging test to be monitored over time. All samples were using 1/4 in. tubing and include geotextile. The head was kept constant at about 14 in.

Table 12. Sample Information for Physical Clogging Test

Sample ID	Gradation	Permeameter Size (in.)	Excess Fines (%)	Material
C1	No. 4 avg.	9	4	RCA
C2	No. 4 avg.	9	2	RCA
C3	as is'	6	0	RCA

The results for sample C1 are shown in Figures 44 and 45. The expected maximum value, based off a previous test performed (sample P11), is shown for comparison. It would be expected that any sample with excess fines should not be able to surpass the flow rate of the "expected maximum" line on this chart. Sample C1 was setup with 4% fines content in the 9 in. permeameter, the flow rate was monitored for 100 days (Figure 44). Inevitably, in permeability testing with excess fines, some fine material will be lost in the effluent water. Since this test was monitored for 100 days it was necessary to collect and recycle the water. The fines lost in the

effluent were allowed to recycle without any filters, through the pump system and into the head tank in an attempt to retain the fines within the sample and to deposit in the geotextile. This procedure was developed to simulate French drains which receive a constant supply of fines within the storm water collected by these systems as well as surrounding soils.. After 100 days of testing the flow rate decreased by about 83% or about 0.0927 cm^3/s per day.

At 44 and 100 days sample C1 was measured with respect to head, to obtain a flow rate vs. head curve as seen in Figures 46 and 47. These results are compared to samples P7 and P11 from the permeability test, to show the reduction in flow rate vs. head with respect to time. As would be expected, the curve of flow rate vs. head shifts lower in the plot as time proceeds.

Sample ID	Gradation	Permeameter Size (in.)	Excess Fines (%)	Material
C1	No. 4 avg.	9	4	RCA
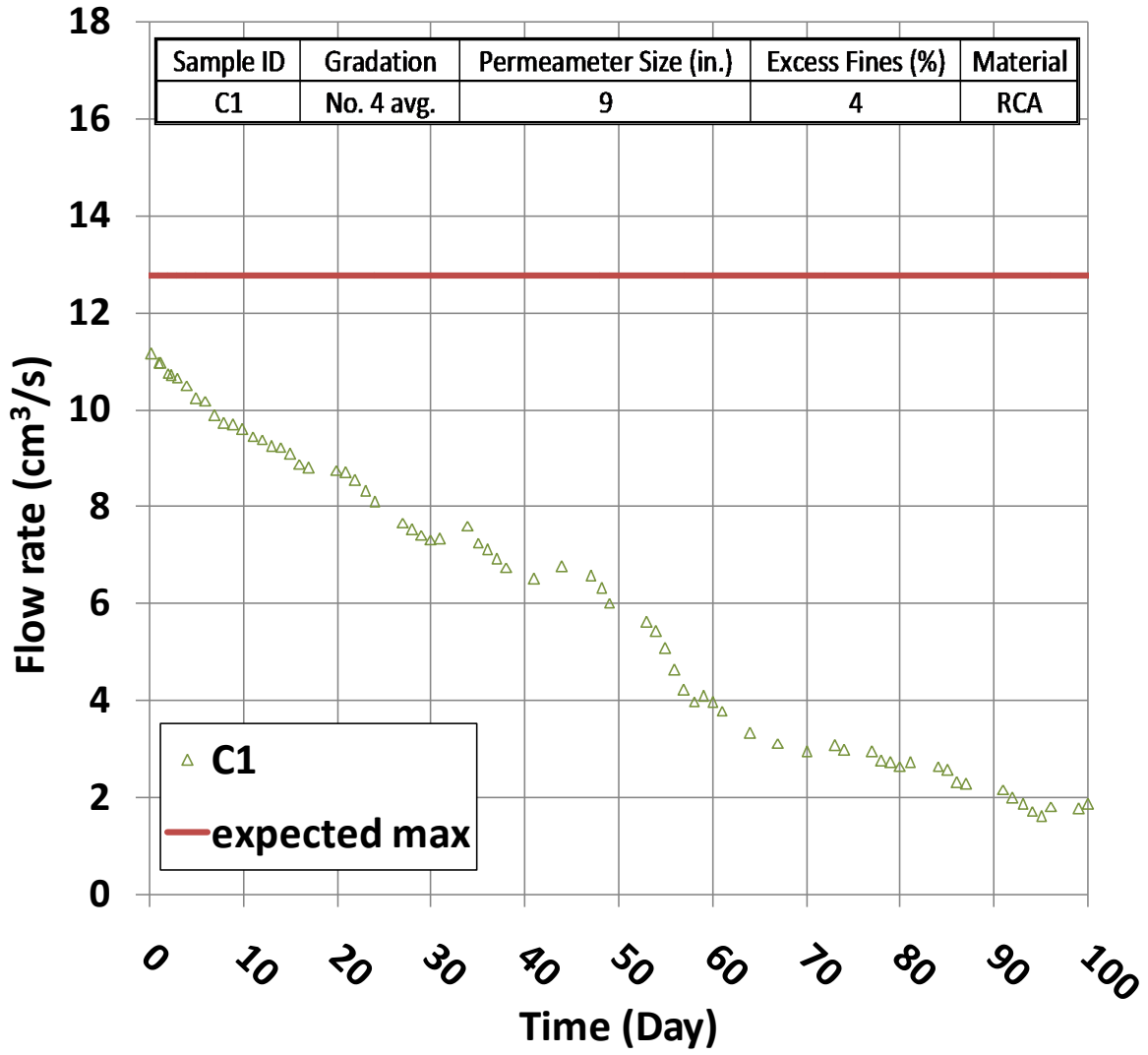
Figure 44. Results for Sample C1 Plotted as Flow Rate vs. Time

Sample ID	Gradation	Permeameter Size (in.)	Excess Fines (%)	Material
C1	No. 4 avg.	9	4	RCA
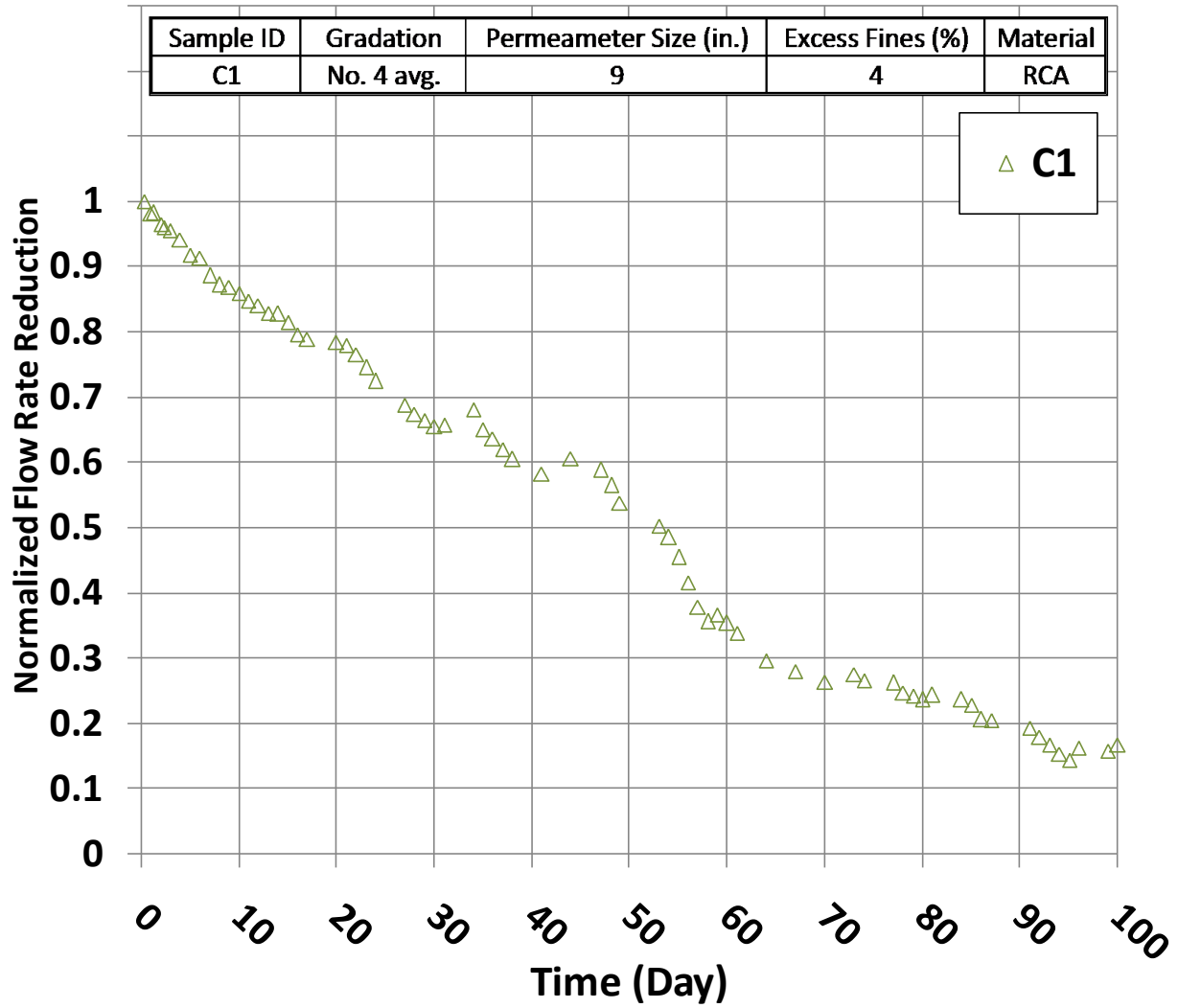
Figure 45. Results for Sample C1 Plotted as Normalized Flow Rate
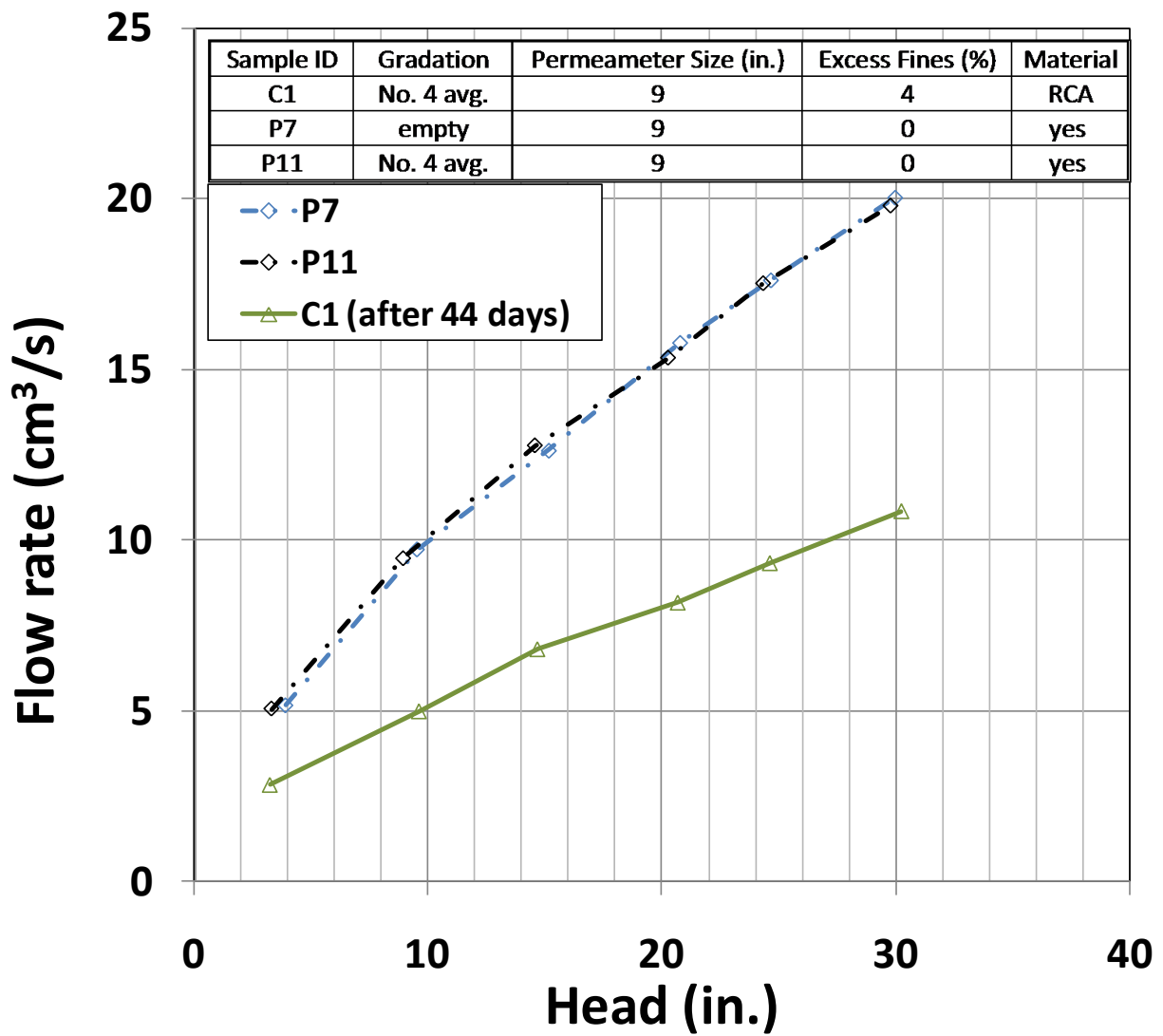
Figure 46. Flow Rate vs. Head for Sample C1 at 44 Days

Sample ID	Gradation	Permeameter Size (in.)	Excess Fines (%)	Material
C1	No. 4 avg.	9	4	RCA
P7	empty	9	0	yes
P11	No. 4 avg.	9	0	yes
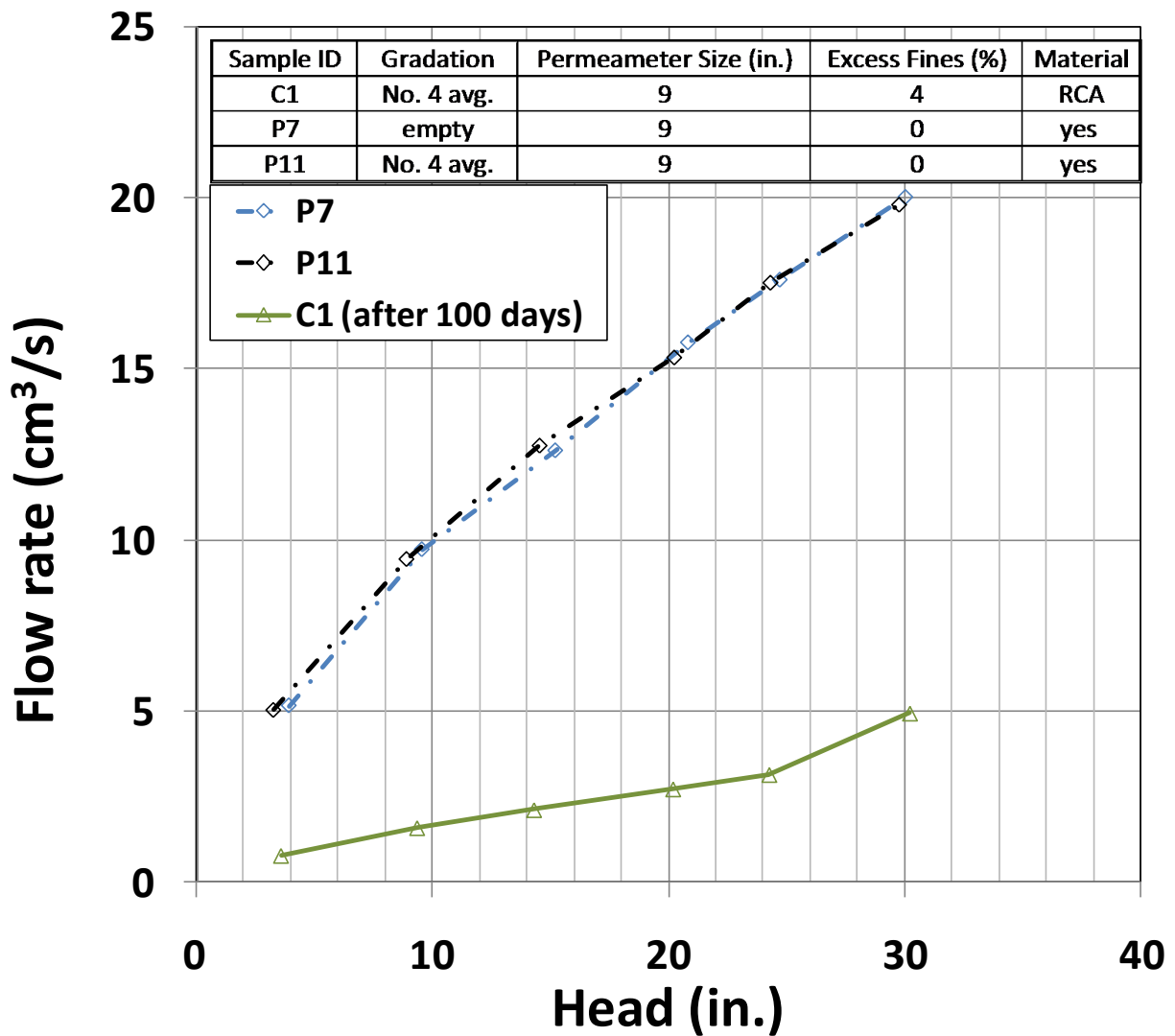
Figure 47. Flow Rate vs. Head for Sample C1 at 100 Days

The results for sample C2 are shown in Figure 48 and 49. This sample included 2% fines and was monitored for 28 days. The results show that the initial flow rate is higher than the initial flow rate for the 4% fines sample but the reduction in flow rate follows a similar trend to that of the 4% fines sample.

Sample ID	Gradation	Permeameter Size (in.)	Excess Fines (%)	Material
C2	No. 4 avg.	9	2	RCA
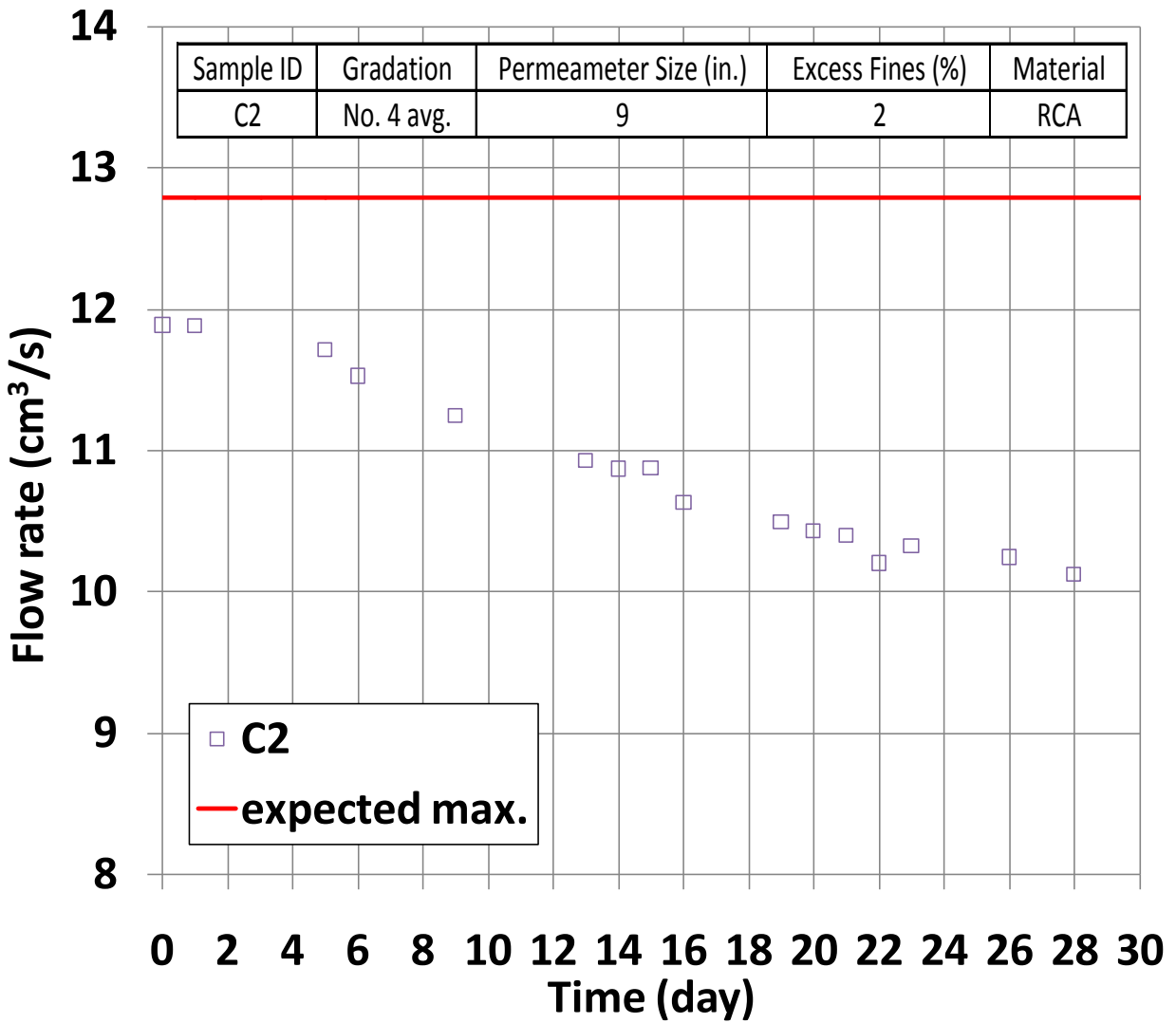
Figure 48. Results for Sample C2 Plotted as Flow Rate vs. Time

Sample ID	Gradation	Permeameter Size (in.)	Excess Fines (%)	Material
C2	No. 4 avg.	9	2	RCA
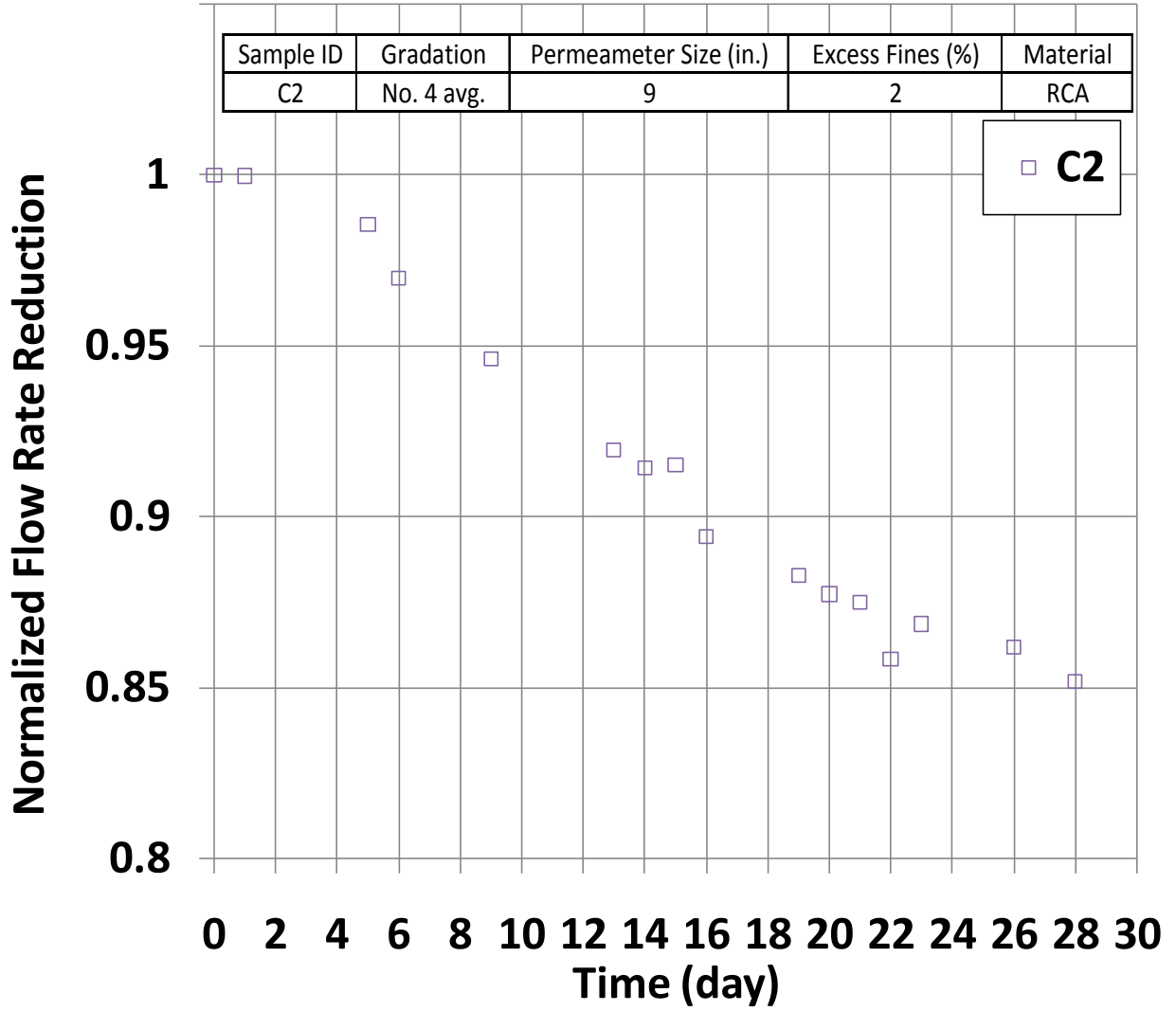
Figure 49. Results for Sample C2 Plotted as Normalized Flow Rate

The sample C3 was prepared with the 'as is' RCA gradation and was tested in the 6 in.

permeameter and was monitored for up to 55 days and the results are shown in Figures 50 and

51. The sample did not contain any excess fines, however, the 'as is' gradation contains a certain

amount of fines without any excess added. The 'as is' fines content was determined by ASTM

C117 in which a sample of RCA was washed over a set of sieves with the No. 200 sieve at the

bottom. Washing continued until the wash water ran clear, and the material retained on each

sieve was collected and the mass lost was measured. The lost mass is attributed to the fines

which were able to pass through the No. 200 sieve, and the fines content was measured at

0.386%. The reduction in flow rate of sample C3 to date is an 18.26% reduction, or about 0.059

cm^3/s per day. As expected, the 0% additional fines sample (C3) initially has about the highest

flow rate achievable at 14 in. of head (as seen in comparison to the 'expected max' red line).

Figures 52 and 53 shows the results from samples C1, C2, and C3 plotted in the same graph for

convenient comparison of all samples.

Sample ID	Gradation	Permeameter size (in.)	Excess Fines (%)	Material
C3	'as is'	6	0	RCA
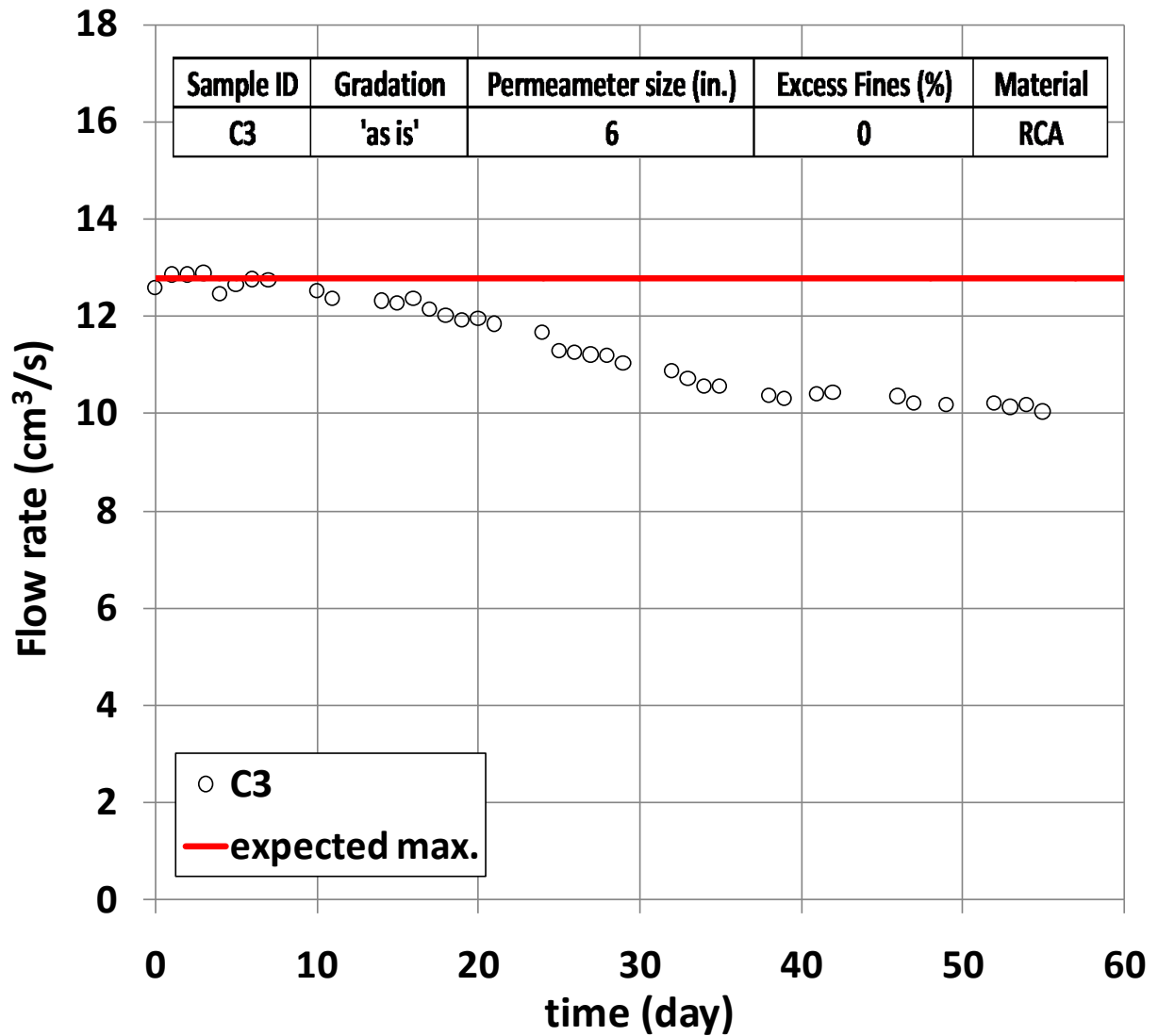
Figure 50. Results for Sample C3 Plotted as Flow Rate vs. Time

Sample ID	Gradation	Permeameter size (in.)	Excess Fines (%)	Material
C3	'as is'	6	0	RCA
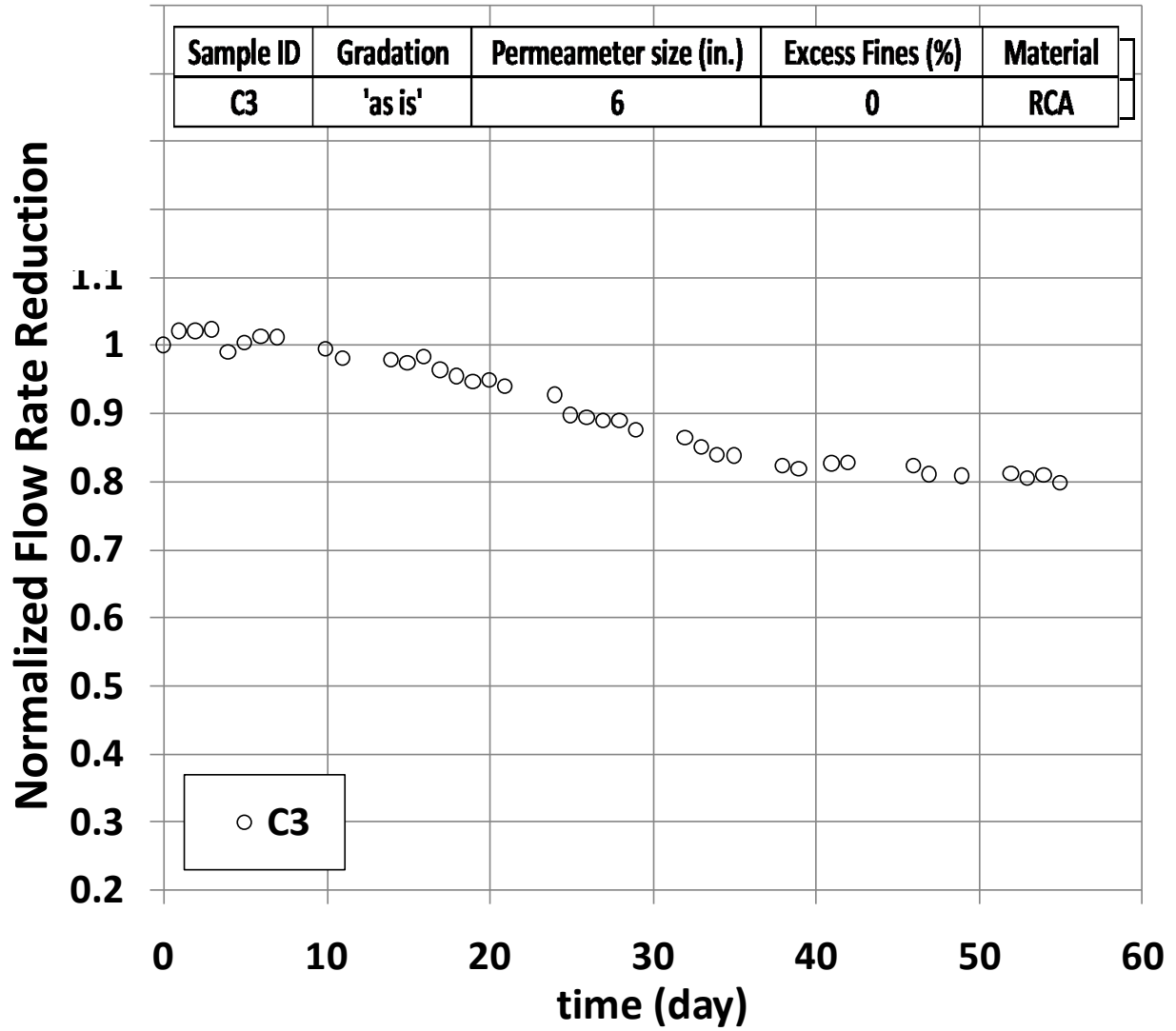
Figure 51. Results for Sample C3 Plotted as Normalized Flow Rate

Sample ID	Gradation	Permeameter Size (in.)	Excess Fines (%)	Material
C1	No. 4 avg.	9	4	RCA
C2	No. 4 avg.	9	2	RCA
C3	as is'	6	0	RCA
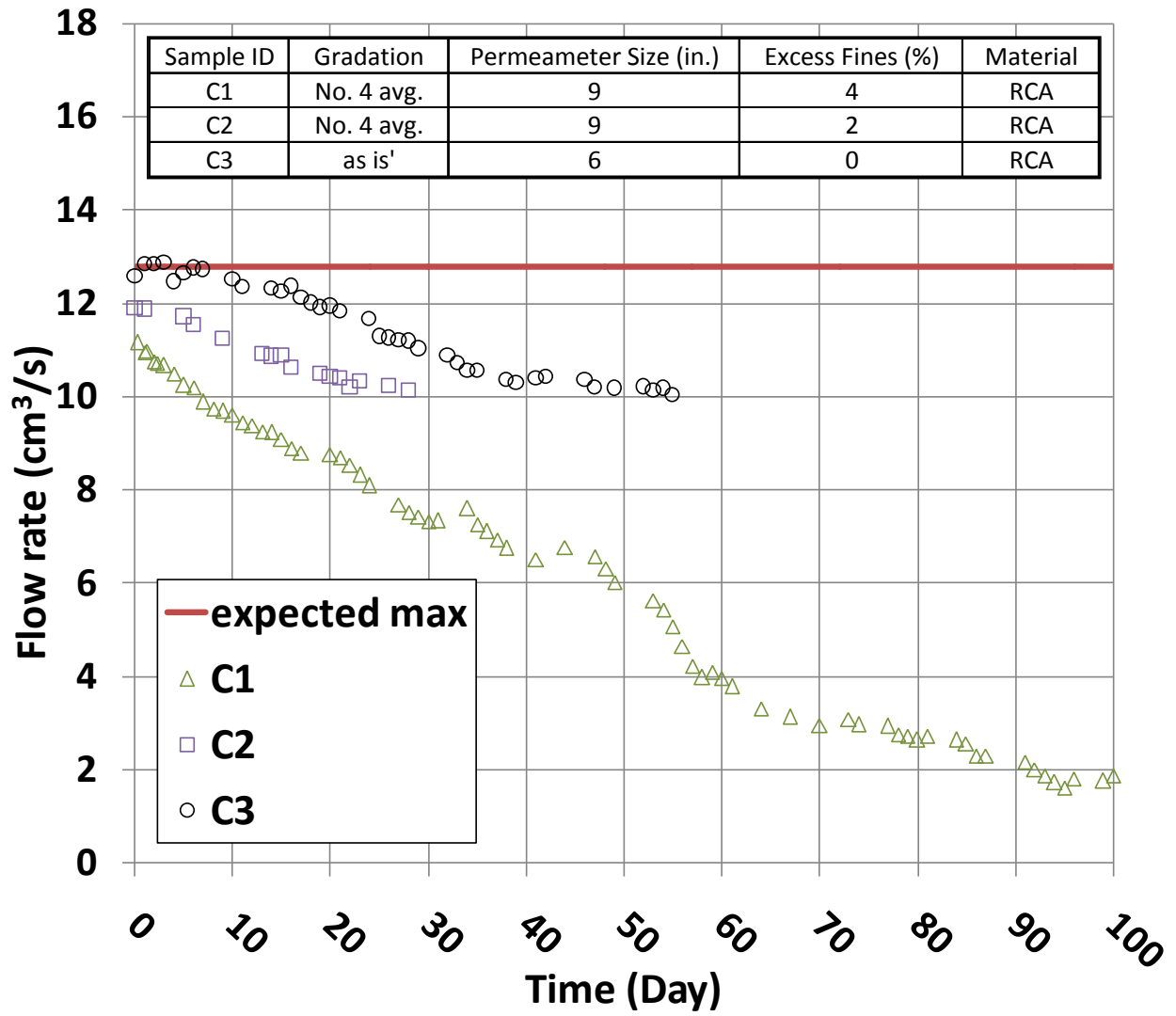
Figure 52. Results for Samples C1, C2, and C3 Plotted as Flow Rate vs. Time

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Sample ID	Gradation	Permeameter Size (in.)	Excess Fines (%)	Material
C1	No. 4 avg.	9	4	RCA
C2	No. 4 avg.	9	2	RCA
C3	as is'	6	0	RCA
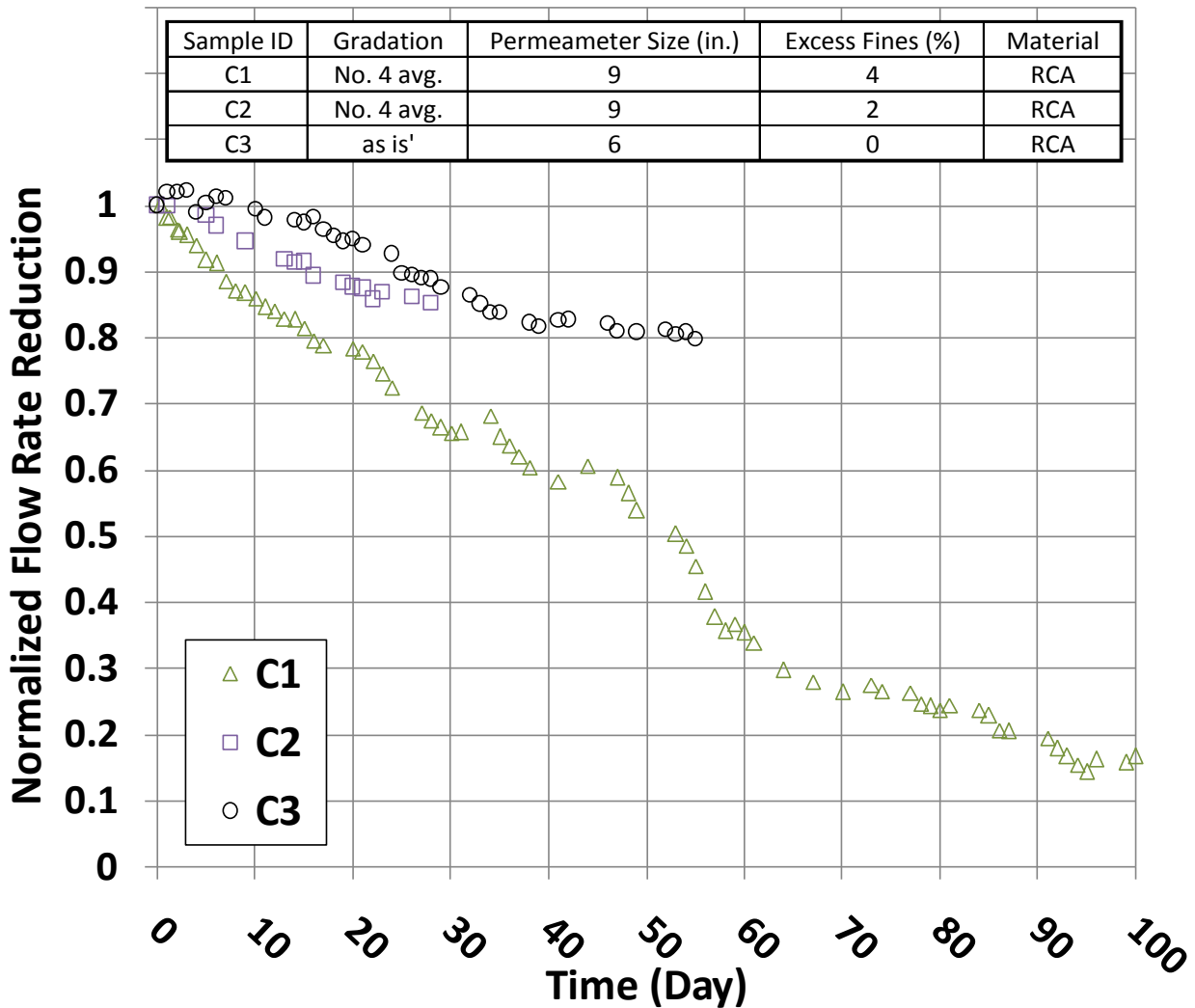
Figure 53. Results for Samples C1, C2, and C3 Plotted as Normalized Flow Rate

The results from the physical clogging test confirm that the increase of fines leads to a greater reduction of drainage performance. The initial flow rates measured with 0, 2 and 4 % fines were lower with an increasing amount of fines. Over time the flow rates for all samples were reduced through the process of clogging, that is, the deposition of fines on the geotextile

through the re-circulation of fines. For the duration of testing, all samples utilized the same source for recycling water, so the re-circulating of fines can be assumed to be distributed evenly to all permeameters. However, more fines addition may accelerate the buildup of clogging material; thus, the 4% fines sample exhibits faster reduction of flow rate.

6.4 Evaluation of Calcite Precipitation Potential by an Accelerated Calcite Development Procedure

By using CO_2 the accelerated process of precipitating calcium carbonate can be conducted. The calcium contributed by the RCA is finite, and therefore the maximum possible calcium carbonate precipitate can be extracted. The procedure to precipitate calcium carbonate from RCA is described below.

1. Obtain 5 kg of 'as is' RCA

2. Place RCA in a container and fill with tap water until all RCA is covered by water

3. Bubble CO_2 through the water for 5 hours at a rate of $10ft^3/hr$

4. Filter out RCA fines using the ASTM D5907 filtration equipment

5. Place filtered water in an oven at 110°C for 4 hours

6. Remove the water and the calcium carbonate precipitate solution from oven and filter again using ASTM D5907

7. The water and calcium carbonate will now be separated, retain the filtered water and repeat the process with the retained water until negligible calcium carbonate is precipitated

Two approaches were used with this procedure. The first method is a short term test, in which the cycle is only repeated several times. After the first cycle with RCA and water, the filtered water is retained and additional cycles are performed on the cycled water only. This method is useful for material characterization (e.g. aggregate type, or. effect of fines). The second method is a long term test, in which the filtered water is added back into the RCA sample for each cycle. This method is used to determine the total amount of calcite that can be precipitated over a lifetime of the RCA.

This experimental study accelerates the calcite production by injecting CO_2 directly into the solution. A portion of the gaseous CO_2 is dissolved into the solution and reacts with H_2O, resulting in carbonic acid (H_2CO_3). The increase in carbonic acid encourages the dissolution of free calcium ions and calcium hydroxide ($Ca(OH)_2$). Therefore, any process that increases the CO_2 content in the solution also increases the dissolution of calcium ions (decreased calcium carbonate solids). It should be noted that equations 6.1, 6.2, and 6.3 are all reversible reactions, that is, the reaction can occur towards the right hand side of the equation or to the left hand side of the equation. This experiment takes advantage of this principle by dissolving the most possible calcium ions, filtering RCA solids, and then precipitating the calcium carbonate out of

solution. The calcium carbonate is precipitated by heating up the calcium-rich solution in the oven to decrease the solubility of CO_2 in the water. Figure 54 shows the solubility of CO_2 in water at different temperatures. A photo of the filtration equipment (as required by ASTM D5907) is shown in Figure 55.
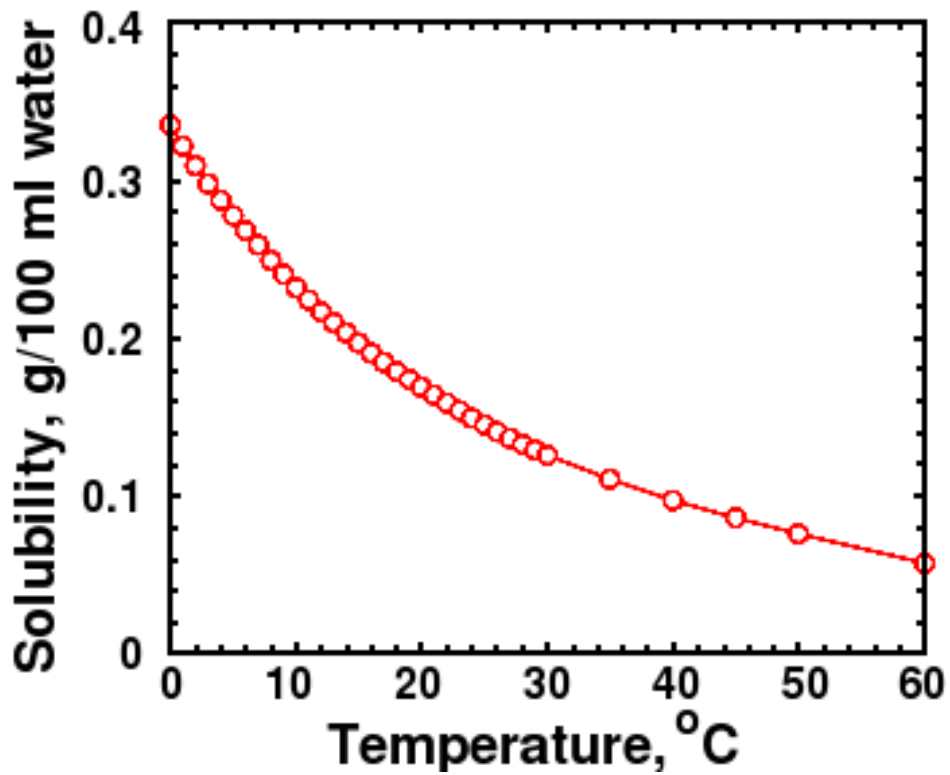
Figure 54. Solubility of CO_2 in Water at Various Temperatures (from Nelson, 2003)

Figure 55. Filtration Equipment Required for ASTM D5907

6.4.1 Short Term Calcite Production Method

The results from the short term calcium carbonate precipitation Test are shown in Figure 56. In the first cycle, the RCA produced about 1.6 g of calcium carbonate. Each cycle after the first produces a decreasing amount of calcium carbonate for the same amount of CO_2 provided.
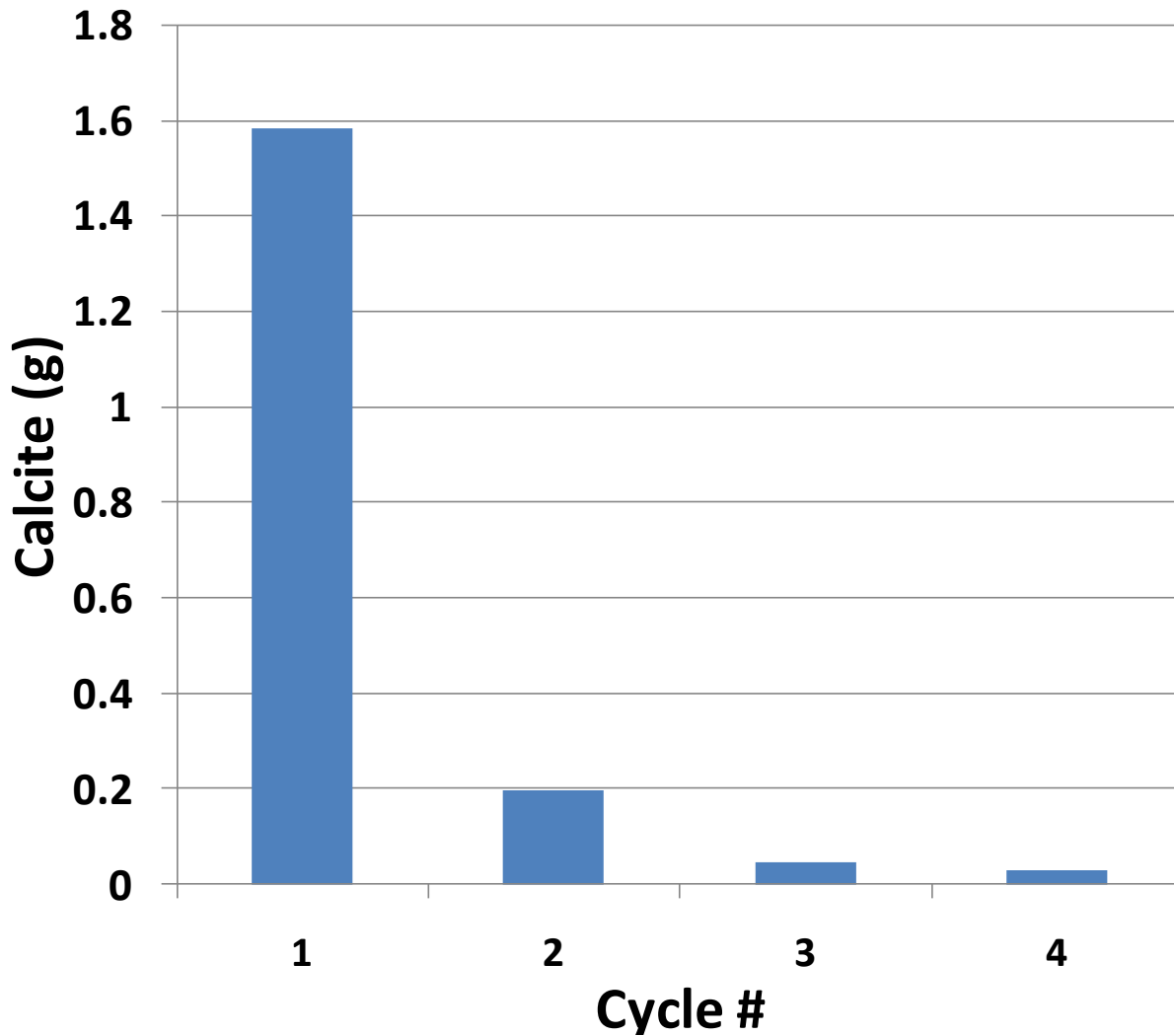
Figure 56. Calcium Carbonate Obtained from Initial 5 hours of CO_2 Injection

The pH was monitored throughout this test and the procedural times chosen were based from pH readings. The pH of the RCA-water solution is an indication of the CO_2 content. The pH was measured before RCA and water mixing, during CO_2 bubbling, and during the heating process in the oven. The pH measurements are shown in Table 13. The first pH measurement

taken was for the pH of tap water which came out to be 8.3. When the water and RCA was mixed, the pH raised slightly due to the dissolution of hydroxides from the RCA. Within the first 30 minutes of CO_2 introduction the pH reach about the lowest value throughout the duration of CO_2 injection. This indicates that CO_2 is reacting with H_2O and forming carbonic acid, which is indicative of the lowered pH. However even though the water has become saturated with CO_2 it may still be necessary to provide enough carbon such that all of the calcium can later form calcium carbonate precipitate. For this reason, the CO_2 injection time was increased to 5 hours.

After the introduction of CO_2, the solution was filtered to remove the RCA fines. The filtration process utilizes a vacuum pump to force the solution through the filters; this subjects the solution in the filter flask to negative pressure. The decreased pressure in the flask encourages the dissolved CO_2 to come out of solution, and decreases the carbonic acid, hence the increased pH as seen in Table 13. After filtration, the solution was placed in the oven to raise the temperature of the water such that the solubility of CO_2 will be decreased. Since CO_2 is leaving the solution, carbonic acid is decreasing and the pH is increasing. After 4 hours of heating the pH has stopped increasing at about 6.78 and it is assumed that all of the calcium and carbonate has reacted to form calcium carbonate precipitate. However, the solution has not returned to the initial pH of 8.6, this is most likely due to other hydroxides (sodium and potassium) still dissolved in the water which does not react to form calcium carbonate.

Figure 57. Photograph of the Filtration of RCA Fines from Water

Table 13. pH Measurements for Calcium Carbonate Precipitation Test

Description	pH
Tap water	8.28
RCA & water	8.60
0.5 hr. CO_2	6.00
1 hr. CO_2	5.95
1.5 hr. CO_2	5.98
2 hr. CO_2	6.00
2.5 hr. CO_2	6.01
3 hr. CO_2	6.04
3.5 hr. CO_2	6.04
4 hr. CO_2	6.02
4.5 hr. CO_2	6.02
5 hr. CO_2	6.03
after filtration	6.47
0.5 hr. heating	6.51
1 hr. heating	6.59
1.5 hr. heating	6.66
2 hr. heating	6.73
2.5 hr. heating	6.77
3 hr. heating	6.78
3.5 hr. heating	6.78
4 hr. heating	6.78

The calcite precipitation potential has also been evaluated with the effect of fines addition. RCA was washed and 0, 2, 4, and 6% fines were added to observe the effect of fines on the calcite production generated from two cycles of CO_2 injection. The same procedure used for all previous samples was used again here. The results of this test are shown in Figure 58. The results show that with a higher percentage of fines, the more calcite that can be precipitated.

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While washed RCA can still produce calcite, the addition of 6% fines can double the calcite produced of just washed RCA with 0% fines.
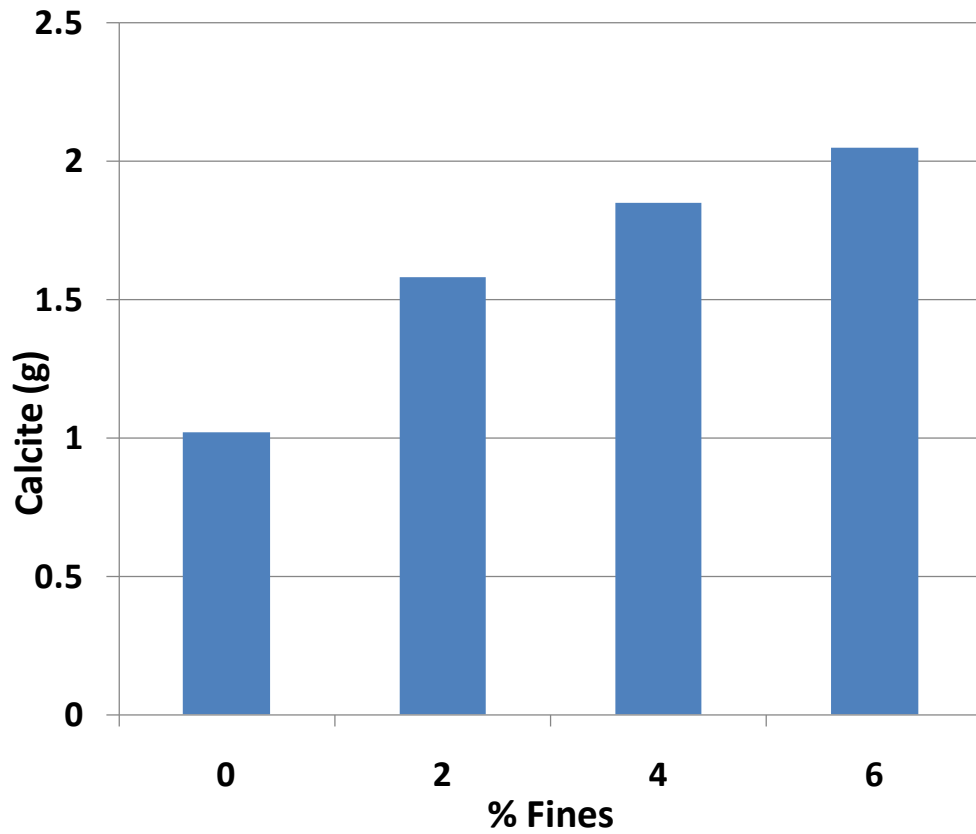

Figure 58. The Effect of Fines on Calcite Precipitation

6.4.2 Long Term Calcite Production Method

Testing was conducted to determine whether in fact all of the available calcium is being extracted with the initial introduction of CO_2 into RCA & water. A new 5kg sample of 'as is'

RCA was obtained. Since the pH reached a minimum within the first 30 minutes of the previous test, the pH for this test was measured once per minute during CO_2 introduction. It was determined that within the first 6 minutes, the pH will no longer decrease, indicating the saturation of CO_2 in water. A method was developed to reduce the amount of necessary CO_2 and to reduce testing time. With this sample of RCA, the same procedure was used as described in section 6.2.2 except the CO_2 introduction time was adjusted to 6 minutes, and each cycle was performed by reintroducing the water back into the RCA while the CO_2 was administered.

The results for 24 cycles are shown in Figure 59. Clearly this process reveals that the calcium carbonate can be extracted with each subsequent cycle. The amount precipitated in each cycle however is considerably less than what was obtained from 5 hours of CO_2 injection. This is most likely due to the availability of carbon for longer injection times. While 6 minutes is all that is required to minimize the pH, the solution still needs the most possible carbon to form more calcium carbonate. Figure 60 shows that there is a decreasing trend in the 24 consecutive cycles of CO_2 precipitation grouped by 6 consecutive cycles. Grouping 6 cycles at a time exemplifies the trend of decreasing calcium carbonate .When this process is continued the RCA will reach a point in which the majority of the calcium has been extracted and reacted with $CO_2$to form the maximum possible calcium carbonate from the 5kg sample. This information will be useful for estimating the total possible calcium carbonate potential from a known quantity of RCA. Over time it can be expected that the total calcite production can be up to 8.8 to 9 g which is less than 1% of material by weight.
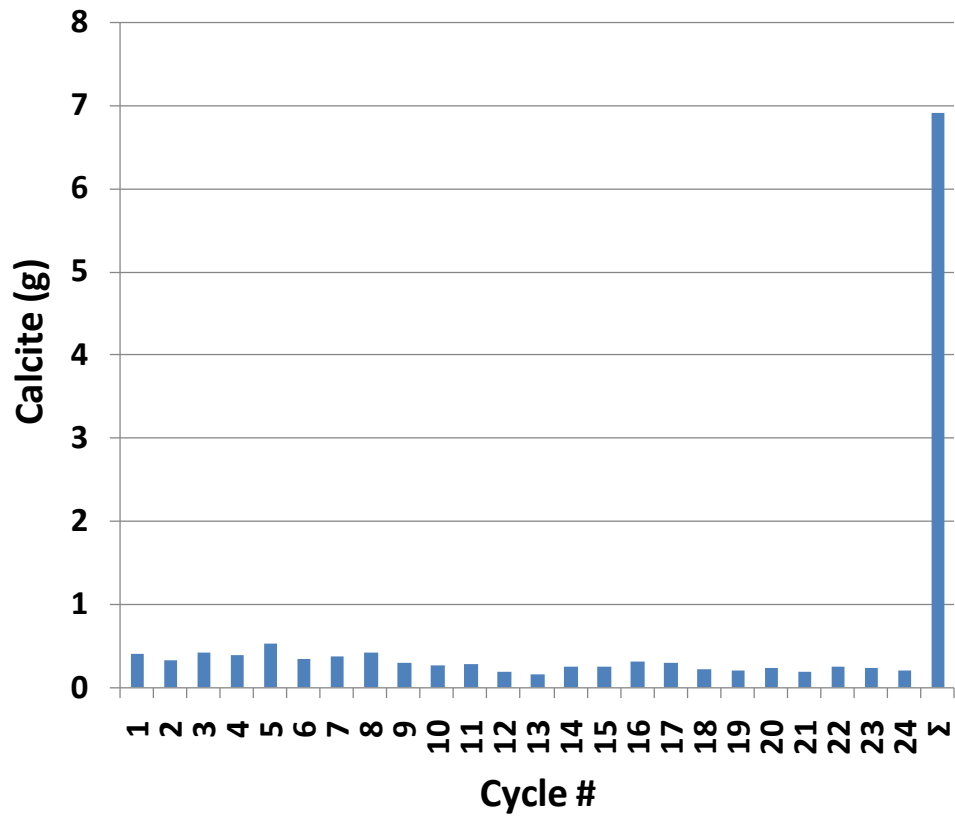
Figure 59. Results from the Iterative Process for Calcium Carbonate Precipitation
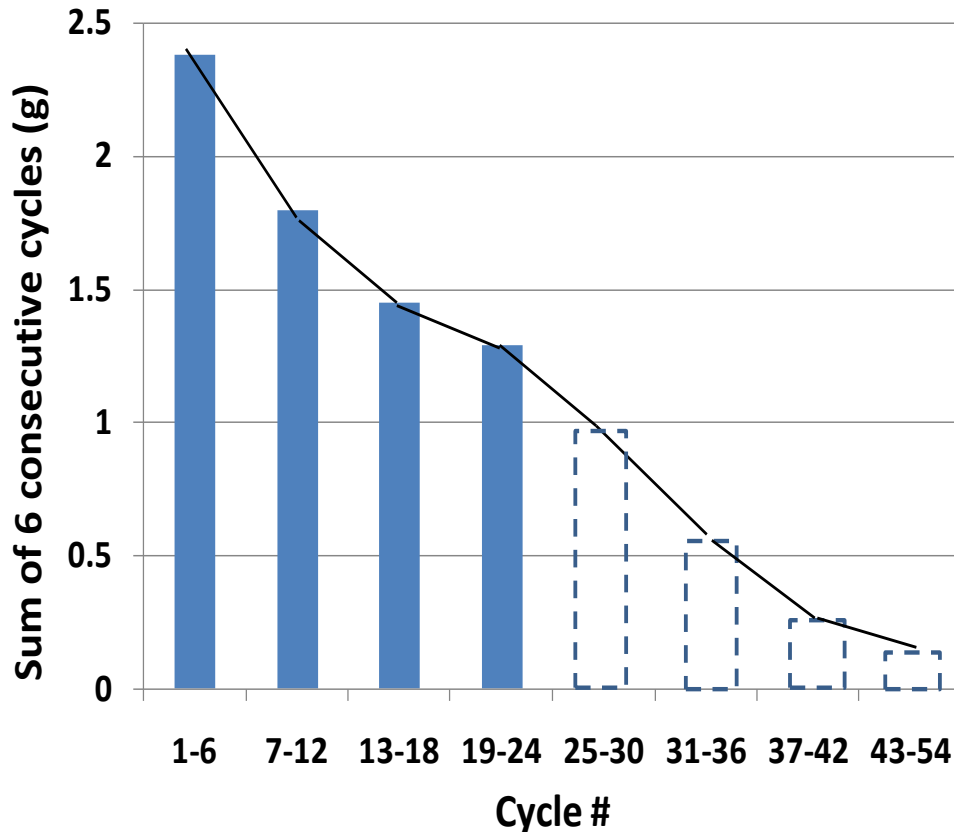
Figure 60. Decreasing Trend of Consecutive Calcium Carbonate Precipitation Cycles and

Predicted Calcium Carbonate Reduction

6.5 Summary

The clogging potential of RCA fines has been evaluated. It has been determined that the

introduction of fines into a drainage system can be detrimental over a sufficiently long period of

time. For example, over 100 days a sample of RCA with 4% fines addition (sample C1) has

decreased in flow rate by about 80%. Sample C2 was tested with the No. 4 average gradation and

2% fines. The initial starting flow rate for C2 was higher than sample C1 and decreases with a similar trend to the other samples. The C3 sample of 'as is' RCA was tested with 0% additional fines and the initial flow rate begins at about the maximum possible flow rate as expected, and begins to decrease with the accumulation of fines on the geotextile.

The precipitation of calcium carbonate has also been evaluated. The calcium carbonate solids may act as fines and to further reduce the flow rate. However the process used to precipitate the calcium carbonate was a much accelerated process and the infield RCA under normal environmental conditions may take a considerably long time to accumulate. Up to 7 g of calcium carbonate has been precipitated from 5 kg of No. 4 RCA. This is equivalent to 0.14% by weight of calcite precipitate. An infield French drain may be susceptible to a detrimental amount of calcite precipitate over its lifetime. Further studies should include the study of calcium carbonate precipitation considering the variables of temperature, pressure, gradation, detention time, and heating time, to develop procedure to quickly (within several days) determine calcium carbonate precipitation. Additionally, further studies should include the actual rate of precipitation of infield drains, such that a laboratory protocol can be used to predict the calcium carbonate precipitation of infield drains.

CHAPTER 7: SUMMARY AND CONCLUSION

7.1 Summary

RCA has been used as a construction material in pavements or structures, but has not received a lot of attention as a drainage material in exfiltration trench such as French drains. There are several concerns with using RCA as a drainage material, especially in regards to the excess fines leading to reduced filter fabric permittivity, rehydration of RCA fines and the precipitation of calcium carbonate.

Chapter 2 provides the background and literature review regarding the use of RCA in exfiltration trench systems. A survey with questions about using RCA was complied and issued to the state highway agencies across the U.S. No state reported using RCA in French drains or exfiltration trenches but several state agencies report using RCA as base layer material in pavement construction.

In chapter 3, the physical properties of the RCA such as the unit weight, specific gravity, and percent voids have been evaluated. The aggregate handling simulation was also developed and the aggregate washing methods of suspension, agitation and pressure washing have been tested. One series of tests were conducted by hand mixing/agitation, while an additional series of testing was conducted using an automated process. The results have showed that RCA has a large potential to generate fines under abrasion and is very susceptible to break down from

abrasion during transportation, stockpiling, or placing. It was found that the most effective method to remove fine particles that can attribute to geotextile clogging is the agitation and pressure washing.

Chapter 4 describes the potential of RCA rehydration (or recementation) under saturated conditions. Compressive strength, pH, time of setting, and hydration temperature tests were used to evaluate rehydration. All testing methods utilized to determine rehydration of RCA proved that RCA shows no tendency to rehydrate when mixed with water.

In chapter 5, drainage performance of RCA with different percent fines was evaluated. And optimum design of the hydraulic system was carried out by running permeability tests with varying tube size and permeameter sizes. The permeability of RCA was measured using the No. 4 gradation (average, upper, and lower limits). Additionally the 'as is' No. 4 gradation was tested. And the effect of fines on RCA permeability was also evaluated. The No. 4 gradation of RCA does not restrict water flow and thus was found to be an acceptable material to allow for the transportation of water. Increasing the fines addition causes the reduction of RCA permeability; especially 4% fines leading to a 50% reduction in the permeability.

Chapter 6 details the clogging test in which the permeability was monitored with time and the reduction of flow due to the excess fines content was observed. The potential of calcium carbonate precipitation of No. 4 gradation of RCA was also evaluated. The clogging tests and addition of RCA fines illustrates that in-field French drain systems will have a tendency to clog

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over time. An accelerated procedure of calcite production was developed and this acceleration procedure includes both short- and long-term simulations of calcite formation It has been determined that RCA has to potential to precipitate calcium carbonate under extreme conditions, that is, the direct injection of large quantities of CO_2. The precipitation rate for in field French drains is beyond the scope of this thesis; however it is assumed that the laboratory testing method is much accelerated as opposed to the infield French drains.

7.2 Conclusions and Recommendation

Based on the results of this study, the following conclusions and recommendations are made and summarized below.

- RCA has the potential to generate a large amount of fines based on the measured value of L.A. abrasion of 43%. RCA involves aggregate handling procedures such as stockpiling, transporting, and placing, which can generate a significant amount of fines.
- The generation of fines should be carefully monitored during the production, stockpiling, and placing processes. Aggregate cleaning methods should be utilized using a combination of water suspension, agitation, and pressure washing.
- RCA shows no tendency to rehydrate based on the results from chapter 4 in which no heat of hydration, or setting time was observed.

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- Based on the measurements, the RCA No. 4 gradation does not restrict the flow of water through the permeameters. This is concluded based on the flow rates measured from samples with RCA and flow rates through the empty permeameters being identical.

- The effect of RCA fines on the permeability has been found to be significant based on the results with 0, 2, and 4% fines measured over time. Testing results show that 4% fines addition causes a 50% reduction in the coefficient of permeability.

- RCA has the potential to precipitate calcite over a long period of time. This formation of calcite is increased with RCA fines. However with less than 1% of calcite being produced, it may have a negligible effect when compared to RCA fines only.

- RCA appears to have the preferable qualities to serve as a drainage media in French drain systems. The tendency to produce RCA fines should be carefully considered, and it is recommended that before its use the RCA should be properly treated and should abide to the standards set in place by the FDOT.

APPENDIX

ADDITIONAL FIGURES FOR CHAPTER 5

Sample ID	Gradation	Permeameter size (in.)	Tube Size (in.)	Geotextile
P1	empty	6	3/4	yes
P2	empty	6	1/2	yes
P3	empty	6	1/4	yes
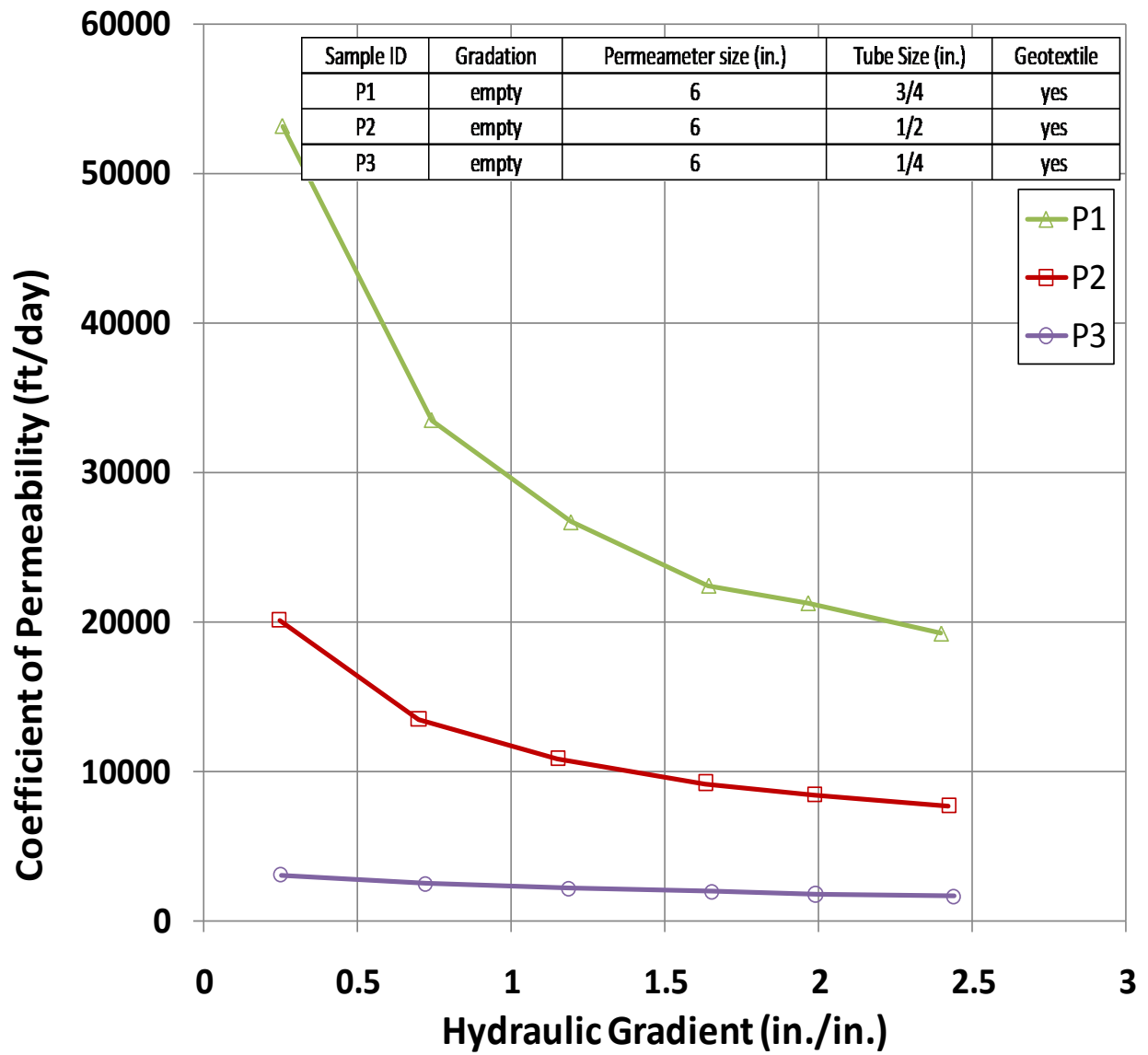
Figure A1. Influence of Tube Size on Permeability with 6 in. Permeameter

Sample ID	Gradation	Permeameter size (in.)	Tube Size (in.)	Geotextile
P6	empty	9	1/2	yes
P7	empty	9	1/4	yes
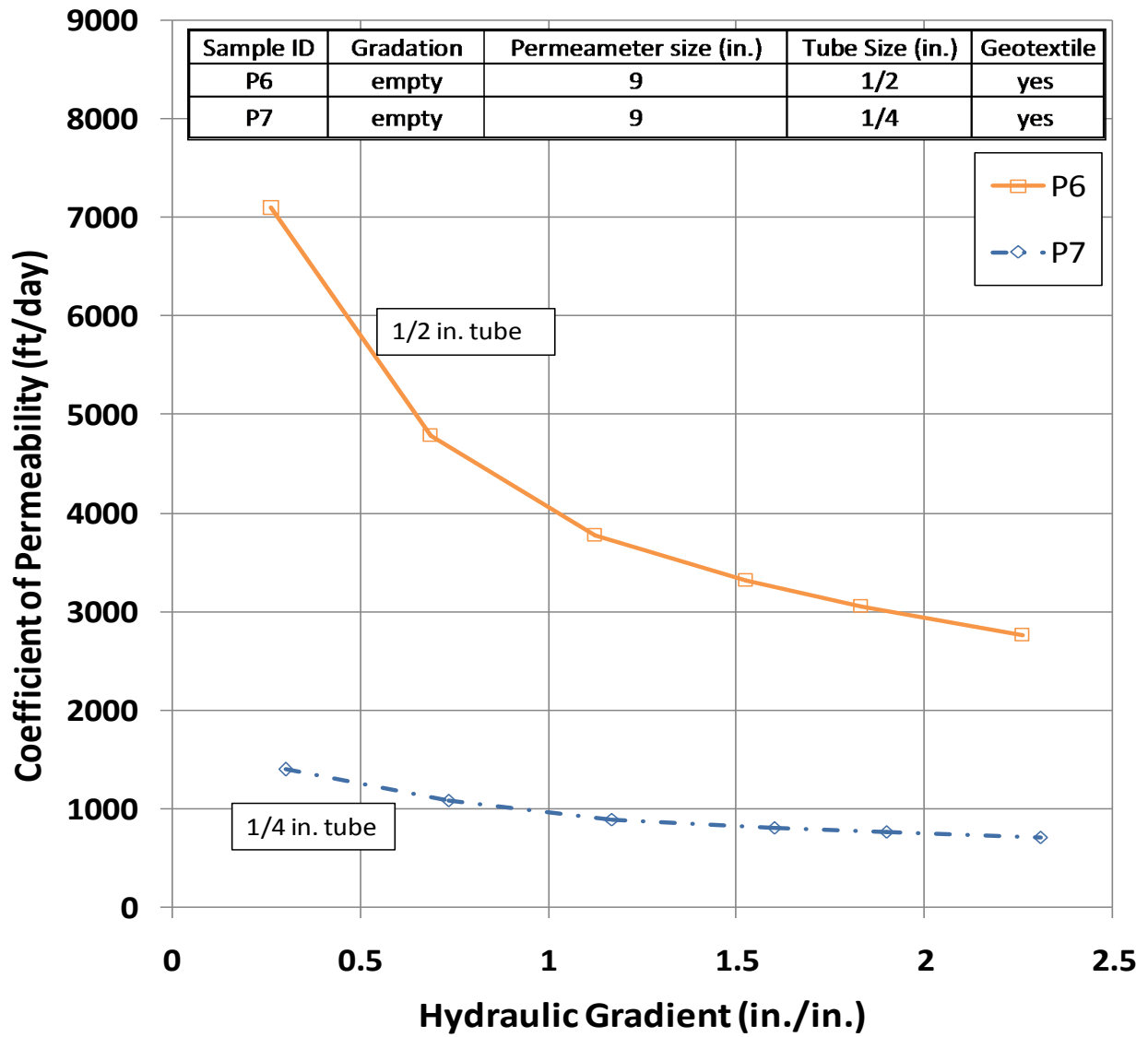
Figure A2. Influence of Tube Size on Permeability with 9 in. Permeameter

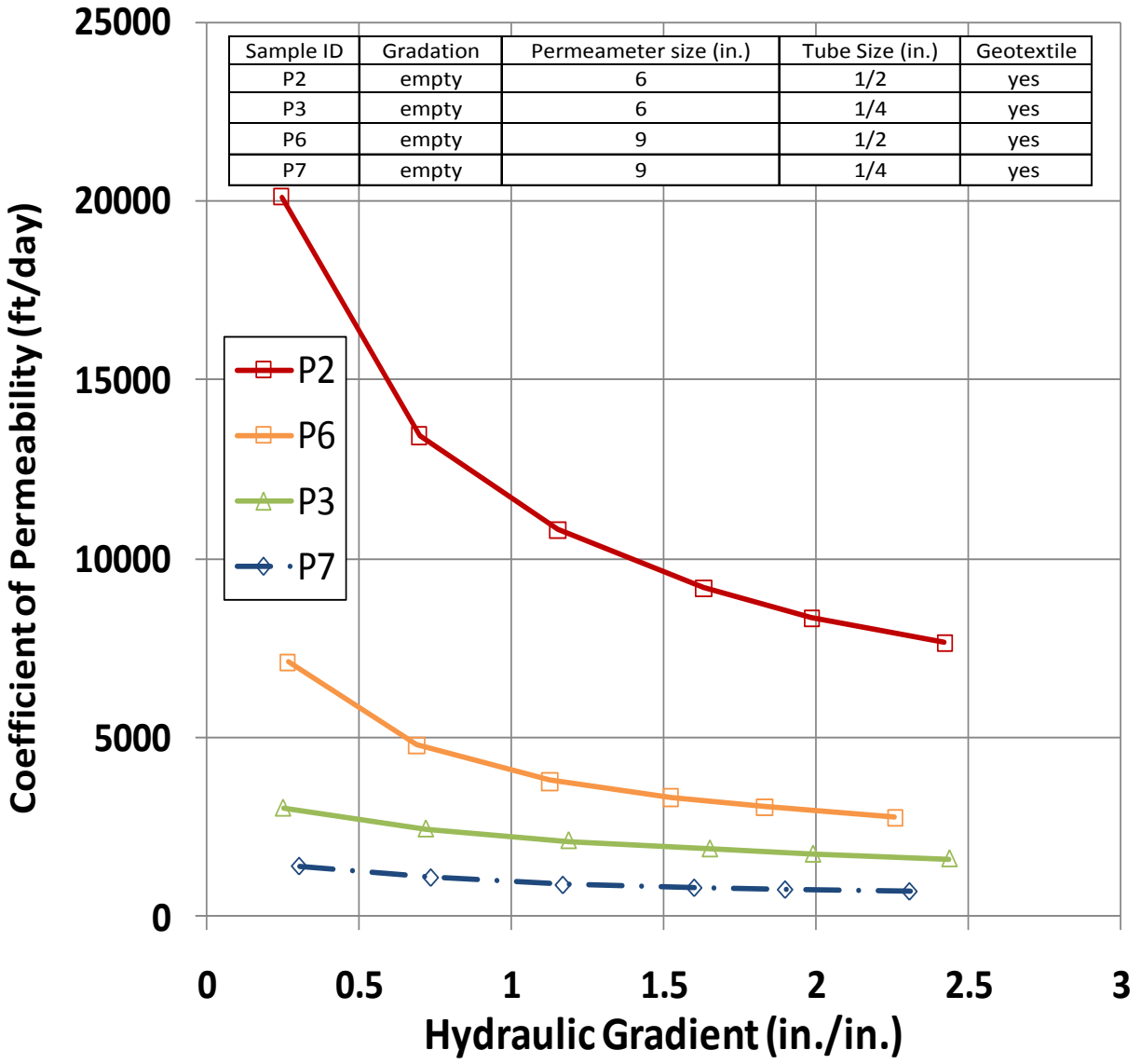| Sample ID	Gradation	Permeameter size (in.)	Tube Size (in.)	Geotextile
P2	empty	6	1/2	yes
P3	empty	6	1/4	yes
P6	empty	9	1/2	yes
P7	empty	9	1/4	yes

Figure A3. Effect of Permeameter Size with 1/2 and 1/4 in. Tube on Permeability
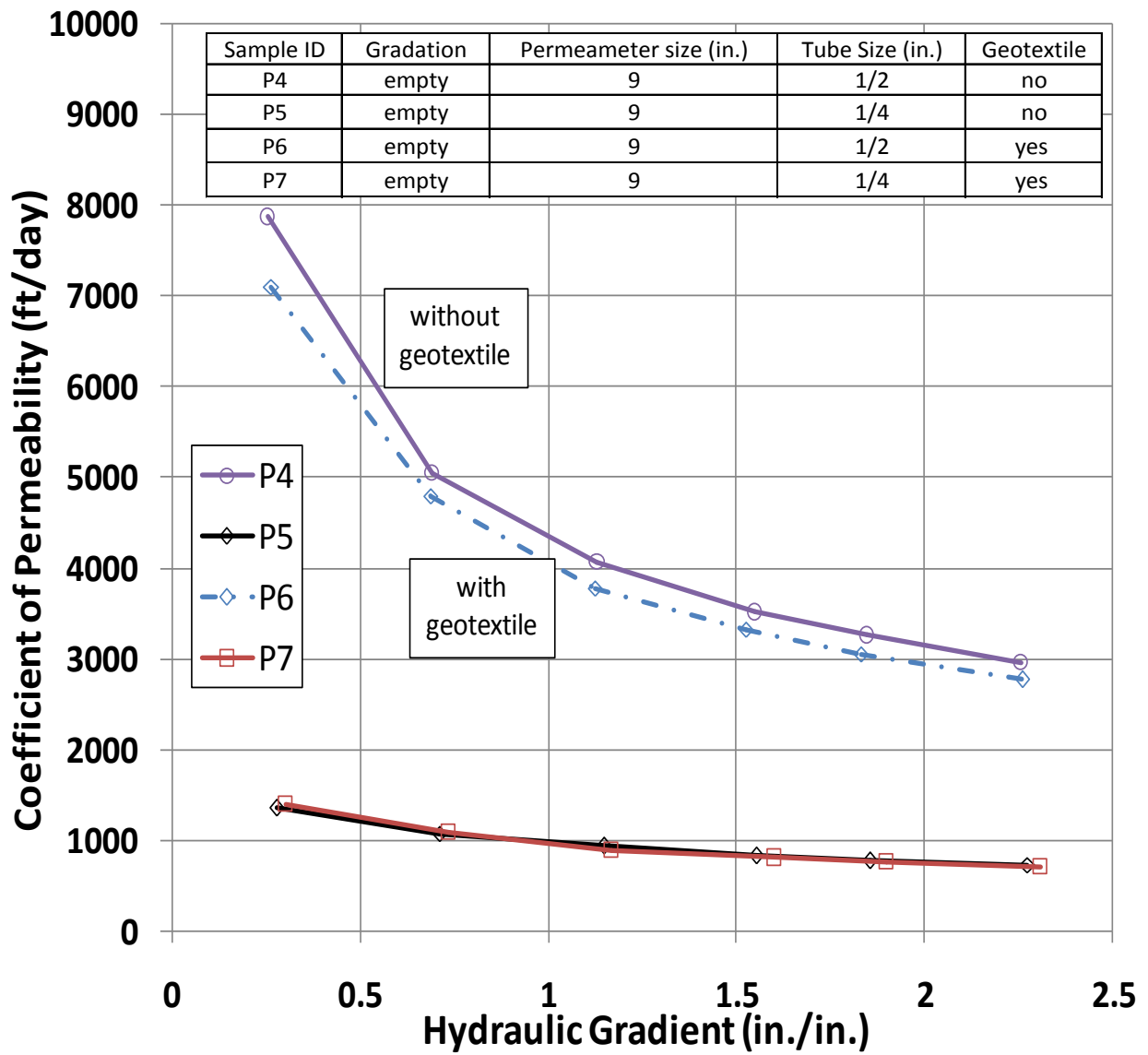
Figure A4. Effect of the Addition of Geotextile with 1/2 and 1/4 in. Tube Sizes on Permeability

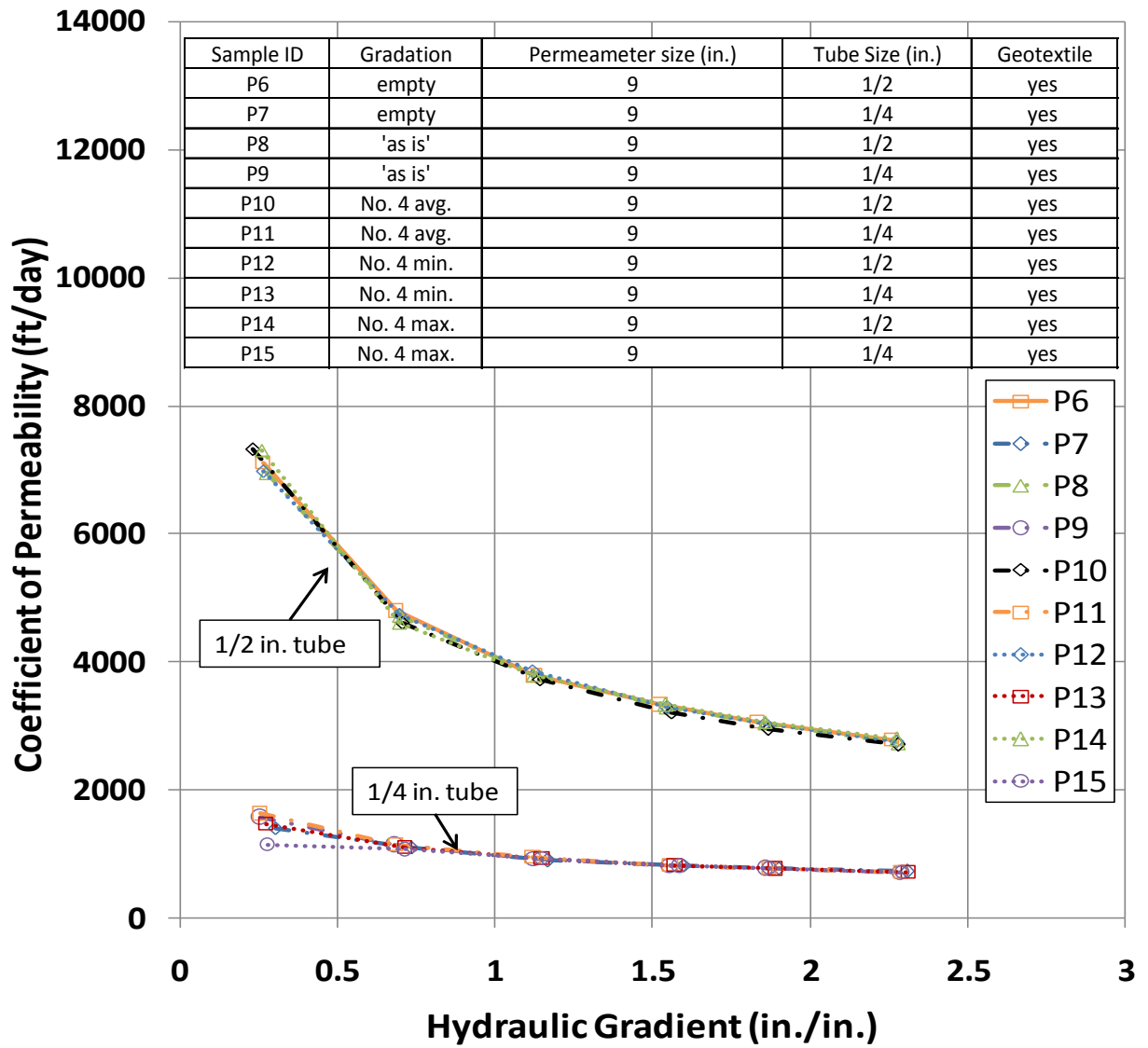| Sample ID	Gradation	Permeameter size (in.)	Tube Size (in.)	Geotextile
P6	empty	9	1/2	yes
P7	empty	9	1/4	yes
P8	'as is'	9	1/2	yes
P9	'as is'	9	1/4	yes
P10	No. 4 avg.	9	1/2	yes
P11	No. 4 avg.	9	1/4	yes
P12	No. 4 min.	9	1/2	yes
P13	No. 4 min.	9	1/4	yes
P14	No. 4 max.	9	1/2	yes
P15	No. 4 max.	9	1/4	yes

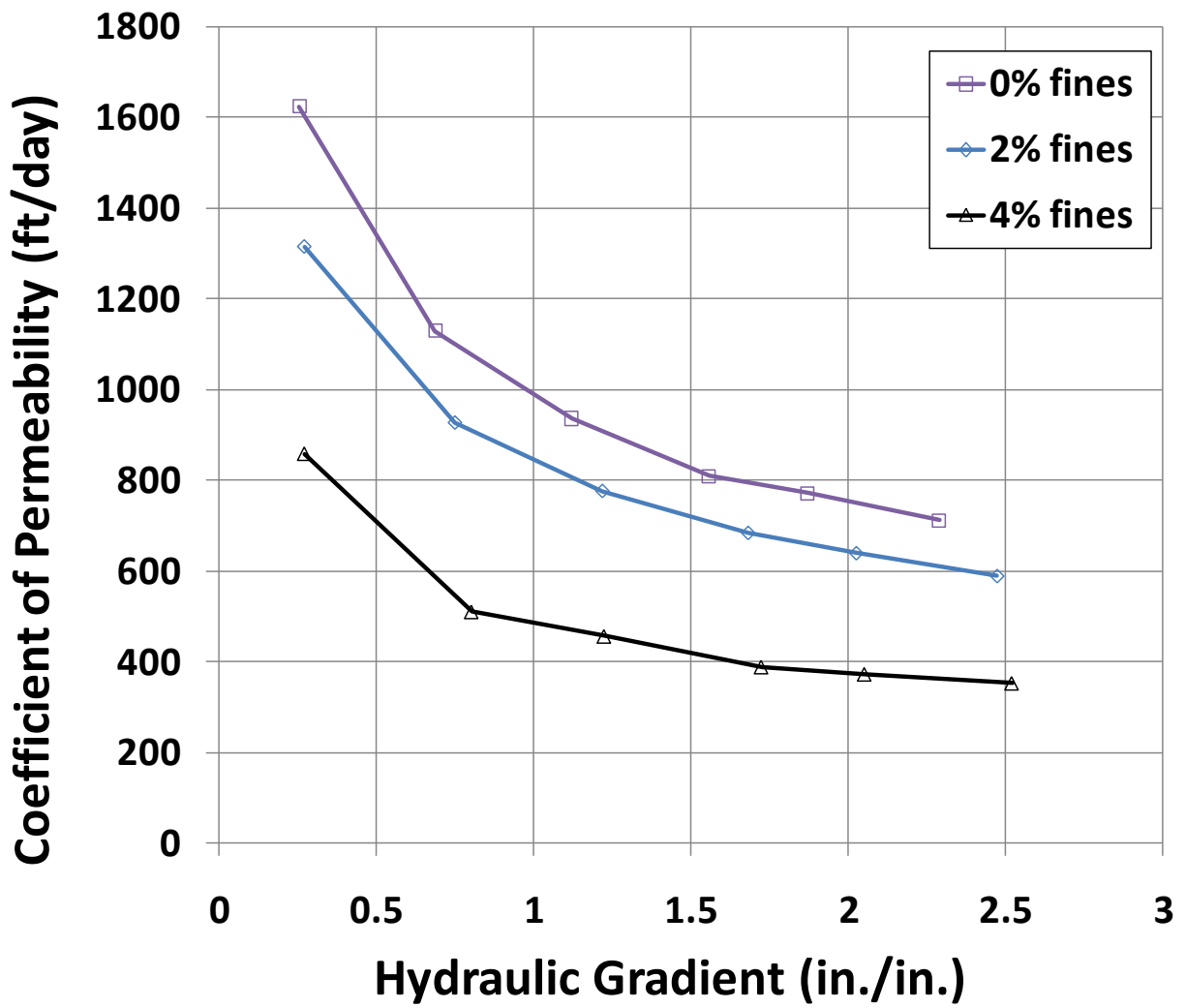Figure A5. Results for Different RCA Gradations in the 9 in. Permeameter as Permeability

Figure A6. Permeability vs. Hydraulic Gradient with 0, 2, and 4 % Fines Addition

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