

# Evaluation of Use of Crushed Hydraulic Cement Concrete (CHCC) as an Additive to Base Course/Subbase Material

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AS AN ADDITIVE TO BASE COURSE/SUBBASE MATERIAL**

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## ABSTRACT

All new pavement systems constructed under the jurisdiction of the Virginia Department of Transportation (VDOT) require drainage systems. These drainage systems are constructed with perforated pipe and coarse aggregate that surrounds the pipe. Additionally, to separate the coarse aggregate from the base course and to create a filter, the drainage system also contains nonwoven geotextile that surrounds the coarse aggregate. Currently, the use of crushed hydraulic cement concrete (CHCC) as base course in new pavement systems is not allowed in VDOT projects because of the concerns associated with CHCC potentially clogging the geotextile of the drainage system to an extent that the serviceability of the filtration system is compromised. The basis of this concern is primarily due to the limited literature from the research conducted around the late 1990s. However, these studies are often inadequate in details and also present results that are contradictory and more importantly are not based on the specific geotextile used by VDOT. Recently due to the awareness of sustainable practices, there is interest throughout the U.S. to recycle CHCC and use it as base course aggregate. If allowed, this practice would result in the CHCC or blends of CHCC/virgin aggregate (V.A.) to be in direct contact with the geotextile.

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## **INTRODUCTION**

The production of roadway aggregate from crushed hydraulic cement concrete (CHCC) (also sometimes referred to in the literature as recycled concrete aggregate – RCA) is not a new concept and has been around for many years. In Europe, the interest started at the end of World War II, when some countries had to deal with the issue of trying to find a suitable place to deposit their rubble that contained concrete pieces (Buck, 1977). Although in the U.S. the first use of CHCC also started at about the same time, the first signs of wider acceptability of reuse started in the mid-1970s (Wade et al., 1997).

Low production cost, fast production time, public awareness of being able to recycle materials that would otherwise be sent to disposal facilities, and political pressures to enhance sustainable practice has led to a substantial increase in the use of CHCC in highway applications over time (Bennert et al., 2000; Cooley and Hornsby, 2012). According to Gonzalez and Moo-Young (2004), 38 out of 50 states in the U.S. in 2004 were already using CHCC as part of the base aggregate. A more recent survey conducted by the University of Wisconsin-Madison shows that CHCC is considered the most reclaimed material in the U.S. to construct base course (Edil et al., 2012). As of 2012, in 8 states (27% of the surveyed states) the annual use of CHCC to construct base course was exceeding 75,000 tons per year. However, an unpublished survey conducted by AASHTO in 2015 that was sent to Virginia Center for Transportation Innovation and Research (VCTIR) reveals that out of 27 state department of transportation (DOT) agencies that participated in this survey, there are still some that limit or prevent the usage of the CHCC as base course. In some states such as Maryland (MSHA, 2013) specifications special provision section 900.03 and Michigan (MDOT, 2012) specifications section 902.05, the usage is allowed but only if CHCC is placed 30 to 90-cm (1 to 3 ft.) away from the underdrain systems. In other states such as Alaska, Kentucky, and Virginia, the use of CHCC is completely prohibited if the pavement systems contain underdrain systems. In Virginia, the particular restrictions associated with using CHCC in projects are outlined in VDOT Specifications (2007), Section 203.02a as:

1. not permitted to be used in reinforced cement concrete;

2. not permitted to be used in combination with other materials in contact with geotextile fabric when such fabric is used as a drainage item; and
3. not permitted to be used as backfill or bedding for the perforated pipe.

The primary reason for the existing restrictions on the use of CHCC in the base course is associated with the concerns regarding the potential of leaching out, precipitation, and deposition of tufaceous constituents from CHCC. The underdrain systems constructed in Virginia contain geotextile that is wrapped around the coarse drainage aggregate surrounding the perforated drainage pipe. This geotextile serves as a separator between the base and drainage aggregate and also as a filter to minimize the migration of the fines from the base aggregate into the underdrain system. In the case of tufaceous constituents from CHCC, the concern is associated with clogging the geotextile and eliminating (or significantly minimizing) the filtration performance, which hinders the performance of the drainage of the pavement systems.

Precipitation of calcium-based tufaceous constituents from the leachate of CHCC has been previously reported from field and laboratory observations (Gupta and Kneller, 1993; Tamirisa, 1993; Snyder and Bruinsma, 1996; Steffes, 1999; Gupta and Dollimore, 2002). Steffes (1999) reported several cases of clogged wire mesh rodent guard of the side-drains in Iowa and claimed that the clogging was due to the formation of tufaceous material from CHCC used in the base course. However, previous field studies also present conflicting results when it comes to CHCC possibly clogging the geotextile filter fabric. In some cases, an abundance of tufaceous constituents were observed on the geotextile surface and in other cases very little was observed even after 3 to 5 years of service life but the reasons for the discrepancies have not been explained (Sherman et al., 1994; Snyder and Bruinsma, 1996; Snyder, 1995). Snyder and Bruinsma (1996) proposed several recommendations to minimize the potential of CHCC to precipitate tufaceous constituents, which consisted of (1) eliminating the finer fraction (passing U.S. number 4 sieve) when creating base course aggregate from CHCC, (2) using geotextiles with high permittivity, (3) designing the drainage systems that will allow annual flushing, and (4) blending CHCC with virgin aggregate. However, these researchers did not provide a specific threshold for the virgin aggregate percentage that should be mixed with CHCC.

VDOT already recognizes the potential for the recommendations made by Snyder and Bruinsma (1996) to improve the use of CHCC; however, based on the conversations with local facilities in Virginia, it was determined that eliminating the CHCC fines is not practical. Therefore, a specific study was needed to particularly evaluate the properties of the CHCC produced in Virginia and determine a specific threshold to mix CHCC with virgin aggregate to evaluate the suitability of this blend to be used in the presence of typical geotextile filter fabric used in Virginia (as described in VDOT Specifications Section 245.03(c)). The study described in this report specifically focused on addressing this need.

## **PURPOSE AND SCOPE**

The purpose and scope of this study were to examine the potential clogging of geotextile filter fabrics by mineralization of leachate from CHCC in base course and subbase material under laboratory conditions.

Primary objectives included:

1. Evaluate the clogging potential of VDOT 21B virgin aggregate, 100% CHCC, and blends of the CHCC with VDOT 21B aggregate to geotextile typically used in VDOT underdrain systems;
2. Determine a methodology and identify relevant soluble ion concentrations (such as calcium, magnesium, sodium, sulfate, and potassium) for estimating the suitability of CHCC source for use adjacent to geotextile typically used in VDOT underdrain systems; and
3. Provide guidelines to revise VDOT specifications as it relates to appropriate percent blends of CHCC/virgin aggregate and estimating the suitability of CHCC source.

Secondary objectives included:

1. Document the production of CHCC at a plant where the samples are collected and provide information regarding the handling of produced CHCC before it is shipped to the project site;
2. Provide a summary of previous studies related to the use of CHCC in the presence of geotextile based underdrain systems;
3. Evaluate the Atterberg limits of virgin aggregates and CHCC (100% and blends) used in this study and compare the results against the VDOT required limitations;
4. Evaluate the changes in gradation of CHCC after compaction following compaction tests and characterize any changes in gradation before and after compaction in the laboratory.

The remainder of this report is organized to present the research details associated with each of the above-listed objectives.

## **METHODS**

The following tasks were performed to achieve the study objectives. These tasks are listed based on the order that these research activities were conducted in order to address each of the specific objectives of this project as listed below:

1. An extensive literature review was conducted. This task was conducted to address the secondary objective number 2.
2. CHCC material production processes were observed in a selected plant and documented. This task was conducted to address the secondary objective number 1.
3. 100% CHCC and 100% virgin aggregate (V.A.) with VDOT 21B gradation were sampled. This task was conducted to address the secondary objective number 3.
4. Available nonwoven geotextiles were evaluated and Mirafi 140N nonwoven needle punch geotextile was selected based on its hydraulic properties in coordination with



- VDOT engineer. This task was conducted to be used as part of an effort to address primary objective numbers 1 and 3.
5. 100% CHCC, 100% V.A. and 3 CHCC-V.A. blends with different proportions were evaluated for their mechanical and index properties. This task was conducted to address the secondary objective number 3.
  6. Changes in the CHCC gradation due to compaction was evaluated. This task was conducted to address the secondary objective number 4.
  7. 100% CHCC, 100% V.A. and 3 CHCC-V.A. blends with different proportions were evaluated for their chemical properties and leaching behavior. This task was conducted to address the primary objective number 2.
  8. A laboratory aging and field stockpiling program was developed and implemented on 100% CHCC. This task was conducted to address the primary objective number 2.
  9. Specimens from laboratory aging and field stockpiling were evaluated for the changes in their mechanical characteristics, chemical properties, and leaching behavior. This task was conducted to address the primary objective number 2 and 3.
  10. Geochemical modeling was utilized to model the chemical precipitation of tufa from CHCC, V.A., and their blends. This task was conducted to address the primary objective numbers 2 and 3.
  11. Constant head hydraulic conductivity and Gradient Ratio (GR) tests were conducted to evaluate the hydraulic compatibility of CHCC with VDOT 21B gradation and a selected nonwoven geotextile used in VDOT UD-4 edgedrains. This task was conducted to address the primary objective numbers 1 and 3.

## **Literature Review**

An extensive literature review was carried out for this project in order to create a synthesis review reference for Virginia Transportation Research Council (VTRC) and VDOT engineers on the subject of potential for CHCC tufa formation and clogging of drainage geotextiles used adjacent to CHCC base course/subbase layers. The literature review was conducted by searching various databases related to geotechnical and transportation engineering, geochemical processes, and waste material management sources such as but not limited to (i) the catalog of Transportation Libraries (TLCat), (ii) Transport Research International Documentation (TRID), (iii) the Transportation Research Board Research in Progress (RiP) and Research Needs Statements (RNS) databases, (iv) the Catalog of Worldwide Libraries (WorldCat), (v) Elsevier Publishing and ScienceDirect online database, (vi) Wiley online library, (vii) Springer publishing and SpringerLink online database, and (viii) ICE Virtual Library. After identifying the related literature to the scope of this project, the identified documents were reviewed to summarize the relevant past studies on the subject.

## **Material Sampling for Characterization**

### **Crushed Hydraulic Cement Concrete (CHCC)**

#### *Material Production*

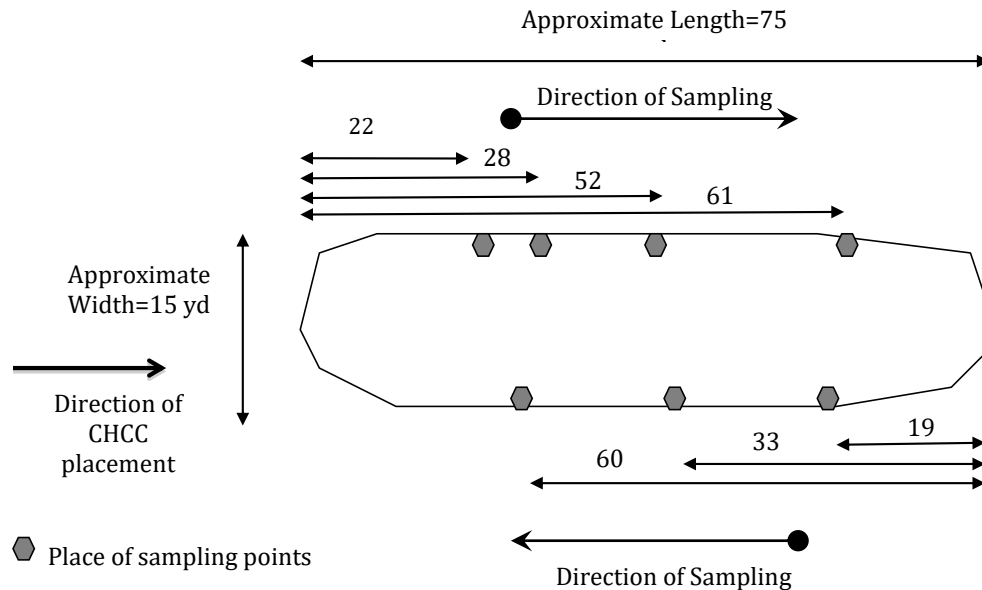
GMU team visited several quarries in northern Virginia, where CHCC material is produced and stockpiled before use in construction projects. Based on the information collected on the material production schedules provided by quarry officials, Luck Stone Centreville quarry was identified as the source for the CHCC material. CHCC produced in this facility consists of hydraulic cement concrete from many different origins including but not limited to concrete from demolished structures, curb and gutter, pipes, and washouts. Unless created from a specific road project, it is very common for CHCC to contain this type of variety of concrete (Abbaspour et al., 2016a, 2016b). At this particular location, the research team was told that on average it takes a year to deplete the created stockpile before crushing additional concrete. In the meantime, all of the concrete brought to the site from different job sites is stockpiled in a separate adjacent pile. After coordinating with quarry personnel, the GMU team traveled to the production site during the production period, observed and documented various processes including removal of metals and deleterious material from waste concrete, crushing, screening and stockpiling the freshly produced CHCC by capturing photographs from each of these production steps. All samples were collected at the same time within a week of production of the stockpile to obtain freshly produced CHCC. The samples were collected following a random sampling procedure as described in the following section.

#### *CHCC Sampling*

Considering the inhomogeneity of the concrete source within the CHCC stockpile, a random sampling procedure was followed to obtain representative samples with minimal segregation based on the steps described below:

1. From the existing large stockpile for base course CHCC, about 70 m (230 ft.) long, 7 smaller stockpiles were created.
2. Locations along the existing large stockpile where the materials were taken to create smaller stockpiles were selected following the ASTM D3665 procedure prior to arriving at the site. Figure 1 shows a schematic plan of the existing large stockpile and location of randomly selected 7 sampling points.
3. Small piles created with approximately 1.80 m by 1.80 m by 1.50 m high (5.9 ft. × 5.9 ft. × 4.9 ft.) in size. Each small pile was thoroughly mixed with a front-end loader and reduced into about a quarter of its initial size.
4. Material collected from each of the small piles were then mixed by creating another pile.
5. Mixing of this new pile was achieved by loading half of the pile from one side onto the front-end loader, rolling it over, and then repeating this procedure from the opposite side.
6. After mixing is completed, the pile was reduced to half of its size following the quartering method (per ASTM C702) and samples were obtained with a shovel.
7. The leftovers of the material from the 7 small piles were mixed to create a pile for field aging study

Samples were obtained and placed in sandbags and each bag was filled to weigh about 20 kg. Overall 65 bags of CHCC material obtained from the facility totaling about 1.3 tons of material. Additional information on the sampling procedure followed by the GMU team and documented photographs are available from authors upon request via email. This random selection procedure was followed throughout the whole study even when creating samples in the laboratory to produce representative samples for each test.



**Figure 1. Schematic Plan View for the Proposed Sampling Locations (Measurements in meter, Not to Scale)**

### **Virgin Aggregate (V.A.)**

Several material production quarries in northern Virginia, producing aggregate with VDOT 21 gradation specified in VDOT specifications Section 208, were visited and V.A. samples were collected for initial evaluations. Based on the geological source of the material, the V.A. aggregate from Chantilly Crushed Stone quarry was selected as the source rock of the aggregate is identified to be dominantly of diabase type. Diabase is known to include very stable minerals and is considered to be relatively inert in terms of chemical reactions compared to CHCC cement paste. V.A. material used in this research was systematically collected from this quarry and tested for its physical characteristics, chemical properties, and leaching behavior in the form of 100% V.A. and different blends of CHCC/V.A. as is discussed in following sections.

### **Nonwoven Geotextile**

The geotextile used in this study was nonwoven geotextile that satisfies the filtration design requirements for VDOT UD-4 edgedrain configuration (VDOT, 2008).

## **Mechanical and Index Properties**

The physical properties of collected freshly produced CHCC as well as V.A. material were evaluated by measuring the index and geotechnical properties of them. These properties include grain size analyses (in accordance to ASTM Standard D422), Specific gravity and water absorption of coarse and fine particles (in accordance to ASTM Standards C127 and C128 respectively), Atterberg limits (ASTM Standard D4318), and compaction characteristics using standard effort (per ASTM Standard D698).

## **Changes in Gradation of CHCC after Compaction**

In addition to the above characterization, part of the secondary objectives of this research focused on particularly evaluating the changes of gradation of CHCC after compaction. This evaluation was performed to understand the sensitivity of the CHCC to produce additional fines due to compaction. To investigate this, two pairs of identical CHCC samples were prepared with controlled gradation by sieving and remixing material with specific proportions. The first two specimens were used for grain size analyses before compaction and the other two were compacted using standard Proctor hammer (per ASTM D698) and vibratory hammer (per ASTM D7382) under unsaturated condition (moisture content close to corresponding optimum moisture). After compaction, the samples were sieved to determine grain size distribution and the results were compared to the initial gradation results.

## **Aging of CHCC**

As part of CHCC material characterization, an aging process was designed and conducted in this project. Understanding the changes in both the chemical and physical properties of CHCC was considered important in this study because based on the observations, it was determined that the majority of the CHCC produced in the Commonwealth of Virginia is stockpiled for some time before used in projects. The duration of the stockpiles generally appeared to be one year but there were exceptions where the produced material was depleted faster or much slower. To simulate the effects of stockpiling, two experimental approaches were taken in this study, as described in the subsequent sections. The samples produced from these aging procedures were then used to obtain samples to evaluate the changes in the physical and chemical properties of CHCC and to perform geochemical modeling to estimate the potential minerals within CHCC that may result in such leachate composition.

## **Laboratory Aging of CHCC**

The purpose of the laboratory aging procedure was to observe the changes in the controlled environment. There is no standard to age CHCC in the laboratory although there is a standard to evaluate the effect of wet/dry cycles on the soil-cement, changes in water content, and volume of the mixtures (ASTM D559). However, this standard is not designed to test the unbound aggregate or to enhance the carbonation process as it consists of cycles of soaking compacted material in tap water and oven-drying it. Moreover, the standard was discontinued in 2012 without any replacement. In this study, an aging procedure was developed in order to

simulate the effect of stockpiling on CHCC under field conditions (particularly observed in Virginia). The total amount of water applied over a one-year period, average room temperature and humidity, and the chemical composition of the water used to wet the CHCC were all selected based on the typical field conditions observed in northern Virginia.

Specifically, for the laboratory aging, a synthetic rainwater solution was created. This synthetic rainwater was developed based on the average of ion concentrations and pH of rainwater measured for the Commonwealth of Virginia as reported by the National Atmospheric Deposition Program (NADP, 2012). Table 1 depicts the reported concentrations of natural rain. Synthetic rainwater was produced by adding a specific amount of salts,  $\text{NaNO}_3$ ,  $\text{Na}_2\text{SO}_4$ ,  $\text{CaCl}_2$ ,  $\text{Ca}(\text{NO}_3)_2$ ,  $\text{K}_2\text{SO}_4$ ,  $\text{MgSO}_4$ , and  $(\text{NH}_4)_2\text{SO}_4$ , to obtain the same cation concentrations as shown in Table 1. The pH of the solution was considered acceptable at  $4.8 \pm 0.2$  and was adjusted by adding sulfuric, nitric, and hydrochloric acids.

**Table 1. The reported annual average of dissolved ion concentrations for natural rainwater in the Commonwealth of Virginia (after NADP, 2012)**

Cations	mg/L	Anions	mg/L
$\text{Na}^+$	0.1	$\text{Cl}^-$	0.2
$\text{Ca}^{2+}$	0.1	$\text{NO}_3^-$	0.6-0.75
$\text{K}^+$	0.03	$\text{SO}_4^{2-}$	1
$\text{Mg}^{2+}$	0.025	<b>pH</b>	4.8
$\text{NH}_4^+$	0.2-0.25		

The average humidity and temperature conditions in the laboratory were selected as  $80 \pm 5\%$  and  $18.3 \pm 2.8^\circ\text{C}$  respectively based on the 4-year average (from 8/1/2009 to 8/1/2013) of recorded high humidity and temperature from a weather station nearby where the field aging took place (Weather Underground, 2013). The carbonation rate is found to be at its maximum at a relative humidity of 40% to 80% in equilibrium with the pore moisture of concrete (Kurdowski, 2014), which is in agreement with the test condition established in this study. However, the main goal of the aging study was not to create an accelerated method to produce calcite or to achieve the highest carbonation degree, but rather to create a condition similar to what may happen in the field under natural conditions in a controlled environment, where certain variables could be kept constant, including humidity and temperature, and eliminating the effect of changes in many variables.

In order to simulate the rainfall events (wetting), CHCC was watered on a weekly basis using the synthetic rainwater creating a partially submerged condition for CHCC. The amount of water used was selected based on the monthly average of the total precipitation recorded at the same station for the same period of time. This procedure allowed CHCC to dry in about every 9-days, creating 39 wet/dry cycles in a year. From the aging procedure, CHCC samples were collected before the beginning of each wetting cycle to extract leachate to be used in chemical evaluations. Each sample for leachate extraction and chemical analysis was created by mixing samples from at least eight randomly selected locations within the CHCC pile. Also, CHCC samples were periodically collected to evaluate the changes in physical properties.

Laboratory aging tests started as soon as the CHCC samples were collected from the field. These were considered freshly produced CHCC as the samples collected from the field

stockpile was only about a week after the crushing operations. These aging tests were performed in GMU's ecology laboratory that is located on the rooftop of the science building constructed with glass rooftop to allow direct sunlight into the room and programmable temperature and humidity controls (Figure 2).

### Field Aging of CHCC

The purpose of the field aging procedure was to allow the CHCC to age naturally (not in a controlled environment) and be able to compare the results from the controlled environment to the results obtained from the field. This was thought to be an important step because although laboratory aging procedure was designed to simulate the natural aging under controlled condition, the condition in the laboratory is never exactly the same as in the field (for example the effect of freezing was not captured in the laboratory). Field aging was conducted with a stockpile of CHCC that was specifically created and left uncovered in the field. The material was exposed to every natural event that occurred within the year such as raining, sunlight, and freezing and thawing. CHCC samples were collected every month (about every 30-40 days) from this pile. In order to avoid the segregated material on the surface of the pile, all samples were collected from at least 30 cm (1 ft.) below the surface and then mixed and reduced to desired sample size to be used to obtain moisture content, pH, electric conductivity, and leached concentrations of elements. Although initial duration for field aging was set for 1 year (same as laboratory aging), it was decided to continue this procedure for another year based on the discrepancies observed during the first year. The pile was initially created in Luckstone facility but after a year transferred to the GMU campus and monitored for another year (Figure 3).



**Figure 2. GMU (a) ecology laboratory and (b) laboratory aging setup for CHCC**



**Figure 3. CHCC pile created for field aging process (a) as it is located at Luckstone facility, Centreville, Virginia and (b) after it is being transferred to GMU campus**

## **Material Chemical Properties and Leaching Behavior**

### **Leach Tests**

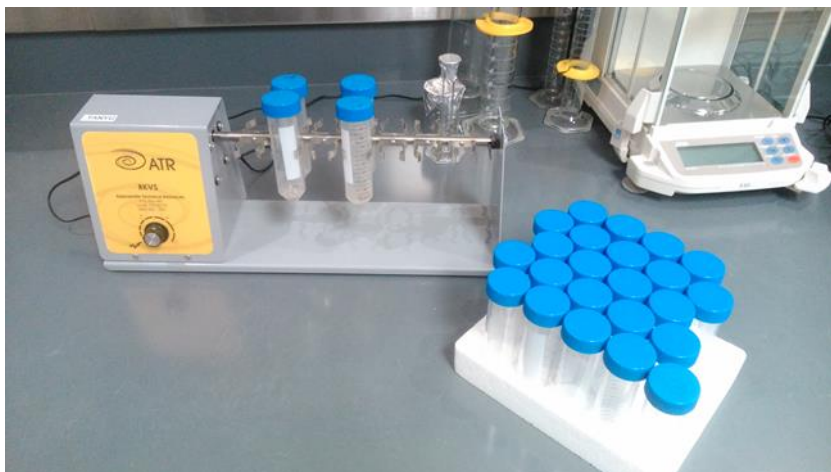
Periodically during the aging procedure, CHCC samples were collected both from the field and laboratory. The collected samples were used for chemical analyses and evaluation of the physical properties. The chemical analyses were performed both on solid particles and also through the leachate generated from CHCC. In order to generate leachate, two different methods were used: (1) a method based on 18-hour agitation time and (2) another method based on 5 minutes agitation time. Details of these methods are described below but the reason to evaluate these two different methods was to determine whether or not the shorter test method could be used for quick evaluations of CHCC stockpiles in the future if VDOT were to approve the use of CHCC to be used as base course aggregate.

#### *ASTM Batch Water Leach Test (WLT)*

This is a common test method used in many research studies to extract leachate from the batch of material and it is based on the procedures outlined in ASTM D3987. This test method was primarily used to extract leachate from the laboratory aging and in all cases duplicate leachate samples were extracted. Generating leachate from CHCC required solid samples to be air-dried and sieved through U.S. No. 4 sieve (4.75mm). Each specimen was weighed to  $2.50 \pm 0.01$ g and then placed in 50 ml plastic centrifuge tubes. ASTM type II de-ionized (DI) water was added to the samples with solid to liquid (S:L) ratio by mass of 1:20. For each test, 4 tubes were used to collect the desired amount of extracted leachate and samples were agitated at a rate of 29 rpm with a mechanical rotator for  $18\text{h} \pm 15\text{ min}$  (Figure 4). The liquid samples were set aside for 5 minutes before they were poured into a beaker and divided into two samples. Each beaker used in this process was acid washed and dried before usage. One of the samples was filtered through  $0.45\text{ }\mu\text{m}$  nylon filters using 60 ml plastic syringes. 50ml of the filtered sample was acidified to  $\text{pH} < 2$  using high-purity nitric acid solution ( $\text{HNO}_3$ ) and stored at  $4^\circ\text{C}$  for chemical analysis. The



second portion of the sample, unfiltered, was used for determining the pH, redox potential (Eh), and electric conductivity (EC).



**Figure 4. Apparatus needed to extract leachate following ASTM batch method**

#### *USGS Leach Test (USGSLT)*

Hageman (2007) described a quick method that is used by U.S. Geological Survey to extract leachate from solid waste and showed its usefulness in extracting leachate in the field from different varieties of soils and mine wastes to collect data such as pH, electrical conductivity, and leachate to determine element concentrations. In this study, the suitability of this method was evaluated as it provides an easy method with no need for specific laboratory equipment to extract leachate, especially when collecting samples in the field for example from the CHCC stockpiles.

For each test, a 50 g sample, air-dried and sieved through 19 mm ( $\frac{3}{4}$  in sieve), is added into a 1-liter plastic bottle with  $1000 \pm 0.5$  ml DI water (same S:L ratio of 1:20 as for WLT). Then the bottle is shaken vigorously by hand for 5 minutes and then set aside for 10 minutes (Figure 5). The leachate samples from this solution were created following the same procedure as for the WLT method (both filtered and unfiltered samples) and were set aside for chemical analyses and for evaluating the pH-Eh and EC.





**Figure 5. Apparatus needed to extract leachate following USGS method**

## **Chemical Analyses**

### *Solid Samples*

Chemical analyses included the evaluation of both the liquid and solid CHCC samples. Solid-phase analyses included the measurements of mortar and carbonate contents and mineralogy and elemental analyses were measured. Mortar content (MC) of CHCC particles was measured following acid treatment procedure (Akbarnezhad et al., 2013). For this measurement, CHCC samples were reduced to that material passing a 25.4 mm (1 in) sieve and retained on a 16 mm ( $\frac{5}{8}$  in) sieve. Each sample weighed about 250 g and was soaked in 250 mL of 3M HCl acid for 24 hours. After 24 hours, samples were washed, oven-dried and the weight of the particles larger than 2 mm (0.079 in) was recorded. Dissolved material and finer particles were considered as mortar content and taken into account by calculating the weight loss after each cycle. These cycles continued until the weight loss for each sample became less than 1% of the initial weight.

Solid CHCC samples were tested for carbonate content in accordance with ASTM D4373 (using dissolution in 1M hydrochloric acid in a sealed chamber and measuring the pressure changes due to CO<sub>2</sub> release) to evaluate the changes in carbonation over time during the laboratory aging process. Pure (100%) calcite was used to calibrate the chamber and the pressure gauge; therefore, the results were presented as “calcite equivalent”.

Mineral contents of solid samples were determined using Quantitative X-Ray diffraction (QXRD) analyses (in accordance with Bish and Post, 1993, and Raudsepp and Pani, 2003) and the elemental composition of the samples was determined using X-Ray Fluorescent analyses. These tests were performed at Electron-Microbeam/X-Ray Diffraction Facility of Department of Earth, Ocean & Atmospheric Sciences, the University of British Columbia located in Vancouver, Canada.

## *Liquid Samples*

The liquid phase analyses included measuring pH, redox potential (Eh), electric conductivity (EC), and total leached concentrations (TLC) of elements. The element concentrations in the leachates were measured via Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). pH-Eh and EC of the leachate solutions obtained from CHCC were measured using a pH and conductivity meter probes in GMU. Leached metal concentrations of major and minor elements were determined by a commercial laboratory (Bureau Veritas laboratories) located in Vancouver, Canada.

## **Geochemical Modeling**

The chemical analyses of the leachate results were used in geochemical modeling to determine the potential solid-phase precipitation. The analyses were performed in GMU using MINTEQA2 software. MINTEQA2 uses chemical equilibrium in solutions for water and calculates the existing species of elements by coupling multiple chemical (non-linear) equilibrium expressions with linear molar balance expressions and then solving them by minimizing the free energy of the system. Additional details regarding the MINTEQA2 geochemical modeling analysis method can be obtained from (Allison et al., 1991). Geochemical modeling was performed using TLC of elements as well as recorded pH-Eh-EC as input parameters, which were obtained from WLTs and USGSLTs.

## **Mechanical and Index Properties**

The changes in the physical properties of CHCC with aging was evaluated by measuring the index and geotechnical properties of freshly produced CHCC as well as aged material after 12 months. These properties include grain size analyses (in accordance to ASTM Standard D422), Specific gravity and water absorption of coarse and fine particles (in accordance to ASTM Standards C127 and C128 respectively), Atterberg limits (ASTM Standard D4318), and compaction characteristics using standard effort (per ASTM Standard D698).

## **Potential of CHCC to Clog the Geotextile Used in VDOT Drainage Systems**

The most commonly accepted laboratory method to determine the permeability of the soil-geotextile systems is based on what is referred to in the literature as the Gradient Ratio (GR) test. The GR test setup was initially developed by the U.S. Corps of Army Corps of Engineers (USACE) in 1972 (Calhoun, 1972). The apparatus was designed based on the same concept as the constant head permeability test, but the chamber was modified to evaluate the soil-geotextile filter interaction under constant head flow conditions. A schematic drawing of a gradient ratio test setup that is used to-date depicted in Figure 6.

The setup consists of three chambers. The top chamber is connected to the constant head inlet reservoir. The pressure head inside this chamber is monitored by a manometer connected to this chamber (i.e., referred to as U manometer). The middle chamber is the space that soil sample (CHCC material in this case) is placed over the geotextile fabric and both soil and geotextile

samples are secured in place using a metal screen on top and bottom of the specimen. The pressure head in the soil specimen is measured using manometers placed in two levels. Two manometers are located at 75 mm (3 in) above the bottom screen (i.e., referred to as A manometers) and two manometers at 25 mm (1 in) above the bottom screen (i.e., referred to as B manometers). The bottom chamber, in a similar way as the upper chamber, is connected to a constant head outlet reservoir and the pressure head in this chamber is monitored using the D manometer.

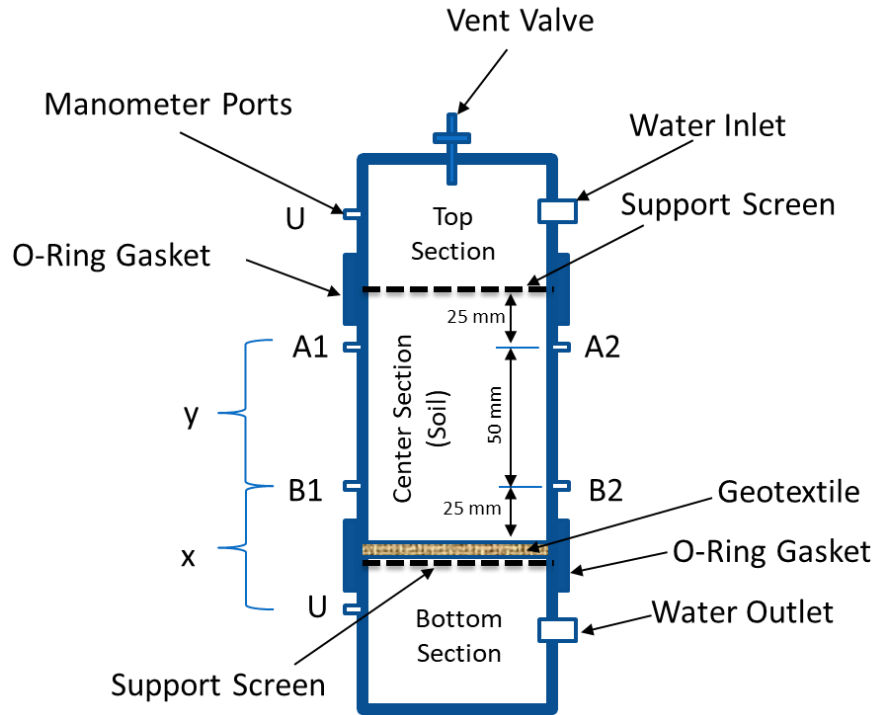


Figure 6. Schematic setup of the gradient ratio test chamber (modified after Fischer et al., 1999)

The differences between pressure readings in manometers A and B, within 50 mm (2 in) soil layer in middle section) represents the flow gradient of the pure soil and the differences in pressure head between manometers B and D represents the flow gradient of the soil plus geotextile and the ratio between these gradients is a criterion to evaluate clogging (Equation. 1).

$$GR = \text{Gradient } x / \text{Gradient } y \quad (\text{Eq. 1})$$

Gradient ratio shows the ratio between the pressure head loss within the soil only (hydraulic gradient in soil) and the pressure head loss in soil/geotextile layer (hydraulic gradient in soil/geotextile). Theoretically, the pressure head loss within the soil layer and soil/geotextile layer should be equal (or within an acceptable range) if clogging of the geotextile (fully or partially) does not occur during filtration. ASTM in 1990 established a standard (ASTM D5101) as a procedure to evaluate the soil-geotextile clogging potential for soils with a plasticity index less than 5. According to this ASTM standard, GR equal to or slightly higher than one is an acceptable performance for any geotextiles. Fannin et al. (1994) evaluated several factors affecting the GR test results on the clogging potential of gravelly and sandy soils on nonwoven

geotextiles (needle-punched and heat bonded) and confirmed the suitability of this method to use for clogging evaluation of granular soil with nonwoven geotextile.

Aydilek and Edil (2002, 2003) evaluated the filtration performance of wastewater treatment sludge in the laboratory and in the field using different woven and nonwoven geotextiles with apparent opening size (AOS) varying from 0.15 mm (0.006 in) to 0.664 mm (0.026 in). For comparison, these geotextiles were also tested with silty sand having the same particle size distribution as the sludge. Permittivity tests and image analyses were performed on the geotextile samples before and after the GR tests. The researchers showed that the GR criterion set forth before has certain limitations when used as an indication for clogging and proposed a new approach called permeability ratio ( $K_R$ ) to evaluate the clogging potential. The advantage of the using of  $K_R$  value over GR is that the permeabilities of the whole system and the soil layer are taken into account in  $K_R$  calculations. They concluded that a  $K_R$  value up to 3 is an acceptable filtration performance of soil and geotextile. Permeability ratio is defined (as in Equation 2) as the ratio between the calculated permeability of soil within middle 50 mm (2 in) of the center chamber and the calculated permeability of the whole system, which includes soil and geotextile.

$$K_R = k_{soil} / k_{system} \quad (\text{Eq. 2})$$

where  $k_{soil}$  and  $k_{system}$  are computed as equations 3 and 4:

$$k_{soil} = QL_1 / Ath_{(A-B)} \quad (\text{Eq. 3})$$

$$k_{system} = QL_2 / Ath_{(U-D)} \quad (\text{Eq. 4})$$

where:

- $Q$  = quantity of water discharged,
- $L_1$  = distance between manometers A and B (50mm),
- $L_2$  = overall length of the specimen,
- $A$  = cross-sectional area of the specimen,
- $t$  = total time of discharge,
- $h_{(A-B)}$  = difference in the head on manometers A and B.
- $h_{(U-D)}$  = difference in the head on manometers U and D.

Consistent with the previous researchers, the hydraulic properties of the material used in this study were evaluated using constant head apparatus in accordance with ASTM Standard D2434. The filtration performance of CHCC and geotextile was evaluated in this study using GR tests per ASTM D5101. Chambers used in this research had a diameter of 15.24 cm (6 in) and the specimen's height was 10 cm (4 in). Five chambers were set up for this program in GMU's Sustainable Geotransportation Infrastructure (SGI) laboratory. The water passed through the sample discharges out to the faucet located at the ground (not circulated back into the sample). Before starting the actual tests, the measurements were calibrated with no soil specimen in them to measure the head loss within the hoses, fittings, and the chamber itself. Preliminary experiments showed that this procedure is suitable to evaluate the clogging phenomena associated with the use of CHCC adjacent to geotextile.

The GR tests performed in this study had some deviations from the ASTM procedure. These deviations include the maximum particle sizes of the specimen, duration of tests, and the maximum applied hydraulic heads for each test. The maximum particle size of 19 mm (U.S.  $\frac{3}{4}$  in sieve) was selected for GR tests based on the maximum particle sizes suggested in ASTM D2434 (not ASTM D5101) in order to avoid any need for correction factors suggested by ASTM standards for different oversize particle diameters. This ensured having consistency in sample properties and preparation between compaction, permeability, and GR tests. ASTM D5101 suggests the duration of tests for applied hydraulic gradients ( $i$ ) of 1, 2.5, and 5, to be 48 hours, 2 hours, and 46 hours respectively. Our initial tests proved that these durations are not long enough for the system to reach flow stability. Therefore, all of the tests at any applied hydraulic gradient were continued until stability was achieved by the outflow discharge (system permeability), manometer readings, and permeability ratios as described by Abbaspour et al. (2018). The criteria for stability was set as the absolute fluctuation difference less than 10% for any of the mentioned values in comparison to the average of the last five consecutive readings. This deviation made the tests much longer than what was suggested in ASTM. The maximum applied gradient was set to 5 as opposed to 10 that is suggested by the ASTM standard. This was done to keep the tests completed within a reasonable time frame ( $\sim$  less than 3 months per test) and  $i > 5$  was not of any interest for current research purposes. Considering the investigated application (road base/subbase), the applied gradient of 1 is considered as the typical gradient (Luettich et al., 1992) and gradient higher than this value is highly unlikely to occur unless the road structure is totally inundated.

After each test, soil samples were exhumed from the center chamber and divided into 4 different thicknesses: (i) 25 mm (1 in) layer from the top, (ii) middle 50 mm (2 in) layer immediately below the top layer, (iii) 6 mm (0.24 in) layer in the bottom immediately placed over geotextile, and (iv) a middle 19 mm (0.76 in) between the 6 mm and 50 mm layers. These layers were analyzed for any noticeable change in grain size distribution. Geotextile used in the tests were air-dried after each test and preserved for further analysis. From these geotextiles, selected samples were sent for thin sectioning and image analysis in order to determine the reduction in pore size distribution ( $R_{PSD}$ ) after filtration (in accordance with the procedures developed by (Aydilek et al., 2002). Remaining of the geotextile samples were used to determine the reduction in their permittivity ( $R_{\psi}$ ) after the test. The permittivity of geotextile samples was evaluated following ASTM D4491 procedure.

The testing program for filtration performance included three main stages:

In the first stage, freshly produced CHCC was aged in the laboratory and samples of freshly produced and 4, 9 and 12 months old were used in the GR tests. All CHCC was tested in GR chambers based on their as-is gradation (without oversize particle). Also, one V.A. sample (with as-is gradation) and one coarse fractionated CHCC sample (larger than 4.76 mm or Number 4 sieve) were tested. All samples were compacted to 95% of maximum dry density achieved by standard effort (per ASTM D698). Duplicate and triplicate tests were conducted on all of the as-is CHCC/geotextile and VA/geotextile samples but not for coarse fraction CHCC. V.A. tests were used as a control and a coarse fractionated CHCC test was used as a comparison because it had no fines and consequently was not expected to show any signs of particle migration. A total of 14 tests were conducted at this stage.

In the second stage, a parametric study was conducted in order to evaluate the effects of varying fines content ( $<75\ \mu\text{m}$ ) and relative compaction (RC) during the preparation of the samples. In these tests, RC was varied from 95% to 100%. Virgin aggregate samples were prepared with controlled gradation close to VDOT base/subbase unbound 21 aggregate but fines content percentage ( $<75\ \mu\text{m}$ ) varying between 5%, 7.7%, 9%, 11%, and 13%. Fines content of 7.7% was included in the testing program because this percentage creates an almost identical gradation as as-is CHCC. This allowed the comparison of the CHCC results directly with V.A. results. Triplicate tests (third repeat tests) were conducted only if it was found necessary. A total of 13 tests were conducted at this stage.

In the third stage, different blends of CHCC and V.A. was prepared with the gradation similar to as-is CHCC (7.7% fines,  $<75\ \mu\text{m}$ ). The percentages (by weight) used for these samples are determined based on recommendations of VDOT TRP members as:

- Blend 1: 10%CHCC +90% V.A.
- Blend 2: 20%CHCC +80% V.A.
- Blend 3: 40%CHCC +60% V.A.

A total of 3 tests were conducted for the final stage of filtration tests. The CHCC material that was used for this stage was freshly produced CHCC which was air-dried, bagged and preserved. This material did not experience the wet/dry cycles.

## **RESULTS AND DISCUSSION**

### **Literature Review**

Past studies on CHCC used as unbound base/subbase material focus on three main issues: property changes during stockpiling, chemical leaching and precipitation, and clogging of drainage systems. These are discussed below along with a number of case studies.

#### **Changes in CHCC Properties Due to Stockpiling Before Usage**

CHCC is typically produced either in-place at the job site to be re-used at that particular project or demolished concrete is hauled to a plant from different sources and broken into specific gradation and stored until it is sold. The time it takes to sell all of the produced CHCC is a function of the supply and demand balance in a given area. If there is a potential to use CHCC in a major construction project, the quarry owners will have to start producing the CHCC several months in advance and sometimes even a year or so in order to produce the quantity so that when the construction operation starts they are not short of supply to hinder the project deadlines. It is not very common but there are also stockpiles of CHCC found in some quarries in Virginia that are more than 10 years or older. When CHCC is produced and stored at a stockpile, it is exposed to atmospheric conditions such as rain and excessive heat and the frequent wetting and drying of the material may have an effect on the leaching composition (and in colder regions, freezing and

thawing may also have an effect). It is known that several degradation mechanisms are working on Portland cement concrete and its by-products from the time the concrete is molded until its initial service life and afterward (Kurdowski, 2014; Roy, 1986; Taylor, 1997).

Although several researchers looked at changes in one or a few particular properties of CHCC with time, changes in chemical properties and leaching behavior of CHCC with aging under field conditions and effects of acting degradation mechanisms have not been studied in the past. Sadecki et al. (1996), reported findings of a study where three different stockpiles were constructed in a field in Shakopee, MN and the leachate collected from these stockpiles were evaluated and monitored over a one-year time period. The stockpiles in this study were constructed with (1) coarse-grained CHCC, passing 19mm sieve( $\frac{3}{4}$  in), and retained on 4.75mm sieve (0.187 in), (2) fine-grained CHCC, 100% passing number 4 sieve, and (3) dense-graded recycled asphalt pavement (RAP). The parameters monitored from the leachate included but were not limited to, pH, conductivity, suspended solids, volatile solids, alkalinity and leaching of calcium, magnesium and alkali elements and heavy metals. The stockpiles were constructed over polyethylene sheets to help to collect all runoffs. Chemical analysis showed a decrease in pH of leachate for both CHCC stockpiles over time (from 10.5 to 9.7 for coarse CHCC and from pH around 12 to 9.5 for fine CHCC). No trends were observed for leaching the alkali elements and total solids in the collected effluent. Statistical analysis showed that for recycled concrete piles, there was no correlation between the concentration of total dissolved solids (TDS) and the amount of rain at each event. However, leaching of heavy metals and magnesium (as mean value) from coarse CHCC was observed to be generally higher than fine CHCC and leaching of calcium was observed to be higher for fine CHCC rather than coarse CHCC.

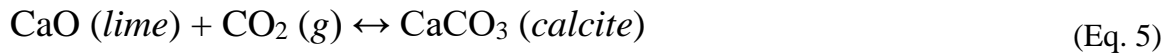
Steffes (1999) conducted leaching tests by allowing distilled water to flow through a box containing CHCC material periodically and letting the material to dry after each cycle. The pH values of the water collected from the boxes were recorded on a weekly basis for one year. Results of the tests showed that pH values of the water collected from the CHCC boxes rose to the range of 12.5, and then gradually decreased and leveled at around 11.5 at the end of the tests after one year. Although considerable amounts of deposited material were observed around the outlet holes of the boxes, the researchers did not record (or report) the chemical composition of the leachate and the depositions. Decrease in pH of leachate and changes in leaching concentration of different elements from CHCC material undergoing aging was also reported by several other researchers and these changes were attributed, in general, to occurrence of the carbonation in the CHCC (van der Sloot, 2000; Engelsen et al., 2012; Chen et al., 2013).

Another aspect of the leaching behavior of CHCC such as pH-dependent leach of elements, which were done in adjusted pH conditions, has been studied extensively in the past (Engelsen et al., 2009, 2010; Chen et al., 2012, 2013). However, the information regarding the changes in chemical properties and leaching behavior of CHCC with time was not comprehensive enough to investigate the effects of aging and degradation process (e.g. carbonation) and none of these studies provided measurements on changes in carbonate content of CHCC. This is most likely because either the objectives of those studies were not necessarily to investigate the carbonation effect or CHCC was not being tested for aging conditions reflecting actual field conditions.

Carbonation is one of the on-going degradation processes acting on cement paste and concrete. An outer layer of carbonated material is developed in the hardened concrete in contact with atmospheric carbon dioxide, which has a lower pH than the uncarbonated cement paste (Roy, 1986). When CHCC is produced and stored at a stockpile before being consumed in projects, it is exposed to atmospheric conditions such as rain. Wetting and drying cycles during stockpiling may enhance the carbonation process and have an effect on the leaching composition of CHCC (Silva et al., 2015). Kitamura et al. (2015) showed that leaching behavior and element mobility of waste material (i.e. fly ash) may be affected by the precipitate formation of the secondary mineral especially under wet conditions when this secondary mineral is sparingly soluble (such as gypsum). Therefore, understanding the changes in the chemical properties of CHCC (aging) within a time period that is realistic (such as a year) is of great importance for geotechnical, material, and environmental engineers.

### **Effect of Chemical Properties and Leached Ions on Precipitation of Tufa**

The calcite precipitation potential from CHCC is mainly attributed to the existing of free lime (CaO) in CHCC cement paste (Gupta and Kneller, 1993; Tamirisa, 1993; Snyder, 1995; Snyder and Bruinsma, 1996; Gupta and Dollimore, 2002). This assumption is based on findings from an earlier study on the weathering effect of slags and the occurrence of tufa formation from base layers containing steel slag aggregate (Narita et al., 1978). Free lime (CaO) is one of the components of the un-hydrated Portland cement and it is known that it can be transformed into calcite in presence of carbon dioxide as shown in Equation 5 below (Langmuir, 1997).



However, the CaO content of the hydrated cement paste is a matter of question. Based on these assumptions, Tamirisa 1993, measured the free lime content of CHCC and steel slag samples by using the ethylene glycol test (Sugar test) and found out that the free lime content of the CHCC samples is much less than 1% (0.375% or less). Gupta and Kneller (1993), measured the free lime content of two CHCC samples collected from different quarries in Ohio by using the Ethylene Glycol method and compared it to the leached calcium concentrations from the same CHCC samples and other steel slag samples. Free lime was only detected from one of the two CHCC samples and its quantity was measured as less than 1%. Whereas, the free lime content of steel slag aggregates investigated in this research ranged from 4% to 25% by weight. In a more recent study, Gupta and Dollimore (2002) also measured and compared the amount of free lime in the CHCC samples using the same analytical Ethylene Glycol test method and confirmed the absence or very low amount of free lime in the solid samples (only one sample out of 44 showed free lime content higher than 1%). These previous research investigations confirm that although existing of free lime may be an indicator of the potential precipitation of tufaceous material from steel slag, it is neither the main source of leached calcium ion from CHCC material nor an indication for precipitation of such constituents from CHCC.

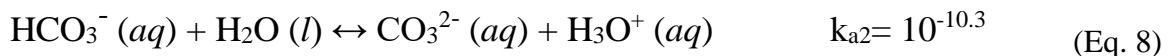
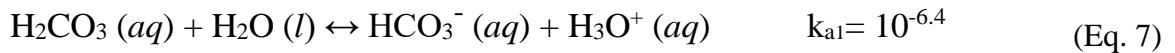
It is known that any kind of solid-water interaction phenomena at the interface, e.g. adsorption, dissolution, precipitation, nucleation, and crystal growth, are dependent on the activity of the existing ions in solution and related kinetics (Stumm and Morgan, 1996; Sparks, 2003). Therefore, evaluating the activity of calcium and carbonate ions in solution are



determinative in order to understand carbonate chemistry and any carbonate-based precipitate potential (Stumm and Morgan, 1996; Drever, 1997; Langmuir, 1997). However, the leaching behavior of CHCC is not limited to the calcium-based compounds and leaching of other elements (Major, minor or trace) can have a noticeable contribution to the solid phase precipitation from CHCC leachate (Engelsen et al., 2006). Although the X-Ray diffraction (XRD) tests conducted on collected tufaceous depositions from highway underdrains show that these depositions consist of mainly calcite, the same results show that existing of other carbonate species such as dolomite is also noticeable (Gupta and Kneller, 1993; Tamirisa, 1993). The co-existence and stability of any of these species are dependent on the leached concentration of major elements (i.e. Ca, Mg) and the thermodynamic condition of the environment (Drever, 1997). Considering these observations and based on an analytical work by Drever (1997), the ratio between concentrations of magnesium (Mg) and calcium (Ca) ions,  $C_{Mg^{2+}}/C_{Ca^{2+}}$ , (also the ratio between activities of same ions,  $\alpha_{Mg^{2+}}/\alpha_{Ca^{2+}}$ ) is assumed to be another affecting parameter in calcite precipitation potential from CHCC (Gupta and Kneller, 1993; Tamirisa, 1993; Snyder, 1995; Song et al., 2011, Nam et al., 2014).

However, the analytical calculations provided by Drever (1997) are related to thermodynamic equilibrium for the alteration of calcite or aragonite to form dolomite in natural water depositions by comparing the ion activity for Ca and Mg cations in the solution and not related to the potential of calcite formation. Based on his calculations, Drever (1997) suggested that for  $\alpha_{Mg^{2+}}/\alpha_{Ca^{2+}}$  ratio (the activity of  $Mg^{2+}$  divided by the activity of  $Ca^{2+}$ ) higher than 0.6, dolomite is more stable than calcite. Although researcher mentioned that there is a noticeable controversy associated with this number especially because “dolomite is very unreactive at low temperatures and it is almost impossible to make dolomite grow in the laboratory, he concluded that most probably “calcite is unstable with respect to dolomite where the ratio  $\alpha_{Mg^{2+}}/\alpha_{Ca^{2+}}$  is higher than 1. Based on the definition provided by Drever (1997) for the calcite/dolomite stability calculations, it seems that this parameter (concentration or activity ratio of Mg and Ca ions) is not an indication for precipitation of calcite from CHCC material either.

In an attempt to explain the formation of calcium carbonate precipitation in road drainage systems constructed using CHCC base aggregate, Bruinsma et al. (1997) developed a chemical model based on existing carbonate chemistry in natural waters (Stumm and Morgan, 1996; Drever, 1997; Langmuir, 1997) and suggested equations to explain the pH condition at each step (See Equations 6 thru 11). In this model, the main source of calcium ion in CHCC leachate is assumed to be portlandite [ $Ca(OH)_2$ ], which is a byproduct of cement hydration. The rainwater in equilibrium with the atmosphere has a pH of less than 7. The acidic source of the rainwater is the dissolution of the atmospheric carbon dioxide ( $CO_2$ ) in the rainwater and formation of carbonic acid and bicarbonate. The theoretically calculated pH of rainwater equilibrated only with  $CO_2$  gas under atmospheric partial pressure condition is 5.7 (Stumm and Morgan, 1996).



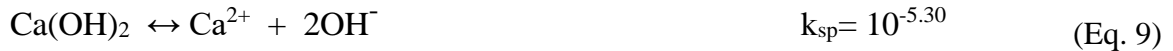
where:  $\text{H}_2\text{CO}_3$ : carbonic acid

$\text{HCO}_3^-$  : bicarbonate ion

$\text{H}_3\text{O}^+$ : hydronium ion

$\text{CO}_3^{2-}$  : carbonate ion

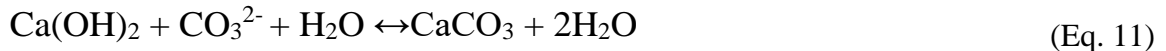
Based on the model described by Bruinsma et al. (1997), the slightly acidic rainwater percolates through the pavement of the road section into the CHCC base layer. At this stage, the existing portlandite in the CHCC material dissolves into the base layer pore water and dissociates into calcium and hydroxide ions (Equation 9).



The system where the water percolates through within the base layer is assumed to be closed to atmospheric carbon dioxide because of the pavement structure and the equilibrium pH of the system using portlandite solubility and thermodynamic relationships for the Ca-H<sub>2</sub>O-CO<sub>2</sub> system is calculated as 11.75. Once the leachate infiltrates through the CHCC layer and reaches to the drainage system, it gets in contact with the atmospheric CO<sub>2</sub> source because the drainage system is connected to the atmosphere and partial pressure of the CO<sub>2</sub> ( $P_{\text{CO}_2}$ ) is again fixed at  $10^{-3.5}$  (which is the partial pressure of the CO<sub>2</sub> in the atmosphere). At this stage, the produced carbonic acid reacts with the leachate, which is mainly a weak base solution containing calcium hydroxide (Weak Acid-Weak Base reaction) and forms the calcium carbonate (CaCO<sub>3</sub>) (Equation 10).



When equations 6 to 10 are combined, the precipitation of calcite can be described as equation 11.



The production of calcium carbonate (calcite) causes a reduction in the concentration of carbonic acid and based on Le Chatelier's law, the CO<sub>2</sub>- H<sub>2</sub>O equation (Equation 6) proceeds towards the right side (production of carbonic acid). This allows the continuous formation of calcium carbonate in the drainage systems. Calcite is poorly soluble in pure water and its solubility is pH-dependent (Stumm and Morgan, 1996). At this stage, if the solution becomes supersaturated with respect to calcite, precipitation occurs in the drains and the pH of solution drops to 8.3. The calculated pH conditions from this model are in good agreement with the previous findings of other researchers as noted by Muethel (1989) and Tamirisa (1993). In this 1997 model, it is assumed that (a) each step is long enough to achieve equilibrium, (b) standard condition exist at every step ( $T=25^\circ\text{C}$  and  $P=1\text{bar}$ ), (c) no other constituent participates in dissolution/precipitation process, (d) the  $P_{\text{CO}_2}$  in the underdrain is equal to the atmospheric  $P_{\text{CO}_2}$ . Although there are several assumptions and simplifications accompanying these equations, this model gives an insight view and understanding of the possible condition in an underdrain when CHCC is used as the base material. However, this model also has limitations. It does not 100%

predict tufaceous precipitation and also does not give any idea about solid form of precipitation (amorphous/crystalline), exact place of the deposition (within the filter fabric, within the perforated pipe, in the outlet, etc.), crystallization rate, and adherence probability of such deposition into fabric filaments.

As a summary, it is accepted that calcite precipitation is a function of ion activities in the solution as well as pH conditions, temperature, and  $P_{CO_2}$  (Langmuir, 1997). Also, the process that leads to the precipitate formation of a particular mineral should thermodynamically be in favor of nucleation and formation of such mineral (Drever, 1997). Ignoring these factors may lead to an unrealistic determination of precipitation potential. These factors are most probably responsible for the different observations by the researchers over the years in terms of variations in tufa depositions from different CHCC sites.

### **Potential of CHCC to Clog the Geotextile Used in Drainage Systems**

The previous studies were based on soaking the exhumed geotextiles that have been in contact with CHCC into an acid solution and based on the observations that the remnants on the geotextile to react with acid, conclusions were made that the calcium-based compounds were precipitating from CHCC. This observation by itself is not enough to prove that chemical precipitation occurs. There are possibly two different mechanisms that may result in the clogging of geotextile. These mechanisms may work independently or together.

1. **Migration of fines:** As for the V.A., the CHCC also contains particles that range in size. Under hydrodynamic flow pressure, these particles may migrate and some of the particles will pass through the geotextile and some may be entrapped over the surface. If the abundance of particles gets entrapped, this may result in clogging of the geotextile openings resulting in what is referred to as physical phenomena.
2. **Precipitation of compounds:** Based on the equilibrium chemistry described by Bruinsma et al. (1997) (as described previously), there is a potential that calcite may precipitate from CHCC. If this occurs and if it continues to occur over time, the abundance of precipitated calcite may clog the openings of the geotextile resulting in what is referred to as chemical phenomena.

Differentiating between the chemical and physical phenomena cannot be achieved by simply soaking the geotextiles in acid solutions because in both cases the particles may be reactive to acid as they all come from the CHCC. Therefore, this is a complex problem. Based on Bruinsma et al. (1997) model, in order to precipitate calcite, the system requires atmospheric carbon dioxide, however, tests that are open to atmospheric conditions do not provide enough evidence in terms of being able to determine a true reduction in permeability. This is because, by definition, permeability is measured under saturated conditions. In this study, when the proposal for the research was written, the proposed approach was based on first conducting aging procedure in the laboratory to allow any chemical phenomena to take place and then obtaining samples from the aged CHCC to perform hydraulic conductivity tests to capture the effects of physical phenomena (and the effects of previously occurred chemical phenomena). One of the observations in this study showed that the grain size distribution of the CHCC slightly changed

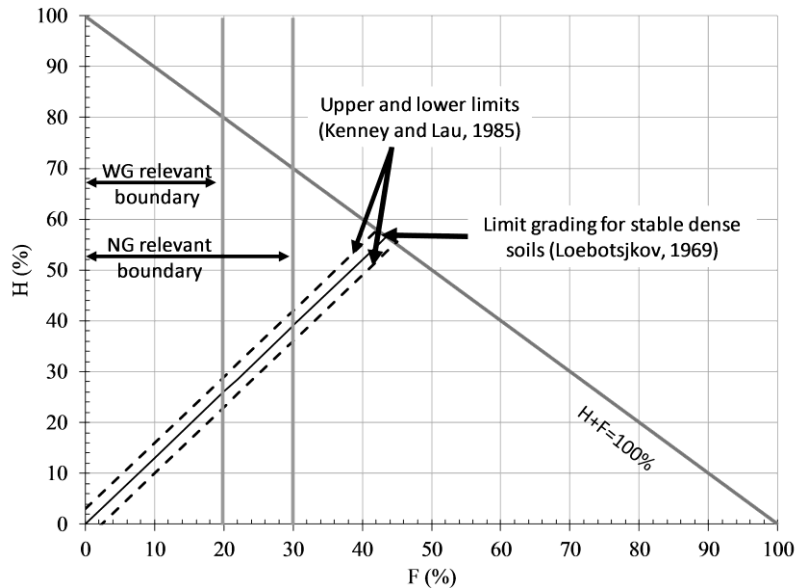
with aging. The potential effect of this change is certainly captured in the clogging evaluation tests performed in this study.

### *Internal Stability of Unbound Base Layer*

Internal stability of soils is particularly dependent on the likelihood of the fines within the soil skeleton to move. This phenomenon is referred to as suffosion and depending on the magnitude it can initiate and result in the clogging of the geotextile (Kenney et al., 1985; Kenney and Lau, 1985; Lafleur et al., 1989; Luettich et al., 1992).

Minor suffosion can lead to the formation of a stable soil structure (Lafleur et al., 1989); however, the occurrence of major suffosion may lead to internal erosion and piping (Schober and Teindl, 1979). Lafleur et al. (1989) explained the self-filtration process that occurs during the downward flow in the internally stable soils. In this process, the soil reaches a stable base-filter system after a minor loss of fines. Based on the self-filtration concept, Lafleur et al. (1989) classified the internally stable and unstable soils into three categories using their grain size distribution. Based on his classification, linearly graded soils are considered as internally stable. However, gap-graded aggregate and soils with upward concave gradation are susceptible to internal instability and erosion. Kenney and Lau (1985) suggested a graphical analysis in order to evaluate the internal stability of the soils under seepage forces. In addition to predicting the occurrence of internal erosion (e.g. piping) in filtered soils, the evaluation of internal stability is even more important when there is geotextile used as filter fabric in sub-drains and side-drains. This is because the occurrence of fines migration (suffosion) may lead to deposition of the migrated particles over or within geotextile filaments. Consequently, this phenomenon may lead to blinding and/or clogging of the geotextile and loss of its filtration performance.

An example of evaluating the susceptibility of a soil to be internally unstable suggested by Kenney and Lau (1985) is demonstrated in Figure 7. This graph is created by plotting the percent fines from grain size diagram ( $F$  - horizontal axes) and the difference between the four times the particle diameter size ( $4D$ ) and the particle diameter size ( $D$ ) corresponding to each percent fines content ( $H = F_{4D}\% - F_D\%$  - vertical axes). The drawn diagonal line indicates the suggested boundary by Kenney and Lau (1985) between stable and unstable soils, which describes the required minimum value of  $H$  for stable gradation. Soils that their relevant portion of grading fall below this boundary is prone to suffosion in certain particle sizes. These ranges of relevant particle sizes are defined for two types of gradation, widely graded (WG) with shape factor,  $C_u$  greater than 3 and narrowly graded (NG) with  $C_u < 3$ .



**Figure 7. Graphical analysis of suffusion**

### *Clogging of Drainage Systems (with or without Geotextiles) Adjacent to CHCC*

The following section summarizes the case studies where the performance of the drainage systems components (with or without the existence of filter geotextile) in adjacent with CHCC material were evaluated and reported. In all of these cases, tufaceous depositions were observed in or around the outlet of drains or in basins constructed near the drain outlets.

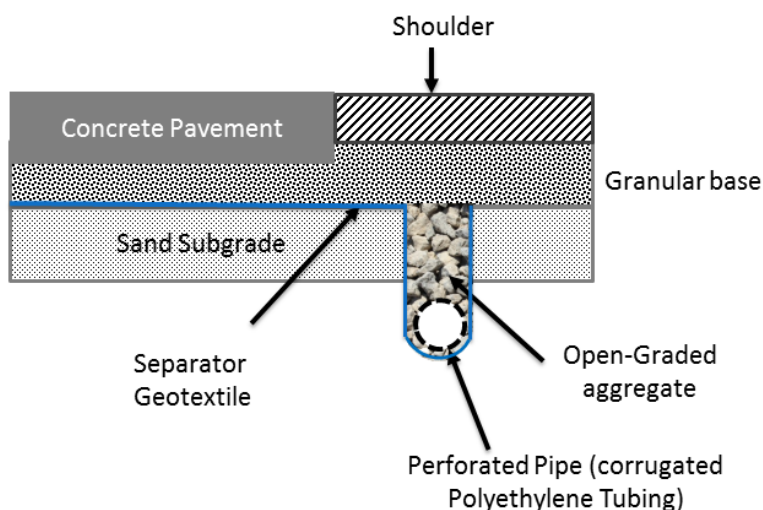
#### *Case study from Ohio: I-75 highway*

The majority of the case studies from Ohio are based on the use of steel slag as base/subbase aggregate and in all of these studies deposition of tufaceous material and major geotechnical problems were reported (Feldmann et al., 1982; Gupta and Kneller, 1993; Tamirisa, 1993). Only one case study is mentioned in the literature regarding the use of CHCC in Ohio and at that site, no major problems were reported although deposition of tufaceous material was observed (Gupta and Kneller, 1993; Tamirisa, 1993). The case study with CHCC is reported to be part of the reconstruction project as part of I-75 within Hancock County located around Findley, OH. CHCC at this site was used to construct the subbase although information regarding the type of pavement and drainage system constructed at this particular site is not provided. A typical cross-section for interstate highways in northern Ohio involves 25 cm (10 in) of a rigid pavement (Portland cement concrete, PCC) over 15 cm (6 in) of subbase; therefore, it may be assumed that the thickness of the CHCC at I-75 was most likely at least 15 cm (6 in). The typical drainage system under the road shoulder consists of 15cm (6 in diameter) perforated pipe overlain by coarse aggregate both of which are placed in the 75 cm (2.5 ft.) deep trench (Feldmann et al., 1982). As part of the research at the site with CHCC subbase, Gupta and Kneller (1993) and Tamirisa (1993) collected two samples from particles that appear to be tufaceous deposits located around the drain outlets and analyzed their chemical composition. Based on the evaluation, the samples consisted of 25 and 34% (by weight) of insoluble residue (ISR) and 52 and 61% of calcite. Although no information about the chemical composition of the coarse aggregate used in the drainage system was reported, assuming that the aggregate was not

calcareous, the finding of 50 to 60% calcite content on collected samples indicate that the particles observed at the drain outlets were coming from CHCC. In conclusion, researchers did not recommend that the use of CHCC should be abandoned.

I-94 test sections near Galesburg, Michigan, U.S.A.

Hansen (1995) reviewed the pavement performance of two test sections in the I-94 highway near Galesburg, Michigan which was constructed in 1985 and 1986 (M-10). All sections were constructed identical with open-graded aggregate gradation per MDOT (2012), with less than 3% finer than 75  $\mu\text{m}$  (passing number 200 sieve), but the westbound sections were constructed with CHCC and the eastbound sections were constructed using virgin aggregate (V.A.). The geological rock type of V.A. and CHCC were not defined in this report. A typical cross-section of the constructed sections is depicted in Figure 8.



**Figure 8. Typical cross-section of I-94 highway constructed in 1985-86 (modified after Hansen 1995)**

A field investigation of underdrain outlets revealed that at one of the four sections constructed with CHCC the drain outlets were totally clogged (no flow) and at the other two sections, they were partially functional (partially clogged). The outlets of the V.A. sections did not show any signs of clogging. Based on this observation, the researchers stated that CHCC sections clogged due to tufaceous precipitate deposition. However, the condition of the pavement with the CHCC drainage section was described as excellent after 10 years of service and the sections of the pavement with the V.A. drainage section required a total replacement. This observation was attributed to a better physical performance of CHCC with respect to the used V.A. Although in the study the researchers mentioned that the perforated pipe in the underdrain system was wrapped with geotextile, no evaluation of geotextile filtration performance was conducted in the study.

According to Federal Highway Administration (FHWA, 2003), Michigan DOT has constructed roadways since 1983 using CHCC in different projects listed as M-10, I-75, I-94 (mentioned above), I-95, I-96, US-41, and two other projects in Detroit Metro region. CHCC was used at these sites; however, no information was provided in FHWA's report regarding the performance of possible drainage systems constructed at these projects. Since the FHWA report

does not include any issue encountered as direct use of CHCC in base/subbase layers, it may be assumed that the performance of these sections was satisfactory.

#### Case studies from Iowa: I-29/I-35/I-80/US-151 highways

Several interstate and local highway sections were constructed using CHCC and blends of CHCC and virgin aggregate in Iowa since the early 1990s (Ceylan et al. 2013). The observation of tufa deposits in the outlets of the underdrains in Iowa was first reported by Steffes (1999). In recent years, Iowa DOT conducted an extensive drainage outlet monitoring program and published the results in two phases in 2013 and 2015 (Ceylan et al., 2015, 2013; Kim et al., 2016). A summary of information about the highway sections with CHCC subbase that were inspected as part of this study is presented in Table 2.

**Table 2. List of highways section constructed using CHCC or CHCC/V.A. blends in Iowa (Ceylan et al., 2013)**

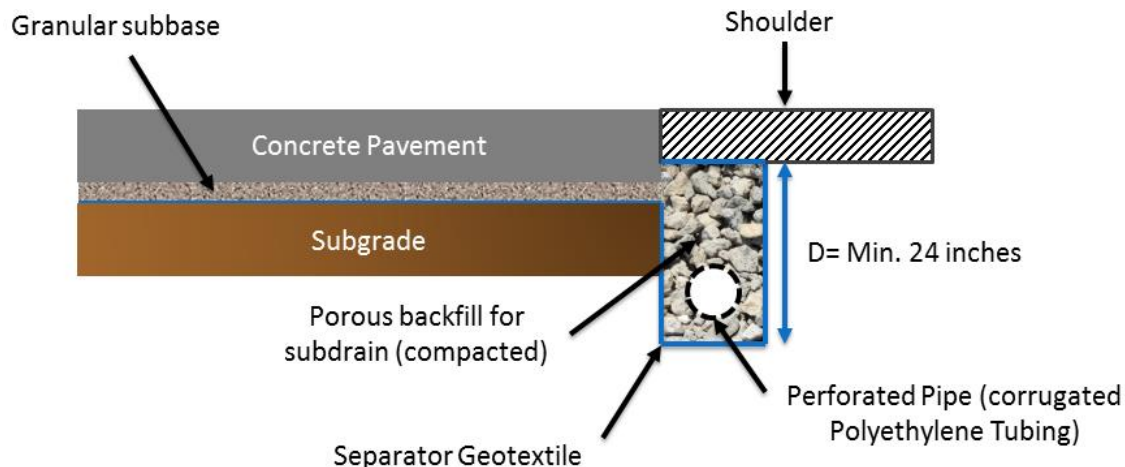
Road ID	Construction year	Pavement	Subbase	Underdrain pipe
I-35N	2003	JPCP	CHCC	6" Corrugated steel 4" Corrugated plastic
I-35S	1993	JPCP	CHCC	6" Corrugated steel
I-80W	1991 ~1997	JPCP	CHCC	6" Corrugated steel 4" Corrugated plastic
I-80E	1990 ~ 2003	JPCP	CHCC	6" Corrugated steel 4" Corrugated plastic
I-29N	1992 & 1999	JPCP	CHCC	6" Corrugated steel
I-29S	1994 - 1995	JPCP	CHCC	6" Corrugated steel 4" Corrugated plastic
US-151N	1992 2003	JPCP	CHCC CHCC/V.A. blend	6" Corrugated steel 4" Corrugated plastic
US-151S	1993 2003	JPCP	CHCC CHCC/V.A. blend	6" Corrugated steel 4" Corrugated plastic

Notes: JPCP: Jointed plain concrete pavement  
V.A.: Virgin aggregate

A typical cross-section of roads with rigid pavement in Iowa is depicted in Figure 9. According to the Iowa DOT specifications, the granular subbase material should have less than 6% passing number 200 sieve ( $<75 \mu\text{m}$ ) (Iowa DOT, 2016). As can be seen from Figure 9, the geotextile is mainly used as the separator (not for filtration) and the subbase aggregate is extended into the drainage layer overlying the perforated drainage pipe. Iowa DOT design manual also allows for use of geotextile around perforated pipe and geotextile is typically used in the underdrain systems in highway sections to enhance the filtration/retention performance of the perforated pipe (Iowa DOT, 2010). However, the inspection program did not include the inspection of the geotextile conditions and all of the observations were made from the outlets of drains.

The results of the first phase of inspection revealed that 35% of the outlets in rigid pavement sections constructed using CHCC were blocked (partial to 100% blocking was observed) due to deposition of tufaceous constituents and about 34% of the outlets were blocked due to other reasons (sedimentation/soil deposition) (Ceylan et al., 2013). Estimated percentages were calculated by dividing the pipe section area filled with deposition by the total pipe cross-section area for each outlet based on visual observation and field measurement. In the second

phase of inspection, two years later, it was noted that the amount of outlet blockage was slightly higher than the initial phase. However, the researchers concluded that this difference is negligible (Ceylan et al., 2015). Inspection of the sections constructed with CHCC and V.A. blends (the percentage of the blends were not reported) in newly constructed roads (US-151 constructed in 2003) showed fewer outlet blockages.



**Figure 9. Typical cross-section of rigid paved road in Iowa (modified after Ceylan et al. 2013; Iowa DOT 2016; Kim et al. 2016)**

Based on these findings, the researchers recommended the use of CHCC and V.A. blends as opposed to 100% CHCC (although they did not specify the geological origin of the V.A.). However, it should be noted that at the time of the inspection, the sections with blends were in service for about 10 years less than the sections of the same road that were constructed with 100% CHCC (constructed in 1992 and 1993). This study did not clarify whether or not the underdrains were flushed and cleaned as part of general maintenance during their service life, but the reported conditions and photographs showed none or very limited signs of regular maintenance.

The researchers in this study also found out that the use of any type of rodent guard or gate greatly contributes to the accumulation of tufa and blockage of the outlet. This is most likely because these kinds of features impede the flow, which in turn contributes to ponding and water accumulation in the pipe and consequently, higher deposition occurrence.

#### I-90 site near Austin, MN

During the reconstruction in 1985, the base course aggregate was replaced with CHCC and after two years in service, the drain outlets were inspected periodically (Snyder and Bruinsma, 1996; Snyder, 1995). The pavement profile and the drainage layer constructed at this site are very similar to the one constructed in Iowa as depicted in Figure 8. MnDOT class 5 gradation was used for the CHCC, which consists of 3 to 10 percent fines (passing sieve number 200) (MnDOT, 2016).

During the first inspection (1987), it was noted that some of the drain pipes were  $\frac{1}{4}$  filled with deposits of material (Snyder and Bruinsma, 1996; Snyder, 1995). In another follow-up



inspection in 1994, it was revealed that the major deposits formed in or around the concrete pipe headwalls. The pipes had been maintained periodically since construction and at the time of inspection, all of the drains were reported to be in working condition (no blocked drain). In 1989 and later in 1993, samples from the geotextile surrounding the drain pipes were exhumed and tested for their permittivity in order to determine the accumulation of tufaceous deposits. (Snyder and Bruinsma, 1996; Snyder, 1995) reported that permittivity tests of geotextile samples exhumed from the bottom of the pipe in 1989 showed about 45% and in 1993 about 55% reduction compares to the nominal permittivity of the particular geotextile. The reduction in permittivity for geotextile samples obtained from the top of the pipe was reported as 55% in both years. In addition to the standard permittivity tests, geotextile samples were also soaked in some type of acid (not specified in the manuscript) and then washed using Alconox solution and permittivity of fabric was also measured after each of these steps. The results showed an increase in permittivity values after being acid-soaked and washed by Alconox ( $1.2$  to  $1.48 \text{ sec}^{-1}$ ) to values often much higher than the claimed nominal permittivity (Snyder, 1995). Permittivity test results presented by Snyder (1995) in this study contain some important discrepancies. The publication refers to Typar 3733 as the geotextile used in this study and reports the permittivity of this geotextile as  $1.1 \text{ sec}^{-1}$ ; however, the manufacturer specifications indicate permittivity of  $0.7 \text{ sec}^{-1}$  (TYPAR, 2016). The minimum permittivity requirement based on MnDOT specification for filter geotextile is  $0.7 \text{ sec}^{-1}$  (MnDOT, 2016). This means that the design of the underdrain system in the I-90 highway was incorrect from the beginning and the recorded decrease in permittivity should be expected due to existing of fines migration and other blocking processes. Even if the permittivity of virgin geotextile was  $1.1 \text{ sec}^{-1}$ , the measured permittivity values after washing with Alconox should not be higher than the permittivity of virgin geotextile, unless the sample was damaged when it was exhumed from the ground. Moreover, the use of acid treatment is not a suitable method to determine the carbonate-based tufa (precipitated) depositions. Mortar content (MC) of CHCC consist of crushed hardened cement paste (HCP) and it is very well known that calcite as well as calcium silica hydrate (C-S-H) and calcium hydroxide (or portlandite, CH) exist in HCP as a byproduct of hydration of cement (Taylor 1997) and all of these constituents are soluble in acid. In other words, the deposition of materials on the geotextile samples might be due to the particle migration phenomenon and not because of precipitation of carbonates.

Snyder (1995) and Snyder and Bruinsma (1996) also reported similar inspection and permittivity tests on geotextile samples exhumed from Trunk Highway 212 sections near Glencoe, Minnesota, which was constructed using V.A. base. At this location, the geotextile samples had experienced an even higher reduction in permittivity, leading to values lesser than acceptable permittivity criteria based on MnDOT specifications. This is another evidence for incorrect design and selection of compatible soil/geotextile for filtration purposes.

#### Lakeville testbeds, MN

Snyder (1995) reported the construction of 7 test sections, each 23 m (75 ft.) long  $\times$  3 m (10 ft.) wide, in 1989 near Lakeville in MN, where 3 of the test sections consisted of blends of CHCC and V.A. In the first of these sections, the used CHCC had fine fractionated gradation (100% passing number 4 sieve). In the second section, the used CHCC had coarse fractionated gradation (100% retained number 4 sieve). The used V.A. had MnDOT class 5 gradation but the

geological makeup of used V.A. in this project is not known. In the third test section, the used CHCC was blended with open-graded limestone V.A. The test sections were constructed over polyethylene sheets and berms were constructed around them in order to avoid the entry of runoff or any contact with groundwater. All sections had a slope of 1.5% and edge drains were placed at the lower end of the cross-sections. The material in all sections was placed uncompacted and 15 cm (6 in) thick. The edgedrains in first and third test sections consisted of the perforated pipe only; whereas, edgedrain in the second test section had perforated pipe wrapped in geotextile fabric. Thrace-LINQ GTF (Formerly Exxon) EX-130 geotextile was used in this study. The nominal permittivity of EX-130 geotextile as produced in the present day is  $2.0 \text{ sec}^{-1}$ ; however, the nominal permittivity of the geotextile in this research was reported as  $3.6 \text{ sec}^{-1}$ . The testing was ended in 1992 (3 years after construction) and the drainage systems were inspected for any signs of clogging at the end. Permittivity tests were also conducted on geotextile samples exhumed from the second test section in the exact same way as was reported in the I-90 study (near Austin, MN). When the permittivity of the exhumed geotextile was compared against the permittivity of the virgin geotextile, the results showed a reduction of about 31 to 34 % for geotextile placed in the bottom or top of the drainage pipe. In general, the permittivity results from this testing program showed acceptable ranges for all of the geotextile samples with respect to the MnDOT requirements (specification 3733). When compared, these results were much better than the results obtained at the I-90 project but this is not a surprise because at this site the selected geotextile had much higher nominal permittivity than the one selected for the I-90 project. It should be kept in mind that loose placement of any soil can definitely lead to higher migration of fines under seepage forces and in that sense, these test sections may represent the worst-case scenario and not the representation of the actual base/subbase layer construction. As at the I-90 site, geotextile samples were also soaked in acid (again, type of acid not specified in the report) and washed with Alconox solution. After the acid treatment, the permittivity values showed an increase of about 9% for samples obtained from the bottom of the pipe and 29% for samples obtained from the top of the pipe. After washing with 1% Alconox solution, the permittivity values showed an average increase of about 14 to 41%. The increase in permittivity at this site after acid and Alconox treatments are consistent with what was observed at the I-90 site, which shows that these methods should not be relied on when evaluating permittivity.

Boroscopic inspection of the pipes showed minimal deposits in the drainage systems. Although these deposits were claimed to be carbonate precipitates, no evidence was presented in the published document to distinguish the soil sedimentation from chemical precipitation. Also, in none of the testbeds did the accumulated amount exceed the depth of the corrugation of the pipe. The volumes of outflow from these test sections were measured using a tipping water bucket. A comparison between the amount of rainfall and collected outflow volumes shows discrepancies in the outflow volumes. The outflow volumes for test sections 1 and 2 are lower for rainfall events with high quantity than the events with lower rainfall amount and these differences are very noticeable. Typically, one would expect higher outflow for higher rainfall events and researchers do not address this discrepancy. In addition, the researchers compare the outflow and pH from the open graded layer (third test section) with densely graded layers (first and second test sections) and conclude that only gap graded CHCC is appropriate for the construction of drainable layers. CHCC fines are reported as the principal source of increased pH and precipitation. Bestgen et al. (2016) proved that particle size does not have any effect on the

pH of the leachate extracted from CHCC and release of Ca (which in general is held responsible for carbonate precipitation). Gupta and Dollimore 2002) also reported that the deposition of tufaceous constituents is independent of the particle size for finer fractions and the researchers also showed an increase in some cases for coarser fractions. No permeability values were measured or provided for this project, which would have actually been a better comparison of base course drainage material as different materials have different flow characteristics. The permeability coefficient of the material is also a factor of gradation and the degree of compaction, which determines the void ratio. Therefore, attributing any difference in outflow volumes between CHCC blends and V.A. to tufa precipitate formation seems incorrect and unreliable.

As a result of this study, researchers suggested abandoning the use of wrapping geotextiles around perforated pipes in edge drains based on slightly lower outflow volumes from test sections with wrapped geotextile in comparison to the sections without geotextile. However, researchers did not present enough evidence for such a recommendation.

#### TH 15 near Hutchinson, MN

In 1991, 8 test sections were constructed to mirror and confirm the findings from the test sections constructed in Lakeville in 1989 (Snyder and Bruinsma, 1996; Snyder, 1995). The area of each section was 6 times larger than the Lakeville sections ( $122 \text{ m} \times 8 \text{ m}$  or  $400 \text{ ft.} \times 26 \text{ ft.}$ ) with similar material and gradation as used in Lakeville. At TH 15 site near Hutchinson, there was an extra section (section 8), which was constructed with only coarse fraction CHCC (passing number 25.4 mm (1 in) and retained number 4 sieves). However, laboratory analysis showed the existence of about 10% of material passing number 4 sieve in this section. Despite the similar material gradation and blends, there were also differences between Hutchinson and Lakeville test sections. At Hutchinson, sections were constructed as actual base layers with 130 mm (5 in) thicknesses at sections 1, 2, 7, and 100 mm (4 in) thickness at section 8. All sections were compacted based on MnDOT specifications and there was no isolating sheet from the vicinity used in these sections. Edge drains were constructed on both sides of each section but one side (north) was constructed with just perforated pipes and drainage aggregate and the other side (south) with perforated pipes and drainage aggregate wrapped with geotextile. The testing program did not include a collection of any geotextiles from the test sections. The performance of the test sections was only evaluated by measuring the volume of collected outflow from the edge drains from each section and comparing the values with values obtained from a control section (constructed using 100% crushed natural aggregate). Four rainfall events between 1993 and 1994 were used for the monitoring program.

Accumulation of depositions was reported to be much higher in volume from Hutchinson sections than the Lakeville and this was attributed to the difference in the volume and flow pattern and wetting and drying characteristics of two sites. Based on recorded outflow volumes, researchers concluded that (i) for a comparable grade, natural aggregate showed a significant increase in flow than CHCC, (ii) blending crushed rock with CHCC increases the flow characteristics of the base layer, and (iii) pipes with geotextile wrap yielded less outflow than the ones without geotextile.

With a more careful review of the data presented in this research, one can detect some similar discrepancies in the recorded outflow volumes as to the Lakeville project. Several readings for different rainfalls were missing, which makes the comparison difficult and therefore the conclusions become unreliable. Moreover, in several instances, the outflow volumes from test sections 1 and 2 (CHCC blends) with and without geotextile wraps showed higher values than the control section with natural aggregate, which actually is an indication of a better performance of CHCC blends than the pure virgin aggregate base. Similar to the Lakeville project, no permeability values were reported and it is not clear whether or not the differences in outflow values were due to the difference in permeability values of material or other reasons.

#### *Minnesota Department of Transportation Laboratory Tests*

MnDOT conducted two sets of experiments in 1987. The earliest tests consisted of soaking CHCC samples in a 5-gallon bucket, where geotextile was placed over a sand layer and underneath CHCC. Snyder (1995) pointed out that the geotextile samples, in general, were plugged (a term used by the researcher) within an hour and the pH of the solution rose to 11.5. However, no further detail is discussed in this report regarding the method that was used to determine the plugging of geotextile. In a later test setup, the CHCC was soaked in a bucket, for an unknown duration to produce high pH and the collected leachate from this bucket was circulated in a 150 mm (6 in) PVC pipe with geotextile fabric covering the bottom of the pipe. The pipe was fixed with an inclination; however, neither the inclination degree nor the end outlet system was specified in this report. Moreover, the properties of the geotextile are not provided. During the leachate circulation, the depth of the water accumulated above the geotextile was measured from the beginning of the test and an increase in this depth was observed and reported with time during the test. This increase in depth is inferred as a decrease in permittivity of geotextile. The test was repeated with the same geotextiles after being soaked in acid (acid type not specified) using tap water. This time, the accumulated water over geotextile during water circulation had lower depth in comparison to the first test and this was inferred as evidence for the increase in permittivity of geotextile after being acid washed. The observed residue over geotextile fizzed in the presence of weak acid (unspecified acid) and this was taken as evidence for precipitation of calcite over geotextile.

The report does not clarify whether or not the leachate collected from soaked CHCC was filtered or suspended particles were captured.  $\text{Ca}^{2+}$  ion concentrations were not monitored in these tests and the state of saturation is unknown. It is also not stated whether or not the concentration of  $\text{Ca}^{2+}$  or any other dissolved element changes occurred due to the precipitate formation. In other words, the accumulated residue might be the clotted suspensions or colloids in the leachate because of the recirculation of the same water. These suspended particles are calcareous in nature (including carbonate species) as their source is crushed HCP. As was mentioned previously, effervescing or fizzing of a residue cannot be a proof of calcite existence as calcite is only one of the components in HCP that can react quickly with acid. In addition to precipitate observation, the method used to interpret the change in permittivity of geotextile doesn't mean anything. Without knowing the flow rate, applied head and head loss over the geotextile, no interpretation can be made based on observed water depth. Also, there is no guarantee that the test conditions remained the same during each test. Backed up water can occur

in any condition if the inlet flow discharge is higher than the discharge capacity (permeability) of geotextile. The effect and justification for inclination are also not clear.

In conclusion, researchers pointed out that even if this setup is taken as a suitable simulation for underdrain conditions, the amount of water circulated through geotextile might be equal to tens of years in field condition.

#### *Construction Technology Laboratory Tests*

A series of tests were conducted in Construction Technology Laboratories (CTL) in 1989, which consisted of circulating water over CHCC material in a closed loop and measuring the Ca ion concentration (Snyder and Bruinsma, 1996; Snyder, 1995). An increase in the  $\text{Ca}^{2+}$  release was reported within 7 days of water circulation and reached a steady-state after that. The solid to liquid ratio in this test was not specified; however, the equilibrium concentration of  $\text{Ca}^{2+}$  was reported to be in the range of 700 mg/kg. Researchers of the CTL concluded that no significant calcium leaching occurred. It should be noted that the protocol followed at CTL does not follow any standard testing method. No attempt was made to relate the recorded values from these tests to tufa precipitate formation in underdrain systems.

#### *Michigan Department of Transportation Tests*

Muethel (1989) described a set of tests which consisted of soaking 500 grams of CHCC with different fractions and various particle sizes (Tables 3 and 4) in distilled water with solid to water ratio of 1:1 by weight in a bucket for a week and then drying out the leachate in the bucket and repeating this procedure for another two cycles. The pH of the leachate was monitored during the soaking period and the solid CHCC samples were examined for signs of precipitated residue visually and under a microscope. Floating crystalline constituents were observed over the surface of the leachate, which was referred to as calcite precipitation by the researcher. It is not clear how the researcher confirmed that floating residue on the surface of leachate was precipitated calcite rather than suspended particles.

However, as a known fact based on carbonate chemistry, it is expected for saturated solutions with respect to the  $\text{Ca}^{2+}$  ion to potentially produce some calcite precipitation when exposed to atmospheric carbon dioxide only if the conditions for precipitate formation are suitable (Stumm and Morgan, 1996; Drever, 1997; Langmuir, 1997). The suitable conditions for nucleation and calcite precipitate formation are extremely dependent on the governing mechanism of crystallization, reaction rates, and disequilibrium thermodynamics ongoing in such a complex environment and is very complex (Plummer et al., 1978; House, 1984; Shiraki and Brantley, 1995; Dreybrodt et al., 1997; Finneran and Morse, 2009).

One of the observations in this research was that of the partially submerged CHCC samples there was bright color residue, which was detected on the fully submerged particles. The CHCC particles were inspected under a microscope and the researcher reported the detection of calcite crystal spars intergrowth. Available microscopic images were not of appropriate quality; therefore, this claim could be confirmed independently. However, it is known that each mineral in nature has specific characteristics that are unique (Berry and Mason, 1959). Calcite has

vitreous luster (glassy looking appearance) and transparent to translucent crystals (Gartner et al., 2000). Common forms of calcite appear in the shapes of rhombohedron and scalenohedron with a variation of twinning through rhombohedron shape (Hamilton et al., 1990). Geologists often use these specific characteristics to identify minerals visually (Battey, 1973; Brownlow, 1979).

**Table 3. Different sample fractions used in this study**

Sample Fraction	Passing size, mm (in)	Retained size, mm (in)
1	37.5 (1.5)	25.4 (1)
2	25.4 (1)	19 (3/4)
3	19 (3/4)	12.5 (1/2)
4	12.5 (1/2)	9.5 (3/8)
5	9.5 (3/8)	4.75 (0.187)
6	4.75 (0.187)	0.075 (0.0029)
5G open-graded	See Table 4	

**Table 4. 5G open-graded CHCC gradation**

Size, mm (in)	Percent finer (%)
37.5 (1.5)	100
12.5 (1/2)	17.2
4.75 (0.187)	2.5
0.075 (0.0029)	0.9

Recorded pH values showed alkaline condition (pH>10 for almost all of CHCC leachate samples. Relevancy of soaking the material in a bucket and letting it dry (tests performed by Muethel (1989) to actual underdrain conditions is not known and no attempt was made by the researcher to relate their findings to the tufa deposition in underdrains.

#### *University of Toledo Laboratory Tests*

As part of this study, Tamirisa (1993) looked at the leaching properties of CHCC in the laboratory. Two sets of tests were conducted. The first test setup consisted of soaking CHCC with different gradation and fraction sizes in 150 mm (6 in) (diameter) × 305 mm (12 in) (height) cylinders with S:L ratio of ½ (6000g CHCC and 3000g de-ionized water) which is similar to the concept of MNDOT tests. CHCC was left for soaking for 24 hours and after this period, leachate samples were collected from the bottom of the cylinder on daily basis for 14 days and pH and electric conductivity (EC) of the solution were monitored. After measurements, the collected samples were returned into cylinders. As with other studies performed around this time period, the testing protocol followed in this research does not follow any of the established leachate extraction tests. No justification for any of the steps was presented and the goal of soaking CHCC for 14 days and collecting leachate every 24 hours is unknown to us. The second test setup consisted of a cylinder in which the 1500 g of DI water was added to 3000 g of solid samples. Carbon dioxide was introduced into the water/solid sample from the bottom and bubbling was continued until the pH of the leachate reached the pH of the de-ionized water (slightly less than 7). The leachate was then collected in a beaker and oven-dried and solid residue in the beaker was weighed. This cycle was repeated on the same solid samples (without changing them) until no more residue was observed after oven-drying. The ratio of accumulative weights of residue collected from each sample divided by the initial weight of the solid sample was calculated and referred to as “percent tufa precipitation”. Solid samples included Open-

Hearth (OH) slag, basic oxygen furnace (BOF) slag and two CHCC samples with a coarse fraction, larger than 4.75 mm (0.187 in) and as-is gradation (including both fine and coarse fractions). The researcher found that CHCC samples on average produce residue of about 54% of OH slag and 34% of BOF slag. A comparison between residue collected from coarse CHCC and as-is CHCC also showed that coarse CHCC produces residue 20% (by weight) less than as-is CHCC. Based on this observation, the researchers concluded that eliminating the finer fraction might not be helpful in reducing the Tufa depositions in underdrain pipes.

The researcher did not provide information on the composition of this residue and no justification was provided for the selection of each of the steps of the procedure (e.g. effluent and solid sample weight, duration of soaking, etc.). More importantly, it is not known whether or not the researcher aimed to simulate underdrain conditions and the researcher did not explain the relationship between the test procedure (such as bubbling carbon dioxide or oven-drying collected leachate) and the existing condition in an underdrain system. No correlation can be drawn between the weight of the collected residue and the potential of underdrain clogging used with CHCC base material. The only acceptable conclusion from this study is that it shows the ability of leachate collected from steel slag and CHCC to produce residual precipitate formation once it has dried.

In more recent years, Gupta and Dollimore (2002) from the University of Toledo conducted tests with CHCC using a laboratory setup similar to the one by Tamirisa (1993) but in their tests, the chamber was closed and the pressure inside the chamber was increased during the introduction CO<sub>2</sub> gas. This resulted in a higher concentration of CO<sub>2</sub> in solution and lower pH conditions. The leachate of each sample was collected after 24 hours of passing CO<sub>2</sub> gas and then collected at regular 24-hour intervals and samples were analyzed for concentration of leached elements using the ICP-MS method. This testing program was conducted in order to investigate the leaching behavior of CHCC. Scientific basis of the tests seem plausible to investigate the theoretical relation between the Gibbs free energy, partial pressure of CO<sub>2</sub> gas ( $P_{CO_2}$ ), leached concentration of Ca<sup>2+</sup> ion and related thermodynamics (Buhmann and Dreybrodt, 1987; Dreybrodt et al., 1997; Liu and Dreybrodt, 1997; Xu et al., 2012). However, the relevance of creating a closed system with injected CO<sub>2</sub> gas under high pressure to understand the conditions naturally occur in underdrain systems is not clear. It is known from carbonate chemistry that the concentration of Ca<sup>2+</sup> ion in solution is directly related to  $P_{CO_2}$  in the H<sub>2</sub>O-CO<sub>2</sub>-CaCO<sub>3</sub> system (Drever, 1997; Langmuir, 1997). Therefore, with an increase in  $P_{CO_2}$ , the concentration of Ca<sup>2+</sup> increases. Gupta and Dollimore (2002) also used the ratio of Ca/Mg concentration higher than 0.6 as an indication of tufa precipitate formation based on calcite/dolomite stability calculations provided by Drever (1997). The Mg/Ca concentration ratio higher than 0.6 represents a condition in calcareous geological formations that dolomite theoretically should be more stable than calcite, meaning that with the existence of available Mg<sup>2+</sup> ions, calcite minerals transform into dolomite minerals and vice versa. However, this condition is not a definitive indication of precipitate formation, as the nucleation process and precipitation kinetics are far more complex processes (House, 1984).

Nam et al. (2014) conducted research for Florida DOT in order to evaluate the performance of the coarse and gap graded CHCC to be used in French drains. In the investigated application, CHCC material is intended to serve as the drainage aggregate that encapsulates the perforated pipe and geotextile is wrapped around the CHCC/pipe system. The researchers correctly identified the coupling effects of clogging mechanisms that govern the filtration compatibility of CHCC/geotextile. These two mechanisms are physical clogging, as a result of the migration of fines (suffosion) and entrapment in geotextile filaments and chemical clogging, which is the precipitate formation and crystal growth within geotextile fabric.

Nam et al. (2014) used constant head permeability test methods to measure the filtration performance of geotextile/soil. Researchers observed a decrease in the recorded flow rate values with time and concluded this as the occurrence of clogging. However, it is known that the soil/geotextile system needs a much longer time to reach the stability of the flow in comparison to soil alone (Aydilek, 2000). Researchers terminated the tests after 100 days without confirming that the system had reached stability. Besides the observed reduction in flow rate with time during 100 days, researchers did not provide any other basis to compare and determine the clogged vs. non-clogged systems.

In order to evaluate the chemical clogging phenomena, researchers made an attempt to quantitatively determine the amount of precipitated calcium carbonate following a similar procedure proposed by Tamirisa (1993). In their study, Nam et al. (2014) saturated 5 kg of as-is CHCC with tap water, bubbled CO<sub>2</sub> to this saturated CHCC for 6 minutes at a rate of 0.28 m<sup>3</sup>/hr. and allowed the solution to rest for 20 minutes. After that, the solution is filtered (following ASTM D5907-Standard developed to filter matter in water) and the retained matter on the filter is claimed as the precipitated calcite. The process starting from the bubbling CO<sub>2</sub> into the CHCC/water solution is repeated until the researchers determined that the retained matter on the filter is 0.05 g or less. Overall, this process is referred to in their publications as “Accelerated Calcite Precipitation Procedure” (ACPP). Although this work at first glance seems to be a new way to evaluate the amount of calcite precipitation from CHCC during its lifetime (as is claimed by the authors), several technical issues need clarifications. It is unknown how the researchers confirmed that ACPP truly represents the field conditions and the retained matter was actually calcite. It is known that the tufaceous material from CHCC contains several minerals including but not limited to calcite (Gupta and Kneller, 1993; Tamirisa, 1993) and assuming that all of the precipitants were calcite may not be accurate. More importantly, Nam et al. (2014) did not provide any evidence that the collected residue is actually a precipitate formation rather than particles in the solution entrapped on the filter used. Based on previous literature, it is known that precipitated calcite may exist in the form of colloids and may form particles with particle sizes as small as 5 nm (Stumm and Morgan, 1996). The type of glass filter suggested by ASTM D5907 has a pore size ranging from 0.7 to 1.5 µm (Millipore AP-40, Whatman 934-AH, Gelman type A/E, or an equivalent type of glass fibers), which is too coarse to collect calcite colloids. ASTM D5907 is developed to measure the amount of filterable and non-filterable suspended particles in natural and wastewater and not for extracting leachate or measuring dissolved metals and solids. Nam et al. (2014) did not provide details regarding this discrepancy. Another technical issue with Nam et al.’s (2014) study is all experiments were performed with tap water. It is unknown how



the researchers controlled the potential adverse effects from the chemistry of tap water as the dissolved calcium and magnesium carbonates in the tap water can immensely impact the result of any tests.

## Characterization of Sampled Material

### Crushed Hydraulic Cement Concrete (CHCC)

CHCC (as well as V.A. material) used in this study were characterized to document their relevant geotechnical properties such as grain size distribution, Atterberg's limits, and compaction. Material has been classified in accordance with the Unified Soil Classification system (USCS). The variation in the collected samples was evaluated in the laboratory by running grain size distribution tests on 5 randomly selected samples from the total collected batch. The variation in the gradation of material is presented in Figure 10. The results showed that in general the percentage of the material passing No. 4 sieve ranged from 52.36% to 64.86% and passing No. 200 sieve from 6.12% to 8.84%.

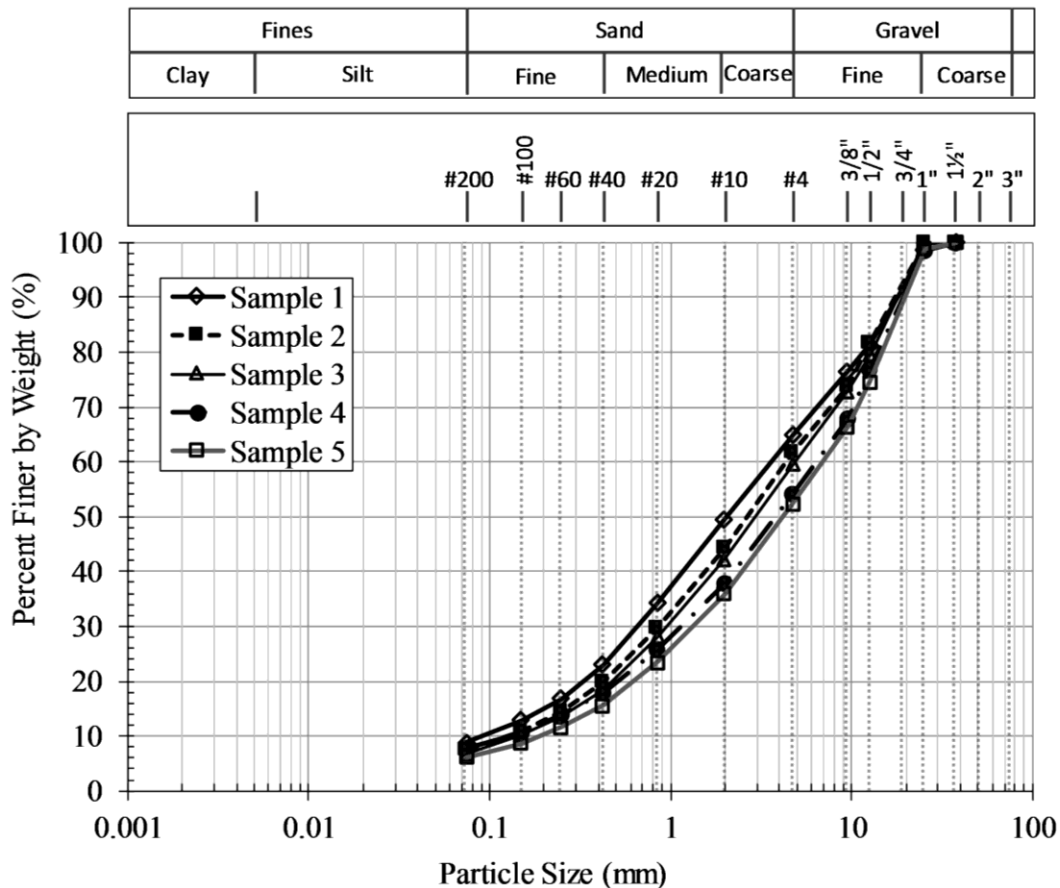


Figure 10. Variation in gradation of the collected CHCC material

Additionally, the specific gravity of CHCC was determined to evaluate the variability within the obtained samples. Summaries of these results are presented in Tables 5 and 6. The compaction curve for CHCC is presented in Figure 11. As can be seen from Table 5, the grain

size distribution of the collected CHCC was within the range of VDOT 21 aggregate gradation. The reported values for other CHCC material found in literature as well as the existing acceptable range in accordance with VDOT specifications are also presented in this table for comparison purposes. The results obtained in this study are in general agreement with the values presented in the previous literature.

**Table 5. Index properties of non-aged CHCC and V.A.**

Properties	CHCC (non-aged)			Virgin Aggregate		
	Number of tests	Average value	Standard Deviation	Number of tests	Average value	Standard Deviation
Atterberg's Limits (per ASTM D4318 & VTM 7)						
Liquid Limit (%)	5	28	0.6	4	19	0.6
Plastic Limit (%)		28	1.4		17	1.9
Plasticity Index (%)		NP	-		2	2.2
Grain size distribution (per ASTM D422)						
Passing 3/8" (< 9.5mm)	5	71.49	3.81	7	62.11	4.58
Passing #4 sieve (< 4.75mm)		58.52	4.68		50.13	3.17
Passing #10 sieve (< 2mm)		41.97	4.88		35.84	2.40
Passing #40 sieve (< 0.43mm)		18.96	2.42		21.40	1.68
Passing #200 sieve (< 0.074mm)		7.67	0.76		10.52	1.72
Compaction using Standard Effort (per ASTM D698 and VTM 1)						
ω <sub>opt</sub> (%)	14.40			7.06		
γ <sub>dmax</sub> , kN/m <sup>3</sup> (lb/ft <sup>3</sup> )	19.20 (122.11)			24.22 (154.04)		

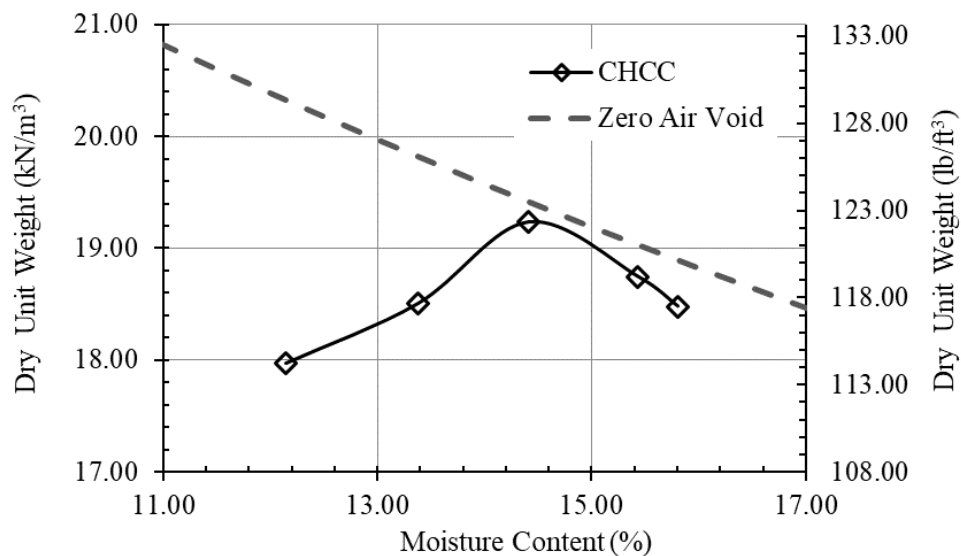
**Table 6. Properties of CHCC collected in this study and comparison against CHCC from other studies**

Properties	CHCC collected in this study			Values reported in the literature			
	Number of tests	Average value	Standard Deviation	Cooley and Hornsby (2012)	Arulrajah et al. (2012)	Edil et al. (2012)	VDOT acceptable range for base material
Specific gravity of Coarse Aggregate (per ASTM C127)							
Apparent Specific Gravity	5	2.79	0.011	2.567 - 2.607	-	-	-
Water absorption (%)		5.09	0.001	5.2 - 10.0	4.66	5.0 - 6.5	-
Specific gravity of Fine Aggregate (per ASTM C128)							
Apparent Specific Gravity	5	2.75	0.013	-	-	-	-
Water absorption (%)		13.06	0.002	-	9.75	-	-
Atterberg's Limits (per ASTM D4318)							
Liquid Limit (%)	5	28	0.58	19 - 37	-	NP	23
Plastic Limit (%)		28	1.35	NP	-	NP	-
Plasticity Index (%)		NP	-	NP	-	NP	5
Resistance to Abrasion							
Micro-Deval (% of Weight loss) (per ASTM D6928)	2.00	16.64	0.84	10% - 20%	-	16% - 20%	45% *

Notes:

NP=non-plastic,

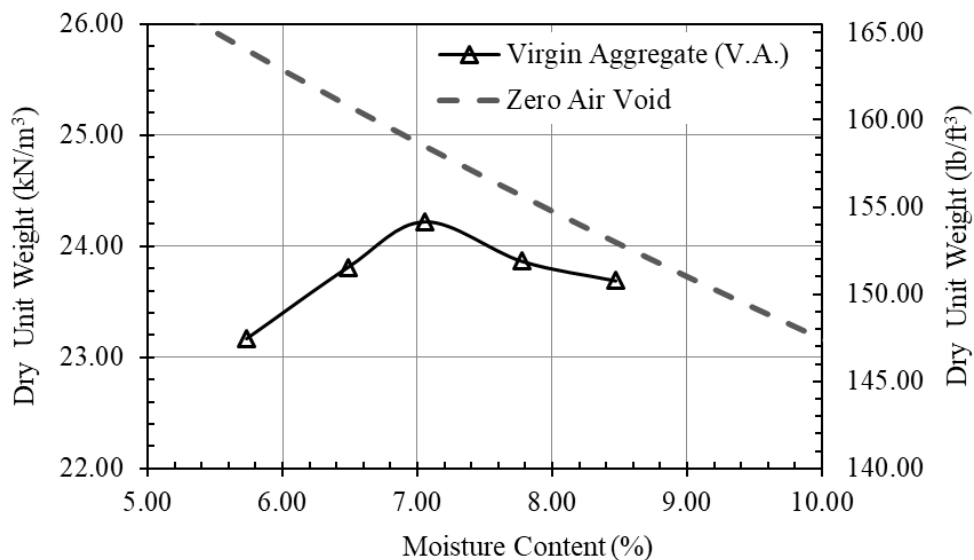
\*: AASHTO T-237 requirement (not VDOT requirement).



**Figure 11. Maximum dry density and optimum moisture content of material from laboratory compaction using standard effort for CHCC (in accordance with ASTM D698 and VTM 1)**

### Virgin Aggregate

Similar to CHCC, V.A. material used in this study was evaluated for its grain size distribution, Atterberg's limits, and compaction properties (Table 5). Material is classified in accordance with the Unified Soil Classification system (USCS). The compaction curve for V.A. is also presented in Figure 12.



**Figure 12. Maximum dry density and optimum moisture content of material from laboratory compaction using standard effort for V.A. (in accordance with ASTM D698 and VTM 1)**

## Geotextile

Properties of this geotextile as reported by the manufacturer are presented in Table 7. This geotextile meets the VDOT requirements for geotextiles specified for drainage systems as outlined in VDOT Specifications Section 245.03 (c).

**Table 7. Technical properties of the nonwoven geotextile**

Manufacturer Information		Hydraulic Properties		Physical Properties	
Name	Mirafi 140N	Apparent opening size, AOS (mm)	0.212	Mass/unit area, g/m <sup>2</sup> (oz/yd <sup>2</sup> )	163 (4.8)
				Thickness, mm (mils)	1.4 (55)
Structure	Nonwoven (NW) Needle Punched (NP),	Permittivity (s <sup>-1</sup> )	1.7	Grab tensile strength, N (lbs)	534 (120)
		Porosity (%)	87	Puncture, N (lbs)	300 (65)
Polymer Type	Polypropylene (PP)			Trapezoidal tear strength, N (lbs)	223 (50)

## Evaluation of Atterberg Limits of CHCC Mixed with V.A.

As shown in Tables 5 and 6, the Atterberg limits of the CHCC, particularly the liquid limit (LL) does not meet the VDOT requirements for base course aggregate as specified in Section 208.03 of the VDOT specifications. The LL of CHCC determined from this study from the average of 5 tests is 28 and the VDOT requirement for the LL obtained from a similar number of tests is around 23 (VDOT requirements change based on the number of tests performed to obtain Atterberg limits).

To evaluate the effects of mixing CHCC with V.A. on Atterberg limits, as stated in the secondary objectives, a parametric study was conducted in this study. Table 8 presents the results when CHCC was mixed with V.A. at percentages recommended by VDOT TRP as 10% CHCC with 90% V.A., 20% CHCC with 80% V.A., and 40% CHCC with 60% V.A. These percent mixtures are referred to in this study as Blends 1, 2, and 3 respectively.

**Table 8. Atterberg's Limits for V.A., CHCC and different blends of V.A./CHCC**

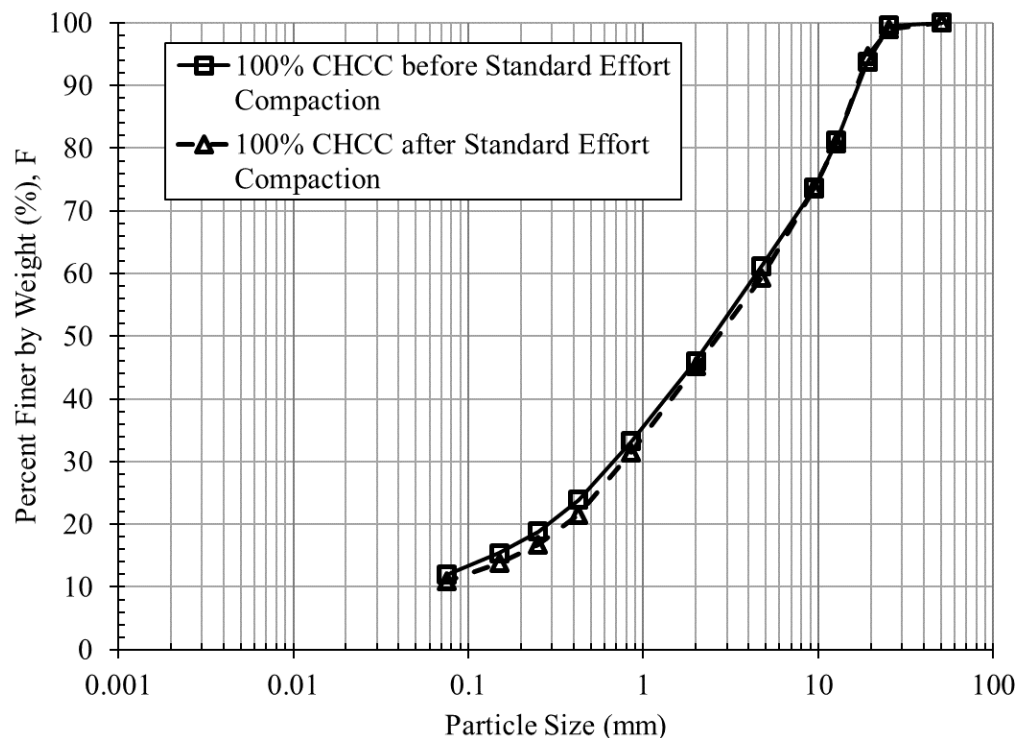
Sample Description	100% V.A.			Blend 1 (90% V.A. + 10% CHCC)			Blend 2 (80% V.A. + 20% CHCC)			Blend 3 (60% V.A. + 40% CHCC)			100% CHCC		
	LL	PL	PI	LL	PL	PI	LL	PL	PI	LL	PL	PI	LL	PL	PI
Test No.	4			3			2			2			5		
Mean	19	17	2	22	20	2	24	21	4	26	24	2	26	24	2
Std. Dev.	0.6	1.9	-	0.2	0.6	-	0.8	0.1	-	0.4	0.9	-	0.4	0.9	-
VDOT Specs	23.0	-	5.0	23.2	-	5.1	23.9	-	5.4	23.9	-	5.4	23.9	-	5.4

The results presented in Table 8 were obtained from at least 2 repeat tests for each blend, which means the results must be compared against the VDOT threshold for the maximum allowed LL as 23.9. The results show that as the CHCC percentage decreases (as the V.A. percentage increases), the LL of the blends reduces; however, the only condition that meets the VDOT specifications is achieved with Blend 1. The LL of Blend 2 is 0.1% and for Blend 3, it is 2.1% higher than VDOT requirements. Based on these results if Atterberg limit requirements are imposed on the CHCC and V.A. blends only Blend 1 would satisfy the requirement.

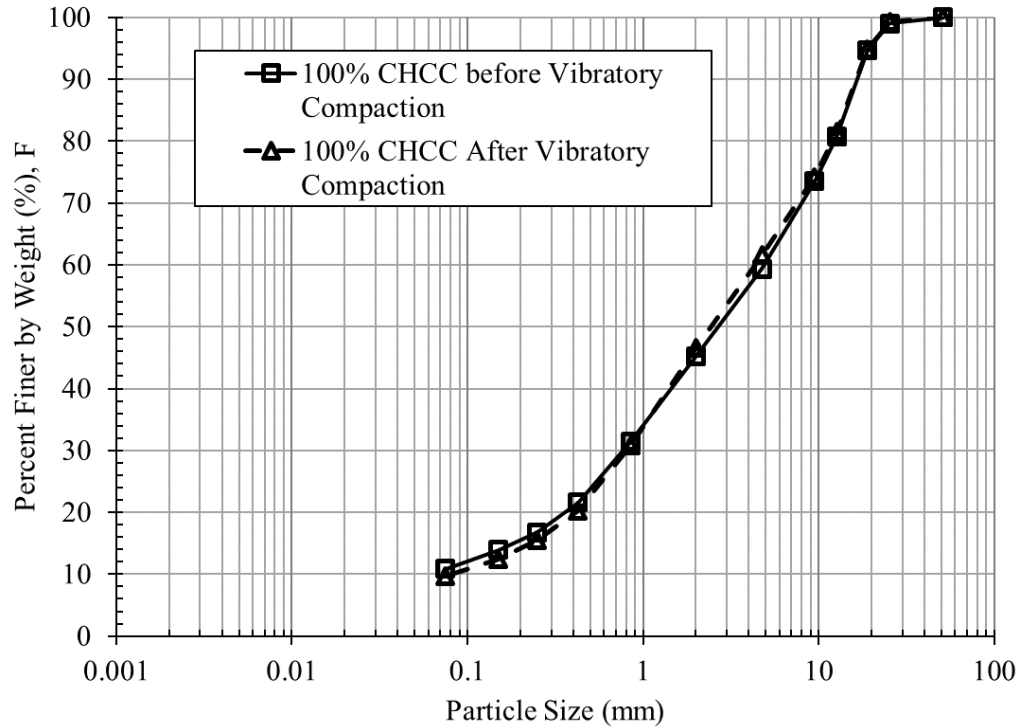
To discuss this constraint, the GMU team met with members of the VDOT TRP on May 7, 2015. During this meeting, the VDOT TRP clarified that the Atterberg limit requirements set forth in the VDOT specifications are for the natural aggregates and all virgin aggregates used as subbase or base course in Virginia must meet these requirements even if they were mixed with CHCC. The group also discussed the meaning of Atterberg limits and how these limits are fundamentally related to the sheet structure of the clay-sized particles (clay minerals) in natural soils. However, in the case of CHCC, the finer particles are not principally clay minerals, but a mixture of a variety of mineralogies. Therefore, it was decided that the Atterberg limit requirements not be imposed on the CHCC or mixtures of CHCC with V.A. used in Virginia when these materials are considered for the purposes of creating subbase or base course aggregates.

### Changes in Gradation of CHCC after Compaction

The results obtained before and after compaction using each of the two compaction methods are presented in Figures 13 and 14. The results showed that in both methods (standard Proctor and vibratory compaction), CHCC is strong enough to not create percent fines that would be a concern when CHCC is used as a base course in the presence of drainage systems.



**Figure 13. Changes in the grain size distribution of CHCC before and after compaction with (a) standard Proctor rammer and (b) vibratory hammer**



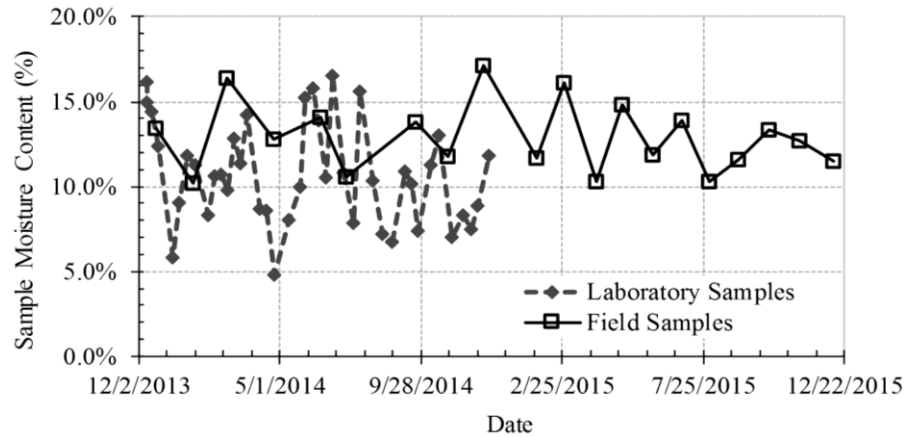
**Figure 14. Changes in the grain size distribution of CHCC before and after compaction with (a) standard Proctor rammer and (b) vibratory hammer**

### **Aging of CHCC**

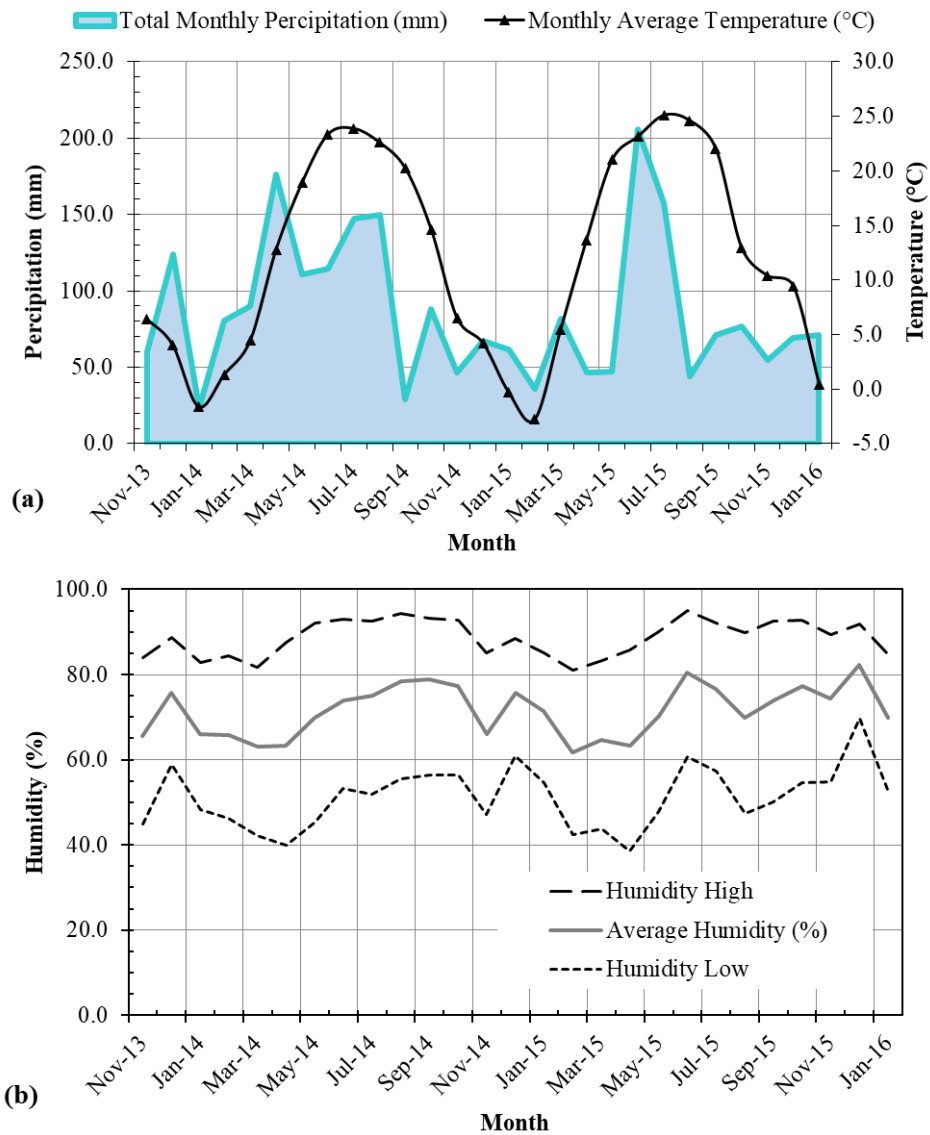
The purpose of the aging procedure was to create CHCC samples for the physical clogging evaluation (which was part of the first primary objective of the study) and to collect necessary information on the chemical properties and behavior of the CHCC over time (which was part of the second primary objective of the study). The following sections provide the background associated with this evaluation, the methods followed. The associated results are presented in the subsequent section.

#### **Monitoring of the Aging Procedures**

During the period of aging procedures, the moisture content of the CHCC from both the laboratory and field were measured (Figure 15). Also, the meteorological record obtained from a nearby weather station, where the CHCC pile was left in place for field aging was tracked. The meteorological data (including records on precipitation amount, temperature, and humidity) is shown in Figure 16. The data was recorded at station CENTREweather (Station name: CENTREweather, Station Code: KVACENTR1, Coordination: 38.845 -77.455) and was obtained from weather underground database (Weather Underground, 2015). This information was tracked to be used during the interpretation of the chemical analyses.



**Figure 15. Changes in moisture contents of laboratory and field aged CHCC**

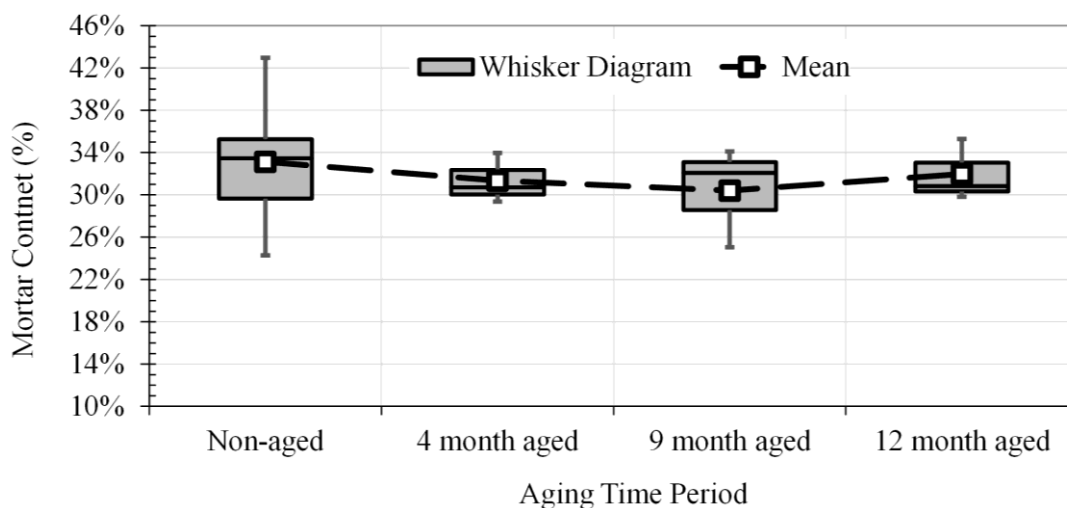


**Figure 16. Meteorological data of the area nearby the CHCC pile. a) total monthly precipitation and monthly average temperature vs. time, and b) measured relative humidity vs. time**

## Effect of Aging on Solid Chemistry of CHCC

### *Changes in Mortar Content (MC) of CHCC*

A statistical representation of measured MC of non-aged (freshly produced) and aged CHCC material is shown in Figure 17. The CHCC samples used for these analyses were obtained from the laboratory aging procedure. Since laboratory and field samples were mixed and collected from the same source (stockpile) it is assumed that the MC of laboratory samples are also representative of field samples. Despite the noticeable variation in the measured MC values, considering the mean and quartiles of data for each aging period, it can be concluded that the MC of CHCC did not statistically change with aging. The variation within the MC of CHCC for each aging time-period is believed to be due to the inherent variability of the collected samples coming from various sources of concrete used to create CHCC.



**Figure 17. Comparison of mortar content of fresh (non-aged) and aged CHCC**

MC tests also allowed the identification of the predominant parent rock that was used to create cement. In the samples collected for this study, the predominant parent rock appeared to be diabase.

### *Chemical Composition and Properties of Freshly Produced CHCC*

Table 9 presents the mineralogical composition of the CHCC used in this study (herein referred to as freshly produced). The total carbonate contents of the CHCC samples were estimated to be around 3.1% (2.7% calcite + 0.7% dolomite). The analyses also show that calcium-plagioclase and quartz are the predominant minerals, which is consistent with the typical mineral composition of the parent material. The predominant parent rock in CHCC is identified as diabase, which is observed after the cement paste was dissolved with hydrochloric acid. Additionally, trace amounts of granite, quartzite, and hornfels were also observed from the samples. The high quartz content is most likely due to the silica sand added to the mixture during the production of concrete.



As can be seen from Table 9, calcium hydroxide (CH) was not detected from the XRD results of the CHCC, indicating the lack of crystalline form of CH (portlandite). Depending on the hydration stage in the pure calcium-silicate paste, CH crystals have variable morphology with persistently good cleavage (Taylor, 1997). However, there are evidences indicating that CH in cement paste may exist in the amorphous or cryptocrystalline forms (intimately mixed with C-S-H) (Taylor, 1997). Based on previous studies, Taylor (1997) explains that the quantitative XRD method tends to underestimate (or in some cases not detect) the CH due to the existence of these forms. Based on the XRD results it can be inferred that the crystalline form of CH (portlandite) does not exist in the CHCC tested in this study, which is most likely due to the age of the paste (leached out or carbonated). However, other forms of CH mixed with C-S-H and silica gel probably exist to some extent. Similarly, C-S-H exists in the amorphous form in the cement paste (Kurdowski, 2014; Taylor, 1997) and cannot be properly characterized using XRD method (due to its poor crystallinity). C-S-H continuously decalcifies and disintegrates during degradation and the carbonation process (Suzuki et al., 1985). However, for partially degraded material, it is expected that some amorphous C-S-H still remains in CHCC.

**Table 9. Mineralogical composition of CHCC used in this study**

Mineral	Ideal Formula	Percent by weight (wt.%)
Actinolite	$\text{Ca}_2(\text{Mg}, \text{Fe}^{2+})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	1.1
Calcite	$\text{CaCO}_3$	2.4
Clinocllore	$(\text{Mg}, \text{Fe}^{2+})_5\text{Al}(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH})_8$	1.3
Diopside	$\text{CaMgSi}_2\text{O}_6$	8.7
Dolomite	$\text{CaMg}(\text{CO}_3)_2$	0.7
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	1.2
Hematite	$\text{Fe}_2\text{O}_3$	0.4
Illite-Muscovite 2M1	$\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	2.9
Ilmenite	$\text{Fe}^{2+}\text{TiO}_3$	0.5
Magnetite	$\text{Fe}_3\text{O}_4$	0.8
Montmorillonite	$(\text{Na}, \text{Ca})_{0.3}(\text{Al}, \text{Mg})_2\text{Si}_4\text{O}_{10}(\text{OH})_2 \cdot n\text{H}_2\text{O}$	5.4
Orthoclase	$\text{KAlSi}_3\text{O}_8$	2
Plagioclase (calcic)	$(\text{Ca}, \text{Na})[\text{Al}(\text{Al}, \text{Si})\text{Si}_2\text{O}_8]$	38.6
Quartz (low)	$\text{SiO}_2$	34.1

Notes:

Results were obtained from XRD analyses of samples with a maximum particle size of 4.75mm.

The lowest detectable level for Quantitative XRD (QXRD) used in this study is 0.5% (wt.%)

Table 10 shows the chemical composition of CHCC and parent material obtained after acid treatment for MC measurements. It can be seen that Ca and Si are taking up about 62% (by weight) of CHCC. It is known that the alite (C3S) and belite (C2S) in clinker hydrate and form calcium silica hydrate (C-S-H) and calcium hydroxide (CH), which takes up to 70-80% of the hydrated cement paste (HCP) in the MC of CHCC. As CHCC is produced from crushed concrete it can be assumed that cement minerals were present during hydration and it is fair to state that the likely hood of having C-S-H in CHCC used in this study is high. The remaining of the HCP consists of calcium aluminates as well as AFt/AFm (tri- and mono- sulfoaluminate) phases (Kurdowski, 2014; Scrivener et al., 2004). Ettringite (AFt) mineral is a by-product of the hydration process (Kurdowski, 2014; Taylor, 1997). The content of ettringite in the HCP

increases during setting and early hardening phases but decreases with time and becomes scarce by the end of the hardening phase and formation of stable structure in HCP (Kurdowski, 2014). Ettringite may also form when concrete experiences sulfate attack (Roy, 1986). In this study, the XRD test results of CHCC did not show any ettringite. This is most likely due to the degradation of the ettringite content of HCP into gypsum and al-hydroxides. The degradation process most probably initiated within the concrete long before the concrete was demolished. Moreover, it is known that ettringite is not easy to quantify by XRD in CHCC material even at levels of 1 to 3%. Table 9 also shows a very low quantity of gypsum (sulfate) in the XRD analyses, which also suggests that the sulfate attack was not the degrading mechanism acting on the concrete source of the CHCC evaluated in this study.

**Table 10. Oxides content of CHCC and parent material**

<b>Chemical composition<sup>†</sup> (with wt. &gt; 1%)<sup>††</sup></b>	<b>CHCC (wt. %)</b>	<b>Parent Material (wt. %)</b>
SiO <sub>2</sub>	46.35	51.70
Al <sub>2</sub> O <sub>3</sub>	12.40	13.05
Fe <sub>2</sub> O <sub>3</sub>	6.98	10.84
CaO	16.01	10.56
MgO	4.12	9.87
Na <sub>2</sub> O	1.71	1.92
K <sub>2</sub> O	1.19	-
SO <sub>3</sub>	0.24	-
LOI	9.94	0.81

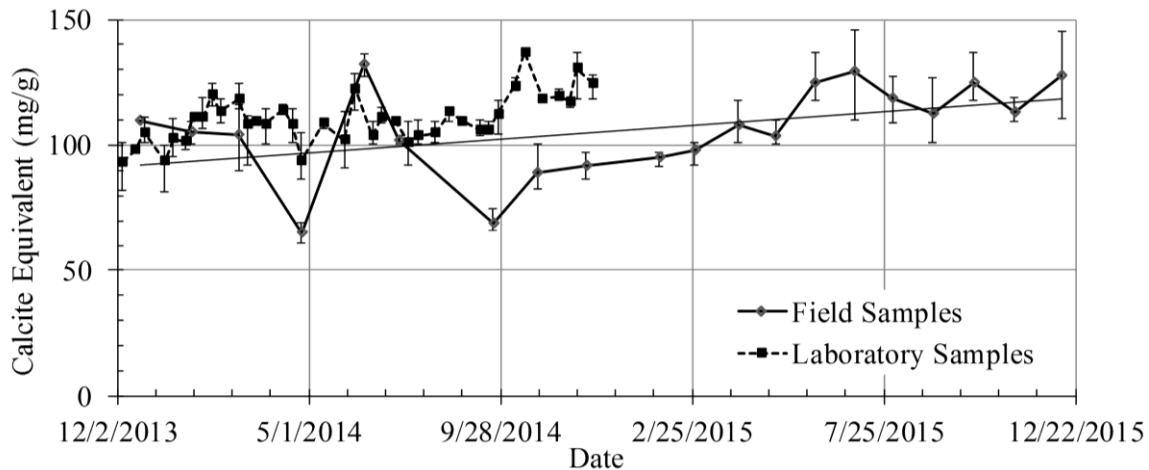
Notes:

<sup>†</sup> -Results were obtained from XRF analyses of samples with a maximum particle size of 4.75mm.

<sup>††</sup> -Except for SO<sub>3</sub>

### *Changes on Chemistry of CHCC*

Figure 18 presents the changes in the carbonate content of CHCC during the aging laboratory. The existing fluctuation in the recorded data may be attributed to the variation in the collected samples on different dates, which cannot be avoided due to the inherent inhomogeneity of material. For field aged CHCC, the range of fluctuations during the first year seems to be much higher than the range of fluctuations during the second year (about 67 mg/g calcite equivalent for the first year in comparison to about 38 mg/g calcite equivalent for the second year). One of the reasons for observing such behavior, in addition to the existing variation in the CHCC pile, may be attributed to the presence of unevenly carbonated CHCC within the pile. This variation appears to decrease with time as the carbonation process continues to convert decalcified C-S-H in the MC into calcite and other carbonated species. Overall, the carbonate content results from field samples show about a 16% increase in the carbonated solid mass with time (from about 110 mg/g calcite equivalent at the beginning of the age to about 128 mg/g calcite equivalent at the end of aging). A linear regression of the data also confirms this overall behavior.



**Figure 18. Changes in Carbonate Content of CHCC Samples with Time**

A comparison of laboratory and field aging was possible in this study because both of the CHCC samples were collected at the same time from the same location and the aging tests were started around the same time. The comparison presented in Figure 18 shows that the carbonate content of CHCC (depicted as calcite equivalent) aged both in the laboratory and field provide similar results; however, the carbonation rate in the laboratory was two times faster than the rate in the field (reaching very similar calcite equivalent values after one year in the laboratory vs. two years in the field). The observed slower rate of carbonation in the field may be mainly attributed to the fluctuation in temperature, the amount of precipitation, and relative humidity. In the laboratory, these conditions were kept constant at a level, which was favorable for the carbonation process. Roy (1986) showed that there is an inverse relationship between the carbonation degree of HCP and the pH of the pore solution. Despite the fact that the measured carbonate content of particles finer than 0.425 mm (0.0165 in) for the field samples reaches the same level as the laboratory samples after two years of aging, it should be emphasized that the measured pH values from field CHCC clearly shows that the carbonation degree of CHCC in the field is not the same as the laboratory samples.

Tables 11 and 12 show the changes in specific mineral contents within CHCC as determined from the samples with maximum particle sizes of 4.75 mm (0.187 in) and 0.075 mm (0.0029 in) (fines content). Although not representative of the whole grain size distribution, this particle fraction is selected as it was expected to have more of the cement paste, powdered as a result of CHCC production, and has less impact on the parent material. Therefore, this fine fraction may have a higher carbonation degree in comparison to the coarser fraction. When Table 11 (which represents data with a maximum particle size of 4.75 mm) is compared with Table 12, the effect of the finer fraction on calcite content of the freshly produced CHCC can be seen (2.4% to 10.5%).

**Table 11. Mineral composition (XRD results) of freshly produced and aged (laboratory) CHCC with a maximum particle size of 4.75 mm**

Mineral	Ideal Formula	non-aged	4 month aged	9 month aged	12 month aged
Plagioclase (calcic)	(Ca,Na)[Al(Al,Si)Si <sub>2</sub> O <sub>8</sub> ]	38.6	27.8	27.3	27.6
Calcite	CaCO <sub>3</sub>	2.4	5.8	8.6	6.7
Diopside	CaMgSi <sub>2</sub> O <sub>6</sub>	8.7	N.D.	N.D.	N.D.
Montmorillonite	(Na,Ca) <sub>0.3</sub> (Al,Mg) <sub>2</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub> ·nH <sub>2</sub> O	5.4	N.D.	N.D.	N.D.
Illite-Muscovite	KAl <sub>2</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>	2.9	3.1	2.9	2.1
Orthoclase	KAlSi <sub>3</sub> O <sub>8</sub>	2	5.1	5	4.1
Actinolite	Ca <sub>2</sub> (Mg,Fe <sup>2+</sup> ) <sub>5</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	1.1	2	2.6	2.2
Clinochlore	(Mg,Fe <sup>2+</sup> ) <sub>5</sub> Al(Si <sub>3</sub> Al)O <sub>10</sub> (OH) <sub>8</sub>	1.3	1.8	1.6	1.3
Dolomite	CaMg(CO <sub>3</sub> ) <sub>2</sub>	0.7	0.8	0.9	1.1
Gypsum	CaSO <sub>4</sub> ·2H <sub>2</sub> O	1.2	N.D.	N.D.	N.D.
Hematite	α-Fe <sub>2</sub> O <sub>3</sub>	0.4	0.6	0.5	0.8
Magnetite	Fe <sub>3</sub> O <sub>4</sub>	0.7	N.D.	N.D.	N.D.
Quartz (low)	SiO <sub>2</sub>	34.1	35.8	34.1	34.6

Note: N.D. stands for not detected.

Table 12 provides additional evidence on carbonation and an insight into the changes in specific mineral contents due to aging. As can be seen, the percentage by weight of calcite increases noticeably (from 10.5 to 23.2 %), while the quantity of dolomite remains the same (0.7 to 0.8%). Gypsum disappeared as part of the aging procedure (from 1.3% to none detect), most probably dissolved, and washed away because of its low quantity during the wetting process. Moreover, magnetite is detected in the freshly produced CHCC (0.8%) but also disappeared in the aged material and simultaneously, hematite quantity doubled because of the aging (from 0.35% to 0.7%). It can be concluded that magnetite is transformed into hematite with time. Transformation of magnetite to hematite and oxidation of Fe<sup>2+</sup> to Fe<sup>3+</sup> as a result of dissolution/precipitation or pedogenesis process is a well-known process in mines and soils (Lagoeiro, 1998; Santana et al., 2001).

**Table 12. Mineral composition (XRD results) of freshly produced and aged (laboratory) CHCC with a maximum particle size of 0.075 mm**

Mineral	Ideal Formula	non-aged	4 month aged	9 month aged	12 month aged
Plagioclase (calcic)	(Ca,Na)[Al(Al,Si)Si <sub>2</sub> O <sub>8</sub> ]	43.85	32.2	30.8	30.2
Calcite	CaCO <sub>3</sub>	10.45	19.2	22	23.2
Diopside	CaMgSi <sub>2</sub> O <sub>6</sub>	8.7	N.D.	N.D.	N.D.
Montmorillonite	(Na,Ca) <sub>0.3</sub> (Al,Mg) <sub>2</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub> ·nH <sub>2</sub> O	6.25	N.D.	N.D.	N.D.
Illite-Muscovite	KAl <sub>2</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>	5.5	4.5	4.7	4.6
Orthoclase	KAlSi <sub>3</sub> O <sub>8</sub>	3.1	4.6	4	4.1
Actinolite	Ca <sub>2</sub> (Mg,Fe <sup>2+</sup> ) <sub>5</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	1	2.8	2.4	2.3
Clinochlore	(Mg,Fe <sup>2+</sup> ) <sub>5</sub> Al(Si <sub>3</sub> Al)O <sub>10</sub> (OH) <sub>8</sub>	2.65	4.2	5.2	5
Dolomite	CaMg(CO <sub>3</sub> ) <sub>2</sub>	0.7	0.8	0.7	0.7
Gypsum	CaSO <sub>4</sub> ·2H <sub>2</sub> O	1.3	N.D.	N.D.	N.D.
Hematite	α-Fe <sub>2</sub> O <sub>3</sub>	0.35	0.7	0.6	0.7
Magnetite	Fe <sub>3</sub> O <sub>4</sub>	0.8	N.D.	N.D.	N.D.
Quartz (low)	SiO <sub>2</sub>	14.05	14.3	14.2	13.8

Note: N.D. stands for not detected.

## Effect of Aging on Leaching Behavior of CHCC

As previously stated, ASTM WLT is one of the most common methods to extract leachate from a batch of solid samples evaluated for chemical analyses. However, the USGSLT method is suggested by Hageman (2007) to be utilized as a quick and simple method to extract leachate in the field and get reliable measurements of leachate conditions and properties without the need for the lengthy process of WLT method. In order to be able to understand the applicability of the USGSLT method to characterize the leaching behavior of CHCC, the leachate from laboratory aged CHCC samples were extracted using both methods. This provided a reliable comparison base between laboratory aged samples and the field aged samples as leachate from field samples were extracted using the USGSLT method as is intended for a field observation procedure. Therefore, the effects of laboratory aging on CHCC are initially presented in the following section and then in the subsequent section, these results are compared with the results of field aging.

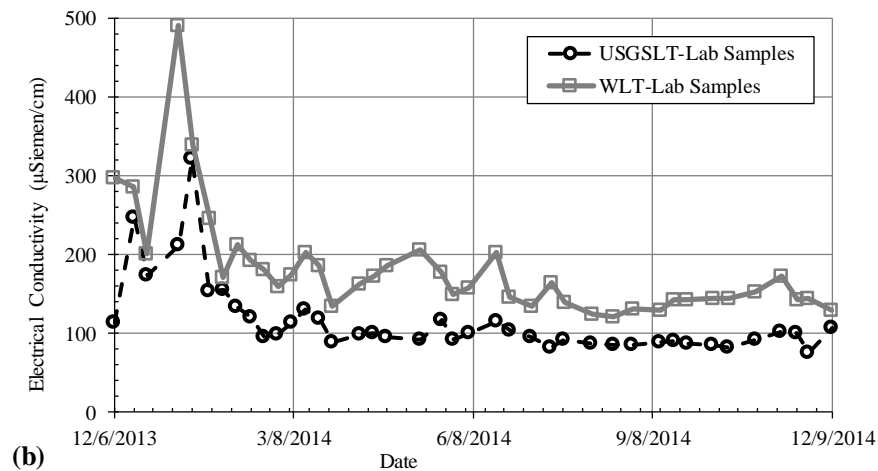
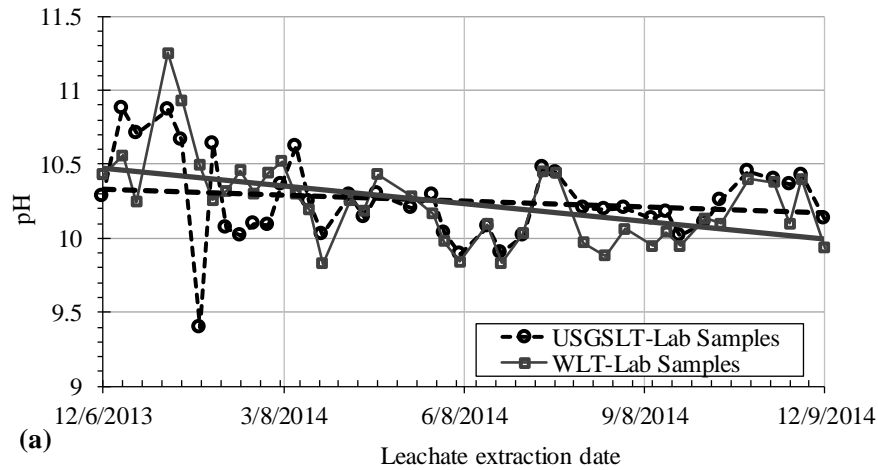
### *Laboratory Aging of CHCC as Determined from Leach Tests*

Changes in pH and EC, which is an indication of ion activity of total dissolved metals in solution, of the leachate extracted using both WLT and USGSLT methods over the twelve months of laboratory aging are depicted in Figure 19. The recorded pH values vary with time with higher fluctuations during the first two months. Changes in pH become relatively smaller as the age of material increases. For instance, the range of measured pH from WLT samples varies between 10.4 and 11.3 (variation of 0.9) during the first two months but this variation becomes limited to the range of 9.9 to 10.3 (variation range of 0.4) during the last month of aging. On the other hand, the change in EC was more evident from 300 to about 120  $\mu\text{Siemens/cm}$  with time (Figure 19b). It should be mentioned that the initially recorded pH range for CHCC material (less than 12) indicates that the CHCC was partially carbonated before the start of the aging procedure.

The changes in total leached concentrations of major elements including aluminum (Al), silicon (Si), iron (Fe), calcium (Ca), magnesium (Mg), and copper (Cu) with aging are presented in Figure 20. As can be seen, Al shows a peak in released concentration at the end of the first month. It is known that Al tends to leach higher at basic conditions at higher pH conditions ( $\text{pH} > 9$ ) (Komonweeraket et al. 2015), which could be the reason to observe higher Al concentration when the pH of the effluent solutions is at the highest ( $\text{pH} = 11.25$ ). Si, on the other hand, shows a completely different behavior with a slight decrease following an immediate increase in the leaching amount by the end of the second month. This can be an indication of the end of the second stage and the beginning of the third stage based on the Suzuki et al. model. After this stage, Si release remains almost constant until the end of the aging process.

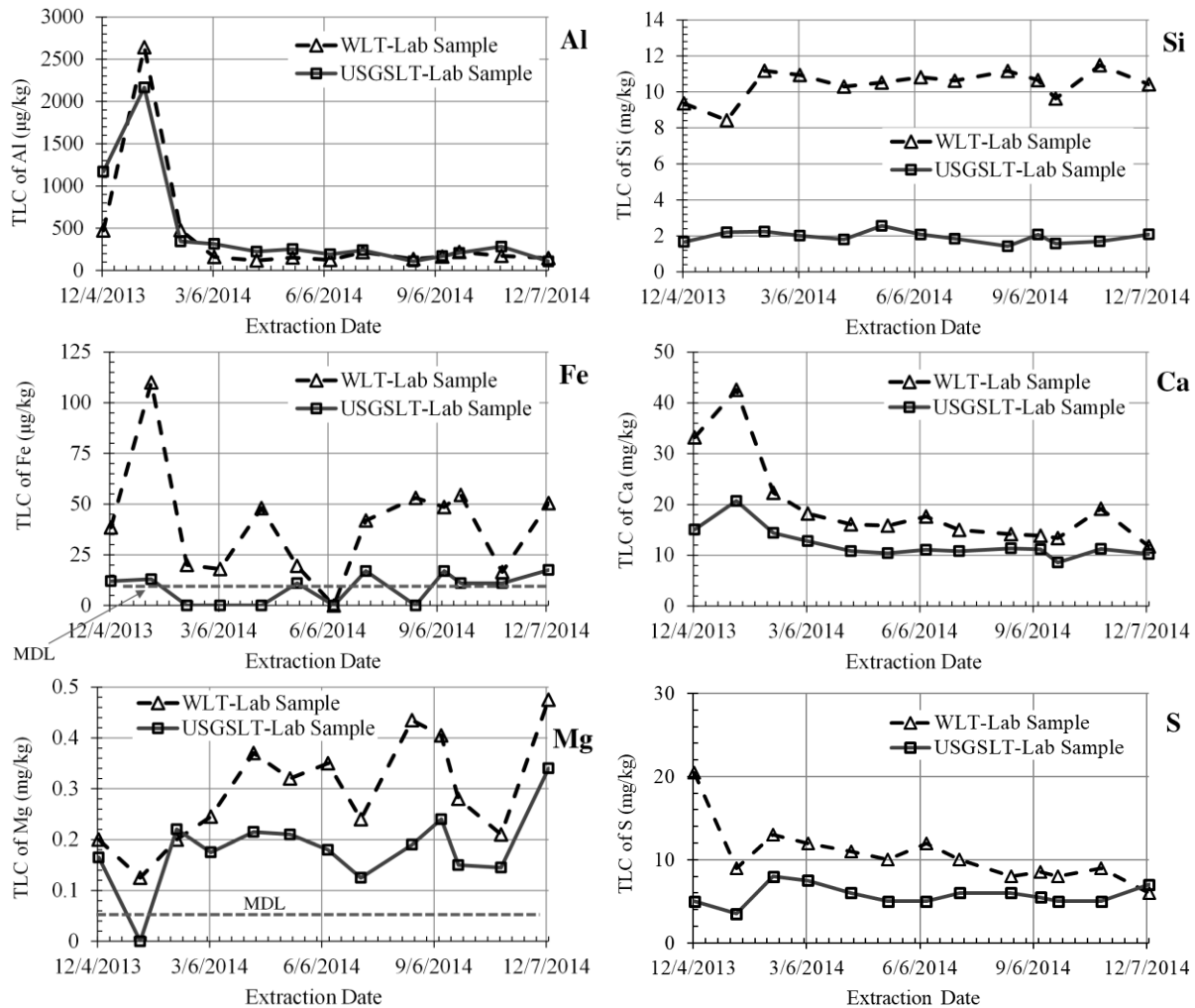
Leaching of Fe doesn't follow any specific trend; however, the high release at the end of the first month can also be observed for Fe. S shows a continuous decrease in TLC with time; although, the rate of decrease for the first 3 months is relatively much higher in comparison to the rest of the aging procedure and decreasing rate slows down afterward. This continued decrease is probably because of the transformation of available sulfur ions into stable minerals. The release of Ca shows a peak by the end of the first month and after that shows a steady

decrease in recorded TLC values. These results are in fair agreement with a model presented by Suzuki et al. (1985) and a high rate of changes in leaching of Ca (and to some extent Al, Fe, and S) might be attributed to the accelerated carbonation rate in the second stage. With the end of this stage and initiation of C-S-H decomposition, the changes in TLC of Ca decreases and approaches to a steady-state. The release of Mg increases with time during the aging process. The content of magnesium in clinker (as MgO) in general is expected to be about 2% (Kurdowski 2014). Taylor (1997) pointed out that magnesium ions show low mobility in pore solution during hydration and C-S-H formation and can form in-situ crystals (e.g. hydrotalcite) within the paste. It can be inferred that the carbonation and C-S-H phase decomposition might enhance the  $Mg^{2+}$  mobility and consequently increase the release in concentration with time.



Note: Each point on these figures represents data obtained at the end of each wet/dry cycle. Straight lines in figure 4a are fitted regression lines in order to show the general trend in changes of pH during the 1 year time period.

**Figure 19. Leachate test results from laboratory samples: changes in (a) pH and (b) EC of leachate**



Note:

- Aluminum (Al), Silicon (Si), Iron (Fe), Calcium (Ca), Magnesium (Mg), and Sulfur (S)
- Vertical axes show the total leached concentration of each element and horizontal axis shows the extraction date of the leachate as part of aging.
- Dashed lines show data from WLT method.
- MDL: Minimum detection limit

**Figure 20. Changes in the leached concentration of major elements with aging**

### *Comparison of USGSLT and WLT Leach Tests on Laboratory Aged CHCC*

A comparison of pH and EC of effluent solutions collected from both WLT and USGSLT during the laboratory aging process can be seen in Figure 19. The ranges for pH values of the leachate extracted using both methods are very close to each other. Unlike the pH, the EC readings reveal that the recorded EC for leachate extracted using the WLT method is considerably higher than the USGSLT method. This means that the dissolved ionic strength for the extracted solution with WLT is higher than USGSLT.

A comparison of leached concentrations of major elements for the duration of the aging test (Figure 20) shows that the leached concentration of these elements obtained from the leachate extracted with both USGSLT and WLT methods from fresh and aged CHCC follow

similar trends. Table 13 presents a statistical analysis of the comparison of the TLC of the elements obtained with both WLT and USGSLT during the 12-month aging period. Overall for all of the elements, TLC obtained from USGSLT method is lower than WLT (except for Al) (i.e.,  $C_{USGSLT}/C_{WLT} < 1$ ). For low concentration ratios such as 0.19 (Si for instance), the results show that in addition to release controlling mechanisms, rate of mass transfer from solid to liquid (or kinetics which is the transport by diffusion inside the solid pores) is a limiting step in element release based on the rate-limiting transport process in solid-liquid soil reactions described by (Sparks, 2003).

**Table 13. Calculated ratio between the measured leached concentration of different elements using USGSLT and WLT methods**

Element	Average $C_{USGS}/C_{WLT}$	Standard Deviation
Al	1.34	0.55
Si	0.19	0.03
Fe	0.37	0.17
Ca	0.67	0.12
Mg	0.66	0.17
S	0.59	0.21
<b>Ionic strength (<math>\mu</math>)</b>	0.64	0.12

Note:

$C_{USGS}$ : Measured concentration extracted using USGSLT method

$C_{WLT}$  : Measured concentration extracted using WLT method

The calculated average ionic strength, which is a direct measurement of the total activity of all dissolved ions, of the solution extracted using USGSLT was about 64% of the one obtained following WLT. Based on the ionic strength calculations (conducted in accordance with Stumm and Morgan 1996), the ionic strength of dissolved Ca and Mg ions consistently takes about 36% of the total ionic strength of the solution (with a standard deviation of 3.6%). This indicates that the overall ion activity of the solution is dominated by these elements especially with Ca because of its high TLC in comparison to any other element ( $>10$  mg/kg). However, for Al and P (not shown here), the ratios between USGSLT and WLT were around (or often higher than) 1. The leaching of aluminum is mainly controlled by the solubility of gibbsite and the release of phosphate is based on surface sorption of phosphate anion (Sparks, 2003). However, phosphate anions may form surface complexes with aluminum sites, which can affect the leached concentration of both phosphorous and aluminum (Sparks 2003). This might be a reason for similar leached concentrations from both extraction methods (i.e., the ratio of  $C_{USGS}/C_{WLT} \approx 1$ ) as the leached concentrations are limited by the complex formation/sorption and are not affected by the time of the agitation.

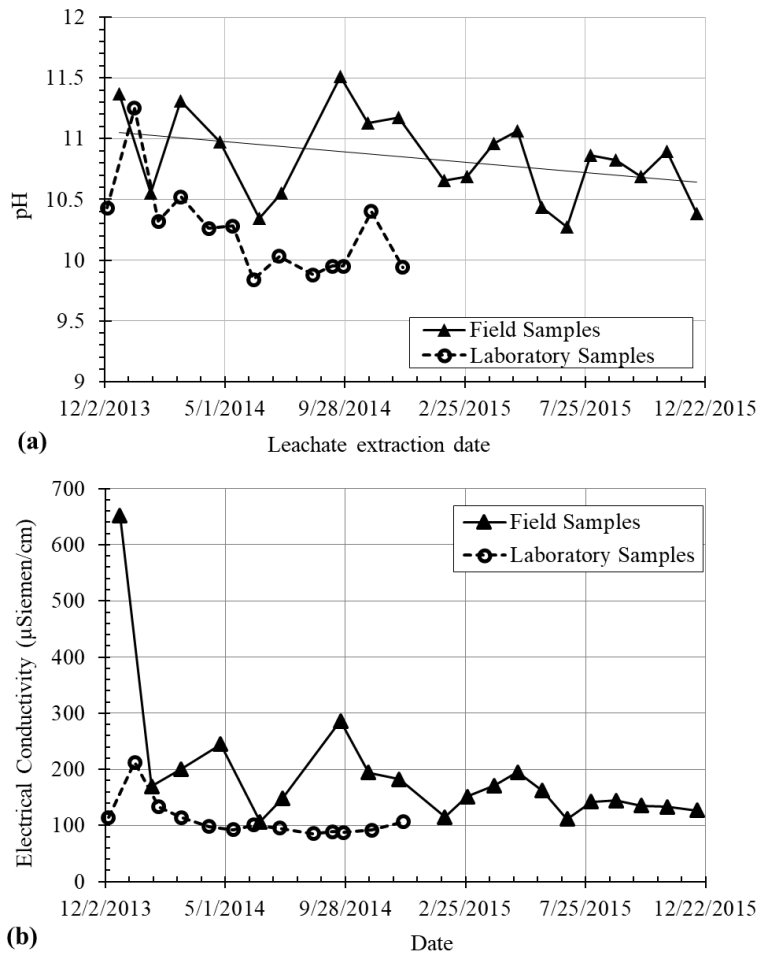
Overall, samples tested with the WLT method showed higher leaching concentrations than the ones tested via USGSLT. Based on this observation, it appears that the time of agitation (5 minutes for USGSLT vs. 18 hours for Batch WLT) may be the main reason for higher dissolved ionic strength in leachate extracted using WLT method.

#### *Comparison of Laboratory and Field Aging*

The comparison of the field and laboratory results could be made based on the results of the leachate samples generated from USGSLT as the WLT procedure was only followed to



evaluate the laboratory samples. Changes in measured pH and EC of the leachate with age from the laboratory and field samples are depicted in Figure 21.



**Figure 21. Changes in leachate chemistry (extracted by using USGSLT method) with aging time from field samples (a) pH and (b) EC**

The data from the field shows fluctuations, which is attributed to the variation in the collected samples on different dates and inherent inhomogeneity of the material. However, despite the existing fluctuation in the recorded pH values throughout the aging, the overall pH values do not show noticeable changes for field aged material. A linear regression line shows a slight decrease in the pH values during two years of aging. However, in the laboratory, the recorded pH values with time decrease a lot more noticeable compared to the pH values from the field even though the aging duration in the field was twice the laboratory. The existing difference between the field and laboratory results is an indication that the CHCC in the laboratory aged more than the CHCC in the field despite the shorter aging duration. Based on the linear regression of the recorded pH values of leachate from field samples, it can be predicted that the field CHCC will reach to the same carbonation level as the laboratory aged CHCC within 3.5 years. When the results from recorded EC values are evaluated (Figure 21b), the EC of the solution in the field decreases drastically during the first month of aging from about 650  $\mu\text{S/cm}$  at the beginning of aging and then stays constant at a level below 300  $\mu\text{S/cm}$  in the upcoming months. This observed trend is also consistent in the laboratory aged material. Overall the results

obtained from the leachate results concur with the results obtained from solid CHCC samples and can be concluded that the aging procedure in the field was much slower than the aging in the laboratory.

## Geochemical Modeling

Geochemical modeling was performed with the chemical analyses of the leachate samples in order to estimate the dominant species of different elements that contribute to the potential of solid-phase precipitate formation. Simply put, the modeling was performed to back-calculate the potential mineral that might have resulted in the observed leachate concentrations.

The modeling is important because some of the elements (e.g. Al, Fe, Si, etc.) can have different oxidation-reduction states and the species existing in the solution are needed to determine which minerals might form and precipitate (Lindsay, 1979). The geochemical modeling is based on equilibrium chemistry, which does not take into consideration the kinetics of reactions and nucleation and crystal formation processes. The calculated precipitations are mainly due to the supersaturation of the solution with respect to related elements and ion activity controlling mechanisms. The results of geochemical modeling are presented in Table 14. In this table, the solid phase precipitation column presents the potential minerals that could form in CHCC based on the dominant species observed in the CHCC leachate. The leachate concentrations used for the geochemical modeling were obtained from the laboratory aging based on the WLT method. The modeling was performed taking into CHCC elemental concentrations of both freshly produced and aged CHCC.

In conclusion, the solid phase precipitate column in Table 14 presents the minerals that could form in the solution. In other words, it is expected that tufaceous deposition composed of all or some of these minerals depending on the super-saturation condition of the solution and nucleation process mechanism. This finding is in agreement with previous research reporting the composition of tufa samples collected from the field (Gupta and Kneller, 1993; Tamirisa, 1993).

**Table 14. Dominant species of specific elements and associated solid phases**

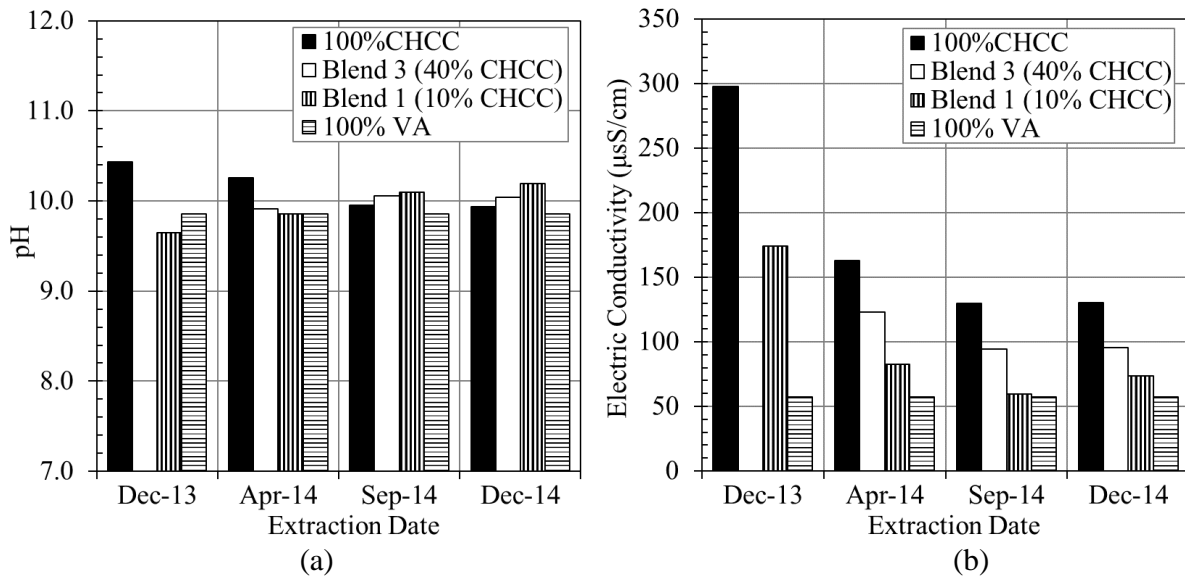
Element	Dominant Species	Solid Phase Precipitation
Al (Alumino-silicates)	Al <sup>3+</sup>	Gibbsite
Si	Si <sup>4+</sup>	Silica (quartz and silica gel)
Fe	Fe <sup>3+</sup>	Hematite $\alpha$ -Fe <sub>2</sub> O <sub>3</sub>
Ca	Ca <sup>2+</sup>	Calcite and dolomite
Mg	Mg <sup>2+</sup>	Dolomite
S	SO <sub>4</sub> <sup>2-</sup>	Gypsum

## Effect of Blending of CHCC with V.A. on Leached Concentrations of Elements

In the previous sections, the changes in CHCC with aging are discussed. In this section, the changes in pH, EC, and TLC of select elements obtained from blends of V.A. and aged CHCC are compared against the results obtained from 100% V.A. and 100% freshly produced and aged CHCC in the laboratory. All of the leachate used in these comparisons was generated based on the WLT procedure. The elements selected for this comparison are the elements typically identified as elements contributing to tufa precipitate formation.

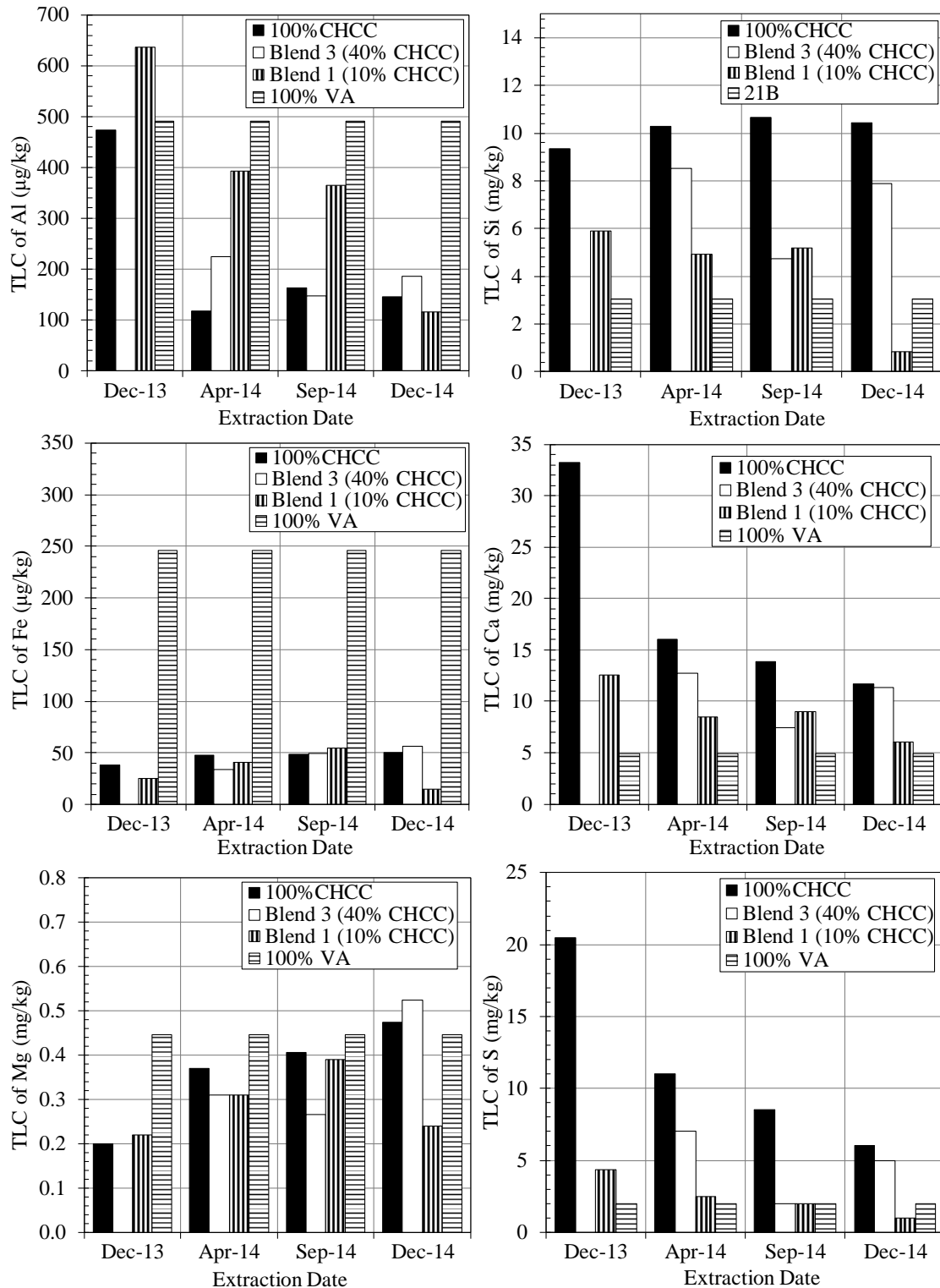
VDOT's TRP members suggested the evaluation of three different blends in this study. In this section two of these blends, one with the lowest CHCC percentage (in this study referred to as blend 1 with 10% CHCC and 90% V.A. by weight) and the one with the highest CHCC percentage (in this study referred to as blend 3 with 40% CHCC + 60% V.A.) are assessed. The main purpose of these tests was to confirm that elements that may cause problems with respect to tufaceous precipitate formation follow a consistent leaching behavior with CHCC and V.A. and blending does not lead to substantial changes in leaching behavior which may be unknown or uncharacterized. The leachate characteristics of CHCC/V.A. blends in comparison to 100% CHCC and 100% V.A. are presented in Figure 22.

Both CHCC and V.A. used in this research have alkaline leachate. The measured pH of the CHCC varied between 9.86 and 10.43 with aging and stayed the same for V.A. as 9.94. The pH of the aged CHCC decreases with time. When the pH of the blends is evaluated, it can be seen that the mixtures of these materials have also alkaline leachate, which is in a similar range for aged CHCC and V.A. (Figure 22a). The effect of blending is even more apparent in the measured ionic strength. Figure 22b shows that EC of leachate from 100% V.A. is much less than 100% CHCC. When the two materials are blended, in all cases blend 1 (with much less CHCC) shows consistently lower EC than blend 3. With an increase in the CHCC amount, the EC of the blend increases. This behavior is expected considering the less active nature of diabase rock in comparison to the CHCC that contains hydrated cement paste.



**Figure 22. Comparison of leachate characteristics of CHCC (non-aged and aged), VA, and their blends (a) pH, (b) EC**

The results of EC show that in general, the release of total metals follows a somewhat linear relation with respect to the CHCC proportion. A similar pattern of behavior can be observed for all the elements contributing to tufa precipitate formation (Figure 23). The release of these elements from blends, in general, fall in between the measured concentration ranges of 100% CHCC and V.A. Theoretically speaking, based on this information, a blend of V.A. and CHCC should produce less tufa than 100% CHCC.



Note: Aluminum (Al), Silicon (Si), Iron (Fe), and Calcium (Ca), Magnesium (Mg), and Sulfur (S)  
**Figure 23. Changes in the leached concentration of elements contributing to tufa precipitation**

## Changes in Geotechnical and Index Properties of CHCC with Aging

Table 15 presents the results of the index properties of the aged CHCC. It can be seen that the specific gravity and water absorption of coarse CHCC did not change with aging (values related to non-aged CHCC are presented in Tables 5 and 6 and are not repeated here). However, for fine CHCC, the specific gravity of aged CHCC is slightly lower and water absorption is slightly higher than the freshly produced CHCC.

This can be attributed to the production of carbonates. The gradation of aged CHCC appears to have more passing 9.5 mm (0.375 in) and 4.75 mm (0.187 in), but the difference for the finer fractions was negligible. The liquid limit test also shows a negligible change between freshly produced CHCC and aged CHCC. One observation that was made during plastic limit tests was that some of the freshly produced CHCC samples had a measurable plastic limit at the beginning and the samples could be rolled out into fine threads; whereas the aged CHCC samples were totally non-plastic. This behavior may be due to the existence of un-hydrated constituents, which are hydrated with time and aging. Compaction characteristics of aged CHCC also do not seem to be changed as a result of aging and carbonation which was expected considering the negligible difference in specific gravity and water absorption of non-aged and aged CHCC.

**Table 15. Changes in the index and physical properties of CHCC with aging**

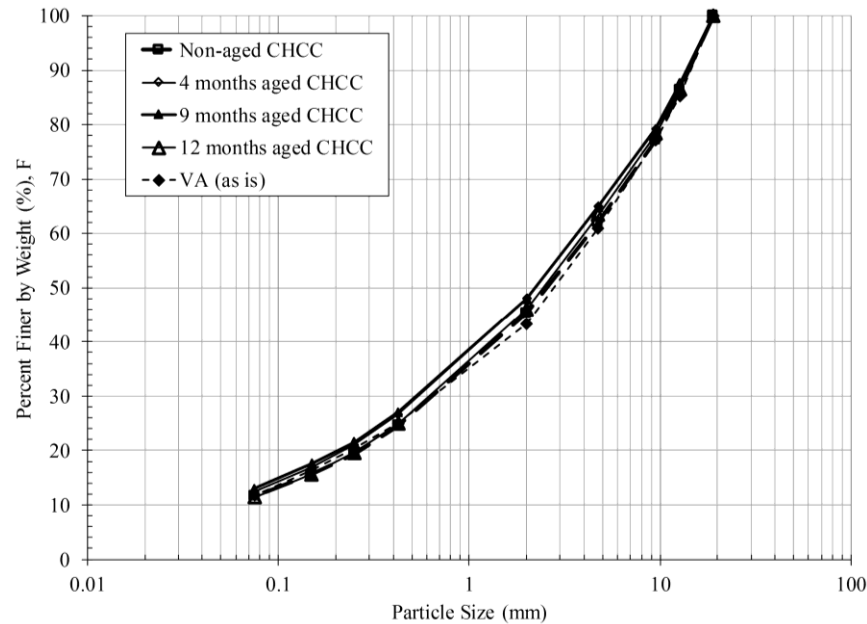
Properties	12 month aged CHCC		
	Number of tests	Average value	Standard Deviation
Specific gravity of Coarse Aggregate (per ASTM C127)			
Apparent Specific Gravity	2	2.77	0.024
Water absorption (%)		4.99	0.001
Specific gravity of Fine Aggregate (per ASTM C128)			
Apparent Specific Gravity	2	2.68	0.141
Water absorption (%)		13.99	0.025
Grain size distribution (per ASTM D422)			
Passing 3/8" (< 9.5mm)	3	86.18	1.720
Passing #4 sieve (< 4.75mm)		52.85	5.860
Passing #10 sieve (< 2mm)		34.43	3.050
Passing #40 sieve (< 0.43mm)		18.22	1.670
Passing #200 sieve (< 0.074mm)		7.73	1.350
Compaction using Standard Effort (per ASTM D698)			
$\omega_{opt}$ (%)	14.30		
$\gamma_{dmax}$ ,kN/m <sup>3</sup> (lb/ft <sup>3</sup> )	19.00 (120.84)		

## Potential of CHCC to Clog the Geotextile Used in VDOT Drainage Systems

### Stage 1: Filtration Performance of CHCC with Nonwoven Geotextile

Grain size distribution and permeability of the CHCC and V.A. used in these tests are presented in Figure 24 and Table 16, respectively. Before the GR tests, all samples have been evaluated for internal stability based on these grain size distributions. The results are presented in Figure 25. All of the samples had uniformity of coefficient greater than 3 ( $C_u > 3$ ) which classified these samples as widely graded (WG) based on a definition presented by (Kenney and

Lau, 1985). A soil is considered as internally stable if the drawn line falls on or above the diagonal stability boundary. As can be seen from Figure 25, CHCC and V.A. samples are somewhat susceptible to internal instability and consequently suffosion. Therefore, some form of particle migration is expected during the GR tests.



**Figure 24. The grain size distribution of used CHCC and V.A. material for GR tests**

**Table 16. Measured permeability of the material**

Material	Void Ratio, $e$	Permeability (cm/s)
CHCC (as-is gradation)	0.275	$4.9 \times 10^{-4}$ to $5.8 \times 10^{-4}$
V.A. (as-is gradation)	0.288	$5.17 \times 10^{-3}$ to $8.64 \times 10^{-3}$

Note: All samples were compacted to 95% of maximum dry density obtained from compaction using standard effort (per ASTM D698)

The results of the GR tests are summarized in Figure 26. The values presented are recorded when the system had reached stability. The definition of stability is provided in the Results and Discussion section for the literature review (pg. 22 and 23 of this report). The relevant applied gradient for base/subbase application and corresponding test values are highlighted with a rectangle in both of these graphs.

Figure 26 presents the GR test results as they relate to  $K_R$  values. All of the  $K_R$  values from CHCC samples as they relate to the base/subbase applications fall below 3 except one test result (4M-CHCC-1). This indicates that the CHCC is not clogging the geotextile based on the criterion suggested by Aydilek and Edil (2003). The overall trends show an increase in  $K_R$  value with increasing the applied head. This is expected because increasing the applied head leads to the increase in seepage force and consequently, more particles move downward. However, increasing the applied pressure head and seepage force can also cause flushing effect on the fines that are already entrapped within the geotextile filaments. With the increase in applied head, higher  $K_R$  values are observed. In some instances, the outflow became cloudy immediately after

changing the applied head, indicating such an effect. Therefore, for these tests, sometimes the  $K_R$  values reduced with an increase in the applied head.

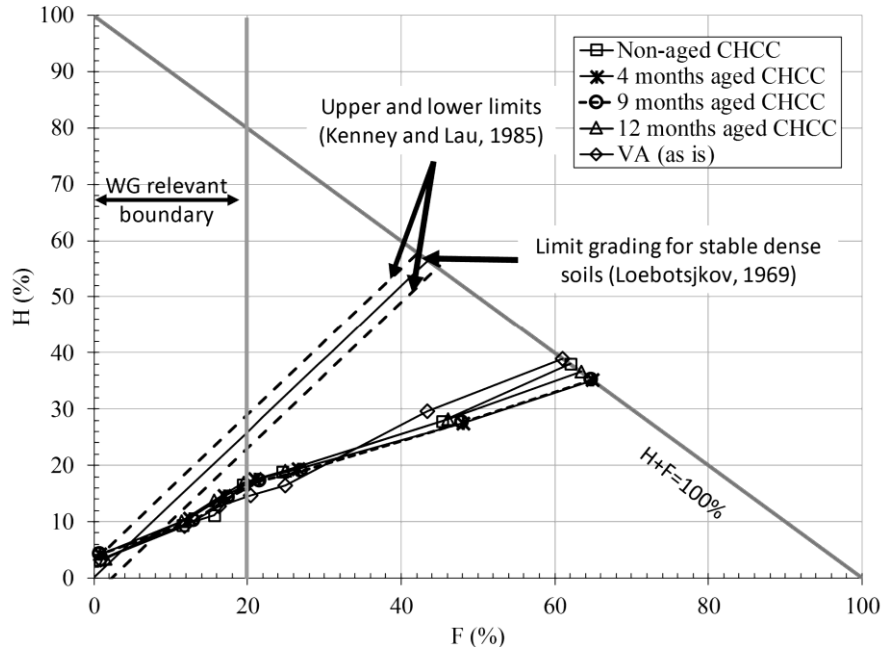


Figure 25. Internal stability of CHCC and V.A. used in GR tests

- |                  |                  |             |              |
|------------------|------------------|-------------|--------------|
| ⊠ V.A. (as is)-1 | ⊞ V.A. (as is)-2 | ● NA-CHCC-1 | □ NA-CHCC-2  |
| ◇ NA-CHCC-3      | ● 4M-CHCC-1      | ■ 4M-CHCC-2 | ◆ 4M-CHCC-3  |
| ▲ 4M-CHCC-4      | ▲ 9M-CHCC-1      | ▲ 9M-CHCC-2 | ✕ 12M-CHCC-1 |
| ✕ 12M-CHCC-2     | ⊕ 12M-CHCC-3     |             |              |

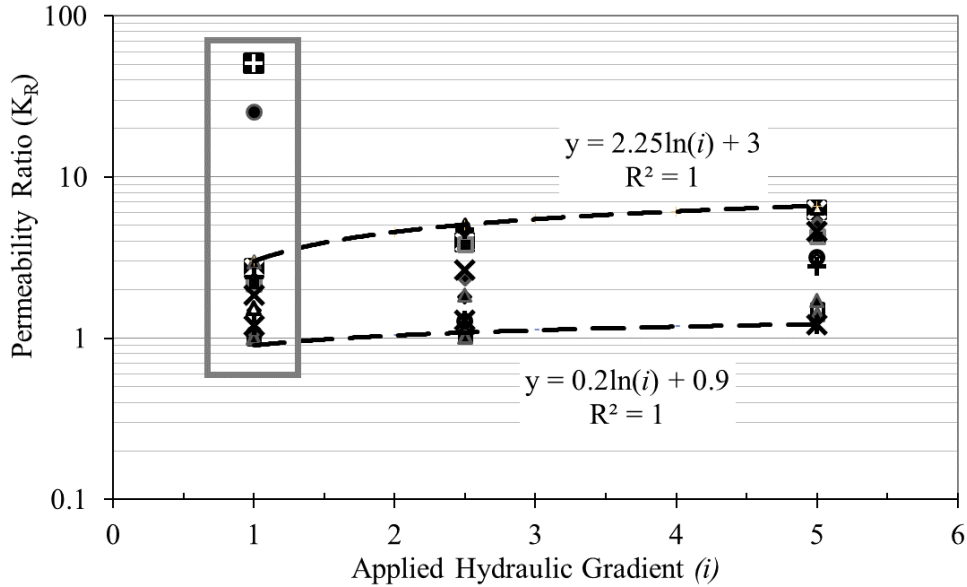


Figure 26. Measured permeability ratio from GR tests vs. applied gradient

Although the obtained  $K_R$  values are close to each other and fit into a region that can be defined with upper and lower envelopes (as shown in Figure 26), the  $K_R$  values do not follow a similar behavior for repeat tests. For instance,  $K_R$  values for 4-month aged CHCC test 1 (4M-CHCC-1) and V.A. test 2 (V.A. (as-is)-2) are 25 and 51 respectively, which based on the criteria defined by Aydilek and Edil (2003) means a totally clogged system. However, the measured permeability of the soil/geotextile system on these tests indicates a scenario far from being clogged because the permeability values range between  $9.23 \times 10^{-4}$  and  $2.31 \times 10^{-3}$  cm/s. The same observation is true for all tests performed in this study, meaning that at no circumstances, the tests reached a totally clogged condition (i.e., no-flow condition).

One possible reason for observing inconsistent behavior from  $K_R$  values can be based on the fact that  $K_R$  is calculated using manometer readings within the soil specimen (manometers A1, A2, B1 and B2 as shown in Figure 6). Although utmost care was practiced during sample preparation and placement, often it was observed that manometers at the same elevation did not read the same pressure head. The manometer ports are installed on the plexiglass wall of the GR chamber and show the pressure head at a point within the immediate vicinity of the port. This makes the manometers vulnerable to detect any potential sidewall leakage that may occur away from these ports. The term sidewall leakage refers to water finding a path to travel adjacent to the side of the chamber as opposed to going through the soil. Although no visible sidewall leakage was observed in the GR tests performed for this study, if it were to occur (even a very minor one), this can affect the pressure head reading. This may lead to zero head loss readings between manometers installed in different elevations. However, it may have little effect on the overall flow condition in the chamber. Another possible reason for observing inconsistent manometer readings and consequently  $K_R$  values can be attributed to existing of non-Darcian flow regimes (transitional and turbulent) which definitely affects the distribution of head-loss throughout the specimen (Scheidegger, 1974).

Another way to evaluate the GR test results is to compare the permeability of soil/geotextile system ( $K_{system}$ ) from each test as opposed to  $K_R$  values as suggested by Aydilek and Edil (2003). Figure 27 presents the results based on  $K_{system}$ , which is determined using only the calculated head losses between the top and bottom chambers (manometers U and D, equation 10). This approach is believed to be more representative of the flow condition in the system than  $K_R$  as long as no side-wall leakage occurs from the sides of the geotextile because both the upper and lower chambers are filled only with water. The geotextile samples were cut with a diameter equal to the outer diameter of the plexiglass chamber (16.6mm). This geotextile sample placed between the perforated steel sheet and plexiglass wall and tightened to prevent the creation of any flow channel in the joint. Considering these observations, it is suggested that  $K_R$  alone is not sufficient in order to evaluate the filtration performance of soil and geotextile using GR tests and  $K_{system}$  values should also be used as part of this evaluation.

The calculated  $K_{system}$  values (as presented in Figure 27) for all tests at  $i=1$  are higher than  $7 \times 10^{-4}$  cm/s. The lowest system permeability observed from these tests belongs to sample 9M-CHCC-2 at  $i=5$  which is in the order of  $10^{-4}$  cm/s. It should be mentioned that these values are in the range of permeability values for clean sand and gravels (Fetter, 2000). Nonlinear regression lines are fitted for the upper and lower bound of the data from CHCC (dashed lines). These regression lines show a general trend applicable to CHCC/geotextile material behavior in



terms of showing the degree of reduction in  $K_{\text{system}}$  that occurs with an increase in applied gradients and also an estimation of CHCC/geotextile system permeability for higher applied gradients.

Table 17 presents the measured reductions in permittivity ( $R_{\psi}$ ) and pore size distribution ( $R_{\text{PSD}}$ ) of geotextiles as well as the corresponding  $K_R$  and  $K_{\text{system}}$  values from each test. Reduction of the permittivity of each of the geotextile samples is the ratio between the permittivity of geotextile after filtration to the permittivity of virgin geotextile. The comparison of these values shows that tests with very high  $K_R$  values do not necessarily experience a higher loss of serviceability of the geotextile.

The role of different pore sizes ( $O_x$ ) in clogging resistance of nonwoven geotextile has been evaluated in the past and different researchers tried to identify a single pore size or a range of pore sizes that determine the filtration performance of geotextile (Millar et al., 1980; Carroll, 1983; Christopher and Holtz, 1985; Fischer et al., 1990; Williams and Luettich, 1990; Christopher and Fischer, 1992; Luettich et al., 1992). As a result, different geotextile pore sizes were suggested by different researchers throughout the years to select the most suitable geotextile. For this study, the reduction of the pore size distribution ( $R_{\text{PSD}}$ ) is determined by obtaining the arithmetic average of the pore sizes that were previously identified by other researchers as effective in clogging resistance of geotextiles. These pore sizes are  $O_{95}$ ,  $O_{50}$ , and  $O_{15}$  as shown in Equation 11.

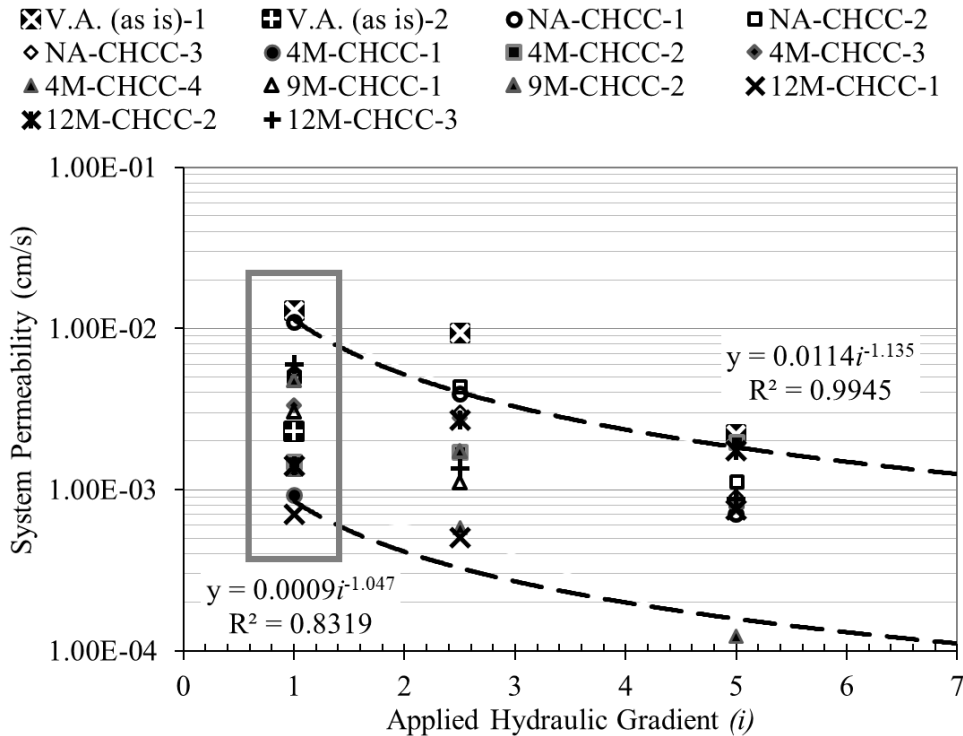


Figure 27. Measured permeability of soil/geotextile systems from GR tests vs. applied gradient

**Table 17. Summary of GR test results at the end of tests**

Sample	Test ID	Void Ratio	$K_R$	$k_{\text{system}}$ ( $\times 10^{-3} \text{cm/s}$ )	$R_\psi$	$R_{\text{PSD}}$
Non aged CHCC ( $>4.75 \text{mm}$ )	NA-CHCC-C	0.611	1	2.06	NA	0.83
Non aged CHCC	NA-CHCC-1	0.271	3.16	0.70	NA	0.76
	NA-CHCC-2	0.292	1.52	1.12	NA	0.73
	NA-CHCC-3	0.3	3.07	0.91	0.73	NA
4 month aged CHCC	4M CHCC-1	0.287	25.13	0.92	0.82	NA
	4M CHCC-2	0.284	4.31	1.96	NA	0.75
	4M CHCC-3	0.286	5.1	0.83	0.42	NA
	4M CHCC-4	0.313	1.72	0.12	NA	NA
9 month aged CHCC	9M CHCC-1	0.293	6.43	0.86	NA	0.71
	9M CHCC-2	0.29	1.41	0.85	0.6	NA
12 month aged CHCC	12M CHCC-1	0.27	4.58	0.75	0.75	NA
	12M CHCC-2	0.277	1.21	1.75	NA	0.78
	12M CHCC-3	0.279	2.8	0.88	NA	NA
V.A.	V.A. (as is)-1	0.283	6.28	2.19	0.67	NA
	V.A. (as is)-2	0.288	51	2.31	NA	0.63

Note: NA=Not analyzed  
 $R_{\text{PSD}}$  is determined from image analyses.

$$R_{\text{PSD}} = (O_{95} + 2O_{50} + O_{15}) / 4 \quad (\text{Eq. 12})$$

where  $O_x$  (mm) is pore size of geotextile that x% of pore sizes are smaller than that specific pore size.

When both the  $R_\psi$  and  $R_{\text{PSD}}$  considered, geotextile samples tested with both CHCC and V.A. experienced about 30 to 40% reduction in their serviceability (Table 17). However, it should be kept in mind that the permeability of geotextile is typically more than 10 times (in this instance 40 times) higher than the permeability of soil (Holtz et al., 1998; Koerner, 2005). Therefore, this 30 to 40% reduction does not result in a condition that is worse than the condition if the filtration was designed without a geotextile (pure soil). The highest reduction in geotextile serviceability is recorded from the test 4M CHCC-3, in which the  $R_\psi$  shows a reduction of about 60%. Even for this sample, the measured  $K_{\text{system}}$  is in the order of  $10^{-3} \text{cm/s}$  at the end of the test (which is based on  $i = 5$ , much higher hydraulic gradient than what is expected from a base/subbase application). It can be concluded that, despite the detected reduction in the serviceability of the geotextile, the overall filtration performance of the system is still within the range that would be considered acceptable (i.e.,  $K_{\text{system}} \approx 10^{-3} \text{cm/s}$ ). Another observation is that the reduction in serviceability of the geotextile appears to occur similarly for both CHCC and V.A. Therefore, under the conditions that the GR tests simulate, the clogging phenomena in geotextile with CHCC is not much different than the geotextile with V.A.

#### *Evaluation of Existing Criteria for Clogging Resistance of Geotextile*

An evaluation of the GR test results to assess the geotextile clogging is also done by comparing the observations from GR tests with the existing clogging criteria in the literature. The available criteria in the literature and their rate of success are presented in Table 18. The rate

of success is defined herein as the ability of the specific criterion from the literature to successfully estimate the behavior of the tests observed from the GR tests conducted in this study.

**Table 18. Criteria for clogging resistance**

Reference	Criterion	Rate of success
Fischer et al. (1990)	$O_{15}/D_{15} \geq 0.8-1.2$	92%
Millar et al. (1980) & Fischer (1994)	$O_{50}/D_{15} \geq 1$	92%
Holtz et al. (1998)	$O_{95}/D_{15} \geq 3$	70%

Note: Percentages of the rate of success presented are determined from Figure 28.

Although the values presented in Table 18 provide an opportunity to quickly assess the suitability of the soil and geotextile combination, many researchers including Williams and Anwar Abouzakhm (1989) and Holtz et al. (1998) suggested that the empirical relationships not to be used in cases of severe conditions or *high importance* of the structure. Instead, testing the filtration performance of soil and geotextile in the laboratory using tests such as GR test is suggested (as was done in this study).

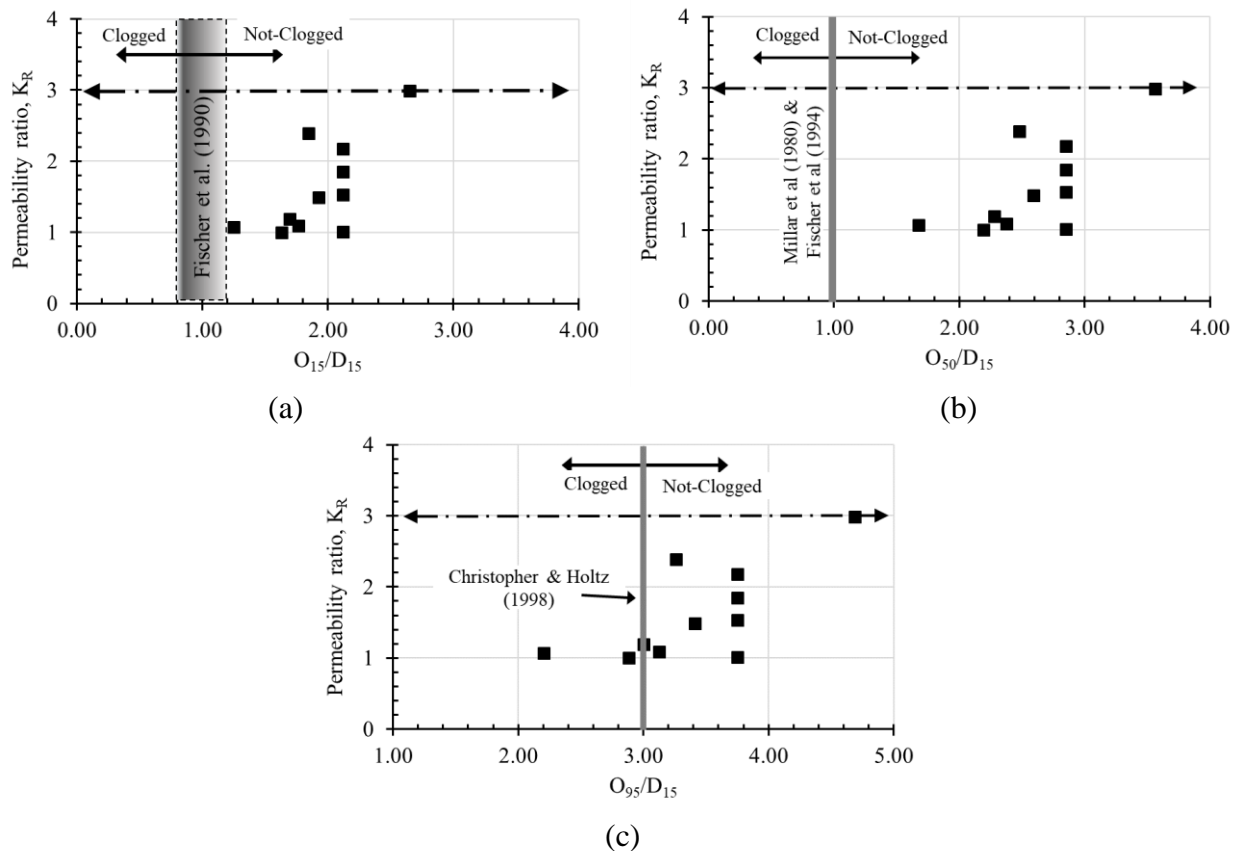
Figure 28 is created to relate the empirical criteria presented in Table 18 with the results obtained from GR tests in this study. A relationship between the  $K_R$  values obtained from GR tests in this study and each of the  $O_x/D_y$  values corresponding to the test conditions are plotted.  $O_x$  values represent the geotextile pore size opening where a specific percentage of pore size (x) of geotextile is smaller than that specific opening size.  $D_y$  values represent the soil grain size where a specific percentage of grain size (y) of soil is smaller than that specific grain size. Both the non-aged and aged CHCC and V.A. test results could be combined in this figure because of the similarities between the grain size distributions of all of these materials (see Figure 24).

Figure 28 shows the previously suggested  $K_R$  criteria by Aydilek and Edil (2003) (i.e.,  $K_R \geq 3$  indicates a clogged system) as well as the boundary defined by other researchers as stated in Table 18. When all of the test results that are within the “not-clogged” zone are compared against the results within the “clogged” zone, it appears that in all empirical relationships shown in Table 18, there are cases that are falsely identified as “clogged”. This shows the importance of performing the actual GR tests and the complexities of determining what is considered “clogged”.

## Stage 2: Effect of Fines Content on Filtration Performance of Soil/Geotextile System

In stage 1 tests, all samples were evaluated based on the as-is gradation, which presents the results based on specific conditions. During these tests, it was observed that one of the V.A. tests showed a very large decrease in  $K_R$  compared to the rest of the tests performed (see Figure 26). This observation triggered the need to perform a parametric study to evaluate the effects of fines (particles smaller than 75  $\mu\text{m}$ ) on filtration performance of base aggregate and nonwoven geotextile system. The main objective of the tests performed in this stage was to identify the threshold of fines in aggregate that VDOT should consider when using geotextiles in the base/subbase layers for drainage. Although tests were only performed with V.A. in this parametric study, the grain size distribution of the samples was selected based on the average gradation of as-is CHCC collected from the field (Figure 24) except the percent fines content.

The fine contents were varied as 5%, 7.7%, 9%, 11% and 13% (Figure 29). Selection of this gradation also makes the findings applicable to the CHCC material as well.



**Figure 28. Evaluation of the rate of success for existing criteria for clogging resistivity of geotextile based on  $K_R < 3$  (a) Fischer et al. (1990) (b) Millar et al. (1980) & Fischer (1994), and (c) Holtz et al. (1998)**

The first set of tests performed in this stage included samples with 5 and 7.7% fines content with relative compaction of 95% (similar to the CHCC tests performed in Stage 1 tests). However, extensive side-wall leakage was observed in the chambers with the 5% fines content. As a result, these tests and all other tests in this stage were repeated with a relative compaction of 100%. Figure 30 presents the results of the GR tests with an applied gradient of 1 (relevant to the subbase/base application). Figure 30a shows that when samples are prepared with relative compaction of 100%, in all cases the  $K_R$  values stay close to 3 or below. However, with relative compaction of 95%, for samples with 9% or higher fines content the  $K_R$  values start to become much larger than 3. Figure 30b shows that regardless of the relative compaction used, as the fines content increases, the  $K_{system}$  starts to reduce systematically. This change becomes more drastic when the fines content of the samples exceeds 9%.

Figure 31 presents the results of the same GR tests at the end of the tests when the applied gradient was 5. The results are consistent with the observations in Figure 30. Once the amount of fines content exceeds 9%, a visible drop occurs in  $K_{system}$  and this behavior is consistent for samples with both relative compacctions.

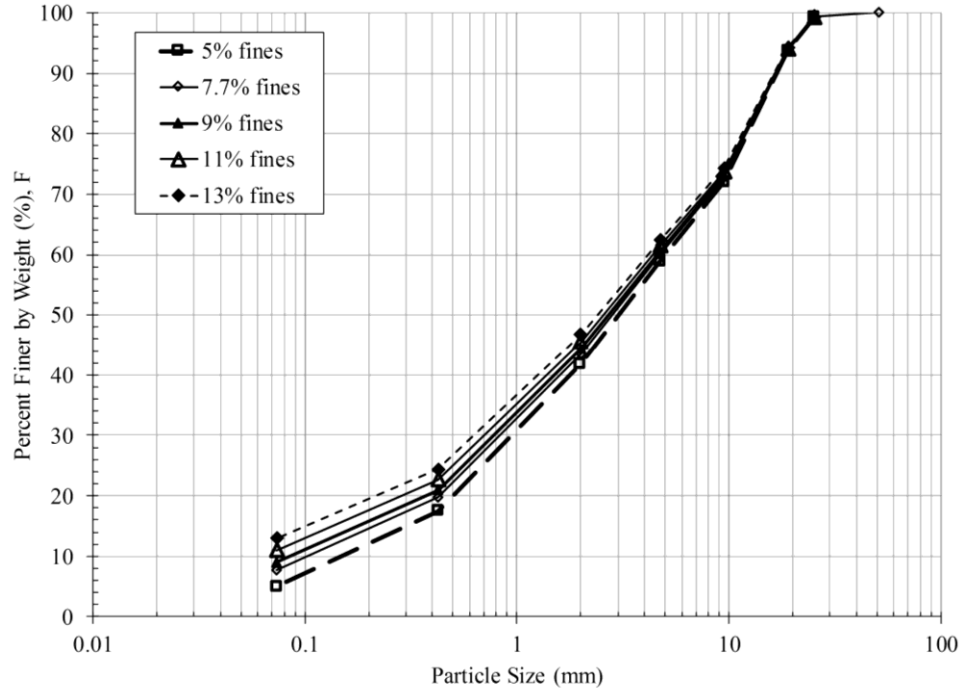


Figure 29. Grain size distribution of samples used for determining fines content threshold from GR tests

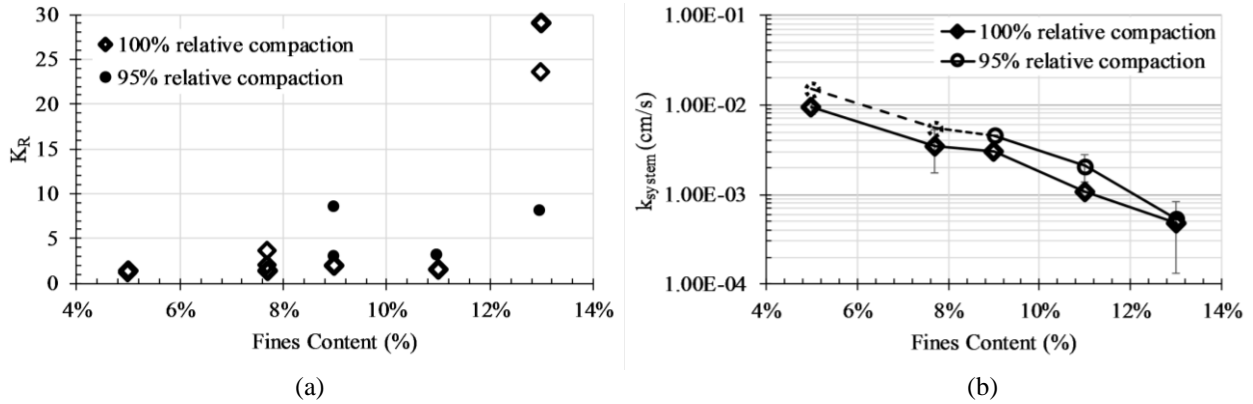


Figure 30. Summary of GR tests with changes in fines content for applied gradient (i) of 1 (a)  $K_R$  vs. Fines content, and (b)  $k_{system}$  vs. Fines content

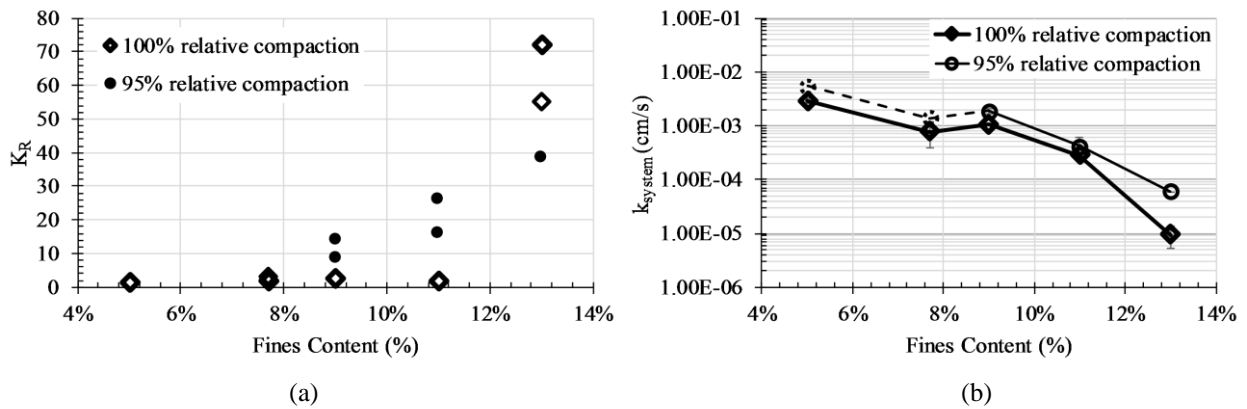


Figure 31. Summary of GR tests with changes in fines content for applied gradient (i) of 5 (a)  $K_R$  vs. Fines content, and (b)  $k_{system}$  vs. Fines content

As mentioned previously, the tests performed with relative compaction of 95% with 5% fines content showed significant side-wall leakage. Even though not as severe, the tests performed at 7.7% also showed some problems. Therefore no results from these tests could be presented in Figures 29 and 30. However, based on the measured  $K_{\text{system}}$  for all other tests, estimation of the test results are drawn on Figures 29b and 30b as dashed lines.

The findings of the tests in Stage 2 may be summarized as:

- The percent of fines content has an effect on the permeability of the system. As the percent fines content increases, the  $K_{\text{system}}$  decreases.
- When  $K_R$  and  $K_{\text{system}}$  are evaluated together, for VDOT 21 aggregate gradation, as long as the fines content of aggregates were kept 9% or below, the system appears to result in acceptable clogging behavior.
- Samples with 5 and 7.7% prepared with relative compaction of 95% in GR tests were problematic. However, this may be due to the limitation of the GR test set-up. It is strongly advised that the performance of the aggregates compacted with relative compaction of 95% is validated in the field before such target compaction is allowed.

### Stage 3: Effect of Filtration Performance of Different Blends of CHCC and V.A.

For this stage, three blends of CHCC and V.A. were prepared with the fines content of 7.7%. The 7.7% fines content was selected because that is the average percent fines of CHCC of the collected samples from the field as previously discussed. All samples were prepared with a relative compaction of 100% as determined from the parametric study in Stage 2. Table 19 summarizes the test results of CHCC and V.A. The percentage of CHCC in each blend was determined based on the conversations with VDOT's TRP members. All blends were created based on percentages determined by weight. When the results are evaluated based on  $K_R$ , in all tests the values are below the threshold that was established by Aydilek and Edil (2003). Table 19 also shows that as the percentage of the CHCC increases in the blend, the  $K_{\text{system}}$  values decrease. However, when the results are evaluated based on both  $K_R$  and  $K_{\text{system}}$ , in all cases the filtration performances are determined as "acceptable".

**Table 19. GR test results with different blends of CHCC and V.A.**

Applied gradient	Blend 1 (10%CHCC)		Blend 2 (20%CHCC)		Blend 3 (40%CHCC)	
	$K_R$	$k_{\text{system}}$ ( $\times 10^{-3}\text{cm/s}$ )	$K_R$	$k_{\text{system}}$ ( $\times 10^{-3}\text{cm/s}$ )	$K_R$	$k_{\text{system}}$ ( $\times 10^{-3}\text{cm/s}$ )
1	2.39	2.73	2.08	3.33	0.98	4.44
2.5	1.49	2.32	3.17	1.27	2.08	5.70
5	11.40	0.27	2.31	1.27	1.98	6.51

### Limitations of the Findings from GR Tests

GR tests provide an opportunity to directly evaluate the drainage performance of the soil/geotextile systems. However, these evaluations are performed based on specific test conditions. One of the most important factors of these tests includes the fact that GR test chambers are closed to the atmosphere and consequently atmosphere  $\text{CO}_2$ . Based on the previous

studies, the major component of the collected tufaceous depositions from the CHCC material (over 55% of the soluble portion) consists of carbonates (Tamirisa, 1993). Therefore, it should be expected that the absence of CO<sub>2</sub> in the chambers or the very low amount of dissolved CO<sub>2</sub> in the inlet water will lead to negligible precipitation of any carbonate minerals. To confirm the lack of any chemical precipitation, during the GR tests the chemistry of inlet and outlet water reservoirs were monitored for Eh, pH, and EC. The results showed that for all measured values, the results from the inlet and outlet water was very close to each other. This observation confirms that the lack of any major chemical activity during the GR tests. One of the other reasons for the lack of chemical activity could be because the GR tests are performed with constant flow through the chambers and consequently very high liquid to solid ratio of the leachate. Therefore GR tests should be viewed as a good indicator to evaluate the physical phenomena but not for the chemical phenomena. However, GR tests are essential to determine the degree of reduction in the serviceability of the soil/geotextile systems.

## CONCLUSIONS

- *Documentation of the production of CHCC after the concrete is hauled to a plant/facility clearly shows that concrete that is recycled typically comes from many different and variable sources.*
- *The variability of the physical properties of CHCC from a given facility after the production appears to be reasonable indicating that during production the producer can implement the necessary quality control methods to control the range of grain size within each stockpile.*
- *The variability of the chemical properties of CHCC from a given stockpile may be evaluated by extracting leachate from CHCC using the USGS field leachate extraction method.*
- *CHCC is a non-plastic material and does not meet the VDOT requirements for LL unless it is only mixed with V.A. at 10% by weight (i.e., 90% V.A.). However, the relevance of performing Atterberg limit tests on CHCC is not clear.*
- *The grain size distribution of CHCC does not change after the Standard and Vibratory compaction tests.*
- *The previous literature on the use of CHCC over geotextile is limited and inconclusive as it relates to the clogging of geotextile due to calcareous precipitation over the geotextile. However, the occurrence of precipitation and crystallization of calcareous tufa from CHCC leachate due to the high release of alkali metals under the right conditions is always a possibility. As such, the potential for precipitation is also shown and characterized using geochemical analyses in this study.*
- *The calcareous precipitates potential appears to be significantly reduced by blending CHCC and V.A.*

- *In the course of this study, no evidence was found that the occurrence of physical clogging (migration of fines) or chemical clogging (precipitate formation and deposition in the geotextile) alone or together may lead to the extensive reduction of filtration capacity of the geotextile and loss of serviceability of the CHCC/geotextile system.*
- *The reduction in serviceability of geotextile when used against the CHCC, V.A., and various blends appear to be at a reasonable level (the system permeability is similar to sandy soils) as long as the fines content is kept under 9%.*
- *The grain size distribution of CHCC or the blends of CHCC/V.A. can be designed to minimize the migration of fines on to the surface of geotextile when the material gets wet. Only a 30 to 40% reduction in geotextile permittivity is observed in this study due to the physical migration of fines; however, it is very evident that the selection of the appropriate geotextile is also crucial for the ability of the CHCC/geotextile system to operate as intended. The tested geotextile in this study was selected to have a permeability at least 10 times higher than the tested CHCC. Therefore, the observed reduction in geotextile filtration capacity did not lead to an incompatible CHCC/geotextile filter system.*
- *Stockpiling CHCC after production does not appear to adversely affect the physical properties or drastically alter the hydraulic characteristic of the CHCC. However, the potential of precipitating solid phases from CHCC reduces with the age of the material as the carbonation process contributes to the lower pH of the leachate and stabilization of constituents. Moreover, the dissolution/re-precipitation mechanism that governs these solid-phase formations is not affected by the carbonation process and the thermodynamic model can be used to estimate the Tufa formation from CHCC at any age.*
- *When the fines content of the material placed over the geotextile used in the edgedrain exceeds 9% as determined from the particles passing No. 200 U.S. sieve size, the permeability of the system may be reduced.*

## **RECOMMENDATIONS**

1. *Neither particulate deposition nor chemical precipitation was found to reduce the filtering capacity of the geotextile; however, because of the limitations of the study, VTRC should initiate a field demonstration to construct an actual size base course from the blend of CHCC and V.A. and an underdrain system with specific geotextile evaluated in this study. The purpose of the field demonstration should be to measure specifically the effect of wet and dry cycles (unsaturated condition) on the loss of serviceability of edgedrains used adjacent to 100% CHCC, 100% V.A., and different blends of them in order to confirm the theoretical findings based on thermodynamic calculations.*

Tentative recommendations to be considered and evaluated during the course of the field demonstration project are:



- *The base materials, CHCC, V.A., and mixtures thereof should conform to the 21B gradation.* This is to ensure that the fines content does not exceed 9% passing the No. 200 sieve.
- *The maximum CHCC fraction in base materials should be limited to 40% by mass.* This will limit the concentration of chemical species in leachate thus minimizing the potential for mineral precipitation.
- *Establish a protocol for sampling and testing stockpiled CHCC using the USGS Filed Leach Test. Recommend a maximum pH value for the test leachate that indicates the CHCC is acceptable for use in base material.* This will minimize the potential for carbonate precipitation from the leachate.

## **IMPLEMENTATION AND BENEFITS**

### **Implementation**

The work described in Recommendation 1 has already begun: VTRC and the TRP defined a follow-up research project to design and construct a field demonstration, and this project is already underway. Construction of the field study site is expected to be completed in the spring of 2021 and monitoring will begin immediately thereafter.

### **Benefits**

At the conclusion of the field study, the necessary information will be available for VDOT's Materials Division to propose revisions to the specification regarding the use of CHCC as base/subbase material in proximity to geotextile fabrics in drainage items. This has the potential of increasing the use of available aggregate materials that will improve the sustainability of the transportation infrastructure.

## **ACKNOWLEDGMENTS**

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