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Effect of reaction temperature and time on the formation of calcite precipitation of recycled concrete aggregate (RCA) for drainage applications

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Abstract. Recycled concrete aggregate (RCA) is widely used as a construction material in road construction, concrete structures, embankments, etc. However, it has been reported that calcite ($CaCO_3$) precipitation from RCA can be a cause of clogging when used in drainage applications. An accelerated calcite precipitation (ACP) procedure has been devised to evaluate the long-term geochemical performance of RCA in subsurface drainage systems. While the ACP procedure was useful for the French Drain application, there remained opportunities for improvement. In this study, key factors that control the formation of calcite precipitation were quantitatively evaluated, and the results were used to improve the current prototype ACP method. A laboratory parametric study was carried out by investigating the effects of reaction temperature and time on the formation of calcite precipitation of RCA, with determining an optimum reaction temperature and time which maximizes calcite precipitation. The improved ACP procedure was then applied to RCA samples that were graded for Type I Underdrain application, to compare the calcite precipitation. Two key findings are (1) that calcite precipitation can be maximized with the optimum heating temperature (75°C) and time (17 hours), and (2) the potential for calcite precipitation from RCA is not as significant as for limestone. With the improved ACP procedure, the total amount of calcite precipitation from RCAs within the life cycle of a drain system can be determined when RCAs from different sources are used as pipe backfill materials in a drain system.

Keywords: calcite precipitation; clogging; french drain; recycled concrete aggregate (RCA)

1. Introduction

Recycled concrete aggregate (RCA) is nowadays considered as one of most popular substitutes of virgin (natural) aggregate in construction sectors including embankments, roadbeds, asphalt and concrete pavements (Brasileiro *et al.* 2016, Mikulica and Hela 2018, Silva *et al.* 2014, Meddah 2017, Verian *et al.* 2018, Behera *et al.* 2014, de Brito *et al.* 2016). Reuse of recycling construction and demolition waste in the production of recycled aggregate concrete is an attractive approach in terms of environment and economy. Recycling concrete involves a relatively simple process (Tam 2008). It includes the process of breaking, removing, and crushing existing concrete into a material with a specified size and quality. Fig. 1 shows a general flow chart of the manufacturing processes of RCA.

It describes the total process steps of RCA recycling from construction waste to RCA stockpiling. From the demolition sites, demolished concretes are transported to a local construction and demolition (C&D) waste recycling facility for primary and secondary crushing, magnetic separation, manual removing of metallic remains, and screening. See ACI 555 (ACI 555R-01) for more information on processing old concrete into recycled concrete aggregates. The quality of concrete with RCA is very dependent on the quality of the recycled material used. Reinforcing steel and other embedded items, if any, must be removed, and care must be taken to prevent contamination by other materials that can be troublesome, such as asphalt, soil and clay balls, chlorides, glass, gypsum board, sealants, paper, plaster, wood, and roofing materials, etc.

RCA is less expensive and exhibits similar physical and mechanical properties to regular virgin aggregates. For instance, many reports have illustrated that RCA has a higher resilient modulus, higher shear strength, lower plastic strain, lower permanent deformation, and higher California Bearing Ratio (CBR) than virgin aggregate (Chakradhara *et al.* 2011, Kou and Poon 2011, Casuccio *et al.* 2008, Achtemichuk *et al.* 2009). In addition, many highway agencies (e.g., State Department of Transportation), including Texas, Ohio, Florida, Minnesota, and Iowa, encourage their contractors to utilize RCA in their roadway construction projects for sustainable practices (Snyder and Bruinsma, 1996). Although the effectiveness of RCA as an unbound aggregate has been proved though many uses of RCA in roadway construction, its use in drainage systems is still not common due to several concerns. Some of RCA's side effects identified are high pH leachate, trace element leaching risks and clogging potential issues due to fines and precipitation (Meuthel 1989, Tamirisa 1993, Snyder and Bruinsma 1996). Snyder

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RCA as a backfill material in a drainage system (Dam *et al.*

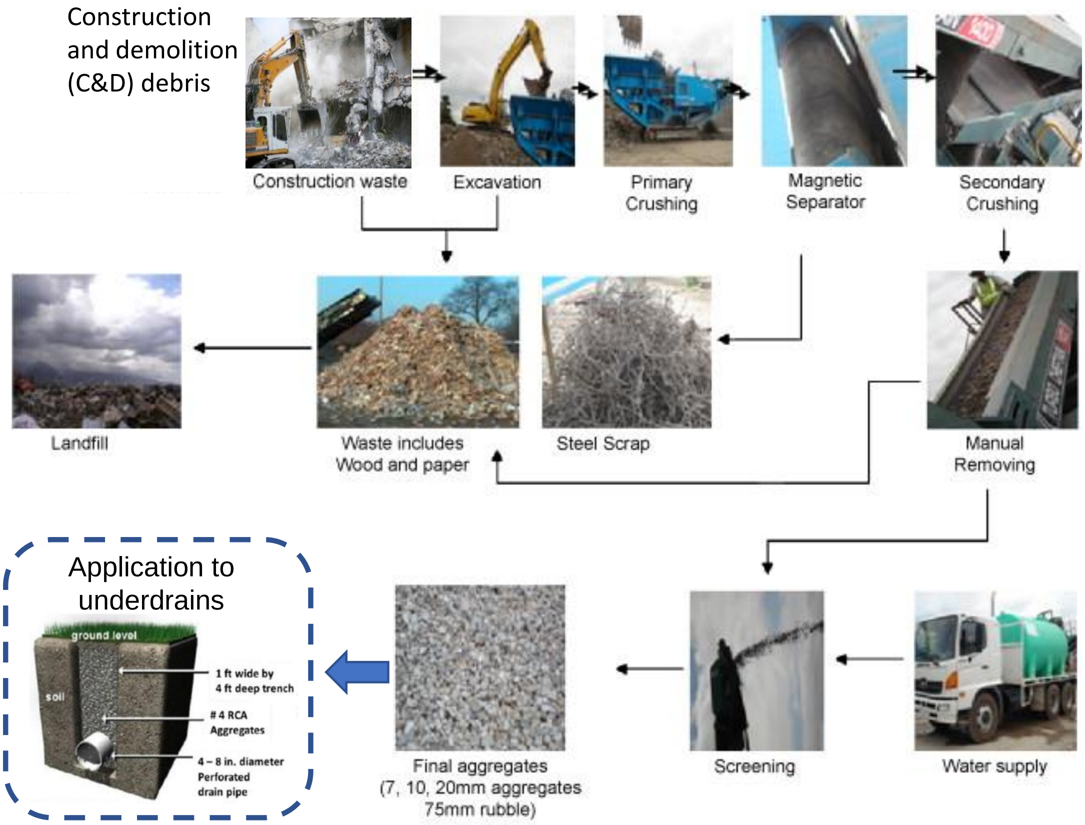


Fig. 1 RCA production process (modified from Tam 2008)

Table 1 Current practice for the use of RCA as a drainage material (DOTs)

Selected highway agency	Current practice of RCA utilization as a drainage material
Michigan DOT	Michigan DOT don't allow RCA as a backfill material in a drainage system
Texas DOT	Texas DOT hesitate to use RCA as a drainage material
Iowa DOT	Iowa DOT allow their contractors to use RCA as a drainage material with the restriction of RCA fine percentage or the blended RCA and virgin aggregate.
Mississippi DOT	Mississippi DOT allows their contractor to use RCA as a substitute of crushed aggregate base and shoulders.
New York State DOT	The current NYSDOT specification doesn't allow their contractor to use RCA as a drainage material. NYSDOT plans to change the specification regarding RCA in the future.
Washington DOT	WSDOT has used RCA for base and subbase materials but not for a drainage material yet.
Oklahoma DOT	Current OKDOT doesn't specifically address the use of RCA in the drainage application. However, technically RCA could be used if it met the specifications.
North Dakota DOT	NDDOT has used RCA as a drainable base layer without any problems.

found that a precipitate from RCA subbase courses would form on filter fabrics wrapping drain outlets. Due to the soluble and reactive chemical components in RCA which can cause clogging issues, an engineer may still be reluctant to use it in drainage applications. One of the main causes of clogging issue is the precipitation of calcite. Several technical reports indicate that 70% of clogged materials on geotextiles of drainage systems made of RCA are calcite related precipitation (Steffes 1999).

Table 1 shows the current practice of RCA utilization as drainage material by Department of Transportations (DOTs). Some DOTs such as Michigan DOT do not allow 2011). Texas DOT hesitates using RCA as a drainage material (Lim *et al.* 2003). Iowa DOT allows their contractors to use RCA as a drainage material restricting RCA fine percentage or the blended RCA and virgin aggregate (Ceylan *et al.* 2013). Some researchers have tried to investigate and identify the mechanism and resulting chemical composition of calcite precipitation from RCA (Behring 2013, Kim *et al.* 2014, Behring *et al.* 2014, Nam *et al.* 2014, 2015, McCulloch *et al.* 2017). Abbaspour and Tanyu (2019) found that, depending on the precipitation process, calcite (and other associated minerals with various morphologies) or gypsum and its associated minerals can be the dominant forms of precipitation. Gupta and Kneller (1993) reported that precipitation samples collected from the RCA site contain approximately 55% $CaCO_3$ and 30% insoluble residue. In addition, some researchers invented new experimental procedures not only to identify the mineral types of precipitation but also to determine the total amount of precipitation from RCA.

Several researchers have previously tried to discover the mechanism and affecting parameter on the calcite precipitation of RCA when it is used as a drainage material (Gupta and Kneller 1993, Behring 2013, Kim *et al.* 2014, Behring *et al.* 2014, Nam *et al.* 2014, 2015, McCulloch *et al.* 2017, Abbaspour and Tanyu 2019). However, there are still lack of studies that evaluate the total amount calcite precipitation from RCA when used as subdrainage materials such as a pipe backfill material in drainage system are lacking. Nam *et al.* (2016) proposed accelerated calcite precipitation (ACP) test procedure that determines the life-cycle amount of calcite from the selected amount of RCA sample. There are 8 steps of ACP procedure. The simplified steps are as follows: 1) Obtain RCA samples, 2) Mix RCA with water, 3) Inject CO2 into the mixture (RCA and water), 4) Filter out the water from the mixture, 5) Please the leachate in an oven, 6) Take the leachate out from the oven and filter out again to separate water and precipitate, and 7) Measure the weight of precipitate. Basically, it provides CO_2 is provided, allowing RCA to geochemically react and produce calcite. The ACP method includes variation in testing conditions of heating and evaporation cycles of RCA leachate in the oven and filtration of any solid particles formed during this process. Since one of the main causes of the clogging potential of RCA is calcite precipitate, it is important to estimate the maximum life-time calcite precipitation of RCA. Moreover, by evaluating the maximum life-time precipitation with different types of RCA can help provide a design guideline, and also provide a potential clogging level indicating blockage on the filter fabrics of a drainage system as severe, moderate, or mild.

The previously developed ACP provided an insight into accumulation of calcite precipitation through accelerated carbonation process. However, there are several parameters that need to be further considered to determine the maximum life-time calcite precipitation in a more accurate and more efficient way. In this study, we aimed at re-evaluating the prototype accelerated calcite precipitation (ACP) to optimize the testing variables and the efficiency of RCA's carbonation process to reduce testing time. The specific objectives of this study were: (1) to investigate the affecting parameters of ACP procedure to find the maximum life-time calcite precipitation from RCA, (2) to apply the improved ACP procedure to RCA samples that were graded for Type I Underdrain application, to compare the calcite precipitation.

2. Calcite precipitation theory

At the end of service life of concrete structures, concrete is demolished, crushed and sieved to produce RCA and the uncarbonated inner matrix is exposed (Karaman and Bakhytzhan 2020, Mohammadi *et al.* 2020, Kalemci and Ikizler 2020, Lukic *et al.* 2020). The carbonation process begins with the exposure of the concrete surface and progresses to the inner part of the concrete. In base/subbase course applications, RCA surfaces are exposed to atmospheric carbon dioxide and the carbonate present in rainwater, described by Eqs. (1) through (3).

$$CO_2\ (g) \leftrightarrow CO_2\ (aq) \tag{1}$$

$$CO_2\ (aq) + H_2O\ (aq) \leftrightarrow H_2CO_3\ (aq)\ \text{(carbonic acid)} \tag{2}$$

$$\begin{gathered} CaCO_3\ (s) + H_2CO_3\ (aq) \leftrightarrow Ca^{2+}\ (aq) + 2HCO_3^-\ (aq) \\ \text{(bicarbonate)} \end{gathered} \tag{3}$$

Saturation of the fresh surfaces of RCA facilitates chemical interactions between the carbonate present in water and RCA in base/subbase courses. These chemical interactions between carbonic acid and dissolved carbonate and hydroxide species released from RCA are highly affected by the surrounding temperature and saturation time, described by Eq. (4).

$$\begin{gathered} H_2CO_3\ (aq) + Ca^{2+}\ (aq) + OH^-\ (aq) \leftrightarrow 2H_2O\ (aq) + \\ CaCO_3\ (s) \end{gathered} \tag{4}$$

According to White (2013), reaction rates, most particularly the calcite precipitation reaction rate depend on the concentration of the reactants, temperature, and the activation energy, which can be calculated with temperature. The surrounding temperature is one of the major environmental factors. The carbonation process is a dynamic equilibrium which is a chemical equilibrium between a forward reaction and the reverse reaction where the rate of the reactions is equal. The continuous energy input (high surrounding temperature) may cause the reaction to move in the backward direction (Walas 1959). In other words, depending on environmental temperature and the reaction time, maximize calcite precipitation can be varied.

3. Hypothesis and methodology

Formation of calcite precipitation is a long-term process through carbonation process. The main chemical components of calcite precipitation are calcium ions (Ca^{2+}) and carbonic acid (H_2CO_3) in the aqueous solution. It is hypothesized that the reaction temperature (particularly during the precipitation process) and reaction time are two main key factors affecting the amount and time of the calcite precipitation in RCA. The methodology of this research involves two steps of: (1) evaluation of the effect of the reaction temperature and time on the formation of RCA's calcite precipitation and (2) modification of the ACP procedure. Fig. 2 shows the flow chart of the performed study. We performed a parametric experimental study varying the reaction time and temperature and measured the amount of calcite precipitation. The findings reflect the ACP procedure to optimize the performance of the test.

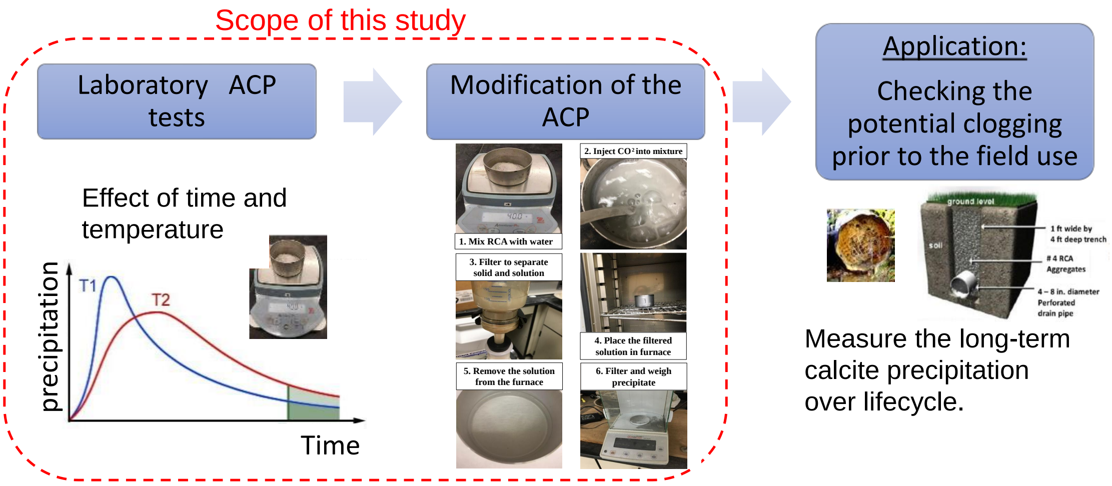


Fig. 2 RCA production process (modified from Tam 2008)

Table 2 Physical properties of Limestone and RCA samples

	Limestone	RCA	Test Method
Specific gravity (oven dry)	2.42	2.16	ASTM C128
Absorption capacity (%)	3.1	6.4	ASTM C127
Bulk density (oven dry, kg.m3)	1375	1210	ASTM C127
Void content (%)	42	43	ASTM C29
LA abrasion mass loss (%)	36	44	ASTM C29

Table 3 Chemical components of RCA and limestone

	Oxygen (O)	Calcium (Ca)	Carbon (C)	Silicon (Si)	Aluminum (Al)	Iron (Fe)	Sodium (Na)
Limestone	37.9	55.3	4.9	1.8	-	-	-
Fresh RCA	30.05	50.93	12.43	3.17	3.42	-	-

4. Materials

4.1 Physical properties

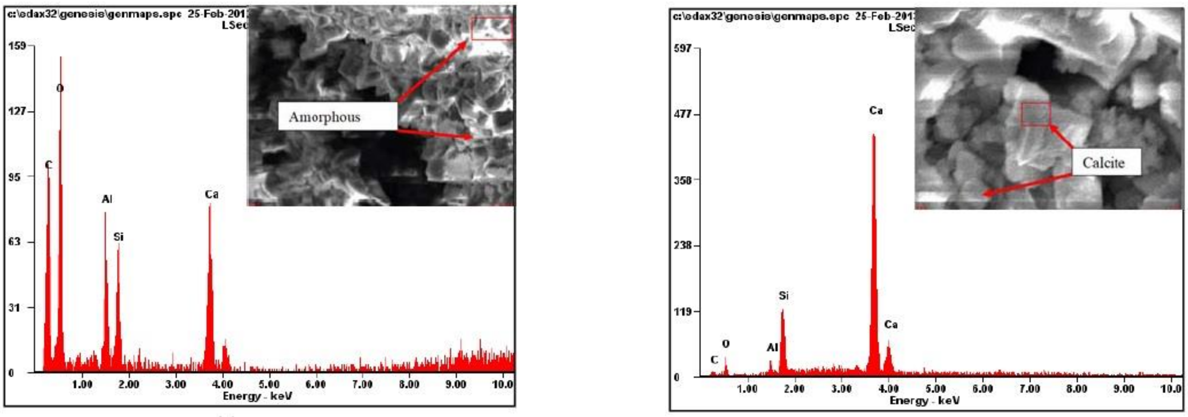
The authors obtained limestone from a local facility and RCA from a construction and demolition (C&D) waste recycling facility in Orlando, Florida. The materials were ground to fines and tested to determine physical properties by using standard procedures. Table 2 shows the physical properties of the tested limestone and RCA along with the standard test names. The results show that the RCA sample had lower specific gravity and bulk density than limestone, but RCA's other properties are more advantageous than limestone. The specific gravity and bulk density of RCA are lower than limestone because of the existence of adhered paste in RCA which is a porous material. The absorption capacity and LA abrasion are higher than RCA, which is also due to the porous nature of adhered paste in RCA.

4.2 Chemical & mineralogical characterization

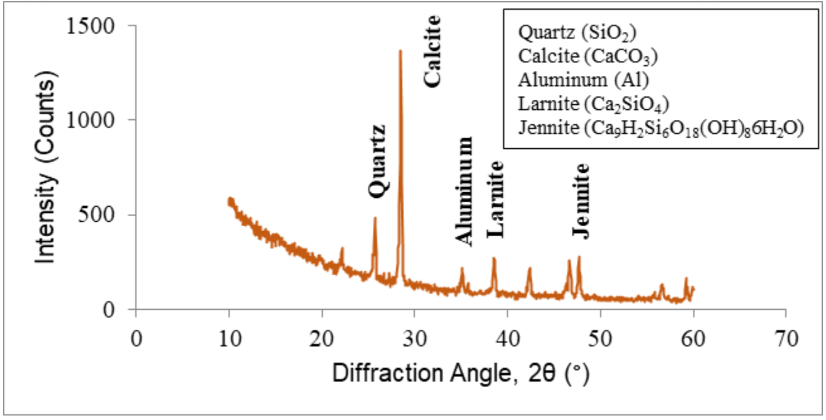
RCA's chemical and mineralogical characterization was investigated. RCA samples were obtained from a local RCA production plant in Orlando, Florida. The sources of RCA are varied, and this RCA includes sample groups that differ in age. In addition, this RCA was kept in an outdoor environment which indicates exposure to the elements. As a result, this sample will be referred to as "weathered RCA".

Scanning electron microscope (SEM), energy dispersive X-ray (EDX), and X-ray diffraction (XRD) examinations were employed to investigate the chemical and mineralogical properties of those weathered RCAs. The surface appearance and chemical characteristics of the weathered RCA were examined using SEM and EDX analyses. The surface morphology and chemical contents are presented in Fig. 3(a) through 3(c). The findings reveal that RCA is made up of amorphous minerals including CSH and other hydrates (e.g., calcite). The Ca/Si ratio is 1.09, the normal ratio of amorphous CSH, according to the EDX result in Fig. 3(a). Calcite is the rhombohedral mineral in Fig. 3(b).

The Ca/Si ratio is 6.1, according to EDX result in Fig. 3(b). This signifies that the majority of this mineral is made up of Ca, which is calcite. Fig. 3(c) shows that the XRD data coincides with the results of the SEM and EDX studies. Calcite, quartz, and some of C-S-H minerals (e.g.,



(a) Data 1 (b) Data 2



(c) XRD

Fig. 3 RCA materials characterization: (a) SEM/EDX data (Spot 1), (b) SEM/EDX data (Spot 2) and (c) XRD data

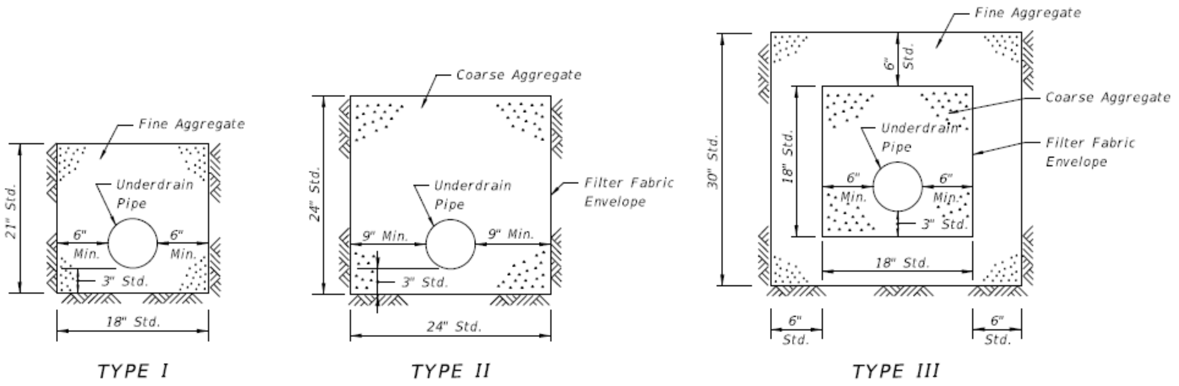


Fig. 4 Underdrains applications for pipe backfill materials

Jennite, Larnite) are the major components of RCA. It is confirmed that Portlandite is absent due to the weathering storage condition (e.g., outside storage). Because the CSH is an amorphous form rather than a crystal, it was not found in XRD data. Table 3 shows the chemical components of RCA and limestone from EDX analysis.

4.3 RCA specimens (for the ACP simulation)

In preparing the testing specimens, the target gradation was for subsurface drainage materials. Fig. 4 shows the cross-sectional views of Type I, II and III underdrains of road. Florida Department of Transportation (FDOT) design standards also specify a Type V underdrain which is more complex. In this study, the gradation curve of Type I underdrain was selected because it is the only design to have only fine aggregate. RCA was collected from RCA recycling company in Orlando, FL was selected and tested to determine the effects of the hydration process on calcite precipitation. All samples were ground and graded to meet the specifications for Type I underdrains which uses only fine aggregate (Florida Department of Transportation, 2012). The gradation curve of Type I is presented in Fig. 5 and the target gradation was selected as the upper limit.

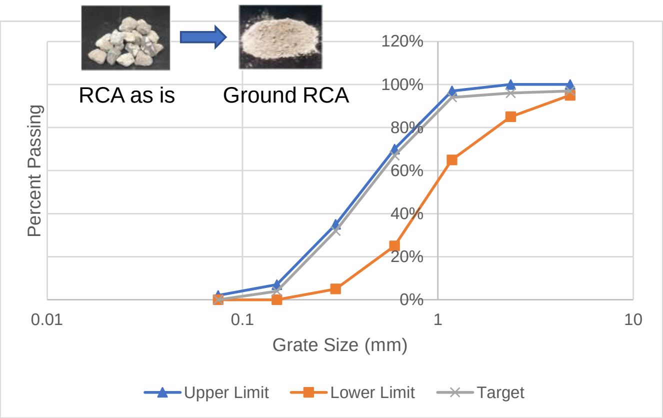


Fig. 5 Gradation curve of the ground RCA (Type I underdrain application)

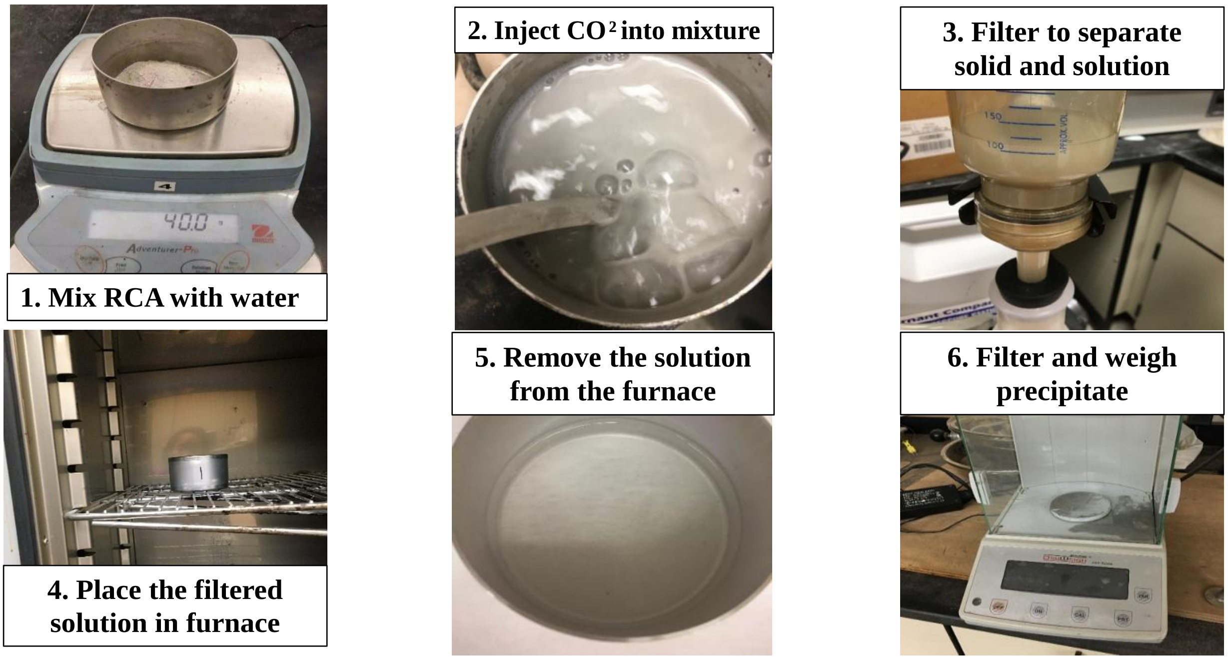


Fig. 6 Visual representation of the prototype ACP procedure with reference to each step

FDOT currently uses limestone as a drainage material.

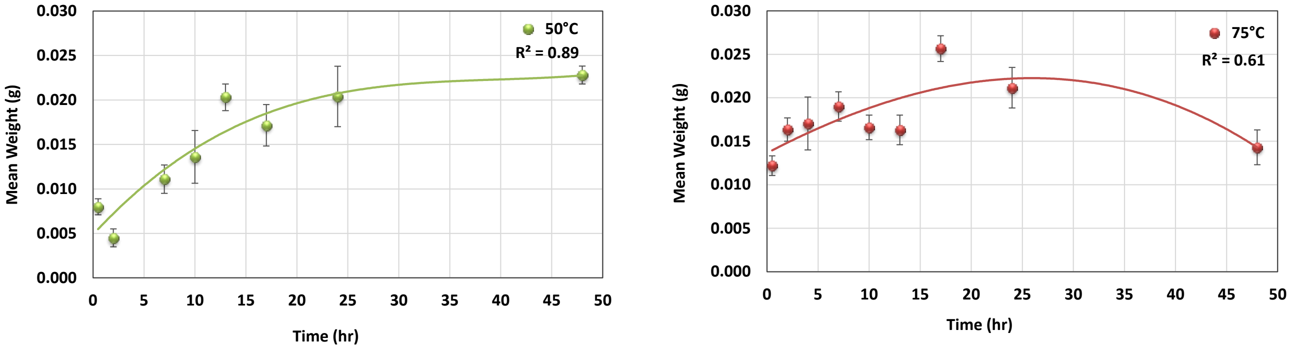
5. Testing method and procedure

5.1 Testing variables for the parametric study

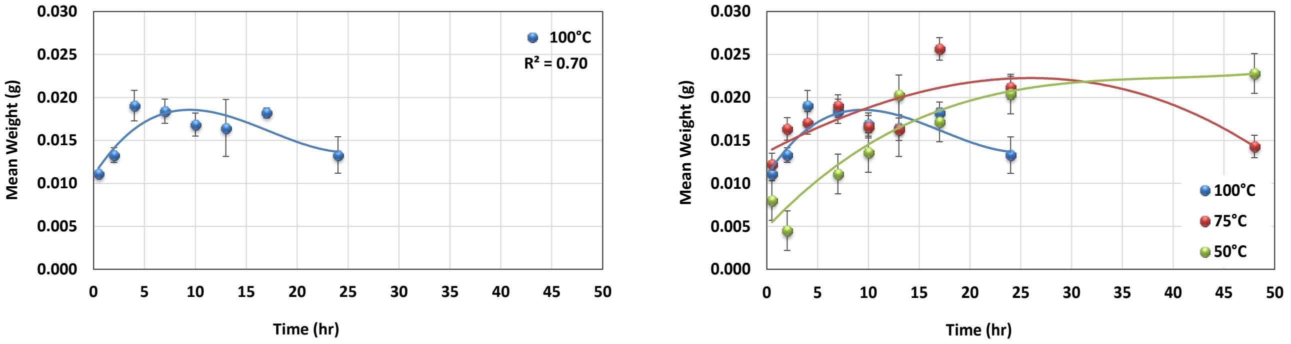
The improved ACP test procedure follows the same basic principles as the prototype ACP procedure with a few changes (reaction time and temperature). The prototype ACP procedure only used the 100°C heating temperature with a 4-hour heating time. The goal of the improved ACP parametric study is to find the optimized heating temperature and reaction time. Therefore, the two key variables investigated in this study are heating temperature and reaction time. Fig. 6 shows the procedure of the prototype ACP. 100 kg of RCA was ground with 6,000 cycles in the LA Abrasion machine for test. 40 g of ground RCA was used for each sample and mixed with 140 g of water. Carbon dioxide (CO_2) was bubbled into the RCA solution at a rate of 10 ft^3/hr over 5 minutes. The CO_2 injection time was set over 5 minutes because the pH of the solution stabilizes after 5 minutes injection. The solid (RCA fines) was then filtered and the leachate was heated. After heating, the leachate was cooled and then filtered to separate the precipitate. The mass of the precipitate was recorded using a high-resolution scale. Samples were heated at a temperature of 100°C, 75°C or 50°C for heating times that varied between 30 minutes and 48 hours.

5.2 Prototype ACP simulation procedure

The Accelerated Calcite Precipitation (ACP) test procedure proposed by Nam *et al.* (2016), simulates the process by which calcium carbonate precipitates in nature (Fig. 2). The prototype ACP procedure begins with submerging the calcium source (ex. RCA) in water (Step 1). The bubbling of CO_2 is analogous to Eqs. (1) and (2) where



(a) @ 50°C (b) @ 75°C



(c) @ 100°C (d) Combined

Fig. 7 Calcite precipitation results with different reaction time at different oven temperature: (a) 50°C, (b) 75°C, (c) 100°C, and (d) Combined

CO_2, in equilibrium with rainwater, dissolved to form carbonic acid (Step 2). The carbonic acid in the solution dissolves the RCA as with limestone in nature (Eqs. (3) and (4)). The RCA is then filtered from the solution (Step 3). The leachate is heated to accelerate calcium carbonate precipitation (Step 4). After the appropriate heating time, the leachate is taken out of the furnace to cool before the precipitate is filtered (Step 5). The leachate is then filtered, and the precipitate is dried at room temperature. The precipitate is weighed after at least 24 hours of drying. The filter paper is weighed on the Digiweigh DWP-B2004 (Step 6).

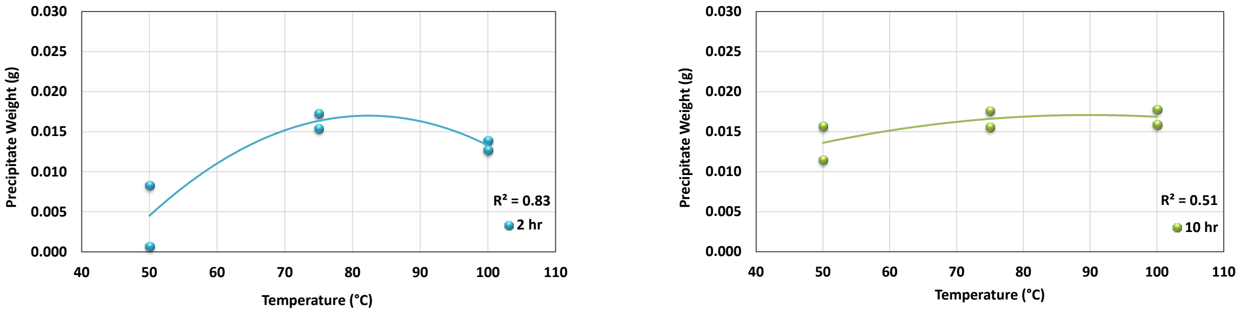
6. Results

6.1 Testing results

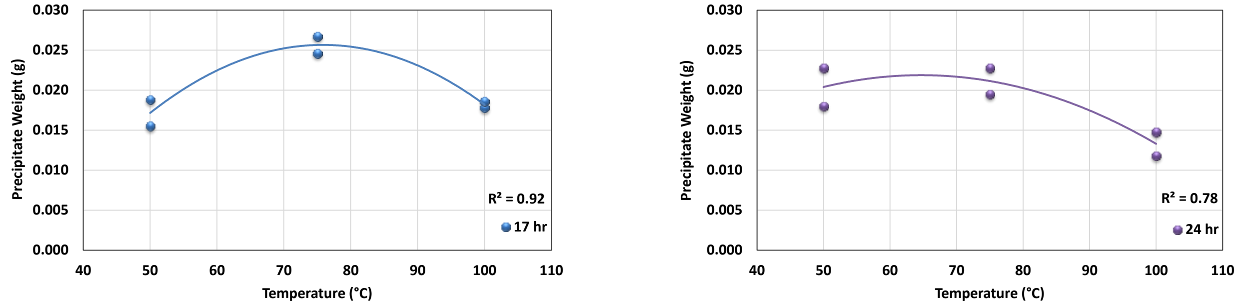
The goal of the improved ACP parametric study is to find the optimized reaction temperature and time. Therefore, the two key variables investigated in this study are heating temperature for the calcite precipitation reaction and reaction time. The recorded data for each heating temperature is presented in Fig. 7. The calcite precipitation yield increased with time for all samples for heating times up to 4 hours. After 4 hours, the behavior of the samples at each temperature is different. Samples heated at 100°C showed decreasing calcite precipitation yield as heating times increased. Samples that were heated at 75°C showed a slight decrease in calcite precipitation to the 13-hour heating time, then a significant increase which resulted in a peak at the 17-hour heating time. Samples heated at 50°C continued the increasing trend with increased heating times to 48 hours.

Increasing temperature can also increase the probability of a reaction. A higher temperature leads to an increase in kinetic energy of particles, which means the velocity of molecules in the system and therefore, the number of collisions of molecules in the system increased. An increase in collision increases the probability of reactions in the system. The higher energy of molecules resulting from the temperature increase provides the ability for the colliding molecules to overcome the activation energy and react, as demonstrated by the Maxwell-Boltzmann diagram. The effect of temperature can clearly be seen in Fig. 7 where the calcite precipitation yields at 63% of the heating times was the lowest for the samples that were heated at 50°C.

Following this logic, one would expect that most of the samples at 100°C to have the highest calcite precipitation yield. The data shows that for 55% of the heating times, the samples heated at 75°C produced the highest calcite precipitation yield. One of the reasons for the higher yield of calcite precipitation at the lower temperature is that the calcite precipitation reaction is reversible so the precipitate can dissolve after the reaction obtains dynamic equilibrium. While higher temperature increases the reaction rate to produce a higher yield of calcite precipitation, the benefit is limited by the equilibrium point of the reaction. The second reason for the higher yield of calcite precipitation at the lower temperature is due to the evaporation of dissolved CO_2. With high temperatures such as 100°C, previously dissolved CO_2 can easily evaporate from the solution.



(a) 2 hr heating (b) 10 hr heating



(c) 17 hr heating (d) 24 hr heating

Fig. 8 Effect of heating time on the calcite precipitation

Table 4 Modified ACP procedure

Procedure	Task
Material preparation	Task1. Mix 40 g of RCA (with a selected gradation) with 140 g water Task2. Inject CO_2 through the water at a rate of 10 ft^3/hr for 5 minutes
Extraction and filtration	Task3. Filter out the water to separate solid and solution
Calcite precipitation	Task4. Place the leachate (the filtered water) in an oven at 75°C for 17 hours Task5. Take the filtered solution from furnace
Calcites obtain	Task6. Filter out again to sperate water and calcite precipitation, and weigh precipitate

Therefore, there is less H_2CO_3 in the aqueous solution to react with Ca^{2+}. Fig. 8 shows the effect of heating time with different hearting temperatures. Even though increasing temperature increases the probability of a reaction, RCA samples with 100°C produced the smallest amount of calcite precipitation after 17 hours of heating.

Although higher temperatures increase the probability of a reaction, the optimum temperature to produce the highest amount of calcite precipitation is affected by not only the chemical reaction between Ca^{2+} and H_2CO_3 but also the speed of CO_2 evaporation from the solution. The prototype ACP procedure used the 100°C heating temperature with a 4-hour heating time. The data from this study shows that the 4-hour heating time maximized the calcite precipitation yield for the 100°C heating temperature. The improved ACP procedure, which maximizes the calcite precipitation yield, will have a 75°C heating temperature with a 17-hour heating time.

6.2 Modified ACP procedure

The main purpose of the ACP method is to quantitatively evaluate the clogging potential of RCA due to the calcite precipitation. Since RCAs have varied physical and chemical properties depending on their sources, an engineer needs a method to estimate the life-time amount of calcite precipitation for the selected RCA. Based on the results of the laboratory experiment, the prototype ACP procedure has been modified, described below. Basically, the modified procedure is same as the prototype procedure developed by Nam *et al*. (2016) except Step 4 (in Fig. 6). The original reaction temperature and time in the oven, producing $CaCO_3$ (calcite precipitation), were 100°C and 4 hours, respectively. However, we found that the combination of 75°C over 17 hours is much more effective in creating $CaCO_3$ compared to the one of 100°C over 4 hrs. Table 4 presents the step-by-step procedure of the modified ACP procedure.

7. Discussion

The result from this parametric study indicates that the ACP procedure with 75°C heating temperature and 17-hour heating time (see Fig. 9) yields the maximized calcite precipitation from RCA (with the aggregate gradation for

Table 5 Economic and environmental quantitative comparison between conventional aggregates and RCA

Aggregate Type	Cost ton ($)	GWP kg CO_2 eq	ODP kg CFC-11 eq	POCP kg C_2H_4 eq	AP kg SO_2 eq	EP kg PO_4^{-3} eq	ADP kg Sb eq
Limestone	48	3.14E-2	2.09E-10	1.03E-5	1.75E-4	3.90E-5	1.39E-9
RCA	25	7.44E-3	1.60E-10	2.14E-6	4.05E-5	9.28E-6	2.12E-10
Difference	23	2.39E-2	4.90E-11	8.16E-6	1.34E-4	2.97E-5	1.18E-9
Reduction rate (%)	47.92	76.31	23.45	79.23	76.86	76.21	84.75

(note: GWP -global warming potential; ODP -ozone depletion potential; POCP - photochemical ozone creation potential; AP -acidification potential; EP -eutrophication potential; ADP - abiotic depletion potential)

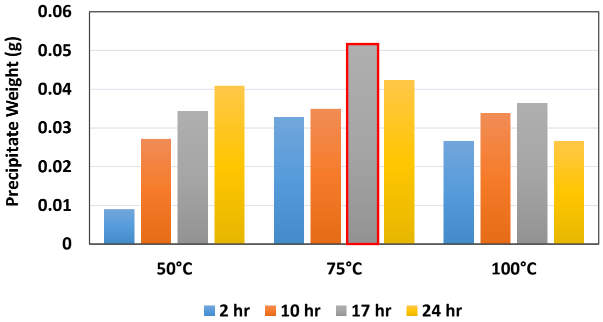


Fig. 9 Calcite precipitation results under varied oven temperature and reaction time

Type I Underdrains). Under this optimized condition (75°C and 17 hrs), the total amount of calcite precipitated was 0.052 grams, which is considered quite low. This is 0.13% of the total mass of tested RCA. A possible reason is as below. As described in the section of hypothesis and methodology, the main chemical components of calcite precipitation are calcium ions and carbonic acid in the aqueous solution. The possible donors of calcium cation in RCA are limestone aggregates, as the main chemical component of limestone is calcite, and portlandite which is a byproduct of cement hydration. RCA contained 45% – 60% limestone aggregates which are covered by cement paste. And the amounts of portlandite in cement paste are quite small compared to other cement hydration products. The outside storage (e.g., rain wash, carbonation, etc.) may have affected the portlandite content. Considering the low amount of calcite precipitation, this result could be the basis for establishing that the utilization of RCA as a backfill material in a drainage system may be acceptable.

In addition, one of the benefits of using RCA is the reduction of CO_2 emissions. The main sources of CO_2 emissions throughout the aggregate production processes are generated from the combustion of fuels used by on site electricity generators, production equipment and transport vehicles. Atmospheric emissions which include dust emission have multiple sources such as blasting, drilling, crushing and traffic on unpaved road, etc. Braga *et al.* (2017) used eight environmental categories, which are abiotic depletion (ADP), global warming (GWP), ozone depletion (ODP), acidification (AP), eutrophication potential (EP), and photochemical ozone creation (POCP) potential, and consumption of primary energy, renewable (PE-Re) and non-renewable (PE-NRe), to compare those environmental measures between conventional aggregate and RCA. Table 5 presents the comparison results of those environmental measures. To evaluate the economic impact of reusing RCA, the material costs of limestone and RCA were also compared. In summary, the economic and environmental quantitative comparison between the conventional aggregates and RCA shows significant cost and environmental benefits of RCA compared to conventional aggregates and reduces GWPAs.

8. Conclusions

In the use of RCA as drainage material, the effects of reaction time and temperature on the formation of calcite precipitation were investigated. The findings were used to optimize the testing condition of the ACP procedure (reaction at 75°C over 17 hrs) such that the amount of calcite precipitation is maximized. The testing results show that increasing heating time and heating temperature increases the energy and probability of increasing the reaction rate within a system, which directly relates to the increased calcite precipitation. However, dynamic equilibrium limits the benefit of increasing temperature, therefore, samples tested with the improved ACP procedure are heated at a lower temperature (75°C) than samples that were tested with the prototype ACP procedure (100°C). Moreover, with high temperatures such as 100°C, previously dissolved CO_2 can be easily evaporated from the solution. Therefore, there is less H_2CO_3 in the aqueous solution to react with Ca^{2+}. Although higher temperatures increase the probability of a reaction, the optimum temperature to produce the highest amount of calcite precipitation is affected by not only the chemical reaction between Ca^{2+} and H_2CO_3 but also the speed of CO_2 evaporation from the solution. The resulting improved ACP procedure uses a heating temperature of 75°C for 17 hours. With the improved ACP procedure, the total amount of calcite precipitation from RCAs within life cycle of base/subbase course or drain system can be determined when RCAs from different sources are used as backfill materials. This study suggests that the improved ACP procedure with a heating temperature of 75°C for 17 hours can evaluate the maximum amount of calcite precipitation from RCAs.

The limitation of this ACP test is that calcite precipitation was measured by the suspended solids in the solution rather than the solids dissolved in water. Some of dissolved calcite which may be in the solution are not large enough to be filtered. Therefore, the future recommendation of this study could be to invent a method to measure the dissolved calcite in the solution.

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