Dredged Material for Stormwater Management

Final Report

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ABSTRACT

More than 1.5 million cubic yards of sediment require annual removal from fifteen federal harbors, and numerous smaller ports for recreational navigation along the Ohio's Lake Erie coast. The top three are Toledo Harbor, Cleveland Harbor, and Sandusky Harbor. Landfill of these materials is costly and depletes land resources. Open water placement of these materials in Lake Erie deteriorates water quality. Economic and beneficial uses of dredged materials have already attracted public's interests. In Cleveland, there are more than 14,000 acres of revitalizing brownfields many containing up to 90% impervious surface which is often used to abate pollutions. However, this approach conflicts with "infiltration" based stormwater practices required by contemporary site-based stormwater regulation. In addition, research shows that devaluation and destabilization of neighborhoods are around these unremediated brownfields, and the impervious surface increases flooding concerns in combined sewer overflow areas where many brownfields are located. Green infrastructure (GI), e.g. green roof, rain gardens et al, emphasizes infiltration and hydrological retention, and could potentially provide a flexible and affordable solution to remediate urban brownfield in Cleveland. The dredged material may supply nutrients for plant growth in GI and raw mineral materials for aggregate production, which has high hydrological retention capacity for GI construction. This project explored the beneficial use potential of dredged material in GI construction for stormwater management on urban brownfields. In particular, it focused on evaluating the performance of lightweight aggregate (LWA) sintered from raw dredge samples within a green roof growing substrate.

The dredged material was dried and pulverized. It was mixed with certain amount of water. Small balls (1/2 in. diameter or less) were made by hand. According to the organic content determined by the thermal analysis, the small balls were preheated to remove crystal water and excessive carbon. Then they were heated to a higher temperature for sintering. After the completion of the sintering, the samples were cooled down to the room temperature for testing its physical properties. Different mix proportions and sintering parameters were tested to produce the LWAs. LWAs were successfully produced with a specific gravity ranging from 1.46 to 1.74, and a water adsorption rate ranging from 10.96% to 23.40%. The lab testing showed a promise to use this material in the field. Two green roof microcosms, one using the dredge LWA and the other using Rooflite® were constructed at the Cleveland Industrial Innovation Center (CIIC). The

field monitoring indicated the dredge green roof material had a comparable performance with the Rooflite®.

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1. INTRODUCTION

1.1 Background

There are hundreds of harbors and ports built along the Great Lakes and other inland lakes across the country. Annually, millions of cubic yards of dredge material are removed from these harbors and ports to maintain economic viability and public safety. For example, each year, more than 1.5 million cubic yards (CY) of sediment requires removal from fifteen federal harbors and numerous smaller ports built along Ohio's Lake Erie coast. Disposal of the dredged material in landfills is costly and depletes valuable land, while open water placement (occurring in most harbors in Ohio) has the potential to deteriorate water quality through siltation, increased turbidity and mobilization of potential contaminants. The economic and beneficial uses of dredged material in the built environment have already attracted public interest. In Cleveland, dredged material moderately contaminated by polycyclic aromatic hydrocarbon is disposed of in a 104-acre confined disposal facility (CDF) (Figure 1-1) maintained by the Cleveland-Cuyahoga County Port Authority. The Ohio EPA is monitoring the levels of heavy metal and organic contaminants in the facility. However, additional capacity of the facility is needed to accommodate the 225,000 CY of sediment that must be disposed of in this facility annually to keep the site operational and maintain its economic viability for the Port of Cleveland.

Figure 1-1 CDF for dredged material in Cleveland (Imagery @2015 Google, TerraMetrics, Map data @2015)

In Cleveland, there are more than 14,000 acres of brownfields many with over 90% impervious surface. Impervious surface is commonly employed on post-industry lands to abate pollutions. However, this practice conflicts with “infiltration” the principle required by contemporary stormwater strategies. In addition, research shows that devaluation and destabilization of neighborhoods are around these unremediated brownfields, and the impervious surface increases flooding concerns in combined sewer overflow areas where many brownfields are located. Green infrastructure (GI), e.g. green roof, rain gardens et al, emphasizes infiltration and hydrological retention, and could potentially provide a flexible and affordable solution to remediate urban brownfield in Cleveland. The dredged material may supply nutrients for plant growth in GI and raw mineral materials for aggregate production, which has high hydrological retention capacity for GI construction.

1.2 Study Objectives

This project explored the beneficial use potential of dredged material for stormwater management on urban brownfields. Specifically, two objectives were addressed in the study: (1) evaluating the suitability of dredged material from Cleveland Harbor for use in green infrastructure e.g. green roof, rain garden etc in brownfield remediation. (2) preparing and producing “green” lightweight aggregate (LWA) with high porous surface and inner microstructure, which is made from dredged material. The “green” LWA was produced through preheating and sintering based on parameters determined from thermal and chemical analysis. The potential of using this LWA in green roof construction was evaluated in the lab and through field study. This project addresses the issues caused by the disposal of dredged material from Lake Erie, by investigating the reuse of the material in GI for stormwater management and brownfield remediation. The practice of GI in brownfield is expected to address stormwater pollution and reduce combined sewer overflow events as well as wastewater treatment cost in Cleveland.

1.3 Scope of Study

An extensive literature review was performed in Chapter 2 to examine the beneficial use of dredged material in built environment. Following the literature review, chemical and thermal analyses were performed for the dredged material samples provided by Cuyahoga River Port Authority to evaluate if the dredged material is suitable for the production of “green” porous

aggregate with certain strength. LWA made from dredged material was manufactured, and the lab testing on its mechanical properties i.e. specific gravity, water adsorption rate, and microstructure was completed. Chapter 3 summarized the experimental plan and testing methods and the findings from experiments are discussed in Chapter 4. Chapter 5 concluded the study and made recommendations for future studies.

2. Literature Review

2.1 Dredged Material

Dredging rivers, lakes and oceans to continue economic and recreational activities is commonly seen as the primary reason for dredging. Sedimentation built-up in rivers, lakes and oceans impairs movement of aquatic vehicles through navigational channels. These large ships and barges require a critical depth to be able to navigate successfully through large bodies of water. As a result, rivers, lakes and oceans need to be dredged periodically. The United States Army Corps of Engineers (USACE)—the body responsible for maintaining sedimentation levels of lakes and rivers—moves approximately 150 million cubic yards of sediments annually through dredging. It is estimated that 109,997,316 cy^3 of dredged material were moved from US ports and harbors in the year 2014 to maintain critical navigation depths (USACE, 2014).

These sediments are commonly disposed back into lakes, rivers or oceans through open water disposal (OWD) or stored on land in a confined disposal facility (CDF). OWD is the most common way to handle dredged material. This method places dredged material in rivers, lakes, estuaries, or oceans through a pipeline or release from hopper dredges or barges. Today, a large portion of the material is currently considered unsuitable for OWD, because OWD has a potential to deteriorate water quality through siltation, increased turbidity and mobilization of potential contaminants. Therefore, a lot of dredged sediments are managed and stored in confined disposal facilities (CDF). Confined disposal places dredged material within upland or dikes which are close to shore via pipelines. CDFs are purposed to provide adequate storage capacity for meeting dredging requirements and to maximize efficiency in retaining the solids and if needed, contaminant control. The continual need to dredge the Great Lakes will load CDFs close to their critical capacities, e.g. the CDF in Cleveland. In addition, CDFs have direct physical impacts including alteration of habitat and changing hydrological conditions in a region (EPA, 2004).

There has been a controversy over use of OWD to manage dredged material. The State of Ohio objected OWD of dredged material in Lake Erie. A law has been enacted by the State of Ohio to prohibit all OWD of dredged material into Lake Erie by 2020 except beneficial use and habitat

restoration projects for clean material (DeWine, 2015). This opposition was due to high levels of contaminants and heavy metals present in the sediments which are considered unsuitable by the Ohio EPA to be disposed into Lake Erie. As the alternative to OWD, the city of Cleveland opted for the dredged sediments to be stored in CDFs that are to be set up along the Lake Erie Cleveland shoreline. The high expense and little economic value of storing dredged material in these facilities have become a thorn to the State's budget, having to produce $302,670,000 to finance the required dredging and construction of CDFs by the year 2024. (Port of Cleveland, 2011). While a seemingly more ecologically friendly alternative, storing material in CDFs are incurring high costs as opposed to OWD methods. The difficulties in storage and handling using CDFs and OWD methods have turned the attention of the City of Cleveland to alternative management strategies. These strategies include beneficially using dredged material for agricultural uses, product development, engineering fill and projects for environmental enhancement. Speaking broadly, using dredged material beneficially allows the reduction of dredging waste handling through OWD or storage in CDFs whilst at the same time benefiting local industries and ecologies. However, using dredged material beneficially comes with its own set of challenges including but not limited to contamination, treatment, and physical and chemical variation within the dredged material. It is therefore necessary to examine the properties of dredged material to evaluate its reuse potential in the built environment.

2.2 Beneficial Use of Dredged Material in the Built Environment

Two forms of dredged material have been studied in this literature review, raw and sintered. Raw dredge is sediment in its original unaltered form, and sintered dredge is the manufacturing and processing of the sediment into an industrial "baked" commercial product. The application of raw dredge is most common and occurs within the categories of beneficial use: habitat; beach nourishment; parks and recreation; agriculture forestry, horticulture and aquaculture; strip-mine reclamation/solid waste management and construction/industrial development. The beneficial use of raw dredge material stems from the growing demand for construction materials and dwindling inland sources. A common practice in many countries around the world is to use dredged material as "*concrete aggregates (sand and gravel); backfill material or in the production of bituminous mixtures and mortar (sand); raw material for brick manufacturing (clay with less than 30% sand); ceramics, such as tile (clay) pellets for insulation or lightweight backfill or aggregate (clay); raw material for the production of riprap or blocks for the*

protection of dikes and slopes against erosion (rock, mixture); and raw material for the production of compressed blocks for security walls at military installations and for gated communities and home subdivisions" (U.S. Army Corp of Engineers 2006).

LWA can be potentially made from sintering dredged material, which can create an ecologically beneficial product as well as an economical alternative compared to the presently produced LWA. Bremmer and Ries (2007) stated "⋯*lightweight concrete [aggregate] is an effective material in enhancing sustainability as compared to other construction materials. In addition LWAs can provide important environmental components for sustainability when it is used for improving water quality as well as when it is used for the growing medium for green roof use to combat the urban heat island effect*." Currently, LWAs are usually made of shale, clay, or slate. Depending on the application both are often mixed with organics or addition soil properties to meet the intended use.

2.2.1 Applications in Backfill, Bricks, and Concrete

There is a wealth of literature available investigating the beneficial use of dredge material in the built environment. The dredged material, composed of gravel, sand, silt and clay, is suitable for use in a variety of construction material such as concrete, masonry and as engineering fills for roads. Zentar et al (2008) performed several tests to determine mechanical behaviors and environmental impacts of road construction using marine dredged sediments from Dunkirk Harbor. The team used a mixed design of granular dredged sediments modified with dredged sands at an optimum mix of 30.8% fine dredged sediments, 61.7% dredged sands, 5.7% cement and 1.8% lime. The material was suitable as a sub base material and base course material for a road accommodating low volume traffic.

Chiang et al (2008) used river sediments mixed with 0%, 5%, 10%, 15% and 20% clay to produce bricks in Taiwan. The bricks constructed using river sediments had compressive strengths from approximately 300kgf/cm^3 to 1200kgf/cm^3 which met code requirements of a minimum 150kgf/cm^3. Besides possessing acceptable compressive strengths, the finished brick contained heavy metals within its matrices preventing contaminated leachates from the brick (Chiang et. al., 2008). The success of using dredged material to manufacture brick has led to researching industrial scale production.

Dredged material also has been evaluated for use as a constituent of concrete or as a filler material. The use of 30% (weight) dredged material and 7% (weight) cement in the concrete admixture seemed to the upper limit, in which any increase in dredged material content would lead compressive strengths to undesirable levels. When dredged material was used to replace sand or other concrete aggregates, there were drops in the workability of the concrete mixtures. Therefore formaldehyde-based superplasticizers were used to counteract the decrease of workability. Millrath (2003) found that the even with the addition of superplasticizers, the workability of concrete might still remain unsuitable for commercial use. More promising is the use of dredged material as concrete filler. Using 30% (weight) of dredged material as filler yielded concrete with sufficient compressive strengths and high flow (Millrath, 2003).

2.2.2 Applications in Landscape

Dredged materials have a varying composition depending on the location of dredging. Commonly, dredged material is composed of sand, silt, and clay, which make it suitable as agricultural topsoil. On other occasions, dredged material may require blending with other residual materials such as organic matter and biosolids to manufacture enhanced fertile topsoil. Often however, potential contamination of dredged materials makes it difficult to be used as top soils. For example, exposure and weathering of dredged materials with high sulfidic content can cause it to become highly acidic and release undesirable metals. Dewatering is required for dredged material to be used as topsoil. Dewatering may require several years, depending on the granular texture of the dredged material and its composition (Daniels et al, 2009).

The application of dredged material to a site has many ecological benefits and can happen at many scales. The type of landscape usually dictates the scale. The landscapes include green roofs, mounds, parks, and wetlands. On a large scale, raw dredged material can be used to create new land, such as the dredged material at Dike 14 in Cleveland, Ohio, and at a small scale, sintered dredge can be used to produce LWA which can be incorporated in the growing substrate to create a habitat for vegetative roof plants. Raw dredge is usually used on larger scales while sintered dredge is used on small scale green infrastructures.

(1) Large Scale

Large scale application of dredge spoil creates land forms in various ecological estuarine environments Gibson, D. J., & Looney, P. B. (1994) recorded vegetation that grew from dredge spoil in Florida after a year of growth. "*Dredge spoil was deposited in late 1990 gulfward of mean high water on Perdido Key, a barrier island off the coast of the Florida panhandle, for a distance of 8 km and averaging 150 m in width*." The hatched area in Figure 2-1 shows the extent of beach nourishment using dredged material at the eastern end of Perdido Key, Florida.

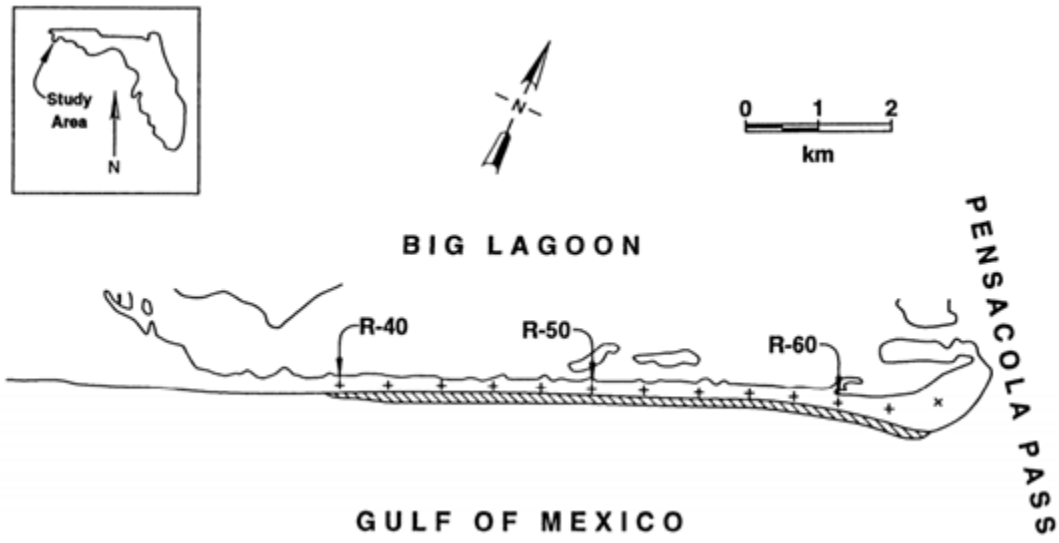


Figure 2-1 Map of the eastern end of Perdido Key, Florida (Gibson and Looney, 1994)

"*The study was conducted in the Gulf Islands National Seashore (GINS) …The island consists of coastal dunes dominated by Uniola paniculata*." The density of plants were an average 997 per ha in the summer of 1991. "*Cakile constricta was the most abundant of ten species colonizing the dredge spoil. Other species with a density of more than 50 plants per ha were Uniola paniculata*, *Iva imbricata*, *Panicum amarum*, and *Oenothera humifusa*." (Gibson & Looney 1994). Table 2-1 summarizes the density and cover of plant species colonizing the dredge spoil below old MHW on Perdido Key in Spring, Summer, and Autumn 1991.

Table 2-1 Density and Cover of Plant Species (Gibson & Looney, 1994)

Species	Spring		Summer		Autumn	
	Density no·ha⁻¹	Cover %	Density no·ha⁻¹	Cover %	Density no·ha⁻¹	Cover %
Cakile constricta	1,742	0.37	997	0.20	184	0.13
Uniola paniculata	*	0.07	465	0.05	541	0.13
Iva imbricata	*	0.07	131	0.02	170	0.05
Panicum amarum	*	+	102	+	94	0.02
Oenothera humifusa	*	0.01	9	+	119	+
Chamaesyce ammannioides	*	+	6	+	9	+
Schizachyrium maritimum	*	0.01	11	0.01	8	0.01
Ipomoea stolonifera	*	+	6	+	3	+
Heterotheca subaxillaris	*	+	2	+	2	+
Froelichia floridana	*	+	—	—	—	—
Total	—	0.53	1,723	0.28	1,130	0.34

* Indicates species present in the density plots; only *C. constricta* numbers were counted in the Spring
+ Indicates species that occurred in the density plots but were absent from the plots used to assess cover
[1] Cover was calculated as the mean cover from plots containing vegetation, whereas density values are based on all plots surveyed

(2) Medium Scale

A medium scale application of dredged material was documented by the team of E. J. Comoss, D. A. Kelly, & H. Z. Leslie (2002). Their study describes "… *how Presque Isle State Park, located along the shoreline of Lake Erie in Pennsylvania, implemented a low-cost and innovative erosion protection project*." The goals of this medium scaled project were to "*combine the beneficial use of dredged material, indigenous plants, and landscaping to reduce sediment loading into Lake Erie, and to protect the recreational aspects of Presque Isle State Park.*" By using materials found on site, Presque Isle State Park successfully slowed down the erosion of the shore line. "…*the park developed a plan that placed riprap off the shoreline of the trail, anchored downed trees from the park in the riprap to function as timber groins, and then filled in the area between the trail and the riprap with sand dredged from a local sandbar*." (Figure 2-2).

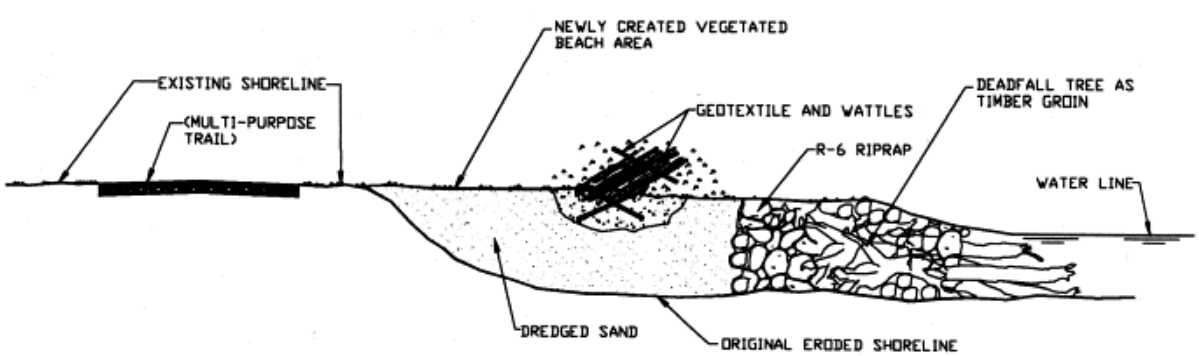


Figure 2-2 Section of Shoreline at Presque Isle State Park (Comoss et al, 2002)

After the sand was dredged from the site and relocated to the newly created beach area, local plants were identified and transplanted. These included beach grass (*Ammophilia breviligulata*), Indian sea oats (*Chasmanthium latifolium*), switch grass (*Panicum virgatum*), choke cherry (*Prunus virginiana*), bayberry (*Myrica pensylvanica*) and black oak (*Quercus velutina*). Aquatic plants were also used to create a balanced ecosystem. These plants included branching bur reed (*Sparganiuma androcladum*), duckweed (*Spirodela oligorrhiza*), and soft-stem bulrush (*Scirpus validus*). After the native species were established on the site invasive species, such as purple loosestrife (*Lythrum salicaria*) and common reed (*Phragmites australis*) were found and removed. This budget friendly project cost $33,000. (Comoss et al, 2002)

(3) Small Scale

Small scale dredge application includes raw soil and sintered LWA for green roofs and bioretention. The use of raw on-site soils in green roofing has been termed "brown roofs or rubble roofs". "Brown roofs are essentially extensive green roofing systems that seek to replicate the original ecological footprint prior to development." Brownfield roofs are also engineered as mitigation for brownfield land that has been damaged by commercial or industrial development (Cantor 2008). Meanwhile, LWA made from sintered clays, shale's and slates are used in the majority of engineered green roof substrates to provide essential plant rooting capacity at fractional weight loads.

A study on plant response to different substrates titled *Green Roof Plant Responses to Different Substrate Types and Depths under Various Drought Conditions* applied various substrates into a 4- × 30-m polyethylene greenhouse. This experiment used three succulents and two herbaceous species to study the responses of drought conditions. The substrates that used sintered LWA to examine structural and hydrologic characteristic. (Thuring, Berghage, & Beattie 2010)

The examination used expanded clay (HydRocks™; Garrick, Cleveland) and expanded shale (Solite®; Northeast Solite, Saugerties, NY). "*The mineral aggregates were mixed with pelletized spent mushroom compost (Laurel Valley Soils, Avondale, PA) to obtain a ratio of 85% mineral to 15% organic matter (v/v).*" The plants were watered 72 mm twice weekly. "*Irrigation was hand applied and the quantity was measured by timing. Plants subjected to early drought*

received no water for the first 2 weeks after planting, while those subjected to late drought received no water in the last 2 weeks of the study period." (Thuring et al, 2010)

The three succulent plants used were white stonecrop (*Sedum album*), tasteless stonecrop (*Sedum sexangulare*), and one ice plant (*Delosperma nubigenum*). The two herbaceous species used were maiden pink (*Dianthus deltoides*) and saxifrage pink (*Petrorhagia saxifraga*). "*The three most resilient species studied here, saxifrage pink, white stonecrop, and tasteless stonecrop, always produced more shoot biomass with increasing substrate depth, regardless of water availability. Ice plant performed erratically and, along with maiden pink, poorly in face of drought during establishment*" (Thuring et al, 2010).

"*The results from this study illustrate how appropriate species selection in the design of unirrigated extensive green roofs may be directed by factors such as substrate type and depth, as well as anticipated drought conditions. This experiment revealed the variability among drought-tolerant species to various treatments, as well as the different plant responses to substrate type during drought*" (Thuring et al, 2010).

2.2.3 Applications in Green Infrastructure

The use of dredge material for green infrastructure is less common. Green infrastructure is a resilient approach to managing wet weather impacts that provides various community benefits (EPA 2015.) At the landscape scale, green infrastructure relies on natural systems approach for the provision of ecological services (Benedict and McMahon, 2006). However, at the site scale and urban context, contaminant concerns can prevent the use of raw and sintered dredge in green infrastructure approaches and techniques. From raw dredge to sintered dredge, the ecological benefits related to reuse, vegetation growth, energy embodiment, insulation, and structural strength compete strongly with other materials. Dredged material has successfully been used in dry and wet climates as well as in seasonal extremes. Urban environments have also used dredged material in green infrastructure to create healthier environments. Yet, a few green infrastructure techniques currently utilize lightweight aggregates sintered from similar materials.

(1) Vegetated roof systems

Vegetated roof systems use LWA in the growing course to provide soil structure and water retentive capacity while being less weight than other soil products. This trade practice is

extremely common in the global, North American and Great Lakes markets. The most common LWA is made from sintering freshly minded clay and shale. Two Lake Erie basin projects using LWA are the Bike Box Living Roof Lab (Cleveland, Ohio) and Tremco Headquarters (Beachwood, Ohio) (Figure 2-3). Dredge is a potential substitute for mining fresh clay and shale.

Figure 2-3 Vegetative Roofs are constructed with lightweight aggregate as a part of the growing course. Left to Right Bike Box Living Roof Lab (Cleveland, Ohio), LWA, and Tremco Headquarters (Beachwood, Ohio)

(2) Bioretention

The technique of bioretention uses LWA on occasion. Bioretention uses designed and engineered soil mix and vegetation for the delay of stormwater and removal of pollutants. In semi-arid conditions LWA has been used within the bioretention mix (Coffman and Strosnider 2009; Coffman et al 2015) (Figure 2-4).

Figure 2-4 Bioretention can be constructed with LWA as a part of the engineered mix. Left to Right Carrington Lakes Bioretention (Norman, Oklahoma), LWA, and Trailwoods Greenstreet (Norman, Oklahoma).

(3) Vegetation

The type of vegetation must be properly matched to the dredge's physical and chemical properties. This means raw dredge vegetation will differ largely from an engineered mix containing a portion of sintered dredge. For example, highly dense, fine particulate dredged silt and clay limit infiltration and possess reduced water availability, and air capacity preventing root development of many horticultural and mature ecosystem species (Anlauf and Reichel 2014). On the other hand engineered bioretention mix can possess high amounts of porosity and low nutrient levels depending on the added sand and organic. It is important to not only match the plant to the dredged material but to match the plant's physiological traits to the expect performance of the landscape or green infrastructure.

In bioretention systems, the aesthetics and functionality are challenged by soil and plant selections that can thrive in both inundation and drought. In these very challenging settings, sintered clay materials, mixed with organics and sand, creates a healthy soil/water conditions for rooting for native and exotic plants (Coffman and Strosnider 2007). The matching of vegetation type to hydro-periods and individual species to soil moisture conditions is critical. Studies on bioretention systems have focused mainly on understanding and optimizing soils, chemistry, and hydrology, while the literature on plants has supported the design profession with publications of plant lists while focusing less on plant physiological traits.

Numerous plants have physiological traits that are beneficial to green infrastructure and enhance the conditions of the surrounding environment. The quality of being phytoremediative and

evapotranspirative are especially important in the green roof growing course. Phytoremediative plants, also known as hyperaccumulators, absorb nutrients from the soil through their roots and then store these nutrients throughout the plants tissue. This process allows for the removal of toxins, such as heavy metals and organic pollutants, from the soil–water environment. The use of this "plant-based" remediation preserves a natural habitat and is less expensive than other remediative processes, can be easily studied, and has the ability to recycle nutrients. Often misapplied in heavily contaminated past land use settings, vegetative remediation is better fitted to moderate and recurrent contamination settings under the idea of 'phyto-technology' (Kennen and Kirkwood 2015). Plants with high evapotranspiration properties effectively extract water from the ground and then release the water as vapor through the plants stomata. This in turn creates a cooling effect when the plants are placed on a vegetative roof. The cooling effect benefits the building by lowering the temperature of the roof and saving energy. The most successful vegetation to implement in a green roof growing course would have both phytoremediative and/or evapotranspirative properties. Numerous grasses, sedges, sedums, ferns, mosses and rushes fit this category but the hierarchy of effectiveness differs by species. The general characteristic of each species play a vital role in its use as a vegetative roof plant.

Xeric Landscapes

Plants that would best suit a vegetative roof constructed using LWA made from sintered dredged material would include various sedums, grasses, sedges, and rushes. Dry climates, which are also usually urban environments, tend to incorporate LWA made from sintered dredged material. For xeric growing habitats there is a tendency to use various sedums and succulents such as, *Sedum acre*, *Sedum album*, *Sedum anglicum*, and *Sempervivum spp.*. The characteristics of sedums, also known as stonecrops, are that they require only a small amount of soil to be successful, they are drought tolerant, they produce shallow roots, and they hold water in their leaves. Although they make great green roof plants, not all sedums have phytoremediative and evapotranspirative properties. The fact that the leaves of sedum hold water indicates that they have limited evapotranspirative value but a few sedums do have phytoremediative properties. *Sedum plumbizincicola*, and *Sedum alfredii* are known to be hyperaccumulators.

Mesic and Emergent Landscapes

Grasses, sedges, and rushes are similar but have different characteristics. Grasses, *Poaceae*, are more commonly found throughout the world and prefer warmer dryer mesic climates, while sedges, *Cyperaceae*, and rushes, *Juncaceae*, prefer a colder and wetter environment that are common in the emergent landscape. The stems of these plant families are also different. Grasses have hollow stems, rushes have solid round stems, and sedges have solid angular stems. The common characteristics of these plants are that they grow fast, they have linear elements, and they have deep spreading roots. Grasses, sedges, and rushes have both phytoremediative and evapotranspirative properties. *Chrysopogon zizanioides*, a grass, *Cyperus rotundus*, a sedge, and *Eleocharis tuberculosa*, a rush, are all commonly used in phytoremediation.

Hydric Landscapes

Wet growing habitats usually include hydric groundcovers, ferns, and mosses such as, *Caltha palustris* marsh marigold, *Athyrium filix-femina* lady fern, and certain pleurocarps. Wetter climates tend to use raw dredged material. Groundcovers refer to quick spreading plants that grow close to the ground. The area that groundcovers cover makes them extremely beneficial for evapotranspiration. Since there is such a density in plant mass and it protects the ground from direct sunlight, groundcovers are an idealistic plant for saving energy due to cooling costs.

Ferns are an ancient variety of plant that have been on the earth 360 million years. Growing in both emergent and hydric landscapes, these plants rely on steady moisture in order to thrive. Ferns grow in groups because of spore dispersal and the lack of flowers and seeds. Growing in groups make this plant beneficial for evapotranspiration. A few ferns that are hyperaccumulators are *Pteris vittata*, *Pteris cretica*, *Pteris longifolia*, and *Pteris umbrosa*.

Mosses are found all over the world and tend to grow in shadier moist areas. These small plants blanket both the natural and built environment. The surface area that moss covers contributes to evapotranspiration but there small size limits the quantity. A few species of moss have been found to be hyperaccumulators. The species that are being used the most are *Scopelophila cataractae* and *Physcomitrella* patens.

Extensive and Intensive Vegetative Roofs

Extensive vegetative roofs are characterized by their shallow growing depth and their low need for maintenance. The growing medium depth of an extensive roof averages less than 6 inches. Being this shallow, extensive roofs are great for stormwater management and do not need fixed irrigation systems. The plants that would best benefit an extensive vegetative roof are sedums and grasses.

Intensive vegetative roofs are characterized by their greater growing depth than extensive vegetative roofs. The growing medium depth of an intensive roof averages 6 or more inches. This extra depth allows for more biodiversity. Intensive vegetative roofs can grow various sizes of plants from mosses and short sedums to shrubs and trees.

2.3 Leaching, Stormwater Management and Nutrient Removal

Transforming raw dredged material helps absorb and hold toxins from entering into waterways through runoff. In order to secure toxins in dredge material the material is sintered and/or combined with a sintered material such as coal ash. In a 2009 study titled *Development of Lightweight Aggregate from Dry Sewage Sludge and Coal Ash*, a LWA was created from dry sewage sludge, the raw dredged material, and coal ash. "*In this study, dry sewage sludge (DSS) as the principal material was blended with coal ash (CA) to produce LWA….. In addition, an environmental assessment of the LWA generated was conducted by analyzing the fixed rate of heavy metals in the aggregate, as well as their leaching behavior*" (Wang et al, 2009). The true value of adding coal ash was its ability to create a higher quality LWA. "*Adding CA improved the sintering temperature while effectively decreasing the pore size and increasing the compressive strength of the product. Furthermore, the sintering temperature and the proportion of CA were found to be the primary factors affecting the properties of the sintered products, and the addition of 18–25% of CA coupled with sintering at 1100 °C for 30 min produced the highest quality LWAs*" (Wang et al, 2009). The process of sintering the combination of dry sewage sludge (DSS) and coal ash (CA) did not completely eliminate the toxins found in the sewage sludge. When tested for nutrient removal the heavy metals leached from the aggregate. "*…heavy metals were fixed inside products generated under these conditions and the As, Pb, Cd, Cr, Ni, Cu, and Zn concentrations of the leachate were found to be within the limits of China's regulatory requirements*." (Wang et al, 2009)

The article *Properties and Microstructure of Lightweight Aggregate Produced from Sintered Sewage Sludge Ash* explores a common method of sintering raw dredge and states, "Sintering at temperatures between 1000 and 1050 °C produces pellets with physical properties comparable to Lytag, a commercially available LWA manufactured from sintered pulverized fuel ash." (Cheeseman & Virdi 2005). "Leaching of heavy metals from sintered bottom ash pellets in water and under acid conditions (leachate pH 2–7) has been investigated. Rapid sintering at relatively low temperatures significantly reduced leaching in water compared to milled ash. Pb and Zn are leached under aggressive acid conditions (leachate pH 3) with 30–40% of the total present available for leaching." (Cheeseman & Virdi 2005)

In order to be effective, vegetative roofs must manage stormwater and nutrient removal in a beneficial way. A study titled *The Effect of a Modular Extensive Green Roof on Stormwater Runoff and Water Quality* analyzes the runoff quantity and quality from an extensive green roof in order to control runoff and nonpoint source pollution. This green roof which is 248 m^2 was installed on September 2, 2009, on a public plaza at the University of Connecticut. The extensive green roof in the study is less than 10 cm thick and consists of a root barrier, drainage material layer, filter fabric, growing media, and vegetation. The growth media consisted of 75% lightweight expanded shale, 15% composted biosolids, and 10% perlite. (Gregoire & Clausen, 2011). The vegetation used in this study included 10 sedum species. Sedums are succulents that hold water in their leaves which make them drought tolerant. The Sedum varieties used were S. album 'Murale', S. foresterianum subsp. elegans 'Silver Stone', S. kamtschaticum, S. kamtschaticum var. floriferum 'Weihenstephaner Gold', S. reflexum, S. selskianum, S. sexangulare, S. spurium 'Dragons Blood', S. spurium 'Fuldaglut', and S. spurium 'John Creech'. From September 2, 2009, until February 1, 2010, water quality sampling was conducted using ISCO 3710 samplers and precipitation and stormwater discharge samples were collected weekly and/or by rainstorm. The research on the effectiveness of the extensive green roofs to reduce stormwater runoff has shown that they intercept, retain, and evapotranspire between 34% and 69% of precipitation with an average retention of 56%. This green roof retained 51.4% of precipitation and the growth media has a maximum water holding capacity of 31.8 %. PO4–P and TP which are Phosphorous concentration derived from Phosphate were not retained well. The runoff samples consisted of 74% copper.

2.4 Summary

Through an extensive literature review, it has been identified that OWD is not suitable for a large portion of the dredged material, and disposal of dredged material at CDFs increases the maintenance cost. Beneficially using dredged material in built environment is an alternative solution to address the difficulties in handling dredged material through OWD and CDF methods. Existing literatures have shown it is possible to use dredged material as concrete aggregates, backfill material, raw material for LWA, ceramics, brick, riprap or blocks manufacturing. The raw dredged material has a potential to be used as topsoil and to enhance the environmental sustainability. The LWA made from sintered dredge may be used in vegetated roof and bioretention systems with potential vegetation identified in this literature review to manage stormwater and remove nutrients. However, due to potential contamination, variations in treatment, physical and chemical properties, it is necessary to examine the properties of the dredged material and the products made from dredged material to evaluate its reuse potential in the built environment.

3. Experimental Design

Following the literature review, dredged material was sampled from CDF 12 managed by Cuyahoga River Port Authority to evaluate if the dredged material is suitable for LWA manufacturing and green infrastructure construction through chemical and thermal analyses. Then the dredged material samples were dried and pulverized. Small balls (1/2 in. diameter or less) were made in the lab. After dried in the air, the balls were sintered in a furnace with varying temperatures between 550°C and 1150°C . After the completion of the sintering, the balls were cooled down to the room temperature and tested for its physical properties i.e. specific gravity and water absorption capacity. Microstructure of the samples was observed using a scanning electronic microsope (SEM). The samples with best performances were used to replace the LWA in a commercial green roof material –Rooflite®. The unit weight, water retention capacity, and drained water quality were tested in the lab. Two green roof microcosms, one constructed using LWA made from dredged material, and the other with Rooflite®, were implemented in the field. The soil moistures of the two green roof microcosms were monitored for six weeks. The experimental design is illustrated in Figure 3-1. The testing methods are discussed in Chapter 3 and the experimental results are discussed in Chapter 4.

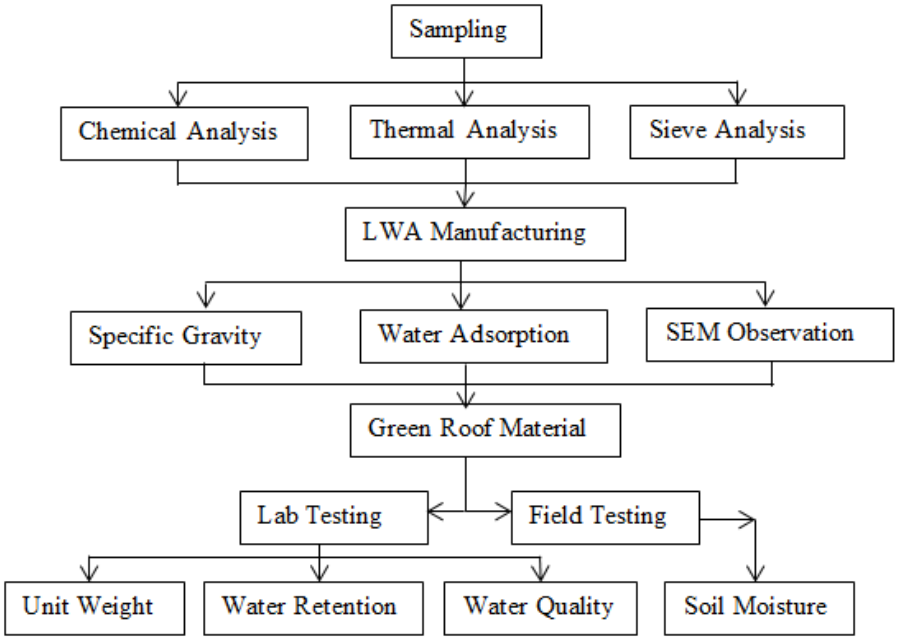


Figure 3-1 Experimental Design

3.1 Dredged Material

3.1.1 Sampling

A total of four samples were taken from the CDF 12 managed by Cuyahoga River Port Authority. Three of them (S1, S2, and S3) were sampled in January, 2015 from the same location indicated as red triangle in Figure 3-2 with a depth of 0-3 feet, 3-6 feet, and 6-9 feet respectively. The sampling was in conjunction with Ohio EPA's sampling assisted by Hull Associates, Inc, and Kurtz Bros. Inc. to monitor the heavy metals and contaminants levels in the CDF. The fourth sample (S4) was taken in August 2015 assisted by Kurtz Bros, Inc, which was a new dredged material poured at the CDF 12 in June 2015. Samples of S1, S2, and S3 are shown in Figure 3-3. S1 is very sandy. S2 and S3 have relatively high silt and clay contents as well as S4.

Figure 3-2 Sampling Location (January, 2015)

(a) S1 (b) S2 (c) S3

Figure 3-3 Appearance of Dredged Material Samples

3.1.2 Heavy Metals and Sieve Analysis

Ohio EPA is working with Kurtz Bros, Inc, and Hull & Associates, Inc. to monitor the levels of heavy metals at the CDF 12 and evaluate the grain size distributions for beneficial uses. Chemical analyses were performed for 38 samples, and sieve analyses were completed for 13 samples, which were collected throughout the CDF 12. The testing results were shared with the research team and they will be discussed in Chapter 4. Aluminum, Antimony, Arsenic, Barium, Beryllium, Cadmium, Calcium, Chromium, Cobalt, Copper, Iron, Lead, Magnesium, Nickel Soluble Salts, Potassium, Selenium, Silver, Sodium, Thallium, Vanadium, and Zinc were measured using EPA Method SW846 6010B. Mercury was tested according to EPA Method SW846 7471A. Total Cyanide and Chromium were evaluated using EPA Method 335.2 and EPA Method SW846 7196A respectively. The contents of gravel, coarse sand, fine sand, silt, and clay were determined by sieve analysis.

3.1.3 Thermal Analysis and Elemental Scanning

Only sample S3 was sent to Robertson Microlit Laboratories for thermal analyses and elemental scanning. The thermal analyses include thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). TGA is used to measure the weight loss of the dredged material sample as a function of increasing temperature. The sample was heated from 20°C to 705°C at 10°C per minute. The temperature was held for one minute at 705°C. The organic contents can be determined from the TGA. The DSC is a thermoanalytical technique which measures endothermic reaction of a sample as a function of temperature. The DSC curve shows evaporation of adsorbed water and crystal water as the temperature increases. In the DSC testing, the temperature was held at 20°C for 1 min, then the sample was heated from 20°C to 600°C at 10°C /min. Multi-element scan provided by Robertson Microlit Laboratories determines the concentration of up to 81 elements in a sample preparation, providing a means to identify the elemental composition of the dredged material sample.

3.2 LWA Manufacturing

3.2.1 LWA Production

The dredged material samples were dried in the air and pulverized. The LWA is produced by mixing the dredged material with certain amounts of water, and firing in a furnace with different temperatures. S1, S2, and S3 were mixed with water and 0%, 5%, 10%, 15%, and 20% (by

weight) of clay (Figure 3-4a). The clay acts as a bonding agency especially for sandy sample material taken from the top layer in the disposal facility. The water content was adjusted to achieve a desired plasticity with a cohesive status. Due to the high clay content in S4, no additional clay was used in the mixture. The raw dredge mixtures were used to make small balls with 1/2 in. diameter or less (Figure 3-4b) in the lab. The fresh balls were dried in the air for minimum 24 hours before firing. The dried balls were packed in a furnace (Sentro Tech ST 1150-458 high temperature box furnace) with a chamber sizing 4"×5"×8" and fired according to a schedule determined from the thermal analysis, which will be discussed in Chapter 4. The samples were sintered at varying temperatures ranging from 550°C to 1150°C (Figure 3-5).

a). raw dredge mixed with clay

b). fresh aggregate balls

c). air dried aggregate balls

Figure 3-4 Aggregates Manufacturing

a) Furnace

b) Sintered Aggregates

Figure 3-5 Aggregates Sintering

3.2.2 Specific Gravity and Water Adsorption Rate

Specific gravity is the ratio of the density of the aggregates made from dredged material to the density of water (Eq. 1). Dry weight (DW), saturated weight (SW), and submerged weight (SmW) of the sintered aggregates can be measured. According to the Archimedies' principle, specific gravity of the sintered aggregates can be determined using Eq. 2. The water adsorption capacity (AC) can be measured using Eq. 3.

$$SG = \frac{\rho_{sample}}{\rho_{water}} \quad \text{(Eq. 1)}$$

Where SG = specific gravity
ρ_{sample} = density of samples
ρ_{water} = density of water (62.5 lbs/ft^3)

$$SG = \frac{DW}{SW - SmW} \quad \text{(Eq. 2)}$$

Where SG = specific gravity of sintered aggregates
SW= saturated weight of sintered aggregates
SmW=submerged weight of sintered aggregates

$$AC = \frac{SW - DW}{DW} \times 100\% \quad \text{(Eq. 3)}$$

Where AC = water adsorption capacity
SW= saturated weight of sintered aggregates
SmW=submerged weight of sintered aggregates

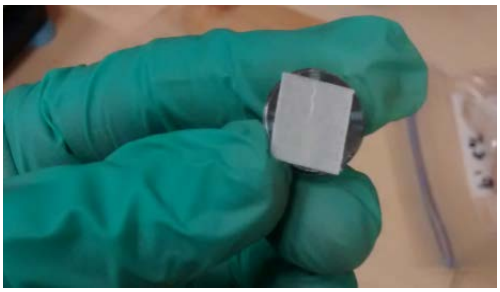
3.2.3 SEM

To understand the physical properties of the aggregates sintered from dredged material at different temperatures, the microstructures of these aggregate were observed using a Hitachi S-2600N scanning electron microscope (1-30 kV) hosted at the Liquid Crystal Institute at Kent State University.

To prepare for a sample for SEM observation, a small particle was sliced from an aggregate using an X-acto blade (Figure 3-6a). Then particle was placed on a magnetic double sided tape which is attached to the stage of a vacuum chamber (Figure 3-6b). The non-conductive surface of

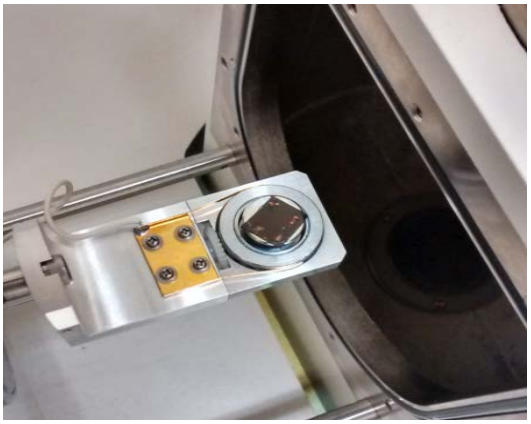
the particle is required to be coated with gold in the chamber which is vacuumed to 50mTorr and purged with Argon gas (Figure 3-6c). The gold atoms were diffused onto the specimen surface with A DC voltage of 6V applied on the top and bottom of the electrode in pulses. Finally, the specimen was placed into the SEM chamber (Figure 306d). Images of samples were obtained at magnification of 2500X.

b) Sampling



a) Double-sided magnetic tape

d) Vacuum



c) Specimen

Figure 3-6 Specimen prepared for SEM

3.3 Green Roof Material

The LWA made from dredged material was crushed into small size of aggregates and used to replace the lightweight mineral aggregate by volume in a conventional green roof material product - Rooflite® extensive mcl in this study. The Rooflite® is used for extensive green roof systems with a balanced blend of LWA (like HydRocks or pumice) and premium organic components. The new developed green roof material made from sintered dredge was tested in the lab for its unit weight, water retention capacity, and drained water quality. In addition, two green roof microcosms were implemented at the Cleveland Industrial Innovation Center using the

dredge green roof material and Rooflite® respectively. The soil moisture contents in two microcosms were measured using moisture probes and recorded by a data logger for six weeks.

3.3.1 Lab Testing

The testing device was built with three polyvinyl chloride (PVC) pipes (12 inches long and 4 inches inner diameter) attached to a 1 inch thick wood board (Figure 3-7a). A wire mesh and a cap with holes were put at the bottom of the PVC pipe, which keeps the solids from clogging the holes and helps facilitate the water drainage. The pipes were filled with 6 inches deep green roof materials with LWA made from the dredged material (Figure 3-7b). Distilled water was poured from the top of the pipe. Drained water was collected using a stainless steel bowl on the floor (Figure 3-7c). Test strips were used to indicate the level of total hardness, total alkalinity, total chlorine, and the PH level. A test to gauge nitrate and nitrite nitrogen levels was also performed.

a) Testing Kit

b) Material loaded

c) Water Collected

Figure 3-7 Lab Testing for Dredge Green Roof Material

3.3.2 Field Testing

Two plant growing tubs with 6 inches depth were prepared for the Rooflite® material (left) and dredge green roof material (right) with a separate drainage course topped with a synthetic drainage layer (Figure 3-8a). Small holes were drilled at the lower left corner to drain the excess water off the tub. The two tubs were filled with materials to the top and watered to the saturation on the first day of installation. Two moisture sensors were inserted at the center of the tubs to record the moisture levels in the two tubs for six weeks (Figure 3-8b).

(a) Drainage Layer in the Green Roof Microcosms

(b) Green Roof Microcosms

Figure 3-8 Filed Testing of Green Roof Materials

3.4 Summary

The experimental plan and methods were discussed in Chapter 3 to assess the potential of using the dredged material to produce LWA, to test the properties of the LWA in terms of specific gravity and water adsorption capacity, and to evaluate the lab and field performances of the

green roof material incorporated with LWA made from the dredged material. The findings of the experiments are discussed in Chapter 4.

4. Experimental Results and Discussions

4.1 Heavy Metals and Grain Size Distribution

The lab testing was performed by Hull & Associates, Inc., and the testing results were shared with the research team. In addition to the heavy metals listed in Table 4-1, other organic contaminants in the CDF 12 were also measured by Hull & Associates, Inc. Because the sintering removes organic contents from the dredged material, the organic contaminants were not discussed in the study.

4.1.1 Heavy Metals

Figure 3-2 indicates the location of sampling for S1 (0-3'), S2 (3-6') and S3 (6-9') in the CDF 12. The contents of heavy metals from the three sampling depths were listed and compared with the Risk Screen Levels (RSL) specified by USEPA for industrial and residential uses in Table 4-1. The RSLs are presented with target cancer risk (TR) of 1×10^{-6} and with target hazard quotient (THQ) of 0.1. The contents of majority heavy metals are lower than the RSL specified for residential uses except Arsenic, Iron, and Manganese. The levels of Arsenic from the three samples are higher than the industrial RSL. The RSLs for heavy metals specified by USEPA are more stringent than soil direct contact standards for industrial and residential uses specified in Ohio EPA's Voluntary Action Programs (VAP). For example, the upper limits for Arsenic listed in 2014 Ohio VAP are 77 mg/kg for the industrial direct contact, and 12 mg/kg for the residential direct contact respectively. The tested Arsenic levels are below the Ohio VAP value for the industrial. The aggregates made from dredged material are expected to be used in the green infrastructure construction to manage stormwater in post-industrial brownfields. In addition, the sintering process to manufacture the aggregate is believed to immobilize the heavy metals in the crystalline structure of the aggregate. Therefore, the toxicity risk of the aggregates sintered from the dredged material due to the heavy metals is low.

Table 4-1 also indicates that the levels of Aluminum, Calcium, Iron, and Magnesium are relatively high. Literatures (Zhu et al, 1997; Arias et al, 2003; Forbes et al, 2004; Ádám, 2007, Leader et al, 2008) state these elements have excellent phosphorus absorption potential. Great Lakes including Lake Erie have been suffering from recurrent harmful algal blooms since the mid-1990s, which is caused by nutrient-rich stormwater runoff. Excess nutrients, particularly phosphorus, are believed to contribute to the algal growth, which is revealed by Heidelberg

University's long- term tributary monitoring program on dissolved reactive phosphorus in Great Lakes. Green infrastructure constructed using the aggregate which is made from the dredged material may also have a potential to improve the water quality by remove phosphorus from the stormwater runoff.

Dredge sample S4 is a newly disposed material in CDF 12. It was not tested for its heavy metal contents. According to the testing results provided by Hull & Associates, Inc, heavy metals from all 38 samples met the RSL for industrial except Arsenic.

Table 4-1 Heavy Metal Contents

Heavy Metals	Soil RSL Industrial	Residental	0-3'	3-6'	6-9'
	TR=1X10^{-6}, THQ=0.1 (mg/kg)		(mg/kg)	(mg/kg)	(mg/kg)
Aluminum	110,000	7,700	3,700	2,700	6,700
Antimony	47	3.1	<0.43	<0.44	<0.52
Arsenic	3	0.67	7.4	6.4	11
Barium	22,000	1,500	24	21	53
Beryllium	230	16	0.34	0.34	0.43
Cadmium	98	7	0.85	0.31	1
Calcium	NS	NS	5,300	7,100	11,000
Chromium	NS	NS	11	22	18
Cobalt	35	2.3	4.9	3.8	8.3
Copper	4,700	310	42	49	36
Iron	82,000	5,500	15,000	16,000	22,000
Lead	800	400	14	15	31
Magnesium	NS	NS	2,000	2,400	4,200
Manganese	2,600	180	210	380	460
Nickel Soluble Salts	2,200	150	28	18	27
Potassium	NS	NS	430	310	960
Selenium	580	39	0.59	<0.31	0.54
Silver	580	39	<0.056	<0.058	0.078
Sodium	NS	NS	79	160	120
Thalium	1.2	0.078	0.21	0.13	0.18
Vanadium	580	39	8.9	13	14
Zinc	35,000	2,300	100	87	170
Mercury	4	0.94	0.026	0.021	0.093
Total Cyanide	13	2.1	0.46	<0.31	<0.44
Chromium(VI)	6.3	0.3	<0.31	0.41	<0.37

4.1.2 Grain Size Distribution

The results of sieve analyses are summarized in Table 4-2. At the sampling site of S1, S2, and S3, the grain size distribution indicates the material is very sandy and most are gravel and sand. Table 4-2 shows the material in the northern and eastern zone of CDF 12 (NE Ave.) is much coarser than that in the central and western area (CW Ave.). Sample S4 was taken from the central and western area in the CDF, which includes more than 70% silt and clay. Clay was used as a bonding agency to mix with S1, S2 and S3 to make the aggregate, while S4 did not need clay due to its high silt and clay contents. After the dredged material samples were dried and pulverized, a No. 16 sieve (1.19 mm sieve opening size) was used to remove plant roots, gravel and coarse sand.

Table 4-2 Grain Size Distribution

Samples	Gravel (3" to # %	Coarse Sand #10 to #40 %	Fine Sand #40 to #200 %	Silt #200 to %	Clay >.005 mu %	Total %
3'-6'	41.7	23.5	29.3	4.0	1.4	99.9
NE Ave.	14.4	16.2	49.9	13.5	6.1	100.0
CW Ave.	0.1	2.2	23.6	48.3	25.9	100.0

4.1.3 Thermal Analysis (TGA & DSC) and Elemental Scanning

TGA and DSC were performed for S3 and the results are presented in Figure 4-1 and 4-2. Figure 4-1 shows there was an initial 2% weight loss at 25°C probably due to the evaporation of water. The weight of the sample did not decrease between 100°C and 200°C. Between 200°C and 700°C, the weight loss was 2.143% due to the loss of crystalline water and burning of organics in the dredged material. DSC testing indicates two peaks in Figure 4-3. The first peak occurred at 184°C which was caused by the loss of absorbed water stored in micro-holes in the minerals included in the dredged material, and the second peak at 555°C possibly was due to the loss of crystalline water and organics in the dredged material. Gases were formed due to the water and organics losses and the dredged material were heated to the point of incipient fusion. The gases were trapped in the melted material. At a higher sintering temperature, a LWA with crystalline structure can be produced. Therefore, it is recommended to pre-heat the dredged material at least to 550°C to generate the gases and heat the material to the point of incipient fusion.

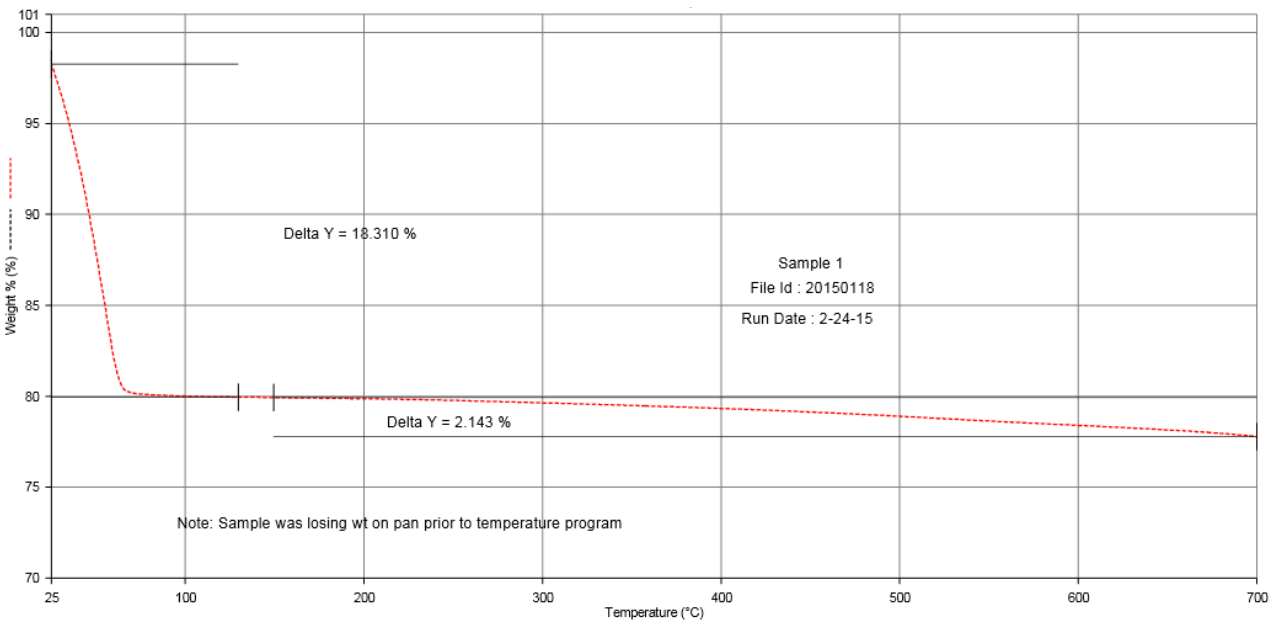


Figure 4-1 TGA Result

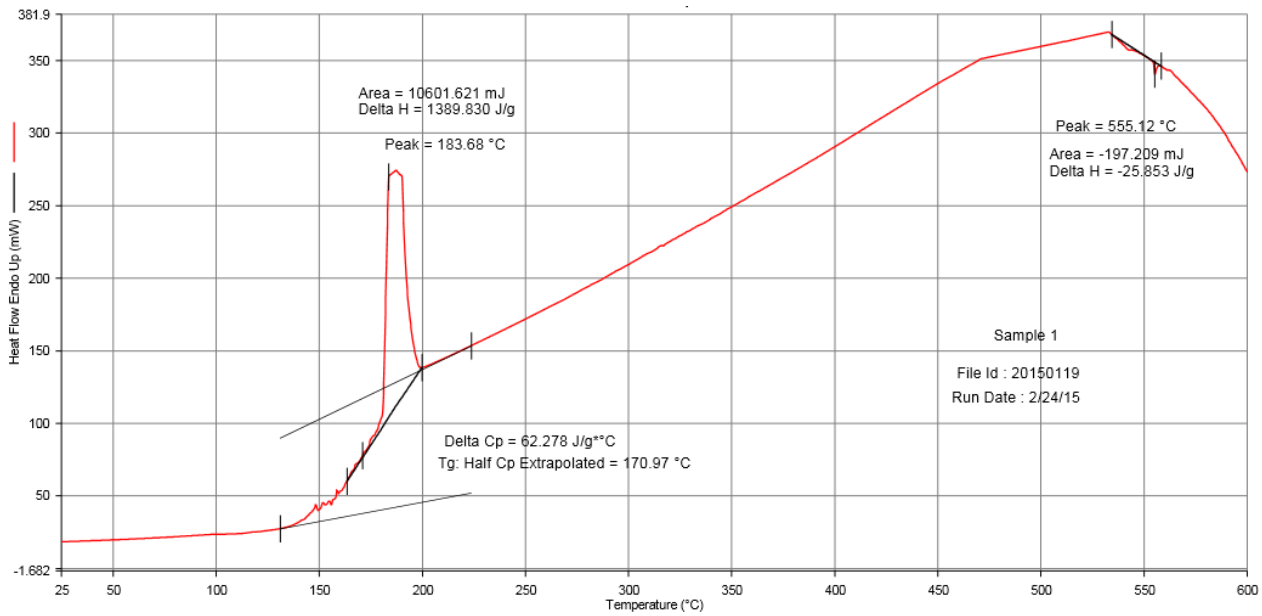


Figure 4-2 DSC Result

The results of multi-elemental scanning for S3 are shown in Figure 4-3. Because a different testing method was used in measuring the heavy metal contents in Section 4.1.1, the heavy metal contents in Table 4.1 are not quite comparable to the results indicated in Figure 4-3. The calibration for the elemental scanning is important for the accuracy of the results. This analysis

was intended to identify the elemental composition (wt%) of a sample preparation. Unsurprisingly, the phosphorus content in the dredged material sample is high as well as iron and magnesium. Both iron and magnesium are reported to have high phosphorus adsorption potential. But it is unknown that how much phosphorus these elements can adsorb.

Results in µg/g unless otherwise noted

H																	He
Li 15	Be <1											B 10	C	N	O	F	Ne
Na 178	Mg 0.4%											Al >1	Si 372	P 414	S	Cl	Ar
K >1%	Ca <1	Sc 2	Ti 0.1%	V 19	Cr 14	Mn 164	Fe 0.8%	Co 3	Ni 11	Cu 15	Zn 31	Ga 3	Ge <1	As 11	Se <1	Br <1	Kr
Rb 19	Sr 23	Y 9	Zr 35	Nb 4	Mo 1	Tc	Ru <1	Rh <1	Pd <1	Ag <1	Cd <1	In <1	Sn 1	Sb <1	Te <1	I 3	Xe
Cs 1	Ba 64	La 11	Hf <1	Ta <1	W 1	Re <1	Os <1	Ir <1	Pt <1	Au 8	Hg <1	Tl <1	Pb 15	Bi <1	Po	At	Rn
Fr	Ra	Ac	Unq	Unp	Unh	Uns	Uno	Une	Unn								

Ce 22	Pr 3	Nd 11	Pm	Sm 2	Eu <1	Gd 2	Tb <1	Dy 3	Ho 1	Er 1	Tm <1	Yb 1	Lu <1
Th 13	Pa	U 3	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Figure 4-3 Multi-element scanning

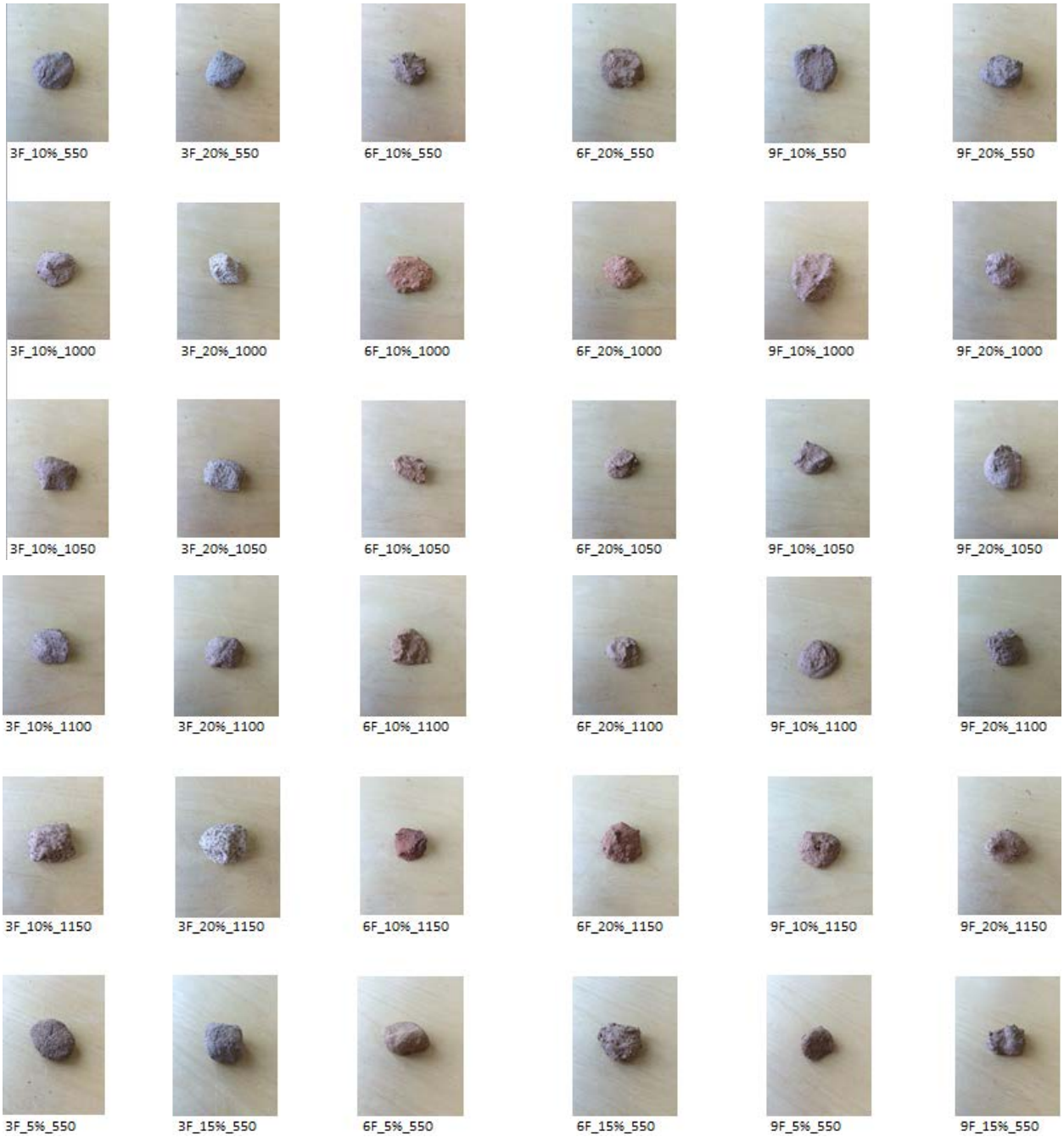
4.2 Aggregates Production

The aggregate manufacturing process includes an initial screening to remove unusable materials, forming pellets by grinding, mixing with water and other mineral admixtures as needed, extruding, and firing in a kiln or furnace. The aggregates can be crushed and graded to suit the needs of customers.

4.2.1 Aggregates Made from Dredged Material

According to the thermal analysis, the aggregates need to be preheated at 550°C, then they need be sintered at higher temperature to gain sufficient strength. S1, S2, and S3 samples were sandy dredged material. They were mixed with 0%, 5%, 10%, 15%, and 20% clay and sintered at 550°C, 1000°C, 1050°C, 1100°C, and 1150°C. All manufactured aggregate samples were recorded in Figure 4-4. In Figure 4-4, 3F_10%_550 represents 10% of dredged material taken from the 0-3ft deep (S1) at the CDF 12 was replaced by clay and the sample was fired at 550°C.

It was noticed that all aggregates sintered at 550°C did not gain enough strength. This is because the strong micro crystalline structure of the aggregate is formed at higher temperatures with minerals fused. The high clay replacements with 15% and 20% made the mixtures too sticky and increase the overall cost of the production, although very hard aggregates were manufactured. It was determined to only use 0%, 5% and 10% clay as the bonding agency in the mixtures with S1, S2, and S3.



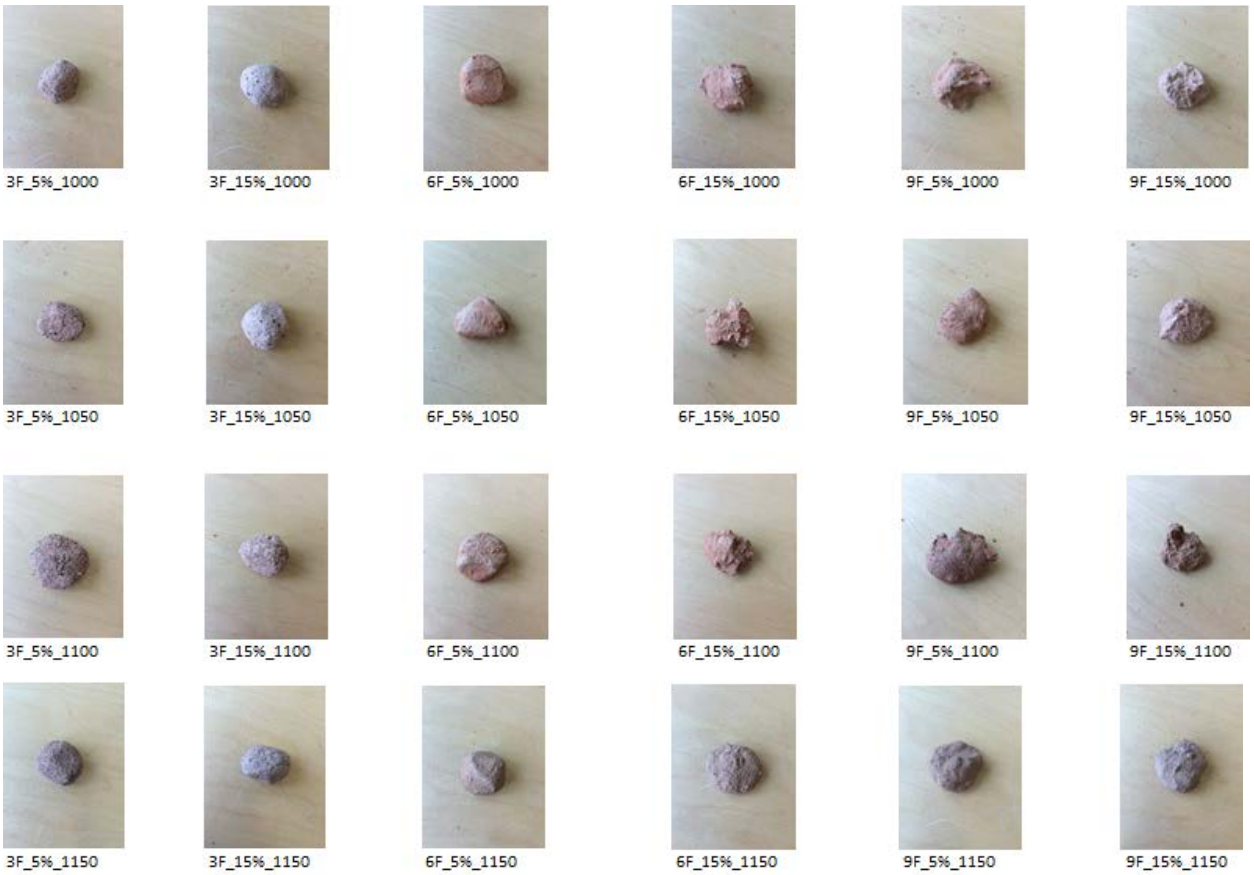


Figure 4-4 Aggregates Made from Dredged Material Samples S1, S2, and S3

S4 sample dredge has high silt and clay contents. It was mixed with water to make the small balls. After all fresh balls dried in the air for at least 24 hours, they were preheated to 550°C and then sintered to 1000°C, 1050°C, 1100°C, and 1150°C (Figure 4-5). These sample aggregates and selected aggregates made from S1, S2, and S3 were tested for its physical properties.

Figure 4-5 Aggregate Made from Dredged Material Sample S4 (from left to right 1000 °C, 1050 °C, 1100 °C, 1150 °C)

4.2.2 Specific Gravity and Water Adsorption

The specific gravities (SGs) and water adsorption rates of selected samples were tested and results are summarized in Table 4-3. In Table 4-3, S1_5%_1100 means 5% of S1 by weight was replaced by clay, and the aggregate was sintered at 1100°C. The SGs of all aggregate samples range between 1.46 and 1.74, and water adsorption rates fall in the range between 10.96% and 23.40%. Comparing to Limestone with SG of 2.6-3.0, Goethite with SG of 3.4-4.0, Limonite with SG of 4.0-4.8, the aggregates made from dredged material are lightweight. The dredged material can be sintered over a relatively wide range of temperatures to produce LWA.

The relationship between SG and water adsorption rate of the LWA made from dredged material is illustrated in Figure 4-6. As the SG increases, water adsorption rate decreases. When SG of aggregates increases, the size of micro-holes decrease, thus the water adsorption rate is reduced. Table 4-3 also shows as the clay content increases (S2_0%_1100, S2_5%_1100, and S2_10%_1100), the SG of the LWA increases, and the water adsorption rate decreases. Aggregates made from S4 were sintered with temperature varying from 1000°C to 1150°C. When it was sintered at 1100°C, its SG reached the maximum value but its water adsorption rate was the least. From Figure 4-5, a black ball was noticed in the third can marked as S4_0%_1100 from the left. The dark color was caused by uneven heating and an enamel surface was formed. Therefore the water adsorption was reduced. The uneven heating affects the understanding on the testing results, but the maximum SG should occur when the aggregates were sintered about 1100°C. The change in nature of the porosity should occur at about 1100°C, which leads to reduced SG at the temperature of 1150°C.

Table 4-3 Specific Gravity and Water Adsorption Rate

Samples	Temperature (°C)	Specific Gravity	Water Adsorption
S1_5%_1100	1100	1.70	14.20%
S1_10%_1100	1100	1.74	12.37%
S2_0%_1100	1100	1.46	23.40%
S2_5%_1100	1100	1.73	12.24%
S2_10%_1100	1100	1.72	11.88%
S3_10%_1100	1100	1.60	14.93%
S4_0%_1000	1000	1.52	22.68%
S4_0%_1050	1050	1.53	22.02%
S4_0%_1100	1100	1.56	10.96%
S4_0%_1150	1150	1.49	19.41%

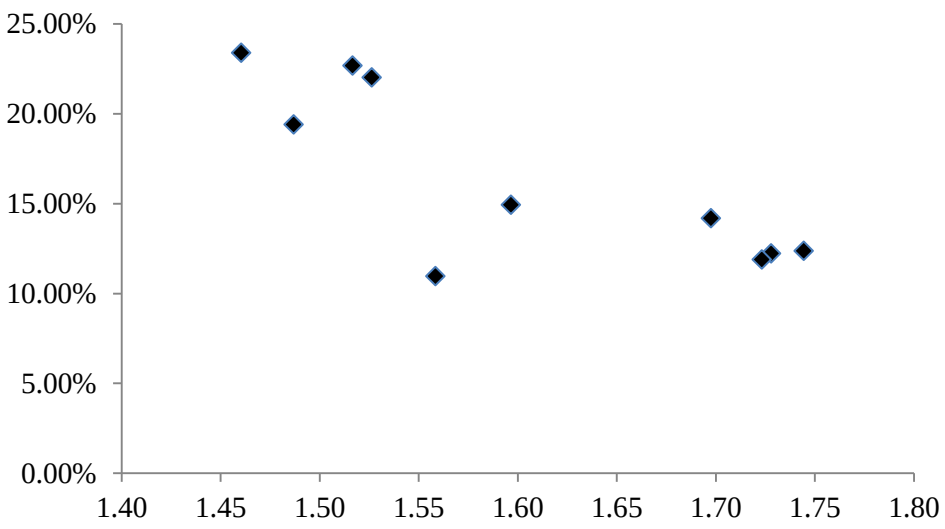
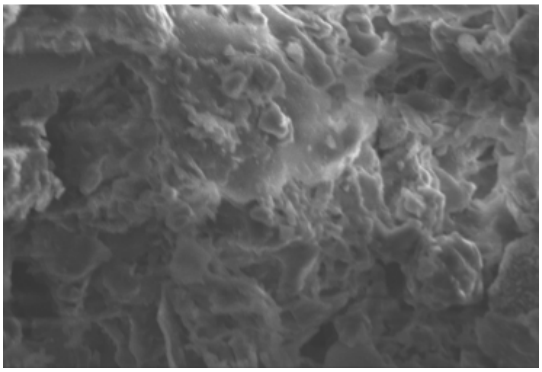


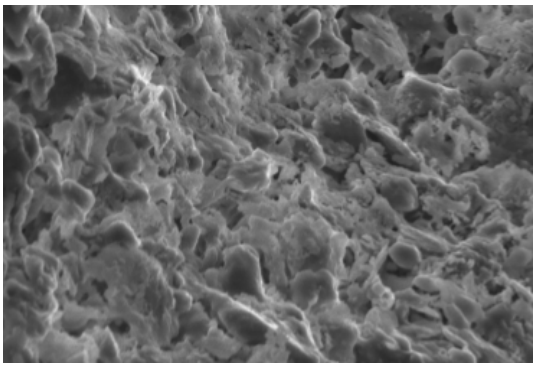
Figure 4-6 Water Adsorption Vs. Specific Gravity

4.2.3 SEM

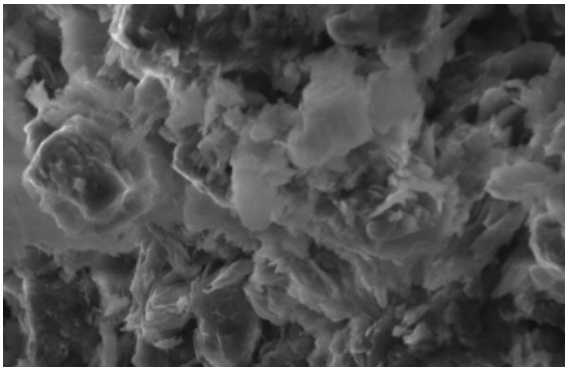
Figure 4-7 shows SEM images of aggregates made of S2_5% sintered at different temperatures. As the temperature increases, the nature of porosity in the aggregate changes. When the temperature increased from 1000°C to 1050°C, the pores were formed on surface of the aggregate and they were connected. When the temperature increased from 1050°C to 1100°C, the pores were discontinued and isolated by enamels with higher density. The isolated pores were enlarged when the temperature was raised to 1150 °C. This may explain why the SG of aggregates may reach the maximum value at about 1100°C. After the peak, the SG reduced due to the isolated enlarged pores.



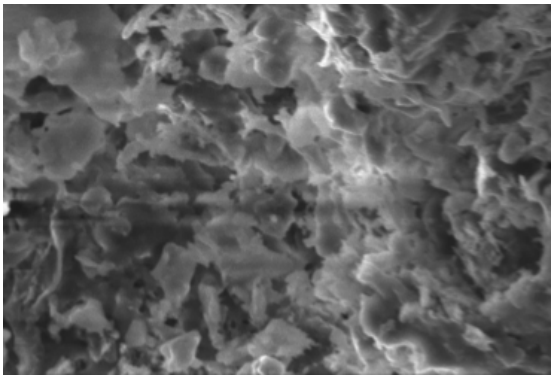
(a) S2_5%_1000



(b) S2_5%_1050



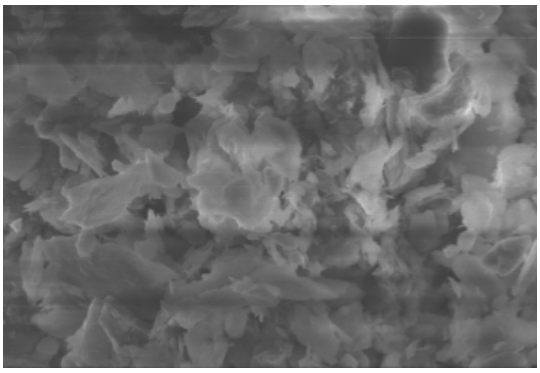
(c) S2_5%_1100



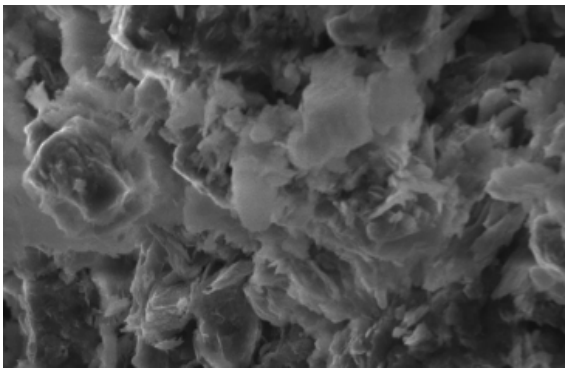
(d) S2_5%_1150

Figure 4-7 SEM S2_5% with Varying Sintering Temperatures

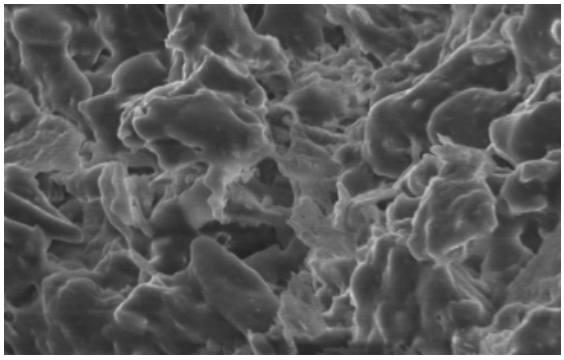
The influence of clay contents on the porosity of the LWA is illustrated in Figure 4-8. With increased clay contents, the pores on the surface were filled with solid particles, which reduces the porosity of the LWA and reduces the water adsorption rate.



(a) S2_0%_1100



(b) S2_5%_1100



(c) S2_10%_1100

Figure 4-8 SEM S2_1100 with Varying Clay Contents

4.3 Green Roof Material

The lab testing has proved that LWA can be produced using dredged material sampled from CDF 12 in Cleveland. Depending on the grain size distribution, clay may or may not be used in the mixtures as a bonding agency. S4 with high silt and clay contents was used for LWA mass production. Although lightweight aggregates can be manufactured using a relatively wide temperature range, 1150°C was selected because of the low SG and relatively high water adsorption rate. As discussed in Section 3.3, the LWA in Rooflite® was replaced by the LWA made from S4 dredge sample. Lab testing and field testing was performed to evaluate the performance of the green roof growing media made from the dredged material.

4.3.1 Lab Testing

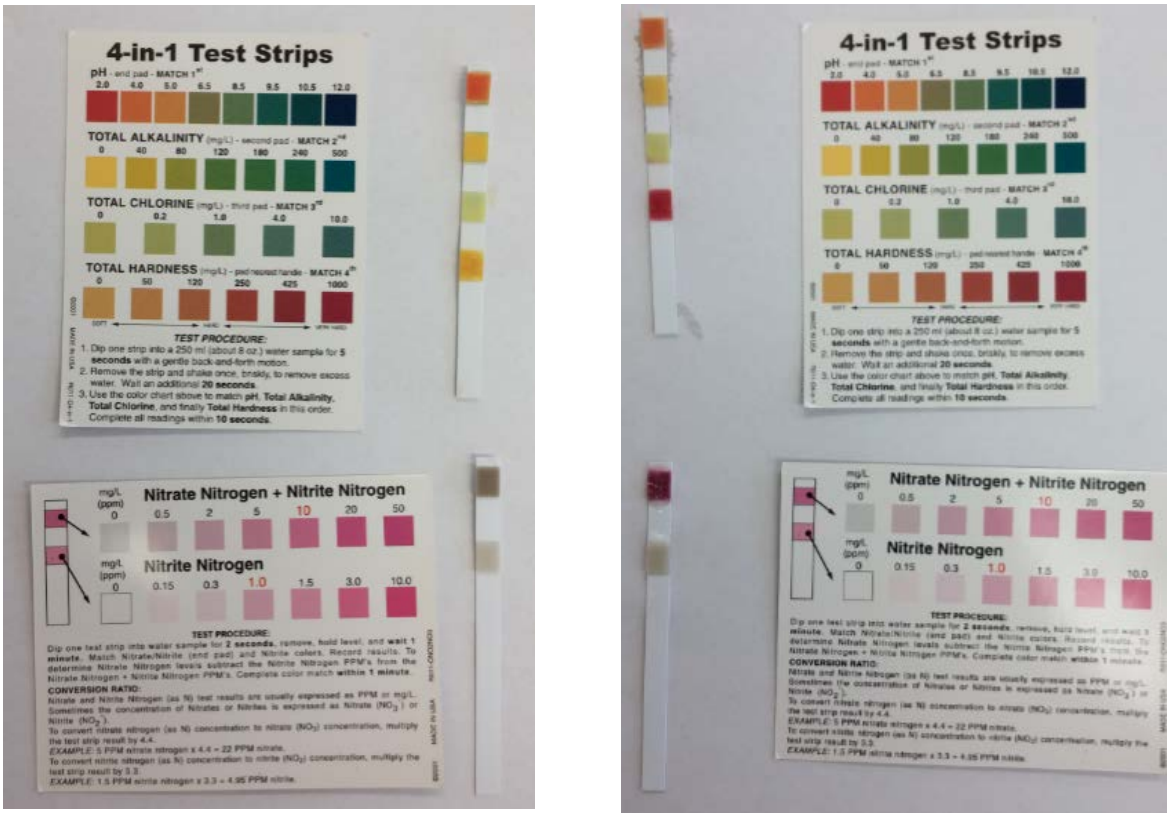
The unit weight, dead load due to the material, and water retention capacity were examined using the testing kit shown in Figure 3-7. The lab testing results are summarized in Table 4-4. The water retention capacity is about 25.50% by weight. The unit weight of Rooflite® extensive mcl ranges between 44 lb/ft^3 and 53 lb/ft^3 (Rooflite®, 2015). The green roof material made from dredged material is heavier than Rooflite® due to higher SG of the LWA made from dredged material.

The pH, total alkalinity, total chlorine, total hardness, nitrate nitrogen and nitrite nitrogen of the drained water from the columns were measured using test strips and compared with distilled water. The results are shown in Figure 4-9. The pH, levels of total alkalinity, total chlorine and

nitrite nitrogen are similar to the distilled water. But the hardness is between 250 mg/L and 425 mg/L, and the nitrate nitrogen is about 50 mg/L (ppm).

Table 4-4 Green Roof Material Made from Dredged Material

	Material Weight (lb)	Water Adsorbed (mL)	Unit Weight (lb/ft^3)	Dead Load (lb/ft^2)	Dead Load (Saturated) (lb/ft^2)	Water Retention (%)
Column 1	2.29	270	52.40	26.20	33.02	26.04%
Column 2	2.39	280	54.72	27.36	34.43	25.85%
Column 3	2.42	270	55.43	27.71	34.53	24.61%
Average	2.36	273	54.18	27.09	34.00	25.50%
Std Dev.	0.06	4.71	1.29	0.65	0.69	0.63%



(a) Distilled Water (b) Drained Water from Column

Figure 4-9 Water Quality Strip Testing

4.3.2 Field Testing

The soil volumetric moisture contents (VMC%) in the Rooflite® and dredge green roof material were measured using moisture sensors. The two tubes were monitored for six weeks and the readings were plotted in Figure 4-10. The dredge green roof material exhibits a consistently

higher soil VMC than the Rooflite®. The first two peaks were caused by two irrigation events and the third peak was due to a rain event. The field implement shows the dredge green roof material has comparable performance with Rooflite® in terms of water retention.

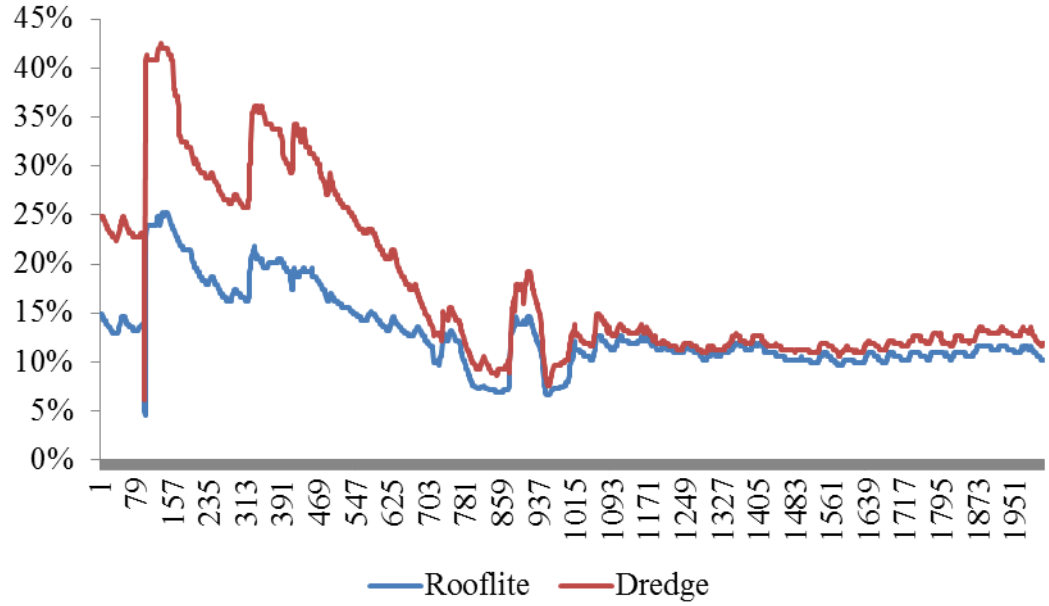


Figure 4-10 Soil Volumetric Moisture Content (%) Rooflite Vs. Dredge

4.4 Summary

The results of a comprehensive experimental plan were presented and discussed in Chapter 4. The dredged material was successfully used as a raw material for LWA production. The LWA made from dredged material was incorporated in the green roof material. The lab and field testing show it has a great potential to be used for stormwater management.

5 Conclusions and Recommendations

5.1 Conclusions

The reuse potential of dredged material from Cuyahoga River and Harbor of Cleveland in green infrastructure construction to manage stormwater runoff was evaluated in this project. The literature review revealed beneficial uses of dredged materials in the built environment. Beneficial use of the material should be emphasized to address the difficulties caused by landfill in the CDF or open water disposal. This study focused on the use the dredged material to manufacture LWA, which can be used in green roof or other green infrastructure construction. A comprehensive experimental plan was proposed by the research team to (1) examine the suitability of the raw dredge in LWA manufacturing, and (2) performance of the LWA in green roof to manage stormwater runoff.

The chemical analyses on heavy metals confirmed there is a low risk to reuse the dredged material in the green infrastructure installed in post-industrial brownfield. The grain size distributions of the dredged material may indicate different potential beneficial uses. For LWA manufacturing, the sandy dredged material can be mixed with certain amount of clay, while clay is not needed for the dredge with high silt and clay contents.

The thermal analysis performed for the dredge samples in this study recommended the fresh aggregates should be preheated at 550°C to convert crystal water and organics to gases at the point of incipient fusion of the minerals in the dredged material. A higher sintering temperature ranging 1000°C to 1150°C is required to produce a LWA with sufficient strength. 1150°C was selected in this study as an optimum sintering temperature because it generates a LWA with low SG and high water adsorption rate. Water adsorption rate decreases as the SG increases. The sintering temperature changes the nature of the porosity of the LWA as revealed in the SEM imaging.

The dredge green roof material has a comparable hydrologic performance with the Rooflite®, a conventional growing media for green roof construction. This project shows dredged material has a great potential to be used for LWA manufacturing, which can be used for green infrastructure construction.

5.2 Recommendations

(1) The chemical analyses show a relative high iron, aluminum, calcium, and magnesium contents in the dredged material sampling from the CDF 12 in Cleveland. Those elements are reported to have phosphorus absorption potential. The LWA made from the dredged material may have a potential to remove the phosphorus out of the stormwater runoff to improve the stormwater quality. Mineral admixtures may be incorporated in and mixed with the raw dredge to produce a LWA with nutrients removal capability.

(2) The current study focused on the function of stormwater management of sintered material in a green roof growing course. Vegetation should be further examined in field trials to identify species suitability for this growing media. Additional, plant studies using raw dredge from Cuyahoga River and/or Harbor of Cleveland would provide, cities, agencies, and nursery trades with information needed to determine proper co-benefit targets.

The Fairfax County Public Works and Environmental Services, out of Fairfax, Virginia, created a series of recommended plant lists for bioretention facilities and intensive and extensive vegetative roofs in partner with Northern Virginia Soil and Water Conservation District and the Fairfax County Park Authority. Although this document does not address dredge, it does provide a comprehensive plant list for the Mid-Atlantic States that is worth examining for potential application within in the Lake Erie basin green infrastructure.

Below is a plant list shown below is to provide a documented resource of plants to use in specific environments. The plant lists includes species from the Fairfax County Public Works and Environmental Services are categorized by use on either extensive or intensive vegetative roofs. The plants chart lists the characteristics and the time of bloom for each plant as well as light and moisture conditions and plant height and spread. Some addition information such as maintenance and suitability is included in the characteristics of certain plants. The plants study is definitely recommended for future studies.

Table 5-1 Recommended Plant List for Future Studies

Scientific Name	Common Name	Hardiness	Soils	
			Phys. Soil Pref.	*Soil Moisture Pref*
Caltha palustris	Marsh Marigold	3 to 7	silt loam	hydric
Chrysopogon zizanioides	Vetiver	9 to 11	sand loam/ clay loam	mesic/ emergent
Cyperus brevifolius	Shortleaf Spikesedge	10 to 11	sand loam/ clay loam	mesic
Cyperus rotundus	Nut Grass	3 to 12	sand loam/ clay loam	mesic/ emergent
Eleocharis tuberculosa	Cone-cup Spikerush	5 to 12	sand	emergent
Festuca arundinacea	Tall Fescue	1 to 12	sand loam/ clay loam	mesic
Melilotus officinalis	Yellow Sweet Clover	1 to 11	sand loam/ clay loam	mesic
Physcomitrella patens	Spreading-leaved Earth Moss		sandy loam	hydric
Pteris cretica	Cretan Brake Fern	9 to 12	sandy loam	emergent
Pteris longifolia	Longleaf Brake	8 to 10	sandy loam	hydric
Pteris umbrosa	Jungle Fern	10 to 13	sandy loam	hydric
Pteris vittata	Brake Fern	8 to 10	sandy loam	hydric
Scopelophila cataractae	Copper Moss	6 to 11	sandy loam	hydric
Sedum alfredii		4 to 9	sand	xeric
Sedum plumbizincicola		4 to 9	sand	xeric

(3) An economic and life cycle costs and benefit analysis would determine the investment opportunities and constrains for a Lake Erie or Great Lakes market product of a sintered dredge product.

(4) The LWA sintered from the dredged material possesses promising traits of hydrological and structural capacities which demand further investigation into various forms of bioretention mixes used in green infrastructure. It is possible new types of green infrastructure and stormwater control measures could be developed using the LWA sintered from the dredged material.

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