Cost-Effective Uses of Lightweight Aggregate Made from Dredged Material in Construction

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16. Abstract

Lightweight aggregate (LWA) can be used in concrete to reduce its self-weight and improve its workability and durability. It could potentially be used as borrow for embankment construction, which is expected to reduce the stresses on the subgrade foundation and reduce bridge approach slab settlement. However, the average estimated cost of LWA in U.S. is $67.5/ton, which is significantly higher than the costs of conventional aggregates. Dredged sediment has been identified as a raw material for LWA production, which may dramatically reduce the cost of LWA. Annually, 1.5 million cubic yards of sediments are dredged from Ohio harbors. This study evaluated the quality of dredged materials taken from the Harbors of Cleveland and Toledo, and their suitability to produce LWA. Engineering properties of LWA, including specific gravity, loose bulk density, friable particles, organic impurities, abrasion resistance, undrained cohesion, free swell, and compressibility were tested in the lab to evaluate its potential for use as a construction material. LWA has been successfully produced in the lab using dredged materials taken from the Harbors of Cleveland and Toledo. Most of their engineering properties met ASTM and ODOT specification values. Based on testing performed in the study, leaching of heavy metals were determined to not be a concern. While the Cleveland samples failed in the abrasion resistance test, the Toledo samples exhibited an excellent potential to be used in construction. The sustainability study concluded that a cost competitive LWA could be fabricated using the dredged material in mass production. The environmental impacts of the dredged material LWA are expected to be lower than the conventional ones made from expanded shale, clay, or slate.

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ABSTRACT

Lightweight aggregate (LWA) can be used in concrete to reduce its self-weight and improve its workability and durability. It could potentially be used as borrow for embankment construction, which is expected to reduce the stresses on the subgrade foundation and reduce bridge approach slab settlement. However, the average estimated cost of LWA in U.S. is $67.5/ton, which is significantly higher than the costs of conventional aggregates. Dredged sediment has been identified as a raw material for LWA production, which may dramatically reduce the cost of LWA. Annually, 1.5 million cubic yards of sediments are dredged from Ohio harbors. This study evaluated the quality of dredged materials taken from the Harbors of Cleveland and Toledo, and their suitability to produce LWA. Engineering properties of LWA, including specific gravity, loose bulk density, friable particles, organic impurities, abrasion resistance, undrained cohesion, free swell, and compressibility were tested in the lab to evaluate its potential for use as a construction material. LWA has been successfully produced in the lab using dredged materials taken from the Harbors of Cleveland and Toledo. Most of their engineering properties met ASTM and ODOT specification values. Based on testing performed in the study, leaching of heavy metals were determined to not be a concern. While the Cleveland samples failed in the abrasion resistance test, the Toledo samples exhibited an excellent potential to be used in construction. The sustainability study concluded that a cost competitive LWA could be fabricated using the dredged material in mass production. The environmental impacts of the dredged material LWA are expected to be lower than the conventional ones made from expanded shale, clay, or slate.

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1. INTRODUCTION

1.1 Background

According to the 2014 National Bridge Inventory, out of 26,986 bridges in Ohio, 2,080 bridges (7.7 %) are structurally deficient, and 4,452 bridges (16.5 %) are functionally obsolete. It would cost the state more than $6 billion to fix these problematic bridges (Grant, 2014). Between 2004 and 2014, 2,687 new bridges were constructed and 1,343 bridges went through major repair and rehabilitation in Ohio (Grant, 2014). Many distresses were caused by bridge bumps resulting from the unexpected elevation change at the edge of approach slab and bridge deck. The change in height may be caused by consolidation settlement of foundation soil, poor compaction and consolidation of backfill material, poor drainage and soil erosion, and seasonal temperature variation. Many new bridge concrete decks, built with high performance concrete (HPC), have been reported to have experienced extensive cracking (Delatte et al., 2007), which severely affects the durability of the concrete structure. HPC is expected to have exceptional physical properties when prepared with high cementitious material content and low water to cementitious material (w/c) ratio. However, HPC with low w/c experiences a considerable chemical shrinkage and self-desiccation during its hydration process, introducing internal stresses due to the high autogenous shrinkage deformation during hardening. Premature cracking occurs if the free deformation of the concrete, caused by the internal stresses, is restrained.

Lightweight aggregate (LWA) could potentially be used as a fill material for embankment construction, which is expected to reduce the stresses on the subgrade foundation and control bridge approach slab settlement. In addition, state DOTs are evaluating the effect of internal curing (IC) using LWA and other high absorptive materials in crack reduction. As an IC agent, LWA was reported to provide better workability, increase compressive and flexural strength, and improve durability of HPC (Delatte et al., 2007; Guthrie and Yaede, 2013; Ideker et al., 2013).

There are fifteen federal harbors and numerous smaller ports for recreational navigation along Ohio’s Lake Erie coast. Each year, more than 1.5 million cubic yards of sediment must be removed from these ports. Landfilling of the dredged material is costly and depletes land resources, while open water placement (occurring in most harbors) deteriorates water quality. Since 1970s, the U.S. Army Corps of Engineers (USACE) has dredged the Cuyahoga River and

Maumee River navigational channels and deposited the dredged material in confined disposal facilities (CDF) (Figure 1), or placed the dredged material in the lake. The USACE plans to dump the material in Lake Erie, or not dredge the entire navigational channels unless a non-federal partner affords the cost of placing the material in the CDFs. The State of Ohio filed a lawsuit on April 7, 2015, against USACE for doing that. In addition, State of Ohio's Senate Bill 1 banns the open water placements of dredged material in Lake Erie by July 2020.   How to treat the huge amount of material removed from the ports in Ohio is a major challenge. Various cost-effective beneficial uses of dredged material were evaluated by Kreitinger et al. (2011). One of the beneficial uses is to produce LWA using the dredged material (Kreitinger et al, 2011, Hammer et al., 2003).

The LWA made from dredged material could potentially be incorporated into the HPC to improve its performance. However, the properties of the LWA made from dredged material must first be evaluated. This study is designed to investigate the potential cost-effective uses of lightweight aggregate made from dredged material in embankment backfill and concrete bridge deck construction.

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

1.2 Study Objectives

Several challenges must be addressed in order to beneficially use the LWA produced from dredged material in construction. They are: (1) assessment of the quality of dredged material and suitability for aggregate production; (2) evaluation of the properties of LWA made from dredged material; (3) cost and sustainability issues; and (4) regulatory issues and public acceptance. Levels of heavy metals and organic contaminations are the top concerns to the general public to use dredged material in construction. Chemical analyses for the dredged material samples taken from the CDF in Cleveland have been completed by Liu and Coffman (2016), funded by Lake Erie Commission, which confirmed the low risk of using the material in the built environment, referring to the risk screen levels specified by U.S. Environmental Protection Agency for industrial and residential uses.

The objective of the study is to examine the engineering properties of the LWA in the laboratory in order to evaluate its potential use as a fill material and an IC agent. The specific objectives of the study include:

1. The evaluation of the engineering properties of LWA made from dredged material in the laboratory.
2. The evaluation of the economic and environmental impacts of the product.

1.3 Scope of Study

An extensive literature review was performed and reported in Chapter 2 to examine the reuse potential of dredged material in the built environment, including as an alternative feedstock in the production of Portland cement, bricks, lightweight aggregates, as well as its both large and small scale experiments in internal curing within concrete. Following the literature review, a series of engineering properties of LWA made from dredged materials taken from the Harbor of Cleveland and the Harbor of Toledo were performed to evaluate its potential to be used in construction. Chapter 3 summarizes the experimental plan and testing methods. The findings from experiments are discussed in Chapter 4. Chapter 5 discusses the sustainability issues of the LWA. Chapter 6 concludes the study and proposes recommendations for future studies.

2. LITERATURE REVIEW

Dredging is important to maintain various economic and recreational activities in U.S. ports and harbors. In 2013, 149 million m^3 (196 million cubic yards, CY) of sediments were dredged from US ports, harbors and waterways, including approximate 3.04 million m^3 (4 million CY) from the Great Lakes harbors and channels (USACE, 2015). Open water disposal is a common and cheap way to handle dredged material. But if the dredged sediment contains high levels of heavy metals and organic contaminants, open water disposal affects water quality and aquatic ecosystems. Considerable amounts of dredged sediment are managed and stored in CDFs. The continued need to dredge the Great Lakes has loaded many CDFs close to their critical capacities. Besides limitations in handling capacities, CDFs have direct physical impacts including alteration of habitat and changing hydrological conditions in a region. The difficulties in storage and handling have given rise to alternative management strategies, involving beneficial reuse of sediments for engineering uses, agricultural and product development, and for environmental enhancements (Millrath, 2003; Sigua, 2005; Daniels et al., 2007; Zentar et al., 2008; Estes and McGrath, 2014; Yozzo et al., 2004; USEPA & USACE, 2007; Kreitinger et al. 2011).

In order to combat potential sustainability issues in Lake Erie caused by large quantities of dredged material from the federal harbors in the State of Ohio, possible applications for recycling this material into the built environment are under investigation. There is a wealth of literature available investigating the beneficial use of dredged 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. This literature review is intended to curate the successes or failures of such studies through summaries of major methods and results. The applications discussed include dredged material as alternative feedstock in the production of Portland cement, dredged material partially substituted into brick production, lightweight aggregates made from dredged material for use in concrete, and both large and small scale experiments in internal curing within concrete. Following the summaries, organized by application, each section includes a brief overview of major findings to be considered in future research.

2.1 Cement

A research team from the University of New Hampshire investigated the use of dredged material as feedstock in the conventional manufacture of Portland cement (Dalton et al, 2004). Collecting samples from New York and New Jersey harbors in 2000, the team examined the process at the bench and piolet scales as well as practical and economic considerations. Primarily, the study focused on the impact of dredged material on traditional performance specifications and manufacturing.

The manufacturing process began by drying raw dredged material in an oven at 60 °C and then sieving the soil through a 300 µm sieve. Next, 10 to 12 percent of the raw feedstock materials needed for Portland cement was replaced by the sifted soil. This mixture then entered a kiln in either a wet slurry or dry state. Although the wet process requires more energy to burn off additional moisture, it may be well suited for manufacture in established wet processing plants due to a possible reduction of the water requirements. After sintering typically for three hours at a gradually reached temperature of 1450 °C, the resulting product, known as clinkers, was removed from the furnace. The clinkers were then ground down and mixed with gypsum to create cement.

During the clinker manufacturing process, it was noted that alkali chloride salts and some metals contained in contaminated dredged soils present possible issues. Chloride specifically holds the potential to reduce final strength and accelerate corrosion of reinforcing steel. However, it was found that most of the chloride along with sulfur, alkalis, and other contaminants would volatilize at approximately 980 °C. Although this creates a possibility for the production of low alkali cements, it also unfortunately generates a maintenance requirement to remove the buildup of these components on machinery. Other notable events in the firing process included the mineral phases of alite and belite. These phases induced rapid hydration with high initial and final strength, or slow hydration, good final strength, and low heat of hydration respectfully. Additionally, concern regarding the presence of metals such as arsenic, cadmium, chromium, copper, lead, mercury, and zinc was not expressed due those elements already occurring in traditional raw cement materials.

The bench scale production of cement consisted of four batches each made with increasing proportions of dredged material: a control of 0 %, 1.49 %, 6.63 % and 12.3 %. In batches of 40 to 45 grams (1.41-1.59 ounces), the materials were fired at 20 °C/min to 1000 °C, and then at 15 °C/min until the furnace reached 1450 °C for a duration of 30 minutes. However, the cooling process occurred slowly in the kiln, sacrificing the rapid cooling time beneficial to Portland cement manufacture. This was due to safety concerns about handling the product at extreme temperatures. After cooling, the clinkers were ground until all material passed through a 200 µm sieve. Six clinker samples were retained and tested for alite content. It was found that full scale manufacturing produced more alite content by percent mass, most likely due to either the restoration of rapid cooling or quartz aiding in the creation of more alite in factory conditions. Furthermore, the varying percentages of dredged material yielded no statistically significant differences with the exception of having an inverse relationship with alite content.

The pilot scale production of cement utilized a sample containing 6.5 % dredged material. At this scale, the analysis detected quartz and a strong presence of belite compared to alite. This further suggested that the presence of quartz (which requires higher temperatures or longer retention times for a reaction with belite to occur) caused the alite phase not to fully form. When strength was tested, the samples performed just under the ASTM C150 values at three and five days, however, surpassed the standards for Type I and II cement by 28 days (though it still underperformed the control cement). Expansion tests revealed a 0.08 % change in length, well below ASTM C150 maximum limit. Additionally, the setting time of 45 to 175 minutes fell within ASTM C150 requirements. Lastly, the free chloride contents all fell below the limits for both reinforced concrete and restressed concrete.

Large scale implementation with 3 to 6 % replacement allows one cement facility to consume roughly 300,000 cubic yards of dredge material annually and to replace fly ash, bauxite and iron by 100 %, 8 %, and 45 % respectively. Moreover, if the percentage is increased to 14 %, the need for bauxite and fly ash could be eliminated from production. Although chloride content increases maintenance, raw material savings and tipping fees can aid in offsetting the additional costs.

2.2 Bricks

Hamer and Karius (2002) investigated the environmental and physical performance results from a large scale experiment in recycling dredged material into brick production. For this pilot test, a mixture of 50 % by weight of sediment from Bremen's Harbor in Germany was combined with 10 % crushed rejected bricks, and 40 % clay. The harbor sediments classified as clayey, slightly sandy silt and met the threshold limits for pollutants in brick production.

After being dried to below 2 % moisture content using excess heat from the kiln, the bricks were dry-molded in a press and fired at 1050 °C. The steam and exhaust air from this process were collected for analysis to test if the waste water could be released into the sewage system. The results exposed an excess of SO_2. To combat this, the study suggests injecting $Ca(OH)_2$ into the flue gas stream.

After manufacturing, two leaching test yielded a liquid/solid ratio of 10:1 as specified in German industrial standards. However, leaching releveled an excess of SO_4 and a slight excess of arsenic. To prevent efflorescence from the SO_4 content, $BaCO_3$ can be added to the raw material. Furthermore, it was found that low pH and large grain sized decreased leaching. However, arsenic was found to increase with heat treatment and low pH levels. This was of concern to the layer of soil and groundwater under an applied layer of dredge material bricks. A process to test the finished bricks for arsenic leaching was outlined in detail within the study. Although a significant portion of the study examined arsenic leaching, arsenic levels in the sampled dredge material were comparable to those found in traditional raw materials.

All other construction tests confirmed that the Bremen harbor sediment bricks were viable as insulated building bricks but not as face or industrial bricks. This limited viability was due to the presence of micro cracks after frost-resistance testing. Limiting organic content to under 1 percent along with an unspecified degree of kiln optimization was mentioned as a solution.

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 which met code requirements. Besides possessing acceptable compressive strengths, the finished brick contained heavy metals within its matrices preventing contaminated leachates from the brick. The success of using dredged material to manufacture brick has led to researching industrial scale production.

2.3 Lightweight Aggregate Implementing Dredged Material

Production of synthetic LWA from dredged material is believed to be one of the more cost competitive alternatives to manage dredged materials (Harborock, 2015). LWA can be made from dredged material if the raw material meets the following two requirements: (1) gases must be formed when the raw material is heated to the point of incipient fusion; (2) ceramics formed under high temperature must have sufficient viscosity to entrap the generated gases. A triaxial diagram (Figure 2-1) was created by Riley (1950) to limit the chemical composition of a material from which a sufficiently viscous glass would be formed by firing.

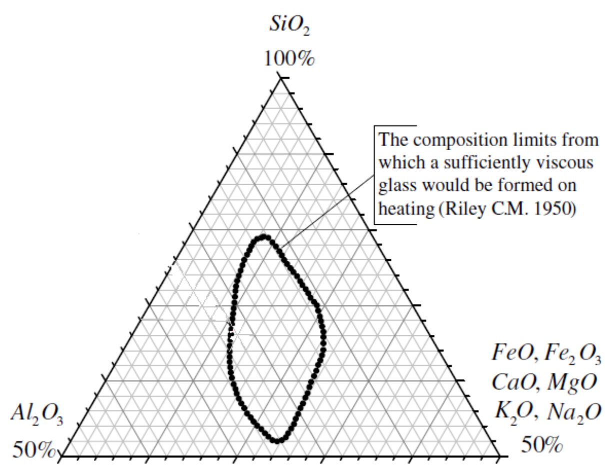


Figure 2-1 Chemical composition limits of raw material for LWA production (Adapted from Tang et al., 2011).

The LWA 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 rotary kiln for mass production (Liu and Coffman, 2016). The dredged material was dried and pulverized, then it was screened to remove undesirable materials, e.g., plant roots, scrap plastics, etc. An appropriate amount of water was mixed with the material to make small pellets (1 in. diameter or less). According to the organic content determined by the thermal analysis, preheating was performed to remove excessive carbon from the small pellets. Then, the pellets were moved to an oven furnace with a higher temperature for sintering. The process of sintering generated gases, which creates porous surface and microstructure within the aggregate. After the completion of the sintering process, the samples were cooled to the room temperature. The small pellets can then be crushed to produce well-graded, coarse and fine lightweight aggregates. Various sintering temperatures (900 °C ~1150 °C) have been tested by Liu and Coffman (2016) to produce LWA (Figure 2-2). The testing indicates the bulk specific gravity of the LWA made from dredged material taken from the Harbor of Cleveland ranges between 1.46 and 1.74, and water adsorption capacity ranges between 11 and 23 %. As the sintering temperature and/or time increased, the water adsorption capacity decreased.

Figure 2-2 LWA made from dredged material taken from the Harbor of Cleveland

2.3.1 Using LWA made from Dredged Material in Concrete

Wang and Tsai (2006) experimented with replacing aggregates in concrete with LWA made from dredged material with particle densities of 800, 1100, and 1500 kg/m^3 (49.9, 68.7, and 93.6 lbs./ft^3), and water to cementitious material ratios (w/c) of 0.28, 0.32, and 0.4. A densified mixture design algorithm was implemented to specify a concrete mixture that would maximize unit weight while minimizing porosity. This study followed ASTM C143 for slump and slump flow, ASTM C39 for compressive strength, ASTM C597 for pulse velocity, and DIN 51046 for the coefficient of thermal conductivity. The concrete maintained its workability after an hour. The compression strength test confirmed that a compressive strength increases with a lower w/c and a higher aggregate density. However, the particle density had the largest impact on ultrasonic pulse velocity. Although a lower w/c helped, a higher particle density was crucial. The electrical resistivity test confirmed that a low w/c also improved electrical resistance. The thermal conductivity test found that although a high aggregate density raised the thermal coefficient, the density was low enough in all tested samples of dredged LWA to still be significantly smaller than traditional concrete, suggesting better heat insulation. Lastly, the shrinkage test resulted in an expansion at 28 days of 100 to 150 x 10^{-6} and a shrinkage at 90 days of 390 to 510 x 10^{-6}.

Wang (2008) tested the durability of concrete containing self-consolidating lightweight aggregate made with dredged material. The samples taken from southern Taiwan were sintered into aggregates with particle densities of 800 kg/m^3 (49.9 $lbs./ft^3$) and 1060 kg/m^3 (66.2 $lbs./ft^3$), which were incorporated into concrete mixtures with three different w/c of 0.28, 0.32, and 0.40, respectively. Furthermore, the groups with a w/c of 0.28 were triplicated and again subdivided into groups of varying raw material percentages. Specific gravity and absorption capacity were tested in accordance to ASTM C127, the slump in accordance with ASTM C134, the velocity of the ultrasonic wave following ASTM C597, the electric resistivity using a resistivity gauge, and the rapid chloride penetrability following ASTM C1202.

Each test performed for this study was measured at 7, 28, and 100 days. The slump and slump flow remained consistent across samples at 25 to 27 cm (10-11 in.) and 51 to 58 cm (20 – 23 in.), respectively. However, this consistency ended as the samples with a low w/c outperformed the others. After about a week, the 0.28 sample achieved the highest compressive strength and reached values of 9 MPa (1,305 psi), 40 MPa (5,801 psi), and 49 MPa (7,107 psi) at 7, 28, and 100 days, respectively. The lower w/c samples continued to outperform in the splitting test, achieving a splitting strength of about 1.7 MPa (246 psi), 1.9 MPa (276 psi), and 2.2 MPa (319 psi), respectively. However, traditional heavyweight concrete maintained a larger splitting strength when compared to concrete incorporated with LWA made from dredged material. Lower w/c also accounted for a slightly higher ultrasonic pulse velocity, reaching values of 3,700 m/s (12,139 ft/s) , 4,000 m/s (13,123 ft/s), and 4,300 m/s (14,108 ft/s), a higher electrical resistivity after 28 days, and lower chloride penetrability.

Although a low w/c of 0.28 outperformed the higher ratios, it was unclear whether this was the optimum value as no values lower than it were tested. Additionally, a superplasticizer was necessary for workability at such low water levels.

Another study performed by Wang et al. (2010) investigated the performance characteristics of high performance concrete developed using LWA made from dredged material. Again, particle densities included 700 kg/m^3 (43.7 lbs/ft^3), 1100 kg/m^3 (68.7 lbs/ft^3), and 1500 kg/m^3 (93.6

lbs/ft^3) and w/c ratios were 0.28, 0.32, and 0.4. Samples taken from seven reservoirs in Taiwan all showed acceptable amounts of heavy metals. Additionally, particle density and absorption capacity were tested following ASTM C127, slump and slump flow following ASTM C143, compressive strength following ASTM C39, and the coefficient of thermal conductivity following DIN 51046.

This study conditionally yielded exceptional expanded aggregates, the gross unit weight ranging from 33 % to 87 % of the original unit weight. This expansion resulted in an impressive absorption capacity of 20 to 40 %, twice as high as expanded materials, and ten times as high as traditional concrete aggregate. However, this study found that LWA sintered in a rotary kiln has a lower absorption capacity (< 10 %). The increased expansion in LWA along with higher sintering temperatures also decreased particle density. Although preferable when absorption is required, a decreased particle density was found to decrease the compressive strength of concrete mixtures. Compressive strength was further depleted with a high w/c ratio. Fortunately, all tested w/c ratios outperformed that of traditional American Concrete Institute design in terms of compressive strength. The higher particle density was also preferable for low thermal conductivity. Lastly, a lower w/c ratio was seen to increase electrical resistivity while all samples of dredged LWA perform significantly better in resistivity than traditional ACI design.

When examining influences of LWA made from dredged material on concrete properties without considering the prospect of internal curing, each study confirmed that a low w/c of 0.28 was successful in conjunction with a superplasticizer. However, no test supplied data on a lower w/c ratio. Additionally, LWA made from dredged material was more porous than traditional aggregates resulting in a decreased compressive strength and increased thermal conductivity. These undesirable traits could be reduced with production processes that increase particle density, however this must be balanced with the desire for high porosity and absorption when internal curing is desired.

2.3.2 LWA for Concrete - Internal Curing

As an alternative to external curing, internal curing has the potential to increase the durability and lifespan of concrete infrastructure by reducing cracking from autogenous and drying shrinkage. Due to the porosity of a LWA produced from sugar cane bagasse fly ash and recycled agricultural wastes, Lura et al. (2014) investigated the viability of pre-wetting the LWA before introduction into the cement in order to achieve superior concrete.

Firstly, a large water absorption is required for success. The tested product measured three times the absorption than required in ASTM C1761, which was 16 % as compared to 5 %. Next, pre-wetted aggregates must rapidly expel their water into the surrounding cement. Both samples of LWA displayed a steep desorption at the first ambient relative humidity measurement of 97 %. In order to achieve this most efficiently, the aggregates must have a coarse pore structure measured by multi-cycle mercury intrusion porosimetry.

When measured for autogenous deformation, the pre-wetted aggregates (at as low as 16 % by mortar volume) limited shrinkage of mortar bars. Higher percentages such as 29 % even encouraged early age expansion and almost eliminated shrinkage. Again, the samples with larger particle size and therefore coarser pores experienced more success. Further testing is needed for more conclusive results on the release of water from the LWA.

Raoufi et al. (2011) examined the relationship of stress development to the material properties of concrete containing pre-wetted LWA in a duel ring test. This test worked by restraining the expansion or shrinkage in concrete between two concentric rings, causing the buildup of residual tensile stresses. In addition, this study used commercial finite element software FEMMASSE HEAT MLS8.5 to digitally simulate the test. Five mortar mixtures were simulated with a w/c ratio of 0.3, 55 % fine aggregate by volume, and between 0 % and 23.7 % of their total volume replaced by pre-wetted LWA. The proceeding test followed ASTM C192 for mortar mixtures, and ASTM C496 for splitting tensile strength and static elastic modulus.

Unfortunately, the simulation exposed a reduction in tensile strength and increase in autonomous deformation with increased percentage of pre-wetted LWA. Furthermore, a consistent coefficient of thermal expansion (COTE) was observed across samples. Once the calculated averages approached the tensile strength of the concrete, cracks formed. The first instance of this occurred around 54 days for the control sample due to a high elastic modulus and autogenous shrinkage, and the latest around 59 days due to the unique initial development of compressive stresses from early age expansion that helped counteract the later tensile stresses from shrinkage.

Along with minimizing the elastic modulus, further factors that were found to reduce cracking include minimizing the difference between the COTEs of the test mixture and the test rings, reducing rate of cooling to below 2.5 °C/hr., and increasing creep and stress relaxation. Although internal curing did not accomplish the last two listed objectives, it overall improved the anti-cracking performance of the specimens when applied moderately (about 16 % replacement).

Internal curing proves somewhat successful across mediums when the following specific conditions are met. Aggregates with larger pores, measured between 0.5 mm (0.0197 in.) and 1.4 mm (0.0551 in.) experienced the most success. Coarser pores absorb more water and then release it during the curing phase. A moderate replacement of 16 % of aggregates is supported with improved performances.

2.3.3 Large Scale Implementation of Internal Curing in Bridge Decks

Guo et al. (2014) examined the effect of internal curing on infrastructure such as bridge decks as well as the consequences of construction and maintenance on traffic. Specifically, the study looked to four internally cured concrete mixtures used in a 2013 study in Indiana, as well as four corresponding control mixtures produced with traditional aggregates. This was an attempt to procure more accurate results than the 2013 test due to many inconsistencies across the past test.

"*The cementitious materials used in the study include Type I ordinary Portland cement, Class C fly ash or ground granulated blast furnace slag (GGBFS), and densified silica fume. The aggregates consist of a normal weight natural fine aggregate and a normal weight limestone conforming to INDOT gradation 9*." The lightweight aggregate that replaced a portion of the traditional aggregate consisted of expanded shale. Just prior to mixing, a centrifuge was used to determine the moisture state of the pre-wetted LWA, confirming an absorption of 18.7 to 20.2 % and a surface moisture of 6.6 to 9.9 %.

Testing began with the casting of a cylindrical sample in the field for each mixture. After one week of curing, the samples were then collected in a laboratory of 100 % relative humidity to prevent external drying. The permeability test found no trend between the internally cured high performance concrete (HPC) and traditional HPC. Migration cell testing reported that the first three IC HPC samples had significantly less tortuosity and chloride diffusion than HPC due to an extended degree of hydration. The service life simulation yielded mixed results, showing half of the IC samples outperformed their counterparts. However, this could be a result of the simulator not accounting for cracking as well as documented variations in mixtures. Fortunately, all samples outperformed traditional Class C mixtures while the IC HPC increases service life to 3 to 4.5 times traditional concrete bridge decks. Additionally, 18 months later IC HPC indicated no shrinkage cracking.

The second part of the project used the Saint Paul metropolitan highway network in Minnesota as a case study. It was shown that internal curing in highway bridge decks could reduce more than 70 % of total life-cycle costs. This was primarily due to the reduced maintenance requirements. The time elapsed before spalling causing the first repairs and replacement was tripled with IC HPC. These savings were enough to offset the initial increase in cost to the user from construction and traffic detour. Although the report noted that the nonlinear programming model developed for this study should be further optimized to include environmental factors and increased population, it could serve as a base to aid future designers in maximizing quality and economic efficiency for highway repairs.

Tia et al. (2015) experimented with the viability of pre-wetted LWA for internal curing in concrete bridge decks and pavement. The study specifically tried to find a solution to high early shrinkage in high strength concrete. In this case, three mixes of internal curing concrete (ICC) and their control counterparts were tested under Florida conditions. The samples had w/c ratios of 0.4, 0.36, and 0.32, and cementitious material contents of 408 kg/m^3 (687 lb/yd^3), 463 kg/m^3 (780 lb/yd^3), and 510 kg/m^3 (860 lb/yd^3), respectively, and material contents of 80 % Type I/II Portland cement, 20 % Class F fly ash, a dry bulk density of 1.23, water absorption rate of 25.2 %, and in the case of the ICC 3.2 kg (7 lbs) of absorbed water per 45.4 kg (100 lbs) of cementitious material.

In mixing, it was found that less water reducing admixture was needed for ICC. Unfortunately, the compressive strength of the ICC fell by 11 %, although it still achieved the required value.

The results also showed that the lower the w/c ratio, the more the ICC dipped close to the lower limit. Moreover, the flexural strength if the ICC fell by 6 %, the elastic modulus of elasticity by 18 %, and the tensile strength by 10 %. Fortunately, as expected, the ICC experienced substantially less shrinkage cracking, taking 2.7 times longer to crack. This correlated with a 10 % lower coefficient of thermal expansion. However, the drying shrinkage of the ICC increased by 24 % from standard. Overall, although the data collected for ICC underperformed in all tests but cracking compared to the control, the difference was marginal compared to ASTM standards.

The mixtures were then cast into slabs in the field. To evaluate structural performance and load induced strains, a heavy vehicle simulator applied repetitive wheel loads and falling weight deflectometer tests were performed. This data was then synthesized into a 3-D finite element model that would estimate stress-to-strength ratios. The critical stress analysis then showed that at critical loading the ratios were just below that of standard concrete.

After three months, the test slabs were examined. As expected, the control slabs exhibited hairline cracks next to the wheel path that were attributed to micro shrinkage cracks from repetitive loading. The two field tested ICC slabs in comparison did not display any cracks. Although the final product achieved the intended goal of reducing shrinkage cracking, it was recommended that a more in-depth field test be performed.

The two large scale studies examined converge on a few constants. Most importantly, both studies observed reduced shrinkage cracks. A low water to cement ratio is needed due to the water included in the pre-wetting. However, there is conflicting data in some instances, suggesting poorer performances than traditional methods. Therefore, further investigation is necessary. Once the results of internal curing become repeatable, the replacement of the conventional aggregates with the LWA made from dredged material can be explored and compared. Overall, despite some unfavorable test results, field testing did yield increased life time as compared to traditional methods.

2.4 Summary

The experiments recorded in this literature review offer encouraging results on the various applications of LWA made from dredged material. Although the dredge material did not result in an overall superior product, the results in most cases met ASTM standards. Therefore, a life cycle analysis is needed for each product to discover if the value of potential cost savings and environmental benefit of dredge material recycling is comparable to the loss in performance.

The primary concerns for each application are as follows. In cement production, chloride content requires increased machine maintenance, and quartz content must be limited for successful alite and belite phases. In brick production, SO_2 content in the kiln exhaust must be reduced by injecting $Ca(OH)_2$ into the flue gas stream, and efflorescence from SO_4 should be reduced by adding $BaCO_3$ into the raw material. Additionally, micro cracking should be reduced by finding an optimal sintering process and when possible limiting raw material organic content to under 1 percent. In aggregate production, a low w/c ratio such as 0.28 in conjunction with a superplasticizer and high particle density was universally more successful. However, the porous nature of the dredge material aggregates decreased strength and increased thermal conductivity. Although porosity is desirable for internal curing, it is not beneficial to traditional application of aggregates. While both the large and small scale studies examining internal curing did not implement dredged material, they did experience success with large size aggregates and coarse pores. The porous aggregates resulted in reduced shrinkage cracking but also reduced strength. The issue of late water release after final set also arose. Nevertheless, large scale studies found that the benefit of reduced cracking outweighed other losses in performance through long term observation and a life cycle analysis that predicted a longer lifespan for the internally cured concrete bridge decks.

The next step in the exploration of dredge material leads to the application of internal curing. As exposed in various studies, their porosity makes the dredge aggregates uniquely qualified for the process. Despite the fact that construction using products made from dredged material have not yet fully exceeded traditional methods, these studies show that these products meet ASTM standards in various applications. Most importantly, the results support the feasibility of addressing the pressing dilemma of excess dredged material through applications in the built environment.

3. EXPERIMENTAL DESIGN

Following the literature review, dredged materials were sampled (Figure 3-1) from CDF 12 managed by the Cuyahoga River Port Authority, and the new Center of Innovation as well as CDF 3 managed by the Toledo – Lucas County Port Authority to evaluate if the LWAs made from dredged material are suitable for construction through testing their engineering properties. The dredged material was first air dried and pulverized. Undesirable materials, e.g., plant roots, scrap plastics, etc. were removed by screening. Small pellets with a diameter of 25 mm (1 in.) or smaller were hand made by mixing an appropriate amount of water with the dredged material. After the pellets were dried in the air, preheating at 550 °C was performed to remove crystal water molecules and excessive carbon based on a thermal analysis completed by Liu and Coffman (2016). Then, the pellets were sintered with a higher temperature to produce the lightweight aggregates. After cooling to the room temperature, the pellets were removed from the furnace. Splitting a pellet into halves, it could be observed that expansion occurred in the sintered products with porous structures generated. The pellets could be further crushed down into small particles. After sieving and mixing according the gradation requirements for concrete aggregates (ASTM C330) listed in Table 3-1, coarse and fine aggregates were developed (Figure 3-1).

Figure 3-1 Dredged material samples taken from Cleveland and Toledo

(a) Coarse (max. 25 mm, 1.0 in.) (b) Coarse (max. 19 mm, 0.75”) (c) Fine (max. 4.75 mm, 0.187”)

Figure 3-2 LWA made from dredged material taken from Cleveland

Lab testing used to evaluate the engineering properties of produced LWA is listed in Table 3-2. In addition, leaching potential of heavy metals from LWA was evaluated according to the Toxicity Characteristic Leaching Procedure (TCLP) developed by U.S. EPA. The testing methods are discussed in Chapter 3 and the experimental results are discussed in Chapter 4.

Table 3-1 Grading Requirements for Lightweight Aggregate for Structural Concrete (ASTM C330)

Nominal Size Designation	Percentages (Mass) Passing Sieves Having Square Openings									
	25 mm (1 in.)	19.0 mm (3/4 in.)	12.5 mm (1/2 in.)	9.5 mm (3/8 in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)	300 µm (No. 50)	150 µm (No. 100)	75 µm (No. 200)
Fine aggregate:										
4.75 mm to 0	-	-	-	100	85-100	-	40-80	10-35	5-25	-
Coarse aggregate										
25.0 mm to 4.75 mm	95-100	-	25-60	-	0-10	-	-	-	-	0-10
19.0mm to 4.75 mm	100	90-100	-	10-50	0-15	-	-	-	-	0-10
12.5 mm to 4.75 mm	-	100	90-100	40-80	0-20	0-10	-	-	-	0-10
9.5 mm to 2.36 mm	-	-	100	80-100	5-40	0-20	0-10	-	-	0-10
Combined fine and coarse aggregate:										
12.5 mm to 0	-	100	95-100	-	50-80	-	-	5-20	2-15	0-10
9.5 mm to 0	-	-	100	90-100	65-90	35-65	-	10-25	5-15	0-10

Table 3-2 Lab Testing for LWA Properties

Property	**Test Method**
Soil Classifications	ASTM D2487 ASTM D4318
Specific Gravity	ASTM C127
Loose Bulk Density	ASTM C29
Compacted Bulk Density	ASTM D698
Undrained Cohesion	ASTM D3080
Compressibility	ASTM D2435
Free Swell Strain	ASTM D4546
Organic impurities	ASTM C40
Clay Lumps and Friable Particles	ASTM C142
Loss on Ignition	ASTM D7348
LA Abrasion	AASHTO T96
Sodium Sulfate Soundness	AASHTO T104
Water Absorption	ASTM C127
Water Desorption	ASTM C1761

3.1 Soil Classifications

3.1.1 Cleveland Sample

Due to the sandy nature of the Cleveland sample, a sieve analysis was performed according to ASTM D2487 *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)* for the purpose of soil classification. After air drying and weighing the sample, it was placed in a mechanical sieve shaker. Following this, the sample was gently disturbed by hand to encourage remaining particles to pass through each consecutive sieve. The sample weight on the individual sieves was then recorded and the percentages of each compared to the total mass were calculated.

3.1.2 Toledo Sample

The clayey nature of the Toledo sample required a soil classification through an Atterberg Limits test (ASTM D4318) for its liquid limit and plastic limit.

To calculate the liquid limit, a small sample was thoroughly mixed with a few drops of water and placed in the dish of the Atterberg apparatus (Figure 3-3), flattened with a spatula so that the surface was parallel to the table, and divided down the center with a curved wedge tool. The crank on the apparatus was then turned, lifting and dropping the dish until the impact vibrations reunite the two sides by a length of 12.7 mm (0.50 in.). The number of blows required was then recorded and the sample was immediately collected and weighed. This was repeated so as to gather five data points where one sample required approximately 25 blows, and at least two samples fell to either side of 25 blows. Lastly, after oven drying, the five samples were weighed again to calculate the water content of each sample. This was plotted by the number of blows verses water content with a linear curve approximated between the points. Using this linear curve, the precise water content necessary for exactly 25 blows to close the gap by 12.7 mm (0.50 in.) was specified as the liquid limit.

To calculate the plastic limit, a small sample was thoroughly mixed with a few drops of water and rolled between the palm and a sanded glass plate until a coil measuring 3.2 mm (1/8 in.) diameter was formed. If the coil was still intact, the sample was kneaded back together and the coil creation was repeated. This continued until the glass plate absorbed enough moisture so that the sample crumbled into segments of roughly 9.5 mm (3/8 in.) in length (for clayey soils) during the process. The sample was then immediately collected and weighed. This was repeated for a total of three data points. Lastly, the three samples were oven dried and weighed to calculate the water content. The average water content was specified as the plastic limit. Next, the plasticity index was calculated by subtracting the plastic limit from the liquid limit. The plasticity index was then plotted against the liquid limit on a plasticity chart for soil classification where specific classifications were dictated by zones on the graph.

Figure 3-3 Atterberg apparatus

3.2 Specific Gravity, Water Adsorption and Bulk Density

3.2.1 Specific Gravity and Water Absorption Rate

The specific gravity and water adsorption rate of coarse aggregates made from dredged material were measured according to ASTM C127 *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*.

First, the sample was submerged in water for 24 hours. Next, the surface dried saturated weight (SW) was found by weighing the sample after drying the surface with a paper towel. To discover the submerged weight (SmW), the sample was placed in a submerged container which hung from a scale and weighed. Lastly, the sample was oven dried and weighed again. The various specific gravities and absorption rates were calculated using the Equations (1) through (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)

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

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

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

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

For increased accuracy, this research performed the specific gravity tests three times on each coarse aggregate sample used throughout the project and averaged the results.

3.2.2 Loose and Compacted Bulk Density

The loose bulk density could not be performed on the fine aggregate gradation used throughout the study due to the majority of the sample having a gradation too fine for the equipment. Because the samples under investigation have a high porosity, the absence of fine particles decrease the specific gravity. Loose bulk density and compacted bulk density were performed for the coarse and fine aggregates according to ASTM C29 and ASTM D698 respectively.

According to ASTM C29, a standard container 0.0028 m^3 (0.1 ft^3) measure was filled a third of the way and evenly rodded 25 times. The next layer filled another third and was rodded. The same procedure was repeated for the top third. The sample was then leveled off so that the voids below the lip of the measure approximately equaled the particles protruding above the lip. The weight of the retained material was then measured and the bulk density and void content calculated.

According to ASTM D698, fine aggregate samples at water contents of 8 %, 12 %, 16 %, 20 %, 24 % and 28 % were placed in three layers into a mold with a volume of 0.944 L (1/30 ft^3), with each layer compacted by 25 blows using a 24.4 N (5.5 lbs) rammer dropped from a distance of 305 mm (12 in.). The weights of samples after compaction were measured and then put in the oven to dry. The dry unit weights were determined to establish a relationship with the water content. The values of optimum water content and standard maximum dry unit weight was determined from the compaction curve.

3.3 Undrained Cohesion (Direct Shear)

Fine aggregates made from dredged material were tested for their undrained cohesion and determined by their direct shear capacities according to ASTM D3080. A small sample was placed within the bottom half of a standardized shear box of known dimensions. After calculating the volume, weight, and then density of the sample within the box, white lithium grease was applied along the top surface of the box. Next, the upper half was set in place with the ridges perpendicular to the force vector and a pin was inserted to align the two halves and prevent premature displacement. The box was then set within the direct shear apparatus and a normal load was applied. Following this, water was added to the box until the sample was entirely submerged. Finally, the pin was removed.

Once the test commenced, the direct shear apparatus mechanically applied an increasing lateral force to the unrestrained top half of the shear box to cause displacement. Readings were then taken from the force gauge at specified intervals dependent on the displacement gauge readings rather than at timed intervals. Once the force gauge readings plateau, the sample was seen to be carrying its maximum possible shear force and the first trial was complete. The process was then repeated twice more with fresh material, each time adding an additional normal force.

3.4 Free Swell and Consolidation

ASTM D 2435 was followed to discover the consolidation of the fine aggregate. A small sample was placed within a standardized consolidation ring of known dimensions with a circular porous stone within the ring above and below the sample. Representing adjacent sand layers in the natural environment, these porous stones also provided a seal to contain the sample within the ring. Once placed within a calibrated consolidation apparatus, the starting positions of the vertical displacement dials were noted. Next, water was added to the ring until the sample was completely submerged. Readings of the swelling as the sample saturates were then taken at rapid specified intervals before the sample was left to saturate for 24 hours.

After 24 hours, another reading was taken and a 24 kPa (¼ tsf) vertical load was gently applied. Readings of the vertical displacement were again taken at rapid specified intervals as the sample compressed. Again, the sample was left undisturbed for 24 hours and another reading was taken. This process repeated every 24 hours for one week, each time doubling the applied load until 1,532 kPa (16 tsf) was achieved. When rebound data was desired, the process repeated for another week, each day unloading the apparatus to halve the applied load every 24 hours.

Figure 3-3 Free Swell and Consolidation

3.5 Organic Impurity

To test for organic impurities based on ASTM C40, a small graduated glass jar was filled with 130 mL (7.93 in^3) of fine aggregate. Next, a 3% sodium hydroxide solution was added to the container until the jar was filled to the 200mL (12.2 in^3) mark. After closing the jar and shaking vigorously, the sample was left undisturbed for 24 hours. Finally, the color of the undisturbed solution within the jar was compared to a glass color standard. If the shade was darker than plate number three, then the sample may contain deleterious organic material.

3.6 Clay Lumps and Friable Particles

The test was performed according to ASTM C142. In order to eliminate dust and previously degraded material, the sample was gently washed by hand and wet sieved over a sieve specified for the sample gradation. Any passing particles were discarded. After oven drying, the sample was then weighed and submerged in distilled water for 24 hours. The degraded sample was then wet sieved over a sieve specified for the sample gradation, oven dried, and weighed again. Finally, the percent loss was calculated as the percentage of friable particles within the sample.

3.7 LA Abrasion

To calculate abrasion resistance, a coarse aggregate sample of five kilograms (11 lbs) was placed in the drum of an LA Abrasion apparatus along with twelve steel balls (Figure 3-4). The drum was then mechanically rotated 500 times at a rate of 32 revolutions per minute. Once complete, the sample was passed through a No. 12 sieve and the percentage passing was calculated. The point of failure is dependent on the intended application of the sample. For the purpose of this study, 40 % loss is considered a failure.

Figure 3-5 LA Abrasion Machine

3.8 Sodium Sulfate Soundness

Fine aggregates with particle sizes ranging from 4.76mm to 9.53mm (No. 4 to 3/8”) made from Toledo samples were tested for sodium sulfate soundness, which provides an index of durability to resist weathering. Sodium sulfate solution was prepared at a temperature of 25 °C (77 °F) and cooled to 22 °C (71.5 °F) for 2 days. A 300 g (0.44 lb) sample was immersed in the solution at 21 ± 1 °C (70 ± 1.5 °F) for 16 to 18 hours. The sample was removed and drained for 15±5 minutes, then it was dried in an oven to constant weight at 110 ± 5 °C (230 ± 9 °F). Five cycles of immersion and drying were repeated to measure the weight loss.

3.9 Water Desorption

LWA is suitable for internal curing if the absorbed water is released readily as the internal relative humidity of sealed hardening concrete decreass due to self-desiccation (ASTM C1761). This test determined the amount of absorbed water that was released when wetted surface dry aggregates were stored in the air of an environmental chamber with a relative humidity of 94 % and a temperature of 23 ± 1 °C (73.5 ± 1.5 °F) (Figure 3-6). Eq 4 was used to determine water desorption at 94 % relative humidity, expressed as a fraction of the oven-dry mass to the nearest 0.01.

$W_{LWA} = \frac{M_{SD} - M_{94}}{M_{OD}}$ Eq.(4)

Where W_{LWA} = Water desorption rate

M_{SD} = Mass of wetted surface-dried sample

M_{94} = Equalibrium mass of sample in the 94% humidity

M_{OD} = Mass of oven dried sample

Figure 3-6 Environmental Chamber

3.10 Leaching

The TCLP leaching test is used by U.S. EPA to evaluate the leaching potential of heavy metals (Arsenic, Barium, Cadmium, Chromium, Lead, Mercury, and Selenium) and to classify the solid waste into non-hazardous vs. hazardous categories. To recycle industrial byproducts, e.g., bottom ash, fly ash, spent foundry sand and other exempt waste in road construction, the Ohio Department of Transportation requires these materials to meet the requirements of the Ohio EPA (1994), Division of Surface Water, Policy 400.007 "Beneficial use of Non-Toxic Bottom Ash, Fly Ash and Spent Foundry Sand and Other Exempt Waste" (ODOT, 2013b). The Ohio EPA policy specifies maximum contaminant levels of leached heavy metals in drinking water, which are shown in Table 6, as well as reporting limits in the proposed TCLP test.

Table 3-3 EPA specifications for the TCLP leaching test

Analyte	Reporting limit (mg/L)	Ohio Primary Maximum Contaminant Levels (mg/L)	Non-toxic Criteria (mg/L)
Arsenic	0.025	0.05	1.5
Barium	-	2	60
Cadmium	-	0.005	0.15
Chromium	0.01	0.1	3
Lead	0.05	0.05	1.5
Mercury	0.0001	0.002	0.06
Selenium	0.05	0.05	-

3.11 Summary

Soil classifications of the dredged material samples used for the LWA production are determined per ASTM D2487 and ASTM D4318 for Cleveland and Toledo samples, respectively. The experimental plan and methods were discussed in Chapter 3 to assess the engineering properties and performances of LWA made from dredged material. Density, cohesion, compressibility, and free swell strain were tested for fine LWA as a fill material. Organic impurity, clay lumps and friable particles, LA abrasion, sodium sulfate soundness, water adsorption and desorption were measured to evaluate the potential of the LWA used in concrete mixtures. The TCLP leaching tests were performed on the dredged material and LWA to evaluate its environmental sustainability. The findings of the experiments are discussed in Chapter 4.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 Soil Classifications

4.1.1 Cleveland Sample

Grain size distribution of a dredged material sample taken from Cleveland is summarized in Table 4-1 and plotted in Figure 4-1. More than 30 % of the sample particles passed No. 200 sieve with an opening of 0.074 mm (0.0029 in.), which are classified as silt and clay materials. The research team did not further sieve the samples down to separate silt from clay. But chemical compositional analyses of the dredged materials were completed using a Hitachi S-2600N scanning electron microscope (1-30 kV) hosted at the Liquid Crystal Institute at Kent State University. The results are listed in Table 4-3.

Table 4-1 Grain Size Distribution

	Sieve Opening (mm/inch)	Mass Retained (%)	Cumulative Retained (%)	Finer (%)
#4	4.76/0.187	0.8	0.8	99.2
#8	2.38/0.0937	2	2.8	97.2
#16	1.19/0.0469	3.6	6.4	93.6
#50	0.297/0.0117	5.2	11.6	88.4
#100	0.149/0.0059	22.8	34.4	65.6
#200	0.074/0.0029	34	68.4	31.6
Pan		30.4	98.8	
Total		98.8	% Loss	1.2

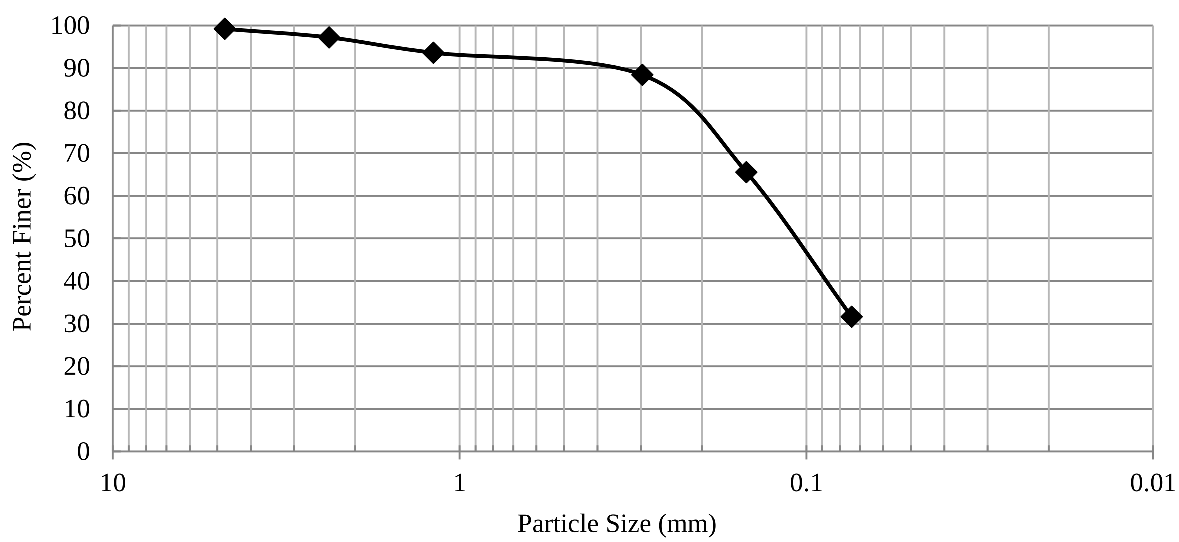


Figure 4-1 Grain Size Distribution

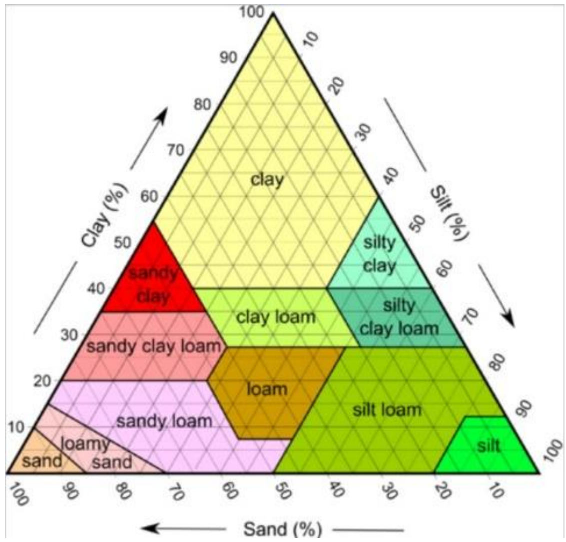


Figure 4-2 Soil Classification

Table 4-1 indicates 68.4% of the Cleveland sample is sand and 31.6% is the mixture of silt and clay. According to the soil classification shown in Figure 4-2, the material is classified as sandy loam.

4.1.2 Toledo Sample

Atterberg limits were measured for dredged material samples taken from two sites in Toledo. Samples of Toledo 1 and Toledo 2 were taken from the new Center of Innovation, and samples of Toledo 3 and 4 from CDF 3. Both sites are managed by Toledo – Lucas County Port Authority. The plasticity indices of the four samples are listed in Table 4-2, and plotted in the soil classification figure in Figure 4-3. According to the classification, Toledo samples are classified as silt clay with high plasticity. Their chemical compositions are listed in Table 4-3.

Table 4-2 Plasticity Index of Toledo Samples

	Toledo 1	Toledo 2	Toledo 3	Toledo 4
Plastic Limit	27.36	38.38	46	39.8
Liquid Limit	54	59	53.4	55.25
Plasticity Index	26.64	20.64	7.4	15.45

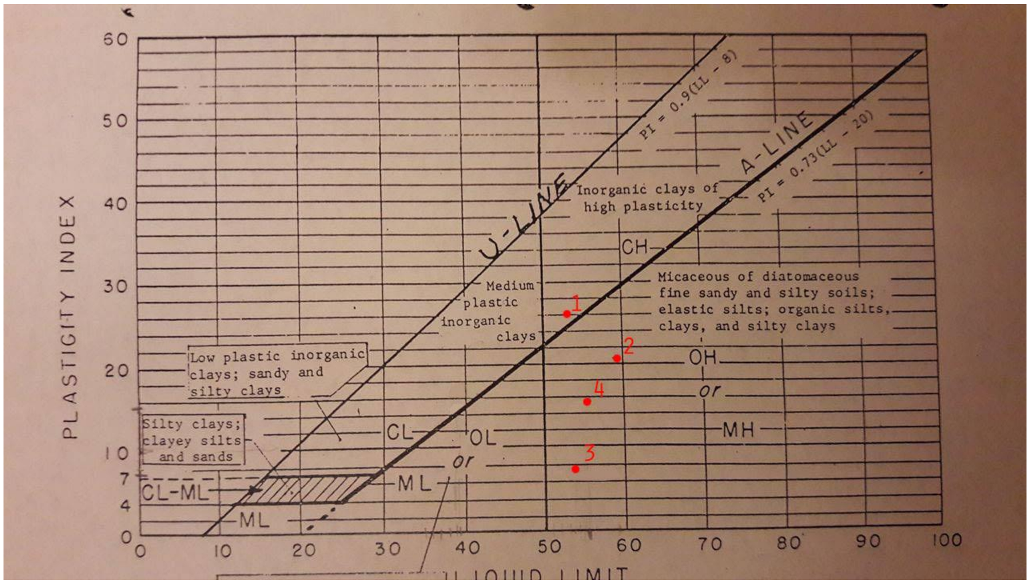


Figure 4-**3** Pasticity Index vs Liquid Limit

4.1.3 Chemical Compositions of Cleveland and Toledo Samples

Table 4-3 summarized chemical compositions of dredged material samples taken from Cleveland and Toledo. As discussed in Chapter 2, two requirements need to be met to produce lightweight aggregates, including:

- gases must be formed when the raw material is heated to the point of incipient fusion
- ceramics formed under high temperature must have sufficient viscosity to entrap the generated gases

Table 4-3 Chemical Compositions of Dredged Materials

Minerals	CLE 1 (wt. %)	CLE 2 (wt. %)	Toledo 1 (wt. %)	Toledo 2 (wt. %)	Toledo 3 (wt. %)	Toledo 4 (wt. %)	Raw Shale (wt. %)
Na_2O	2.13	0.00	0.62	0.19	0.00	0.00	0.76
MgO	1.18	0.00	2.15	1.57	1.20	1.87	1.67
Al_2O_3	15.74	11.94	14.03	15.42	15.57	17.61	18.92
SiO_2	63.99	73.35	48.41	61.44	42.75	59.06	58.29
SO_3	0.92	2.70	7.17	0.71	0.00	0.00	0.9
K_2O	2.72	2.87	2.78	3.73	3.23	3.72	4.1
CaO	5.29	1.55	11.61	7.42	21.25	8.03	0.28
Fe_2O_3	5.93	7.48	9.00	7.82	8.55	8.36	5.86
LOI	2.10	0.11	4.22	1.70	7.46	1.35	7.35

Note: Chemical compositions of dredged materials were determined using Hitachi S-2600N scanning electron microscope (1-30 kV).

Riley (1950) created a tri-axial diagram (Figure 2-1) to limit the chemical compositions of a material from which a sufficiently viscous glass would be formed by firing. The chemical compositions of dredged materials were plotted on the tri-axial diagram but it was interesting to note that several dots did not fall in the limits. However, the expansion of the material did occur to generate porous micro-structure during the firing process to produce the lightweight aggregates using both Cleveland and Toledo samples. The specific gravity of the LWA made from dredged materials is less and water absorption rate is much higher than normal aggregates used in construction, which are discussed below. It would be interesting for future research to re-evaluate the limits on the tri-axial diagram developed by Riley (1950).

4.2 Specific Gravity, Water Adsorption and Bulk Density

Specific gravity and water adsorption were measured for coarse LWA made from dredged material taken from Cleveland and Toledo. Loose and compacted bulk densities were tested for fine LWA.

4.2.1 Specific Gravity and Water Adsorption

The optimum sintering temperature for Cleveland samples has been investigated by Liu and Coffman (2016). 1100 °C was set and used throughout this project in order to compare the performances of the LWAs made from Cleveland and Toledo samples. Different sintering periods were investigated in this project by testing the specific gravity of the samples and water absorption rates for LWAs made from Cleveland samples. The results are summarized in Table 4-4. The relationship between specific gravity and water adsorption rate is illustrated in Figure 4-4.

The specific gravity ranged between 1.41 and 1.51 and water adsorption rate fell in the range from 21.46 % to 26.55%. Bulk specific gravities of natural normal weight gravel range from 2.4 to 2.9. As the specific gravity increases, the water adsorption rate decreases. All testing results followed this trend as indicated in Figure 4-4, assuming no errors occurred during the testing. However, Figure 4-5 shows the lowest specific gravity occurred when the material was sintered for one hour. The low specific gravity usually represents a low density and a low strength. To conservatively investigate the performance of LWA made from dredged material, one-hour sintering time was selected for producing LWA using both Cleveland Toledo samples.

Table 4-4 Specific Gravity of Cleveland Samples vs. Sintering Time

Sample	Wet Weight (g)	Submerged weight (g)	Dry weight (g)	SG	Absorption (%)
10 min	110.49	50.3	88.2	1.47	25.27
20 min	85.49	39.2	68.2	1.47	25.35
30 min	92.7	42.2	74.4	1.47	24.60
40 min	93.5	42.7	75	1.48	24.67
1 hrs	144.9	63.8	114.5	1.41	26.55
2 hrs	148.3	67.7	122.1	1.51	21.46
3 hrs	177.7	80.9	146.1	1.51	21.63
4 hrs	179.3	81.7	146.6	1.50	22.31
5 hrs	169.3	77.6	138.3	1.51	22.42
6 hrs	183	82.7	149.6	1.49	22.33

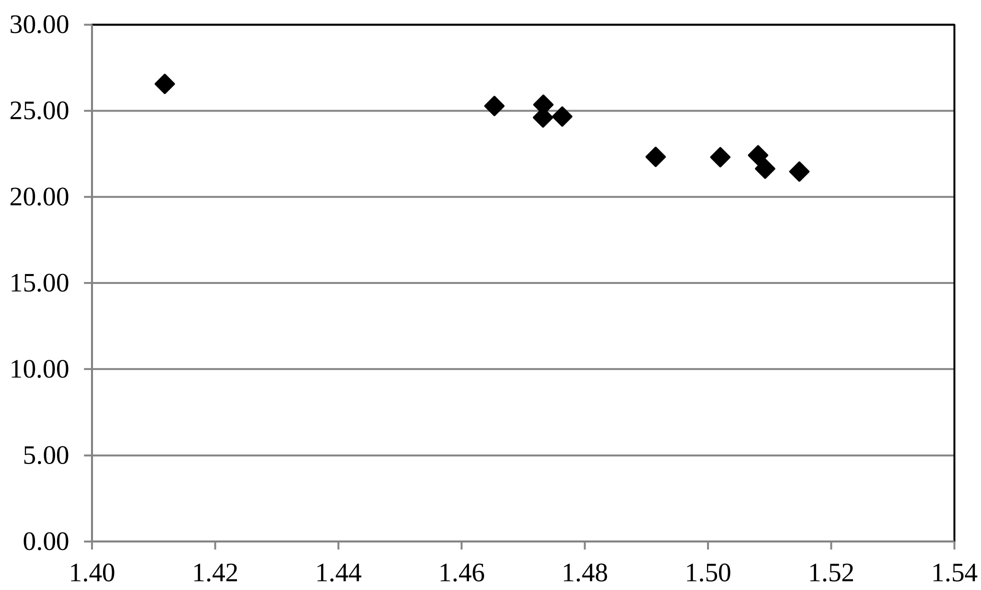


Figure 4-4 Specific Gravity vs. Water Adsorption Rate (Cleveland Sample)

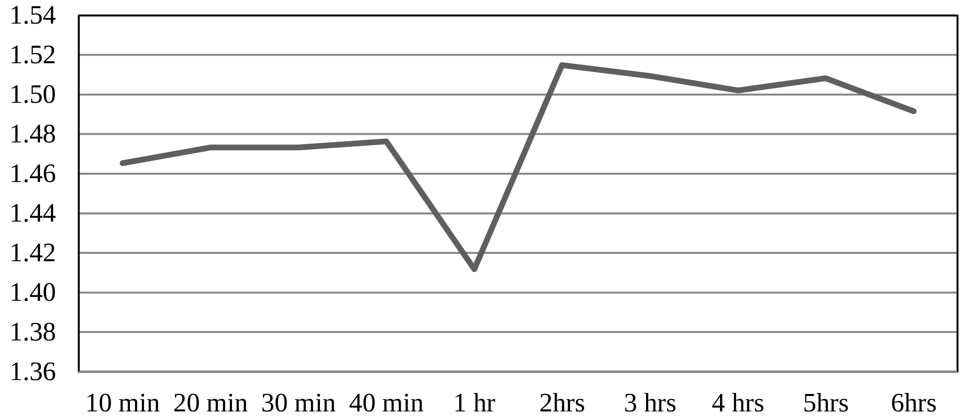


Figure 4-5 Specfic Gravity vs. Sintering Time (Cleveland Sample)

After sintered at 1100 °C for 1 hour, and cooled down to the room temperature in the furnace, expanded LWA was produced using Toledo samples as shown in Figure 4-6, with a specific gravity less than 1.0. But inconsistency was noticed during the production in the lab. This might be caused by non-uniform heating in the chamber of the box furnace. A rotary kiln for the mass LWA production may help address this issue.

In this project, the pellets made from dredged materials taken from Cleveland and Toledo were crushed down into small particles. Gradation standard in ASTM C330 was followed to develop coarse LWAs and fine LWAs. The specific gravities and water adsorption rates of coarse LWAs were tested following the procedure discussed in Section 3.2.1. The results are listed in Table 4-5. Toledo 1 and Toledo 2 are LWAs made from materials taken from the same location (new Center of Innovation in Toledo), as well as Toledo 3 and 4 (CDF 3). Only Toledo 1 and 3 were tested for specific gravity, water absorption, and bulk density, as discussed later in Section 4.3 LA Abrasion Test, and the LWA made from ungraded Cleveland samples did not pass the test with 40% loss as the upper limit. Three additional types of LWA with high silt and clay contents sieved from Cleveland samples were fabricated, each with 100 %, 90 %, and 80 % silts and clays.

Table 4-5 indicates that coarse LWA made from Toledo samples had lower specific gravities and lower water absorption rates than Cleveland samples, under the same sintering schedule. Larger expansion occurred in Toledo samples but the enamel formed at 1100 °C on the surface of Toledo samples caused the lower water absorption.

Figure 4-6 Aggregates made from Toledo 1

Table 4-5 Specific Gravity and Water Absorption

Sample	SG	% Absorption
Toledo 1	1.35	15.6
Toledo 3	1.25	13.58
Cle. 100%	1.44	24.06
Cle. 90%	1.34	26.17
Cle. 80%	1.34	23.75

4.2.2 Bulk Density

(1) Loose bulk density

The testing results are summarized in Table 4-6 for fine LWA made from dredged material, which met ASTM C330 graduation requirements. Natural normal weight sand has a bulk density of 1520-1680 kg/m^3 (95-105 lbs/ft^3). Aggregates with bulk densities less than 1120 kg/m^3 (70 lbs/ft^3) are defined as lightweight.

Table 4-6 Loose Bulk Density

Sample	Bulk Density (lb/ft^3)	Bulk Density (kg/m^3)	Void Content (%)
Toledo 1	54.82	878.13	35%
Toledo 3	52.26	837.13	33%
Cle. 100 %	61.67	987.86	31%
Cle. 90 %	63.42	1015.89	24%
Cle. 80 %	61.87	991.06	26%

(2) Compacted bulk density

Because LWA made from dredged material taken from Cleveland did not pass the LA Abrasion Test, only Toledo samples were tested for the compacted bulk density. Eight fine aggregate samples (Toledo 1) with water contents varying from 8 % to 36 % were compacted in the lab. The highest dry unit weight was 1,176 kg/m^3 (73.4 lb/ft^3) when the water content was 32 %. Toledo 3 samples were not tested. Because all raw dredged materials of the Toledo samples were taken from Maumee River, as indicated in Table 4-3, they have similar chemical compositions. In addition, direct shear tests discussed below in Section 4.4, Toledo 1 and 3 exhibited similar undrained cohesions.

Table 4-7 Compacted Bulk Density

Sample	Water Content (%)	Wet Unit Weight lb/ft^3	Wet Unit Weight kg/m^3	Dry Unit Weight lb/ft^3	Dry Unit Weight kg/m^3
1	8	73.6	1179	68.1	1092
2	12	74.5	1193	66.5	1066
3	16	80.5	1289	69.4	1112
4	20	83.5	1338	69.6	1115
5	24	85.1	1363	68.6	1099
6	28	91.61	1467	71.6	1146
7	32	96.9	1552	73.4	1176
8	36	97.2	1557	71.5	1145

4.3 LA Abrasion Test

LA Abrasion Test results are summarized in Table 4-8. Toledo samples passed the test, but all Cleveland samples failed. But the test indicated as silt and clay contents in the LWA increased, as well as the sintering time, the hardness of the Cleveland sample increased. As indicated in

Figure 4-5, extending the sintering time would increase the density of the synthesized LWA. Although higher sintering temperature was not tested in this project, it is expected the hardness of the LWA will be increased as the sintering temperature increases. However, comparing to Toledo samples, it will be more expensive to produce a LWA with an equal mechanical performance using Cleveland samples.

Table 4-8 LA Abrasion Test

Sample	% Loss	Result
Toledo 1	27.8%	pass
Toledo 3	33.0%	pass
Cle. 100 %	65.9%	fail
Cle. 90 %	69.4%	fail
Cle. 80 %	63.6%	fail
Cle. 100 % 6-hr	53.7%	fail
Cleveland Ungraded	99.9%	fail

4.4 Undrained Cohesion (Direct Shear)

Direct shear tests were completed for fine aggregates made from Toledo 1 and Toledo 3 samples. The testing results for aggregates sizing 0.297-1.19 mm (0.0117-0.0469 in.) are reported in Figure 4-7 to Figure 4-10. The angles of friction of Toledo 1 and Toledo 3 are 51.2° and 53.6°, respectively, and the cohesion are 0.933 psi and 1.01 psi, respectively, under undrained conditions.

The typical angles of friction for dense sand with angular grains fall in the range of 40° to 45°. The synthesized fine LWAs had larger angles of friction because they were crushed down from sintered LWA pellets with more angular grains. For non-consolidated sand, the cohesion is zero. The positive values measured in this test are due to the friction between angular particles.

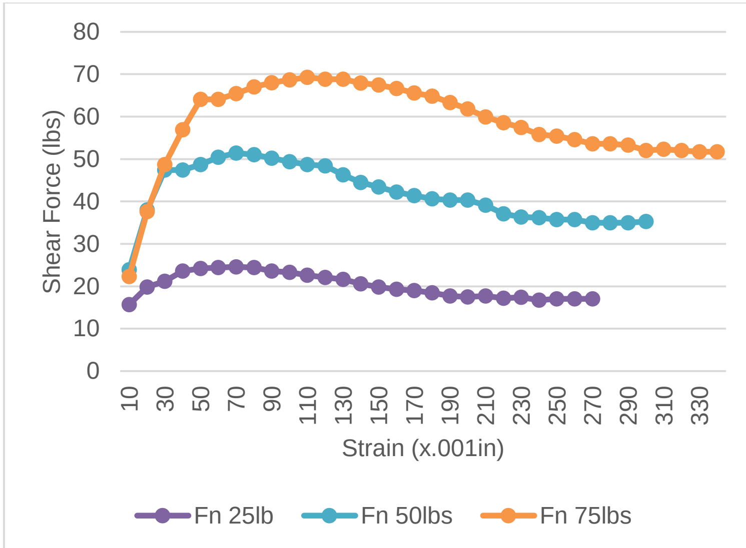


Figure 4-7 Direct Shear of Toledo 1 LWA sizing 0.297-1.19 mm (0.0117-0.0469 in)

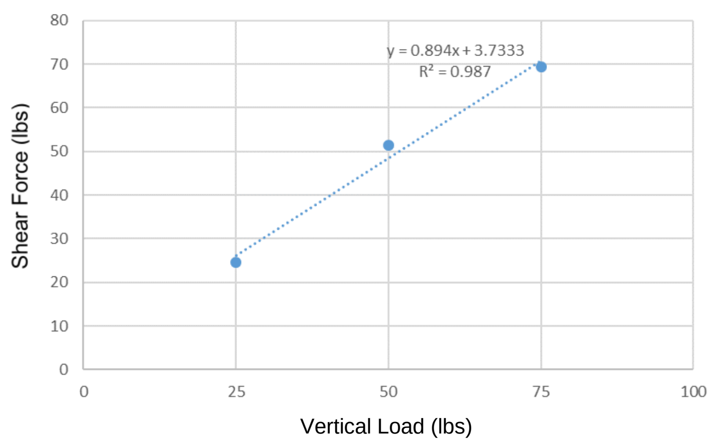


Figure 4-8 Undrained Cohesion Toledo 1 LWA sizing 0.297-1.19 mm (0.0117-0.0469 in)

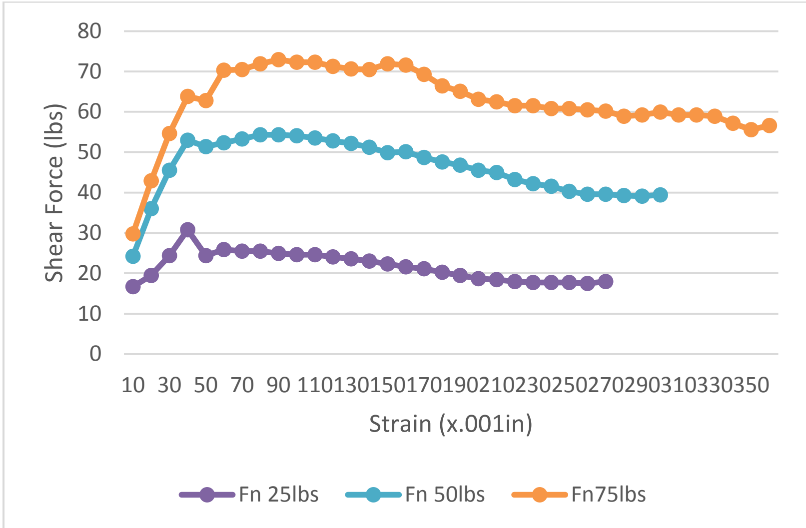


Figure 4-9 Direct Shear of Toledo 3 LWA sizing 0.297-1.19 mm (0.0117-0.0469 in)

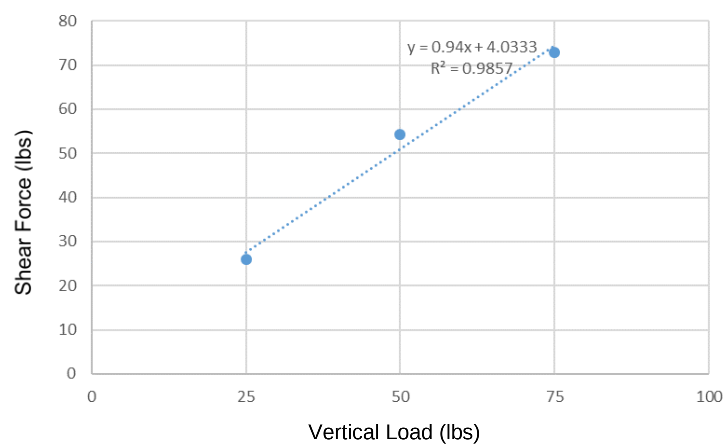
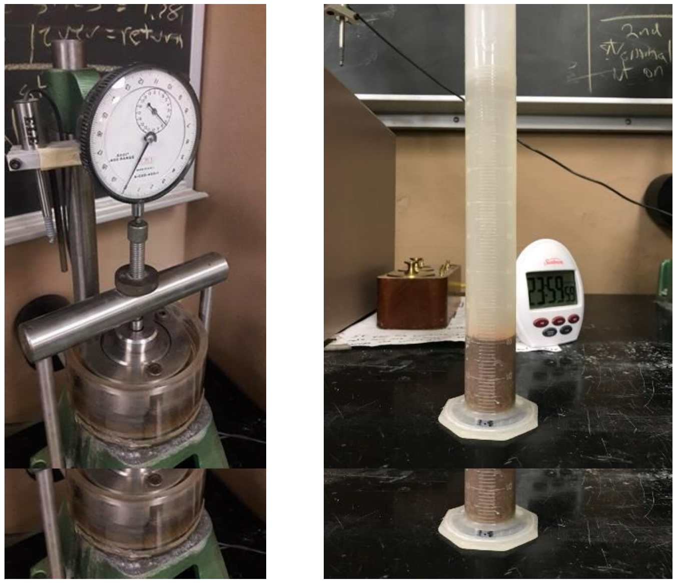


Figure 4-10 Undrained Cohesion Toledo 3 sizing 0.297-1.19 mm (0.0117-0.0469 in)

4.5 Free Swell and Consolidation

Tests for free swell and consolidation of fine aggregates made from Toledo 3 samples under saturated situation were completed. Toledo 1 samples were not measured because they should have similar performances as Toledo 3 samples. Free swells of fine LWA were measured using both consolidation apparatus and graduated cylinder shown in Figure 4-11 (a) and (b), respectively. The recorded swells were 7 percent and 5 percent, respectively. The free swell of soils depend on the soil types with a typical value of 2.5 %. The synthesized fine LWA has a higher free swell than typical soil.



(a) (b)

Figure 4-11 Free Swell

The consolidation of fine LWA is recorded in Table 4-8. Under the pressure of 1,536 kPa (16 tsf), the samples were consolidated 11.6 %, and the density was increased from 1,191 kg/m^3 (74.330 lbs/ft^3) to 1346 kg/m^3 (84.055 lbs/ft^3).

Table 4-8 Consolidation

Pressure (tsf)	Total Settlement (in)	Sample Height (in)	Sample Volume (in^3)	Compacted (lb/in^3)	Compacted (lb/ft^3)	Compacted (g/cm^3)
0	0.000	1.000	4.910	0.043	74.330	1.191
0.25	0.035	0.965	4.738	0.045	77.033	1.234
0.5	0.037	0.963	4.730	0.045	77.153	1.236
1	0.041	0.959	4.709	0.045	77.503	1.241
2	0.050	0.950	4.664	0.045	78.258	1.254
4	0.064	0.936	4.597	0.046	79.395	1.272
8	0.084	0.916	4.496	0.047	81.172	1.300
16	0.116	0.884	4.342	0.049	84.055	1.346
8	0.115	0.885	4.344	0.049	84.007	1.346
4	0.114	0.886	4.352	0.049	83.865	1.343
2	0.112	0.888	4.359	0.048	83.733	1.341
1	0.111	0.889	4.365	0.048	83.615	1.339

4.6 Organic Impurity

The organic impurity tests were performed for both Cleveland and Toledo samples according to ASTM C40. Comparing to a glass color standard, the color of the undisturbed solution was clear for all samples (Figure 4-12), indicating the LWA samples do not contain injurious organic material.

Table 4-9 Organic Impurity

Sample	Color
Toledo 1	clear
Toledo 3	clear
Cle. 100 %	clear
Cle. 90 %	clear
Cle 80 %	clear
Cle. 100 % 6-hr	clear

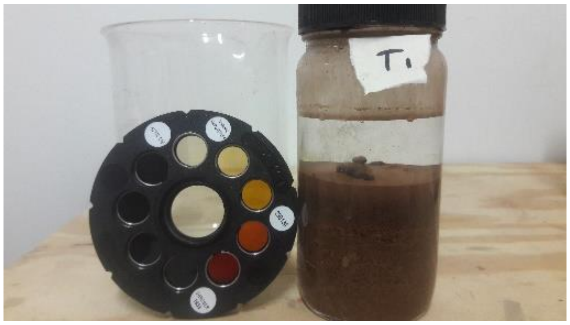


Figure 4-12 Organic Impurity

4.7 Clay Lumps and Friable Particles

Lab testing results for clay lumps and friable particles are summarized in Table 4-10. According to ASTM C142, the upper limit of the total amount of clay lumps and friable particles is 2 percent by dry mass. Toledo samples met the ASTM specification. Cleveland samples had higher percentages of friable particles than Toledo samples. Higher silt and clay contents in the raw material helped reduce the percentages of friable particles, as well as extended sintering time.

Table 4-10 Clay Lumps and Friable Particles

Sample	% CL and FP
Toledo #1	0.2 %
Toledo #3	0.2 %
Cle. 100 %	1.2 %

Cle. 90 %	3.8 %
Cle. 80 %	6.7 %
Cle. 100 % 6-hr	0.9 %

4.8 Sodium Sulfate Soundness

Sodium sulfate soundness tests were completed for fine LWA made from Toledo 1 and Toledo 3. The results are summarized in Table 4-10. Saturating the LWA in a solution of sodium sulfate and distilled water for 16-18 hours then drying to a consistent mass for a total of 5 cycles, concluded a loss percentage of 3.2 % for the Toledo #1 sample and 4.0 % for the Toledo #3 sample. Comparing results with the acceptance criteria specified by ODOT Construction Material Specifications (2016a) Item 703, both the Toledo #1 and Toledo #3 samples met the specifications of concrete fine aggregate per procedure for soundness of aggregate using sodium sulfate.

Table 4-11 Sodium Sulfate Soundness – Toledo 1

	Original Weight (g)	Retained Weight (g)	Individual % Loss	Normal Grade %	Normal % Loss
Passing No. 4, retaining on No. 8	100	95	5.0	10	0.5
Passing No. 8, retaining on No. 16	100	95	5.0	23	1.2
Passing No. 16 retaining on No. 30	100	94	6.0	22	1.3
Passing No. 30, retaining on No. 50	100	99	1.0	22	0.2
Passing No. 50	0	0	0	23	0.0
Total	400				3.2

Table 4-12 Sodium Sulfate Soundness – Toledo 3

	Original Weight (g)	Retained Weight (g)	Individual % Loss	Normal Grade %	Normal % Loss

Passing No. 4, retaining on No. 8	100	94	6.0	10	0.6
Passing No. 8, retaining on No. 16	100	95	5.0	23	1.2
Passing No. 16, retaining on No. 30	100	93	7.0	22	1.5
Passing No. 30, retaining on No. 50	100	97	3.0	22	0.7
Passing No. 50	0	0	0	23	0.0
Total	400				4.0

4.9 Water Desorption

According to ASTM C1761, LWA needs to release at least 85 % of its absorbed water at 94 % relative humidity to effectively internally cure the concrete at the early age. The water desorption rates of fine LWA made from Toledo 1 and 3 are summarized in Table 4-13 and Table 4-14. The Toledo 1 had a higher water adsorption rate than the Toledo 3 sample. But the testing indicates more than 90 % of water absorbed was released after 24 hours in the controlled environmental chamber. In the two tables, M_{SD} is the mass of wetted surface-dried sample; M_{94} is the equilibrium mass of sample in the 94 % humidity; M_{OD} is the mass of oven dried sample; and W_{LWA} is the water desorption rate.

Table 4-13 Water Desorption – Toledo 1

Toledo 1	M_{SD} (g)	M_{94} (g)	M_{OD} (g)	Absorption %	W_{LWA} %
0 hrs	5.0505	5.0505	4.0071	26.04	0.00
24 hrs	5.0505	4.0832	4.0071	26.04	24.14
48 hrs	5.0505	4.0497	4.0071	26.04	24.98
72 hrs	5.0505	4.0447	4.0071	26.04	25.10
96 hrs	5.0505	4.0437	4.0071	26.04	25.13
120 hrs	5.0505	4.0423	4.0071	26.04	25.16
144 hrs	5.0505	4.0404	4.0071	26.04	25.21
168 hrs	5.0505	4.0401	4.0071	26.04	25.22
192 hrs	5.0505	4.0395	4.0071	26.04	25.23

Table 4-14 Water Desorption – Toledo 3

Toledo 3	M_{SD} (g)	M_{94} (g)	M_{OD} (g)	Absorption %	W_{LWA} %

0 hrs	5.1091	5.1091	4.2389	20.53	0.00
24 hrs	5.1091	4.2780	4.2389	20.53	19.61
48 hrs	5.1091	4.2649	4.2389	20.53	19.92
72 hrs	5.1091	4.2622	4.2389	20.53	19.98
96 hrs	5.1091	4.2619	4.2389	20.53	19.99
120 hrs	5.1091	4.2610	4.2389	20.53	20.01
144 hrs	5.1091	4.2597	4.2389	20.53	20.04
168 hrs	5.1091	4.2598	4.2389	20.53	20.04
192 hrs	5.1091	4.2598	4.2389	20.53	20.04

4.10 Leaching

TCLP leaching tests were completed for raw dredged material samples taken from Cleveland and Toledo, as well LWA fabricated using these materials. None of the heavy metals were detected during the tests for sintered samples. But two heavy metals i.e. Cadmium and Chromium, were found from the leachates of the raw dredged material taken from Toledo. The testing results also indicate that the sintering process can help crystalize heavy metals in the LWA.

Table 4-15 TCLP Leaching of Heavy Metals from LWA

Analysis	Toledo Raw (mg/L)	Toledo Sintered (mg/L)	Cleveland Raw (mg/L)	Cleveland Sintered (mg/L)	3745-81-11 (B) Ohio Primary Maximum Containment Levels (Drinking Water Standards or DWS) (mg/L)	Nontoxic Criteria 30x Standard (mg/L)
Arsenic	ND	ND	ND	ND	0.05	1.5
Barium	ND	ND	ND	ND	2	60
Cadmium	0.369	ND	ND	ND	0.005	0.15
Chromium	1090	ND	ND	ND	0.1	3
Lead	ND	ND	ND	ND	0.05	1.5
Mercury	ND	ND	ND	ND	0.002	0.06
Selenium	ND	ND	ND	ND	0.05	-

4.11 Summary

The results of a comprehensive experimental plan were presented and discussed in Chapter 4. The dredged materials taken from Cleveland and Toledo were successfully used for LWA production. However, the LWA made from Cleveland samples failed in the LA abrasion test. Although necessary measures can be taken to address this issue, the cost of production would be dramatically increased. The lab testing indicates the LWA made from Toledo samples has a potential to be used in construction.

5. SUSTAINABILITY OF LIGHTWEIGHT AGGREGATE MADE FROM DREDGED MATERIAL

5.1 Cost analysis

In order to assess the economic viability of repurposing dredged material into a LWA, a cost analysis was performed at three mass production scales. Factors such as labor, electricity, and transportation were considered for factories with an output of 50 t/hr, 100 t/hr and 200 t/hr.

For all three scales, transportation costs were assumed identical and within close proximity to a confined disposal facility. Setting a round trip limit of 161 km (100 miles), a 11.3 m^3 (400 ft^3) truck capacity, a diesel gas mileage of 2.64 kilometers per liter (6.2 miles per gallon), and an east US gas average of $2.785/gallon, the transportation cost per ton was estimated at $6.42.

Labor cost was calculated for both transportation and manufacturing. By applying the 2016 US Bureau of Labor Statistic driver wage of $20.16/hr, assuming a two-hour round trip, and implementing the shipment size used in the transportation cost calculation, transportation labor cost per ton for all three scales was estimated at $5.76. For the calculation of manufacturing labor costs, the 2016 US Bureau of Labor Statistic production worker wage $15.57/hr was used for each scale. The resulting dollars per ton for production labor were $10.43 for a 50 t/hr output, $8.87 for a 100 t/hr output, and $7.71 for a 200 t/hr output.

The cost of electricity in production considered the demands of primary equipment such as a jaw crusher, ball mill, pelletizing machine, and rotary kiln provided by Zhengzhou Jiangtai Heavy Industrial Machinery Co., Ltd., a rotary cooler provided by Henan Fote Heavy Machinery Co., Ltd., and a trommel screen provided by Jiangxi Jinshibao Mining Machinery Manufacturing Co., Ltd.. With an Ohio Edison rate of $0.0765/kWh and machine specifications, total manufacturing electric costs per ton totaled $2.77 for a 50 t/hr output, $2.31 for a 100 t/hr output, and $2.30 for a 200 t/hr output. It should be noted that these estimations employ the repurposing of existing LWA factories. Due to the similar physical nature of the traditional raw clay and the dredged raw clay, it is assumed that LWA could be manufactured from dredge material using the same production process.

When examining transportation, labor, and electricity, the total costs per ton of LWA listed in Table 5-1 results in $19.62 for a 50 t/hr output, $17.60 for a 100 t/hr output, and $16.43 for a 200 t/hr output. Since the production of LWA from dredged material may not differ from that of traditional LWA, the majority of potential cost savings may stem from the elimination of raw material purchase or extraction. According to the United States Geological Survey Minerals Yearbook, the price per ton of clay and shale used in the production of LWA was $14.33 in 2003, $29.17 in 2009, and $31.00 in 2014. For LWA manufacturers that purchase raw material from an outside source, potential savings could be significant when compared to production costs. Moreover, government subsidy or tax abetment to encourage factory repurposing could further reduce the cost of LWA manufactured from dredge material. In the State of Ohio, the LWA is priced approximately $40 per ton. The LWA made from dredged material is cost competitive to the conventional LWA made from virgin expanded shale, clay and slate.

Table 5-1 Cost Analysis for the LWA Made from Dredged Material

Output	Transportation ($/ton)	Labor ($/ton)	Electricity ($/ton)	Total Manufacturing Cost ($/ton)
50 t/hr	6.42	10.43	2.77	19.62
100 t/hr	6.42	8.87	2.31	17.6
200 t/hr	6.42	7.71	2.3	16.43

5.2 Environmental Analysis

Based on the cost study on the LWA, an Economic Input-output Life Cycle Analysis (EIOLCA) was employed to establish an inventory to evaluate the environmental impacts due to the manufacturing (Carnegie Mellon University Green Design Institute, 2008). A mass production scale of 50 t/hr was selected for the analysis. It is estimated that 146,000 tons of LWA is produced per year, assuming 8 hours operation per day in 365 days. A total production cost of $2,793,888 per year can be estimated. A U.S. 2002 producer database was utilized to determine the greenhouse gas emissions and air pollutants from a year production activity. Because the cost analysis was completed using the 2016 U.S. Bureau of Labor Statistic, it was converted into 2002 producer values ($2,093,402.45) using a CPI inflation calculator, which is available from https://data.bls.gov/cgi-bin/cpicalc.pl?cost1=2793888&year1=201612&year2=200212.

The industry and sector selected for this analysis was "brick, tile, and other structural clay product manufacturing" in the broad sector of "plastic, rubber, and nonmetallic mineral products". With the amount of economic activities input for this sector, different categories of results can be displayed, including greenhouse gases, conventional air pollutants, toxic releases etc. A screenshot of the EIOLCA is shown in Figure 5-1. The results of greenhouse gas emissions and conventional air pollutants are summarized in in Table 5-2 and 5-3.

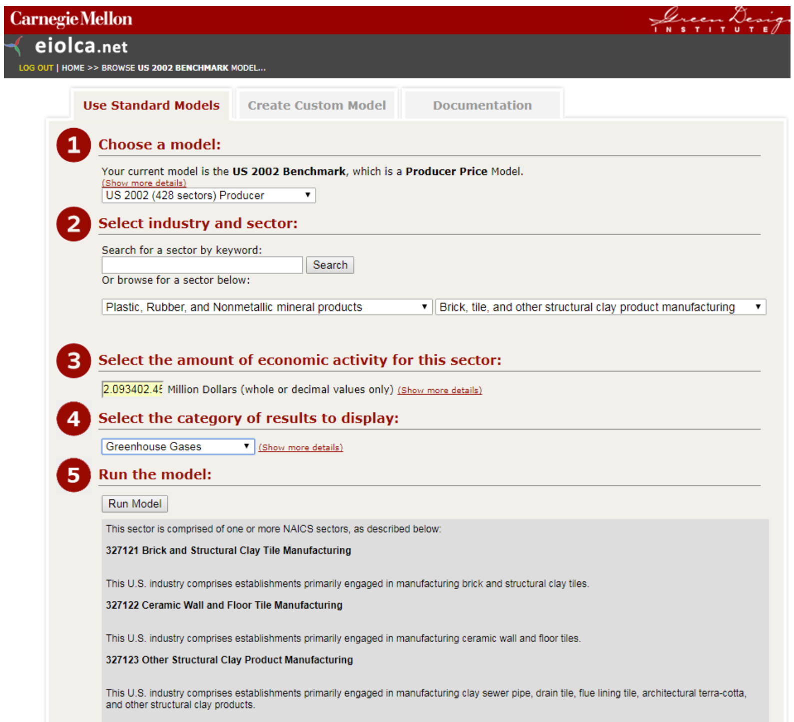


Figure 5-1 EIOLCA

Table 5-2 Greenhouse gas emission from LWA production per year

CO2 Fossil (t CO2e)	CO2 Process (t CO2e)	CH4 (t CO2e)	N2O (t CO2e)	HFC/PFCs (t CO2e)	Total (t CO2e)
3,880	63.2	226	20.7	18.3	4,208.2

Table 5-3 Conventional air pollutants from LWA production per year

CO (t)	NH3 (t)	Nox (t)	PM10 (t)	PM2.5 (t)	SO2 (t)	VOC (t)
10.4	0.219	9.17	5.7	2.1	21	1.58

Based on the data listed in Table 5-1, the greenhouse gas emissions from one ton of LWA made from dredged material is 26.1 kg (57.6 lbs) CO_2 equivalents. The EIOLCA is based on the input dollar amount of economic activities. Because the LWA made from dredged material is cheaper than the conventional LWA, the environmental impacts are expected to be lower as well.

6. CONCLUSIONS AND RECOMMENDATIONS

The potential of using LWA made from dredged material taken from Cuyahoga River and Maumee River in construction was evaluated in this project by investigating the engineering properties and sustainability of the synthesized LWA.

The literature review revealed beneficial uses of dredged materials in construction through cement and brick fabrications. A rich literature is available, discussing the synthesized LWA made from dredged material and other recycled materials, as well as benefits of using LWA in concrete, which are revealed from lab scale and large applications.

An Existing study (Liu and Coffman, 2016) has proven that there is a low risk to reuse the dredged material taken Cuyahoga River in construction. The samples taken from Cleveland are classified as sandy loam. LWA has been successfully fabricated in the lab using the Cleveland sample. The LWA exhibited good performances in the testing for organic impurity, clay lumps and friable particles. However, due to its sandy nature and limited amount of silt and clay in this material, the LWA made from Cleveland samples failed in LA abrasion tests. The abrasion loss of the LWA did not meet the requirements of ODOT Construction and Materials Specifications. This issue may be addressed by increasing the sintering temperature and/or sintering time. However, this practice will increase its production cost.

The LWA made from Toledo samples exhibited excellent performances in meeting requirements specified by ODOT. The specific gravities of coarse LWA tested ranged between 1.25 and 1.35, with a water absorption above 13 %. The loose bulk densities of two fine LWA samples measured were 878.13 kg/m^3 (54.82 lb/cf) and 837.13 kg/m^3 (52.26 lb/cf). The highest dry unit weight was 1,176 kg/m^3 (73.4 lb/ft^3) when water content in fine LWA was 32 %. A high angle of friction was determined from direct shear tests because of the angular grain sizes. Free swell was noticed during the process of saturation, but the final LWA can be stabilized through consolidation. The high void contents of the fine aggregates may help relieve the stresses due to over consolidation. In addition, the LWA samples do not contain deleterious organic material, and they passed the testing for clay lumps and friable particles and sodium sulfate soundness.

The water desorption tests indicate more than 90 % of absorbed water was released in 24 hours in an 94 % humidity environment.

The TCLP leaching test did not detect any heavy metal leaching from the sintered LWA made from dredged material taken from Cleveland and Toledo. But Cadmium and Chromium were found from the leachate of one Toledo samples, which exceeded the nontoxic criteria. The sintering process may help crystalize the heavy metals in the mineral matrices of LWA and reduce the leaching potential.

The sustainability study revealed that a low cost LWA can be fabricated using the dredged material. An EIOLCA was completed to build a baseline life cycle inventory to evaluate the environmental impacts of the synthesized LWA. Due to the lower cost, the LWA made from dredged material will have less environmental impacts than the conventional LWA made from expanded shale, clay, and slate.

The testing performed for LWAs made from Toledo dredged material indicate there is a high potential of using this product as a backfill material in construction, and as an internal curing agent in high performance concrete to reduce the cracking caused by shrinkages. It would be interesting to perform bench scale testing to evaluate the performances of the LWA in backfill and embankment constructions, and in concrete in future studies.

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