Sequestering Lead in Paint by Utilizing Deconstructed Masonry Materials as Recycled Aggregate in Concrete

SERDP Project SI 1548

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Date: 5/27/2008

Revision Number: 1

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to the Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
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1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
15-01-2008	Final Technical Report	Jan 2007 - Jan 2008

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Sequestering Lead in Paint by Utilizing Deconstructed Masonry Materials as Recycled Aggregate in Concrete	W912HQ-07-P-0014
	5b. GRANT NUMBER: N/A
	5c. PROGRAM ELEMENT NUMBER: N/A
6. AUTHOR(S): Kejin Wang, James A. Gaunt, Jiong Hu	5d. PROJECT NUMBER: N/A
	5e. TASK NUMBER: N/A
	5f. WORK UNIT NUMBER: N/A

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Iowa State University Department of Civil, Construction, and Environmental Engineering 394 Town Engineering, Ames, IA 50011	421-20-26 (ISU account number)
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
Strategic Environmental Research and Development Program SERDP Program Office 901 North Stuart Street, Suite 303 Arlington, VA 22203	SERDP
	11. SPONSOR/MONITOR'S REPORT NUMBER(S): 1

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified Unlimited (UU)

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A systematic study has been conducted to establish a rational mix design method for proportioning concrete utilizing recycled, lead-contaminated aggregate for field construction. A variety of concrete mixes was made with different aggregates, cements, and mixture proportions. The physical properties and lead leachability of the aggregates were characterized. The concrete workability, strength, and lead sequestration were evaluated. Eight mix design nomographs were developed. A cost analysis was conducted for hypothetical buildings under different disposal scenarios. The results showed that when appropriately designed and processed, concretes made with recycled, LBP-contaminated aggregates have physical properties that are satisfactory for a variety of constructions. Portland cement can effectively sequester LBP in the recycled aggregate because of its high alkalinity. These successful research results can significantly reduce the cost and environmental impact of Department of Defense (DoD) construction and deconstruction projects.

15. SUBJECT TERMS

Lead-based paint (LBP), recycled aggregate, portland cement, nomograph, leachability

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Kejin Wang
UU	UU	UU	UU	56	19b. TELEPHONE NUMBER (Include area code): 515-294-2152

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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LIST OF ACRONYMS

AEA	air entraining agent
ASTM	American Society for Testing and Materials
a/c, m	aggregate-to-cement ratio
CFR	Code of Federal Regulations
CSA	calcium sulfoaluminate
CTL	Concrete Technology Laboratory
DOT	Department of Transportation
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FM	fineness modulus
LBP	lead-based paint
OD	oven-dried
OSHA	Occupational Safety & Health Administration
PEL	permissible exposure limit
RCRA	Resource Conservation and Recovery Act
SERDP	Strategic Environmental Research and Development Program
SSD	saturated surface dry
TCLP	toxicity characteristic leaching procedure
TSV	Thermal Spray Verification
WET	Waste Extraction Test
w/c	water-to-cement ratio

Unit Abbreviations

^{o}C	degree Celsius
^{o}F	degree Fahrenheit
cm^2	square centimeter
ft	foot
ft^2	square foot
ft^3	cubic foot
g	gram
g/Kg	gram per kilogram
in (”)	inch
Kg	kilogram
lb	pound
mg	milligram
mg/cm^2	milligram per square centimeter
mg/Kg	milligram per kilogram
mg/L	milligram per liter
$\mu g/m^3$	microgram per cubic meter
mL	milliliter
mm	millimeter
oz/cy (oz/yd^3)	flow ounce per cubic yard
pcf (lb/ft^3)	pound per cubic foot
pcy (lb/yd^3)	pound per cubic yard
psi (lb/in^2)	pound per square inch

Acknowledgements

The authors gratefully acknowledge the sponsorship of this project provided by the Strategic Environmental Research and Development Program (SERDP). Support from the National Concrete Pavement Technology Center (CP Tech Center) for the research is also sincerely appreciated. Special thanks are given to the following individuals who made all of the designed research activities possible: Mr. Robert Steffes, Dr. David White, Dr. Zhi Ge, and Mr. Eric Lindquist assisted in test preparation and testing in lab; Mr. John Lathum at the Department of Environmental Health and Safety, Iowa State University, and technicians at Mid-Iowa Environmental, Inc. provided valuable advice on and help in dealing with the lead-based paint wastes that resulted from the research project; and Mr. Row Carr (Ames, Iowa) and Mr. Steve Otto at Holcim Ltd. donated masonry materials and cement, respectively, to the project.

EXECUTIVE SUMMARY

A systematic study has been conducted to establish a rational mix design method for proportioning concrete utilizing recycled, lead-contaminated aggregate for field construction. Two different types of masonry materials (concrete blocks and clay bricks, each from two different sources) were collected, painted with lead-based paint (LBP), and then crushed to simulate recycled LBP-contaminated masonry materials. Physical properties (such as specific gravity, absorption, gradation, and voids) as well as total and leachable lead in the masonry materials were measured. Three types of cement (Type I portland cement, calcium sulfoaluminate (CSA) cement, and portland cement with 5% phosphate addition) were selected for sequestering LBP in the recycled aggregate. A concrete mix design matrix was developed with different water-to-cement ratios (w/c), aggregate-to-cement ratios (a/c), types of cements, and types of masonry materials. The concrete mixtures were designed and manufactured to have three different levels of workability (low, medium, and high) so as to be used for various types of construction (such as foundation and pavement, reinforced beams, columns, and walls). Leachability of lead from the concrete was characterized by the toxicity characteristic leaching procedure (TCLP) and the total lead tests. The compressive strength of the concrete was tested at different ages (3, 7, and 28 days). A cost analysis was also conducted for three hypothetical buildings under three different disposal scenarios.

The following conclusions are drawn from the results of the study:

1. *Characteristics of the Recycled, Lead-contaminated Aggregate* – The original concrete block and clay brick masonry had compressive strengths of approximately 3,000–4,700 psi (pounds per square inch) and 10,700–13,700 psi, respectively. Compared with conventional concrete aggregate, the aggregates recycled from both concrete blocks and clay bricks are generally coarser and had lower specific gravity, higher absorption, and higher volume of voids between the aggregate particles. Due to the low acid neutralizing capacity, as suggested by the pH values of the raw materials, the aggregates recycled from LBP-clay brick masonry had the toxicity characteristic for lead. These aggregates, recycled from LBP-clay brick masonry, also had a significant amount of flat particles.
2. *Lead Sequestering in Concrete* - TCLP test results showed that most concrete samples studied had lead concentrations in the TCLP extracts of less than 5mg/L, and, therefore, are not considered to be hazardous materials. Lead in the LBP-contaminated, recycled aggregate was sequestered in concrete due to the high alkalinity of portland cement. A few concrete samples did have the toxicity characteristic for lead, such as those using recycled aggregate from LBP-clay brick (masonry D). These had high aggregate/cement ratios (a/c or m = 6, rather than the more commonly used a/c or m = 4). No clear relationship was observed between the TCLP and total lead test values. The total lead concentrations in concrete clearly increased with the amount and absorption of the aggregate in the concrete.
3. *Concrete Mix Design* - Well designed and manufactured concrete made with recycled, lead-contaminated aggregate can meet workability and strength requirements for concrete constructions and can abate the lead hazard in recycled aggregates. The mix design nomographs developed in the present study can be easily used by field engineers to ensure the proper selection of mixture proportions. The method for the mix design

nomograph development can be easily adapted for different aggregates recycled from different field deconstruction projects.

4. *Concrete Properties* - Desirable workability of concrete mixtures, with slumps ranging from 1 to 7 inches, can be achieved with the recycled aggregates through proper mixture proportioning, such as selecting appropriate w/c and a/c or m. (Note: Use of a water reducing agent was not included in the present study.) The 3-day compressive strengths of the concrete made with various recycled concrete materials and mixture proportions ranged from 417 psi to 4,891 psi, 7-day compressive strength ranged from 358 psi to 5,188 psi, and 28-day compressive strengths ranged from 782 psi to 6,666 psi. Concrete with such workability range and 28-day compressive strength higher than 3,000 psi can be used satisfactorily for a variety of constructions, including roadways, parking lots, and foundations.
5. *Effect of Cement and Additives* - Use of calcium sulfoaluminate (CSA) cement significantly increased concrete strength at early ages (3 and 7 days) but had little effect on the 28-day compressive strength. The CSA cement was less alkaline than portland cement, and the concrete made with CSA cement had lower pH values than the corresponding concrete made with portland cement, thus being less effective for sequestering lead in the concrete. For one mixture proportion studied, the CSA concrete had the toxicity characteristic for lead, whereas the equivalent portland cement concrete did not. Theoretically, phosphate could react with lead to form hydroxypyromorphite, thus resulting in sequestration of lead. However, such a reaction did not occur in the present study and the addition of 5% phosphate had no significant effect on apparent total lead content, lead leachability, or compressive strength.
6. *Cost Analysis* - The cost analysis for three hypothetical buildings and three different disposal scenarios indicated that the savings from using the LBP-contaminated masonry materials as recycled aggregate in concrete could range approximately from $\$8/ft^2$ to $\$45/ft^2$, depending on the size of the deconstruction project and the applicable environmental protection regulations. Cost savings may result from eliminating LBP removal and waste material disposal, minimizing use of secure landfills, limiting the time and equipment required for sieving and re-grading recycled aggregate, and reducing natural aggregate consumption for concrete construction.

The following activities are recommended for the future study:

1. To improve aggregate gradation and concrete performance, combining the recycled aggregates with natural aggregates is suggested instead of costly sieving and re-grading of the recycled masonry materials. Further research is necessary to design concrete with a combination of natural and recycled aggregates.
2. Supplemental cementitious materials and chemical admixtures are commonly used in modern concrete. The effects of these materials on concrete made with LBP-contaminated masonry materials should be studied.
3. Literature has indicated that concrete made with recycled aggregate often has some durability problems related to drying shrinkage, permeability, freezing-thawing, scaling, alkali-silica reaction, etc. These durability issues should be investigated for concrete made with LBP-contaminated masonry materials.

4. In the present study, only six mixes were prepared using calcium hydrogen phosphate additions at the level of 5% of the weight of cement. A systematic study of the levels of the phosphate addition that might result in conversion of basic lead carbonate to hydroxypyromorphite could result in discovery of a means to sequester lead in a way that renders it insoluble in the highly acidic total lead digestion.
5. The concept of the present study has been proven in the laboratory. A field trial involving an application using portland cement concrete made with LBP-contaminated, recycled aggregate from a deconstruction project is now the appropriate next step for transferring this technology to routine use.

1. INTRODUCTION

1.1 Research Background

In the United States, many structures built prior to and during 1970–1980 contain LBP, which a great hazard to human health. Both the US EPA (Environmental Protection Agency) and OSHA (Occupational Safety & Health Administration) have established rules governing the management of LBP in buildings. According to the US Department of Housing and Urban Development, LBP-contaminated materials are defined as surface coatings containing lead equal to or greater than 1.0 mg/cm^2 or 0.5% by weight. Deconstruction of these structures, many on military installations, is often limited, due to cost and environmental impacts.

Various technologies are available to remove LBP from masonry surfaces. The acceptable techniques for LBP removal can be classified as follows:

1. Mechanical methods, which include wet and dry hand scraping, wet and vacuum sanding, and abrasive blasting;
2. Thermal methods, where hot air or flame, sometimes together with abrasive blasting materials, is applied onto a painted surface at a temperature below 1100^oF. After cooling, the paint is stripped from the material surface;
3. Chemical methods, where chemicals are sprayed onto the material surface to convert LBP into a new insoluble lead-phosphate mineral for on-site or off-site paint stripping; and
4. Encapsulation, where a liquid coating is applied over the LBP and then dries to form a watertight jacket.

Combinations of the above methods are often used in practice.

Unfortunately, there are two crucial shortcomings of most existing LBP removal techniques: (1) many of the methods are time consuming and uneconomical for recycling masonry materials from deconstruction; and (2) the residue of the LBP removal contains a very high concentration of LBP and has to be collected and treated carefully before disposal. Therefore, many deconstructions of masonry buildings simply do not use any LBP removal techniques, and much of the deconstruction debris is disposed in a hazardous waste landfill because of the presence of unacceptable levels of LBP. Clearly, a more cost-effective and environmentally friendly method is urgently needed for remediating and reusing deconstructed masonry materials contaminated with LBP.

From a chemical point view, the degree of the hazard resulting from LBP is often defined by the solubility of lead in a material, which is controlled primarily by the pH of the material and secondarily by the oxidation potential (Eh) of the system. Eh is expressed relative to the potential of the standard hydrogen electrode, which is defined as zero volts at a pH of zero (1M hydrogen ion). An Eh-pH diagram is a graphical presentation of the chemical phases in a system that is thermodynamically stable under various conditions of Eh and pH. The phase boundaries in Eh-pH diagrams are computed using known thermodynamic data and solubilities for the chemical species in the system. The diagonal lines labeled O_2 and H_2 (Figure 1) are the boundaries below

which water will be reduced to hydrogen and above which water will be oxidized to oxygen. All natural and most engineered systems exist between the boundaries of those two very extreme conditions.

Several published Eh-pH diagrams for aqueous lead-carbonate systems indicate that lead is insoluble when the pH value of the material is above six or seven (Garrels and Christ 1965, Brookins 1988). The boundary between lead carbonate ($PbCO_3$) and dissolved divalent lead (Pb^{2+}) in Figure 1 (Cao et al. 2003) was computed using the solubility product constant for lead carbonate and the dissociation constants of carbonic acid, which are not dependent on Eh. As Figure 1 suggests, lead forms insoluble compounds above approximately pH 6.2 in the aqueous lead-carbonate system. Although portland cement concrete is not strictly an aqueous system, the Eh-pH diagram suggests that the solubility (i.e., leachability) of lead at the high pH of cement paste (pH 11 to pH 13) is likely to be inconsequential.

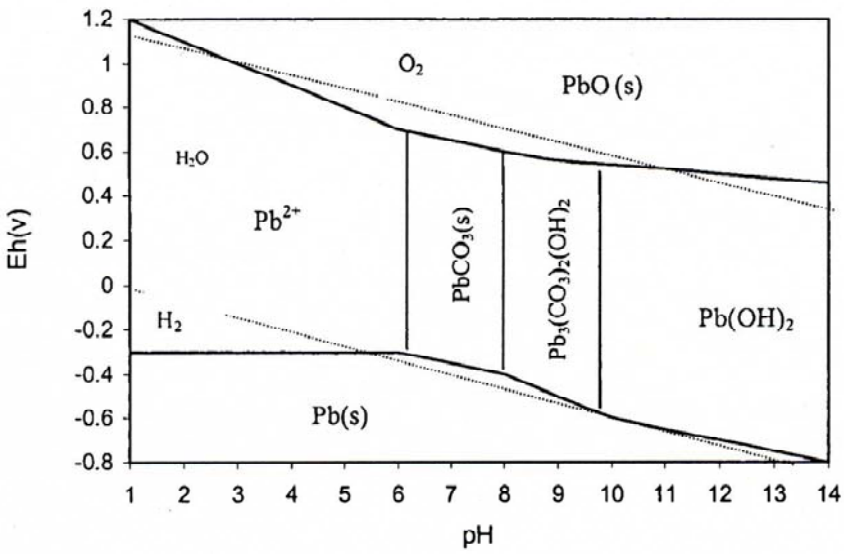


Figure 1. Eh-pH diagram of an aqueous lead-carbonate system

As a result, one promising technique for rendering lead-containing materials non-toxic is to control the pH of the material by adding an alkaline material, such as portland cement or calcium silicates, into the toxic material during the production process. pH is an *intensive* property that describes the concentration of hydrogen ion in a solution, such as in the interstitial pore water in concrete, but does not describe the acid- or base-neutralizing capacity of the system. Alkalinity is an *extensive* property that describes the extent to which a system can neutralize acid. Portland cement is a highly alkaline material with a very high capacity to neutralize the concentrations of hydrogen ions to which concrete roads and structures are likely to be exposed in the field. Portland cement and similarly alkaline materials can be thought of as high-capacity buffers which maintain the pH of concrete well above the level at which lead from LBP-contaminated, recycled aggregate would leach into the environment.

An example of such process additives is Bantox® (TDJ Group, Cary, IL). Bantox® is a mixture of portland cement and CSAs, and it is used as a process additive in foundry and scrap metal

operations before the toxic dust is collected in a bag house. Due to its high alkalinity, Bantox® can effectively neutralize the acidic extracting fluids and sequester lead and other heavy metals. Based on the test results from the TCLP (U.S. EPA Method 1311), the resulting process co-product is a non-toxic, cementitious material, "which can be used as a typical cementitious material in the normal fashion, or can be buried or placed on a surface if no local use for the concrete is required" (Rolle and Rapp 1989).

Another example for controlling toxicity is the use of Blastox® (TDJ Group, Cary, IL). Blastox® is a complex calcium silicate-based blasting abrasive additive blended with non-recyclable blasting materials. Blastox® has been used for removal of LBP from metal structures, such as bridges and elevated water tanks (McGrew 1997, Hock et al. 1999).

Phosphate compounds can also be used as stabilizing additives for lead-based materials. They react with lead and form highly insoluble lead phosphate compounds. These phosphate compounds, such as FESI-BOND™ (Forrester Environmental Services, Meredith, NH), EcoBond LBP (MT2, LLC, Wheat Ridge, CO), and PreTox (NexTec, Inc., Dubuque, IA), do not rely on pH to control solubility of lead.

Using these chemical concepts, the investigators conducted preliminary experiments using portland cement to control the solubility of lead in crushed LBP-contaminated masonry materials by maintaining the materials at a high alkalinity level. The masonry materials (concrete block and clay brick) containing high LBP were crushed and used as recycled aggregate for portland cement concrete. TCLP tests showed that the extracts of LBP-contaminated concrete block and clay brick contained 9.03 mg/L and 25.1 mg/L lead, respectively, which exceeded the lead limit of 5.0 mg/L and would be defined as hazardous wastes. However, the TCLP extracts of the concrete made with 59% and 31% (by volume) recycled aggregate were only 0.10 mg/L and 0.04 mg/L, respectively. This indicated that portland cement effectively sequestered LBP in this type of recycled aggregate and resulted in concrete that did not have the toxicity characteristic for lead. In contrast, when 58% (by volume) recycled brick aggregate was used in concrete, the corresponding concrete had a TCLP extract value of 27.2 mg/L lead, similar to the TCLP extract value of the original aggregate. This test result implied that although highly alkaline portland cement is able to sequester LBP in recycled aggregate, the degree of the LBP sequestering is dependent upon the properties of the recycled aggregate (such as porosity) and the concrete mix proportions (such as the recycled a/c). A reduced a/c and/or addition of alkaline materials in the concrete will assist in achieving concrete that does not have the toxicity characteristic for lead.

Based on the information from available literature and industrial practice, as well as the experimental results presented above, the investigators believe that when concrete is appropriately proportioned, the high alkalinity portland cement in the concrete is able to effectively sequester LBP in the recycled aggregate directly derived from the LBP-contaminated masonry materials. Because no pretreatment (such as stripping) is required for the LBP on the masonry materials, the proposed method can efficiently convert the LBP-contaminated masonry materials from hazardous wastes into new, environmentally friendly construction materials at minimum cost.

Recycled aggregate has been widely used in concrete for road construction, sub-base and concrete pavements (Wilburn and Goonan, 1998). Generally, concrete made with recycled aggregate has about two-thirds the strength and elastic modulus of concrete made with natural aggregate (Frondistou-Yannas 1980). Due to the strength and elastic modulus characteristics, as well as the variability of the recycled products, the use of recycled aggregate for concrete in building structures has been limited. Recently, research has indicated that when mixes are well-designed, recycled aggregate can be used to produce high strength concrete (Andrzej and Alina, 2002). The major concerns for use of recycled aggregates in new construction are now more related to concrete durability, such as drying-shrinkage cracking, carbonation, and freezing-thawing resistances.

The goal of the present study is to develop a technology that allows economical deconstruction of LBP-contaminated masonry structures and substantial recycling and reuse of LBP-contaminated masonry materials for new concrete construction. To accomplish this goal, the study focused on the use of all deconstructed masonry materials in new concrete without applying any LBP removal technique during deconstruction. The major tasks were to characterize the recycled aggregate and to design concrete mix proportions.

1.2 Technical Objectives

The primary objectives of this research are:

1. To provide an effective method for deconstruction of masonry buildings and other permanent structures with minimum environmental impact, cost, and time;
2. To sequester and/or physically encapsulate the lead in painted masonry materials by recycling them as concrete aggregate and mixing them with high alkaline portland cement or phosphate cement materials; and
3. To establish a rational mix design method for proportioning non-toxic, well-performing, and sustainable concrete utilizing recycled, lead-contaminated aggregate for field construction.

1.3 Research Significance

Deconstruction of LBP-contaminated buildings, many of which reside on military installations, has progressed at a slow rate because of high disposal costs and environmental impacts.

In the present research, a cost effective and environmentally friendly process is developed to productively utilize deconstructed masonry materials contaminated with LBP. The present study has demonstrated that highly alkaline portland cement can effectively sequester LBP in recycled aggregate without any requirement for pretreatment of the LBP masonry materials. When properly designed, the recycled LBP-contaminated aggregate can be used as an environmentally friendly, low-toxicity concrete material with good performance, good durability, and excellent sustainability characteristics. Thus, masonry materials contaminated with LBP can be effectively converted from hazardous wastes into new construction materials.

2. MATERIALS AND LBP-CONTAMINATED DECONSTRUCTION WASTE SIMULATION

Different types of masonry materials (concrete blocks and clay bricks) were painted and crushed to simulate LBP-contaminated masonry materials. Physical properties of the masonry materials were measured as well as total and leachable lead. A personal air-quality monitor and wipe tests were also used to monitor airborne lead during the crushing process.

2.1 Materials

2.1.1 Cement

Two types of cement, Holcim Type I ordinary portland cement (which meets the requirements of ASTM [American Society for Testing and Materials] C150) and Polar Bear CSAcement, were used in this study. The oxide composition and chemical composition of both types of cement are summarized in Table 1 and Table 2, respectively. CSA cement is hydraulic cement based on the formation of CSA compounds instead of the calcium silicate compounds in portland cement. As shown in Table 2, the CSA cement had a higher tricalcium aluminate (C_3A) content and high percentage of the $Ca_4Al_6O_{12}SO_4$ phase, which results in a high early strength compared to portland cement. Due a difficulty in obtaining phosphate cement, 5% $CaHPO_4$ was added to portland cement so as to study the effect of phosphate on the toxicity characteristic for lead.

Table 1. Oxide composition of cement (%)

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	TiO_2
Portland cement	62.96	20.96	4.54	3.48	2.91	2.77	-
CSA cement	39.0-41.0	4.6-6.5	36.0-39.0	1.0-2.0	1.5-2.0	9.0-11.0	1.0-1.5

Table 2. Chemical composition of cement (%)

	C_3S	C_2S	C_3A	C_4AF	Gypsum	$Ca_4Al_6O_{12}SO_4$
Portland cement	53.71	19.58	6.14	10.59	0.78	-
CSA cement	0.42	12.59	10.64	0	1.07	73.37

2.1.2 Masonry materials

Four different masonry materials, a total of approximately 2,000 pounds of weight, were collected for this study. Two types of concrete blocks were purchased from H. L. Munn Lumber Co., Ames, IA (masonry A) and Glen-Gary Corporation, Des Moines, IA (masonry B). One type of clay brick (approximately 1,100 lbs in total) was donated by an individual in Ames, IA (masonry C), and the other was purchased from Glen-Gary Corporation, Des Moines, IA (masonry D).

2.2 LBP-Contaminated Deconstruction Waste Simulation

2.2.1 Preparation of LBP

Approximately four gallons of LBP were made by mixing the materials thoroughly with a ball mill (Figure 2) overnight in one-gallon batches according to the following formula:

Basic lead carbonate, 325 mesh, 6.441 Kg
Fisher Scientific Co., Pittsburgh, PA

Refined linseed oil, 0.739 Kg (795 mL)
Scientific Double Boiled Linseed Oil, ADM, Red Wing, MN

Bodied linseed oil, 0.739 Kg (769 mL)
Alinco Z2, ADM, Red Wing, MN

Mineral spirits, 0.649 Kg (838 mL)
AllPro Paint Thinner, Sunnyside Corporation, Wheeling, IL

Figure 2. Ball mill for LBP preparation

2.2.2 Painting of masonry materials

Concrete blocks and clay bricks were painted with LBP (Figure 3). The concrete blocks had a rough surface and high absorption, and they required three coats of LBP to produce a smooth and visible layer of the paint on the surface, one more layer than what was originally proposed. The clay bricks were painted with only two coats of LBP. To achieve a high lead concentration on the masonry materials, all faces except the bottom face were painted. The blocks and bricks were air-dried for at least two days before the next layer of painting was applied. The surface condition of the concrete block (masonry B) and the clay brick (masonry D) after different layers of coating can be seen in Figure 4.

Figure 3. Painting with LBP

(a) Concrete block **(b) Clay brick**

Figure 4. Successive coats of LBP

2.2.3 Crushing of masonry materials

After air drying for at least two weeks after painting, the painted masonry materials were crushed with a Chipmunk jaw crusher. The equipment setup and crushing process is shown in Figure 5. To control the size of the crushed masonry materials, the opening of the jaws was set to 0.75 in.

(a) Before crushing **(b) During crushing** **(c) After crushing**

Figure 5. Crushing process

2.2.4 Monitoring the lead concentration during crushing of masonry materials

The masonry crushing process was done in an 8-ft (width) x 15-ft (length) x 5-ft (height) area enclosed with plastic sheets. The crushing was done in two sessions, each lasting approximately three hours. Approximately 1,000 pounds of painted masonry materials (500 pounds of concrete blocks and 500 pounds of clay bricks) were crushed during each session. Lead was monitored during the crushing process by means of a personal air quality monitor and a wipe test.

A significant portion of this material appeared to be a lead-containing dust that could present a respiratory hazard. To assess the hazard, a personal sample was collected during the crushing operation using an MSA Escort® LC personal sampling pump. The collected sample was analyzed by TestAmerica Analytical Testing Corporation, Cedar Falls, IA. The sample collected during an approximately three-hour, 1,000-lb run revealed an airborne lead concentration of 23.9μg/m^3, which was less than the current OSHA permissible exposure limit (PEL) for lead (50μg/m^3).

Figure 6. Personal air quality monitor

Six 100-cm^2 squares were marked on the plastic sheeting on the floor around the crushing area (see Figure 7). The squares were wiped with a moist KimWipe® to collect dust that fell on the square after crushing (see Figure 8). The KimWipes® were dissolved in 10 mL of trace-metals-grade nitric acid, diluted to 1,000-mL volumes with deionized water, and analyzed for lead by flame atomic absorption spectrophotometry. Larger pieces of masonry that could not be picked up with the moist KimWipes® were analyzed separately. The results are presented in Table 3.

As shown in Table 3, the lead concentration was generally higher when the distance from the crusher was smaller. In addition to the airborne dust from crushing, four of six squares had larger solid particles on them that were flying debris, and could not reasonably be considered dust that might cause a respiratory hazard. Nearly all such larger particles appeared to be clay brick, not concrete block, which is probably due to the fact that the clay bricks were a more brittle material than concrete blocks. Square A had too great a volume of small particles to collect with the moist KimWipe®.

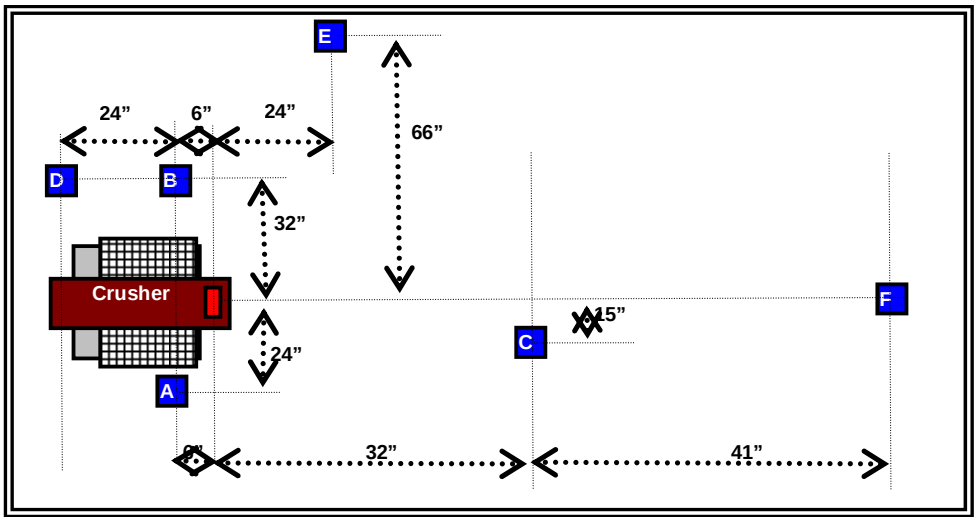


Figure 7. Sketch of arrangement of dust monitoring location

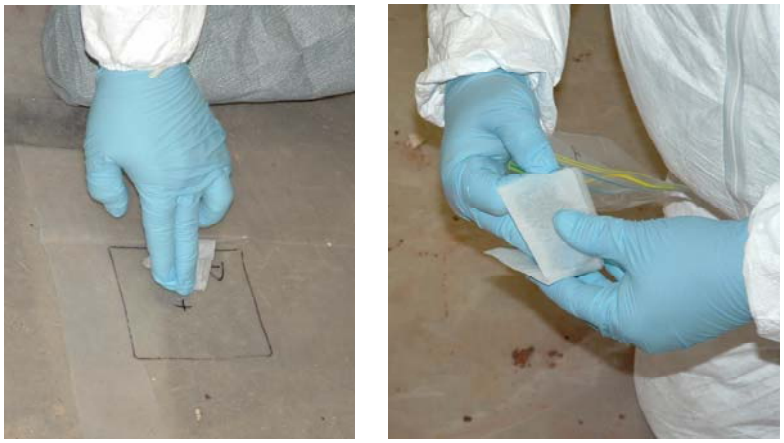


Figure 8. Wipe test

Table 3. Wipe test lead concentrations

Location	Distance from crusher, in.	KimWipe®, mg Pb/100 cm^2	Larger Pieces, mg Pb/100 cm^2	Mass of Larger Pieces, g/100 cm^2
A	24.7	4.44	367	37.23
B	32.6	5.65	30.5	1.89
C	35.3	0.87	--	--
D	43.9	0.25	36.5	0.31
E	70.2	0.43	--	--
F	73.0	0.50	58.5	0.73

The purpose of the wipe tests was to gain a general idea of the pattern of dispersion of lead in the crushing area. The conditions that impacted the dispersion pattern in the laboratory-scale crushing are not equivalent to those of a field-scale operation, and scale-up is not feasible. The crushing area was not symmetrical around the crusher and there were no realistic wind

conditions. The geometry of the crusher probably impacted the dispersion to some extent and the operator's body was large relative to the crusher, which is not a realistic field condition. The wipe tests were not intended to be correlated to any regulatory standard.

3. TESTING METHODS

3.1 Characterizing Recycled Aggregate

3.1.1 Physical properties

The LBP-contaminated masonry was crushed to a particle size range that can be economically processed at a deconstruction site and that fits general concrete structural design requirements. Pictures of samples of the four different crushed masonry materials are shown in Figure 9.

(a) Masonry A

(b) Masonry B

(c) Masonry C

(d) Masonry D

Figure 9. Crushed masonry materials

The specific gravity of the aggregate is a dimensionless ratio relating the density of an aggregate to that of water. Water absorption represents the maximum amount of water an aggregate can absorb and can be calculated based on the difference in weight of aggregate at saturated, surface-dry (SSD) conditions and oven-dried (OD) conditions. It is noted that recycled aggregate generally has higher absorption and may require more water than natural aggregate for its

concrete to reach a given workability. The physical properties of the crushed, unpainted masonry materials, including specific gravity, and water absorption, were tested according to ASTM standards. Prior to the tests, samples of crushed aggregate were sieved with a #4 (4.75mm) sieve. The retained particles were classified as coarse aggregate and the particles passing the sieve were classified as fine aggregate. The specific gravity and water absorption measurements were then performed according to ASTM C127 and ASTM C128 for coarse and fine aggregate, respectively. The moisture content of air-dried aggregate was also calculated based on the loss of weight after oven drying at $110 \pm 5^{o}C$.

The particle size distributions of the LBP-contaminated masonry materials were also measured. Prior to the materials characterization, approximately nine pounds of samples were taken for each of the four masonry materials using a Model SP-2 Porta Splitter according to ASTM C702. The mass of test sample was the minimum mass determined according to ASTM C127. Sieving analysis and bulk density (unit weight) tests were conducted on the painted, crushed masonry materials using an ELE Rotasift™ Laboratory Sifter according to ASTM C136 and ASTM C29, respectively. The bulk density of an aggregate is the mass of the aggregate required to fill a container of a specified unit volume. Bulk density is related to both the specific gravity of aggregate and the voids between aggregate particles. The value indicates the packing and grading condition of the aggregate particles. The grading of aggregate was determined by sieve analysis through a series of sieves.

3.1.2 Lead content and leachability

3.1.2.1 TCLP and WET tests

The leachability of lead from the LBP-painted recycled aggregates and the concrete mixes made with those aggregates was tested using the Toxicity Characteristic Leaching Procedure EPA Method 1311 (TCLP) (U.S. EPA 1992). Extraction was done using a Model LE1002 Environmental Rotator (Environmental Express, Ltd., Mt. Pleasant, SC). Flame atomic absorption spectrophotometric determination of lead was done using a GBC Model 932 Plus Atomic Absorption Spectrometer (GBC Scientific Equipment, Inc., Hampshire, IL).

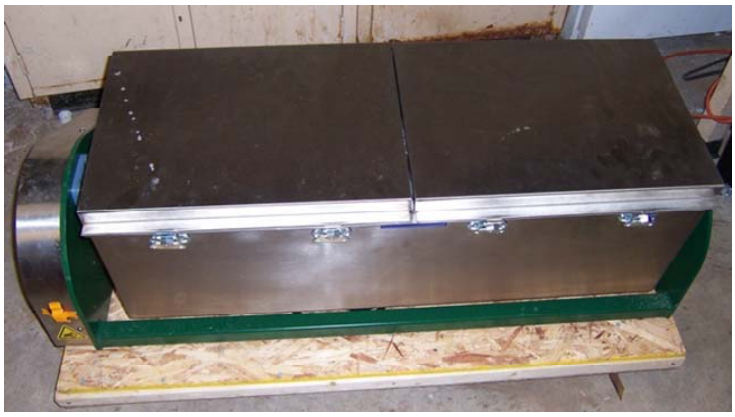


Figure 10. Rotary extractor for TCLP Tests

The California Waste Extraction Test (WET) (California WET 2005) specifies that the extraction shall not be done if the total lead is greater than 1 mg/Kg because all such materials are considered hazardous wastes under California law, regardless of the leachability of lead. Because all concrete prepared in this study had total lead greatly exceeding 1 mg/Kg, no WET test extractions were performed.

3.1.2.2 Total lead test

The harsh acid digestion of EPA Method 3050B for total metals specified in USEPA's SW 846 (Test Methods for Evaluating Solid Waste: Physical/Chemical Methods) caused the large amount of silica in the concrete samples to form a partially dehydrated, gelatinous precipitate that made the samples impossible to filter. The investigator found that the digestion method for sodium and potassium from ASTM C114 (Part 17) (Standard Test Methods for Chemical Analysis of Hydraulic Cement: 17. Sodium and Potassium Oxides) would be more appropriate for these samples than that from EPA Method 3050B. The less harsh acid digestion will easily dissolve the basic lead carbonate used in LBP but will not dehydrate silica. Accordingly, ASTM C114 (Part 17) was used for the sample preparation prior to the determination of total lead by flame atomic absorption spectrophotometry. The reliability of the total lead test was evaluated by replicate analyses of a fortified matrix blank. The results (Appendix A) showed that the test method can quantitatively recover the lead from LBP-painted masonry material samples with good reproducibility. The mean percent recovery of lead was 107.2% of the true value of 10.0 g Pb/Kg with a standard deviation of 4.4%. This established that the milder ASTM C114 digestion was a satisfactory alternative to the EPA SW 846 digestion.

3.1.2.3 pH test

The pH values of all 28-day mixes and painted bricks and blocks were measured. Seven milliliters of distilled water was added to seven grams of powdered sample in a Chemplex SpectroVial and shaken for five minutes on a Spex Mixer/Mill using a steel ball as a mixing pestle. pH was determined using a glass electrode standardized at pH 7 and slope set at pH 10. The pH was recorded after 2–2.5 minutes, at which time the drift in the measurement did not exceed 0.01 pH / 15 sec. Replicated tests were performed to evaluate the reliability of the pH test. The results (Appendix A) showed that the mean difference between the paired duplicates was 0.7% of the average of the two measurements, which was less than the 95% confidence interval of 1.1%.

3.1.2.4 Soluble alkali test

Water-soluble alkalies were determined according to ASTM C114, and the tests were performed at Concrete Technology Laboratory (CTL), Skokie, Illinois. All samples were oven-dried at 60 °C for 24 hours and ground to pass a No. 100 sieve prior to testing. Approximately 100 mL distilled water was added to 10 g of sample in Erlenmeyer flask and shaken for 10 minutes at room temperature. The mixture was filtered and the filtrate diluted with a $CaCl_2$ matrix modifier solution prior to determination of sodium and potassium by flame atomic emission spectrophotometry. The results calculated both as percent (by weight) sodium and potassium

oxides (Na_2O and K_2O) and as total alkali expressed as percent (by weight) sodium oxide (Na_2O).

3.2 Concrete Mixing and Curing

A LWD Lancaster pan concrete mixer (Kercher Industries, Inc., Lebanon, PA) (Figure 11) was used for concrete mixing. During the mixing, the pan of the mixer rotated in a direction opposite to the rotation of a pair of mixing blades, which mixed the concrete mixture in the pan. A separate blade was fixed against the inside edge of the pan and scraped the material off the side, moving it toward the center where the mixing blades were rotating.

The concrete mixing procedure was based on the ASTM C192 lab mixing procedure (multiple-step mixing procedure) and it is described below:

1. Crushed masonry material was mixed with approximately half of the amount of water, together with an air entraining agent (AEA), for about 30 seconds.
2. Cement and the remainder of the water were then added, after which the mixer ran for three minutes.
3. The mixer was stopped for three minutes.
4. The mixer was started again for another two minutes.

Figure 11. Concrete mixing

3.3 Concrete Testing

Immediately after final mixing, the slump of the fresh concrete was measured according to ASTM C143. In this study, the slump test was not only a measurement for evaluating concrete workability but, more importantly, the slump value was used as a control parameter for concrete mix design. Different slumps are required for different concrete construction applications. As shown in Figure 12, concrete with three different ranges of slumps were designed: (1) 1”~2” slump for low workability concrete (generally used for pavements and slabs), (2) 3”~4” slump for medium workability concrete (generally used for beams, walls, columns, and reinforced concrete), and (3) 6”~7” slump for high workability concrete (generally used for heavily reinforced components with complicated shapes). The unit weight of fresh concrete was also measured according to ASTM C138 following the slump test.

(a) Low workability **(b) Medium workability** **(c) High workability**

Figure 12. Different levels of concrete workability measured by slump tests

Nine 3” x 6” cylindrical specimens were prepared from each concrete mixture for measurement of compressive strength at 3, 7, and 28 days. All concrete specimens were cured in a standard curing room at 73.5±3.5°F (23.0±2.0°C) and 100% relative humility immediately after casting. After a 24±8-hour period of initial curing, the specimens were removed from the plastic molds and returned to the curing room for continued curing until the time for the compressive strength tests (Figure 14). The entire sample preparation and curing process followed ASTM C192.

Figure 13. Concrete samples curing

Compressive strength was tested with a Test Mark Model #CM-4000-SD compression strength tester (Test Mark Industries, Beaver Falls, PA) (see Figure 14) according to ASTM C39. The broken specimens from compression testing were then used for the TCLP, total lead, and pH tests.

(a) Sample under compression

(b) Sample after compression

Figure 14. Compressive strength tests

3.4 Sample Preparation for Chemical Tests

After the compressive strength test, one of the three broken cylinders was randomly selected from each mix for chemical analysis. A HILTI® TE805 breaker (Hilti Corp., Tulsa, OK) was used to crush the selected cylinder further so that its particles passed through a 3/8" sieve. The crushed sample was then divided into several parts using a splitter (Cat. No. 23962, Precision Scientific Co., Chicago, IL) and used for the TCLP, total lead, and pH tests. A randomly selected 1/8th split (average mass = 172 g, s.d. = 13 g) was used for TCLP extraction. The entire split was used for TCLP extraction with no further sub-sampling. A randomly selected 1/16th split was powdered in its entirety using a Shatterbox (Spex Industries, Inc., Metuchen, NJ) and used for the TCLP pre-tests and the total lead and pH tests. These samples were approximately 100 mesh and were much finer than the minimum particle size required for the TCLP pre-test (1 mm or finer). The powdered 1/16th splits were sub-sampled for the TCLP pre-tests and the total lead and pH tests.

4. TEST RESULTS

4.1 Characterization of Recycled, LBP-Contaminated Aggregate

4.1.1 Physical properties and particle size distribution

The specific gravity (G_b), and water absorption (Abs%) of unpainted specimens of masonry materials A, B, C, and D were measured according to ASTM C127 and C128. The measurements, together with the moisture content of the air-dried aggregates and compressive strength of the raw masonry materials, are presented in Table 4. It was observed that the recycled masonry materials used in this study had lower specific gravity than natural aggregate (2.4–2.9), while the absorption of the recycled aggregate was much higher than natural aggregate (0.2–4% for coarse aggregate, 0.2–2% for fine aggregate) (Kosmatka et al. 2002). As a result, the recycled

aggregates had a higher water demand in concrete mixing, and the concrete made with these recycled aggregates might have lower strength due to the low specific gravity of the aggregates.

The compressive strengths of the raw masonry materials were measured from cubic samples (2" cubes for masonry A, B, and D; 1" cubes for masonry C). As shown in Table 4, the two clay bricks have much higher compressive strength than the two concrete blocks. The differences in the compressive strength between the two concrete blocks (A and B) and the between the two clay bricks (C and D) were also noteworthy.

Table 4. Specific gravity, absorption, moisture content, and strength of masonry materials

Masonry Material		Concrete Blocks		Clay Bricks	
		A	B	C	D
Coarse aggregate (> 4.75mm)	G_b	2.31	2.33	2.35	2.39
	Abs%	7.36	5.46	5.62	4.10
Fine aggregate (< 4.75mm)	G_b	2.37	2.45	2.38	2.38
	Abs%	8.04	6.43	7.41	6.12
Moisture content %		1.56	1.84	0.34	0.85
Compressive strength, psi		3056	4755	10679	14722

The bulk densities of the crushed masonry materials were measured according to ASTM C29 on both uncompacted (loose) and compacted (rodding) conditions. The results (Table 5) indicated that the bulk density and void contents of the four crushed masonry materials were within the range of aggregate used for conventional concrete (75~110 pcf (pound per cubic foot) and 30%~50% respectively). However, the crushed clay bricks (masonry C and D) did have lower bulk density and higher voids compared to concrete blocks (masonry A and B), which was probably because of the higher percentage of irregularly shaped particles in the recycled clay-brick aggregate.

Table 5. Physical properties of the crushed masonry materials

Masonry Materials	Concrete Blocks		Clay Bricks	
	A	B	C	D
Bulk density by rodding, pcf	85.55	87.85	81.45	85.43
Voids in aggregate compacted by rodding, %	36.79	37.20	41.32	39.92
Loose bulk density, pcf	83.21	81.16	72.59	76.31
Voids between aggregate particle, %	38.52	41.98	47.70	46.33
Fineness modulus (FM)	5.41	5.41	6.72	5.94

The gradation of recycled aggregate was analyzed according to ASTM C136. The gradation curves of the four masonry materials were compared with the aggregate gradation of two conventional used-pavement concrete from the Iowa Department of Transportation (DOT) (C3 and C4). The results (Figure 15) showed that all aggregates recycled from the masonry materials studied were coarser than conventional concrete aggregate, particularly the aggregate recycled

from masonry C. Only 15% and 30% of the crushed brick particles (for masonry C and D, respectively) passed a #4 (4.75mm) sieve, which was much less than the 40% measured for the crushed concrete blocks (masonry A and B). That is, the concrete blocks used in this study had more uniform particle size distributions compared to clay bricks. The 40% of fine aggregate (passing a #4 (4.75mm) sieve) was close to the fine aggregate ratio measured for Iowa DOT C3 and C4 concrete, which indicated a relatively good gradation for masonry materials A and B used in this study. The fineness modulus (FM), which is an index of the fineness of aggregate, was calculated based on the sieving analysis results according to ASTM C125. As shown in Table 5, crushed clay bricks (especially masonry C) have higher fineness moduli, (representing coarser aggregates) than the Iowa DOT C3 and C4 aggregates (FMs of 5.30 and 5.10, respectively). The crushed clay bricks had a lesser amount of finer particles, and the void content between aggregate particles was higher than for concrete block, which was probably resulted from the greater brittleness of clay brick.

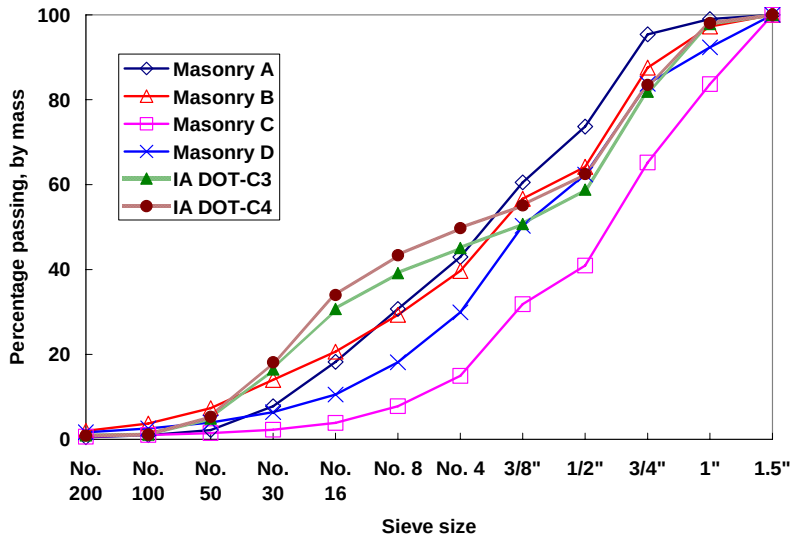


Figure 15. Sieving analysis of masonry materials

4.1.2 Lead content and leachability

TCLP lead, total lead and pH (1:1 w/w) (pH of solution with one part of solid and one part of water by weight) were determined for both the unpainted and the painted masonry materials. Table 6 illustrates that pH values of unpainted clay brick materials in water and in hydrochloric acid (HCl) solution were lower or much lower than those of unpainted concrete block materials. This implies that the clay brick masonry materials have lower acid neutralizing capacities than the concrete blocks. Table 7 shows that the TCLP lead of the two painted concrete blocks (masonry A and B) was 4.17 and 1.29 mg/L, respectively, and it was 142 and 77 mg/L for the two painted clay bricks (C and D), respectively. According to the Resource Conservation and Recovery Act (RCRA), the painted concrete blocks (with three layers of LBP coating) would not be defined as hazardous waste because the TCLP lead concentrations were less than the 5 mg/L limit for the Toxicity Characteristic. However, the painted clay bricks (with two layers of LBP coating) do have the Toxicity Characteristic for lead and would be considered hazardous

materials. The high TCLP lead concentrations in the extracts of the painted clay brick masonry materials may be attributed to the low acid-neutralizing capacity of the clay brick masonry materials, as indicated by their pH values in Table 6. The total lead concentrations of the painted masonry materials were between 5.82 and 10.1 g/kg.

Table 6. Lead content for unpainted masonry materials

Sample ID	Concrete Block		Clay Brick	
	A	B	C	D
pH in H_2O	11.75	11.97	10.15	9.46
pH in HCl	9.3	11.32	1.92	1.8
TCLP pH	NA*	NA	NA	NA
TCLP Pb, mg/L	NA	NA	NA	NA
pH (1:1 w/w)	NA	NA	NA	NA
Total Pb, mg/Kg	< 3.6	< 3.6	< 3.6	< 3.6

Note: NA – Not Available

Table 7. Lead content for painted masonry materials

Sample ID	Concrete Block		Clay Brick	
	A	B	C	D
pH in H_2O	NA	NA	NA	NA
pH in HCl	NA	10.52	NA	1.96
TCLP pH	6.73	7.02	5.11	4.88
TCLP Pb, mg/L	4.17	1.29	**142**	**77**
pH (1:1 w/w)	11.50	11.60	8.23	8.94
Total Pb, g/Kg	15.4	10.1	12.5	5.82

Note: TCLP lead ≥ 5 mg/L indicates a toxicity characteristic for lead.

4.2 Concrete Mix Proportions

Fourteen trial concrete mixes with natural aggregate (limestone and river sand) as coarse and fine aggregate were prepared to determine the mix proportions for concrete with different aggregate-to-cement ratios (3, 4.5, and 6) and three different workability levels (slump of 1”–2”, 3”–4”, and 6”–7”). Mix proportions of the concrete with different masonry materials were then determined according to the results from the trial batches.

Due to the limited time of the project, the present research focused on the concrete made with portland cement. Nine to ten different mix proportions were designed for each masonry material (A, B, C, and D) with portland cement. Three to four mix proportions were developed for concrete made with masonry B or D and CSA cement or portland cement with phosphate. A total of 50 concrete mixes were prepared in this study, and the detailed mix designs can be found in Table 8 through Table 15. A wide range of w/c (from 0.28 to 0.74) and cement factors (397 to 853 pcy (pound per cubic yard) were included. Air entraining agent AEA-92 with a recommended dosage of 0.5–1.0 fl oz per 100 lb (30-60 ml/100 kg) cement was used in all of the concrete mixes.

Table 8. Mix design of concrete with masonry material A and portland cement

	Mix*	a/c	w/c	Cement, pcy	Aggregate pcy	Water, pcy	AEA, oz/cy
1	A-I-m3-SL1.75"	3	0.28	843	2529	234	6.3
2	A-I-m3-SL4"	3	0.31	769	2306	240	5.8
3	A-I-m3-SL6"	3	0.32	805	2414	259	6.0
4	A-I-m4.5-SL2"	4.5	0.32	587	2641	189	4.4
5	A-I-m4.5-SL4"	4.5	0.34	556	2504	191	4.2
6	A-I-m4.5-SL6"	4.5	0.37	541	2436	201	4.1
7	A-I-m6-SL1.75"	6	0.34	446	2679	151	3.3
8	A-I-m6-SL3"	6	0.36	448	2690	162	3.4
9	A-I-m6-SL6.25"	6	0.41	429	2573	176	3.2
10	A-I-m3-SL8.25"	3	0.38	740	2221	285	5.6

*Mix = Type of masonry material (A, B, C, D) – Type of cement (I: Portland cement, II: CSA cement, III: portland cement with phosphate cement) –a/c (m3, m4.5, m6), SL (slump)

Table 9. Mix design of concrete with masonry material B and portland cement

	Mix	a/c	w/c	Cement, pcy	Aggregate pcy	Water, pcy	AEA, oz/cy
1	B-I-m3-SL1"	3	0.34	853	2560	286	6.4
2	B-I-m3-SL3.5"	3	0.35	793	2380	278	6.0
3	B-I-m3-SL6.25"	3	0.40	797	2392	319	6.0
4	B-I-m4.5-SL1.75"	4.5	0.39	591	2661	232	4.4
5	B-I-m4.5-SL4"	4.5	0.42	537	2415	225	4.0
6	B-I-m4.5-SL6.5"	4.5	0.48	533	2401	256	4.0
7	B-I-m6-SL2"	6	0.45	453	2719	204	3.4
8	B-I-m6-SL3.5"	6	0.48	431	2587	206	3.2
9	B-I-m6-SL6.75"	6	0.55	397	2383	218	3.0

Table 10. Mix design of concrete with masonry material C and portland cement

	Mix	a/c	w/c	Cement, pcy	Aggregate pcy	Water, pcy	AEA, oz/cy
1	C-I-m3-SL1.5"	3	0.30	840	2521	248	6.3
2	C-I-m3-SL3.88"	3	0.33	819	2456	266	6.1
3	C-I-m3-SL6"	3	0.36	801	2402	290	6.0
4	C-I-m4.5-SL1.75"	4.5	0.33	571	2571	191	4.3
5	C-I-m4.5-SL4"	4.5	0.36	581	2612	210	4.4
6	C-I-m4.5-SL6.5"	4.5	0.39	563	2534	218	4.2
7	C-I-m6-SL2"	6	0.36	449	2694	164	3.4
8	C-I-m6-SL4"	6	0.42	446	2676	185	3.3
9	C-I-m6-SL6.63"	6	0.44	431	2584	190	3.2

Table 11. Mix design of concrete with masonry material D and portland cement

	Mix	a/c	w/c	Cement, pcy	Aggregate pcy	Water, pcy	AEA, oz/cy
1	D-I-m3-SL2"	3	0.39	814	2443	318	6.1
2	D-I-m3-SL3.75"	3	0.43	800	2400	341	6.0
3	D-I-m3-SL6.25"	3	0.48	735	2205	353	5.5
4	D-I-m4.5-SL1"	4.5	0.50	573	2578	286	4.3
5	D-I-m4.5-SL3.5"	4.5	0.52	555	2496	291	4.2
6	D-I-m4.5-SL6"	4.5	0.56	563	2532	315	4.2
7	D-I-m6-SL1.5"	6	0.56	450	2697	250	3.4
8	D-I-m6-SL3.25"	6	0.60	433	2600	260	3.3
9	D-I-m6-SL6"	6	0.74	427	2563	317	3.2

Table 12. Mix design of concrete with masonry material B and CSA cement

	Mix	a/c	w/c	Cement, pcy	Aggregate pcy	Water, pcy	AEA, oz/cy
1	B-II-m3-SL1.5"	3	0.45	788	2365	355	5.9
2	B-II-m4.5-SL1"	4.5	0.46	597	2684	274	4.5
3	B-II-m6-SL1.25"	6	0.50	454	2723	227	3.4

Table 13. Mix design of concrete with masonry material D and CSA cement

	Mix	a/c	w/c	Cement, pcy	Aggregate pcy	Water, pcy	AEA, oz/cy
1	D-II-m3-SL2"	3	0.46	792	2375	360	5.9
2	D-II-m3-SL6.5"	3	0.44	792	2375	346	5.9
3	D-II-m4.5-SL1.5"	4.5	0.51	588	2645	301	4.4
4	D-II-m6-SL2"	6	0.61	447	2684	272	3.4

Table 14. Mix design of concrete with masonry material B and portland cement with phosphate

	Mix	a/c	w/c	Cement, pcy	Aggregate pcy	Water, pcy	AEA, oz/cy
1	B-III-m3-SL3"	3	0.37	814	2441	300	6.1
2	B-III-m4.5-SL3.25"	4.5	0.41	587	2644	241	4.4
3	B-III-m6-SL4"	6	0.49	427	2560	210	3.2

Table 15. Mix design of concrete with masonry material D and portland cement with phosphate

	Mix	a/c	w/c	Cement, pcy	Aggregate pcy	Water, pcy	AEA, oz/cy
1	D-III-m3-SL3.75"	3	0.43	797	2391	343	6.0
2	D-III-m4.5-SL3.5"	4.5	0.53	567	2550	300	4.3
3	D-III-m6-SL3.5"	6	0.62	443	2660	277	3.3

4.3 Concrete Physical Properties

As mentioned previously, the slump and unit weight of fresh concrete were measured, and compressive strength of hardened concrete was tested at ages of 3, 7, and 28 days. All the results are summarized in Tables 16-23.

Table 16. Physical properties of concrete with masonry material A and portland cement

	Mix	Slump, in.	Un. Wt., pcf	$f'_{c,3}$, psi	$f'_{c,7}$, psi	$f'_{c,28}$, psi
1	A-I-m3-SL1.75"	1.75	133.5	3589	4351	5109
2	A-I-m3-SL4"	4.00	122.7	2424	3033	3861
3	A-I-m3-SL6"	6.00	128.8	2615	3184	3757
4	A-I-m4.5-SL2"	2.00	126.5	1833	2285	2984
5	A-I-m4.5-SL4"	4.00	120.4	1186	1669	2037
6	A-I-m4.5-SL6"	6.00	117.7	961	1455	1831
7	A-I-m6-SL1.75"	1.75	121.3	817	1060	1500
8	A-I-m6-SL3"	3.00	122.2	814	1276	1745
9	A-I-m6-SL6.25"	6.25	117.7	649	940	1323
10	A-I-m3-SL8.25"	8.25	120.2	1497	2219	2522

Table 17. Physical properties of concrete with masonry material B and portland cement

	Mix	Slump, in.	Un. Wt., pcf	$f'_{c,3}$, psi	$f'_{c,7}$, psi	$f'_{c,28}$, psi
1	B-I-m3-SL1"	1.00	137.0	4566	5188	6666
2	B-I-m3-SL3.5"	3.50	127.8	3061	3811	4960
3	B-I-m3-SL6.25"	6.25	129.9	2804	3620	4726
4	B-I-m4.5-SL1.75"	1.75	129.0	1989	2678	3414
5	B-I-m4.5-SL4"	4.00	117.6	1367	1853	2329
6	B-I-m4.5-SL6.5"	6.50	118.2	929	1347	1720
7	B-I-m6-SL2"	2.00	125.0	1197	1516	2112
8	B-I-m6-SL3.5"	3.50	119.4	774	1067	1452
9	B-I-m6-SL6.75"	6.75	111.0	417	571	816

Table 18. Physical properties of concrete with masonry material C and portland cement

	Mix	Slump, in.	Un. Wt., pcf	$f'_{c,3}$, psi	$f'_{c,7}$, psi	$f'_{c,28}$, psi
1	C-I-m3-SL1.5"	1.50	133.7	3232	3771	4758
2	C-I-m3-SL3.88"	3.88	131.1	2691	3683	4389
3	C-I-m3-SL6"	6.00	129.4	2215	2644	3972
4	C-I-m4.5-SL1.75"	1.75	123.4	1173	1947	2846
5	C-I-m4.5-SL4"	4.00	126.1	906	1574	2006
6	C-I-m4.5-SL6.5"	6.50	122.7	700	1289	2249
7	C-I-m6-SL2"	2.00	122.5	NA	1052	1380
8	C-I-m6-SL4"	4.00	122.5	NA	620	1108
9	C-I-m6-SL6.63"	6.63	118.7	NA	358	782

Table 19. Physical properties of concrete with masonry material D and portland cement

	Mix	Slump, in.	Un. Wt., pcf	$f'_{c,3}$, psi	$f'_{c,7}$, psi	$f'_{c,28}$, psi
1	D-I-m3-SL2"	2.00	132.4	4122	4823	5515
2	D-I-m3-SL3.75"	3.75	131.1	3237	4540	5929
3	D-I-m3-SL6.25"	6.25	121.9	2179	2876	3827
4	D-I-m4.5-SL1"	1.00	127.3	2002	2416	4086
5	D-I-m4.5-SL3.5"	3.50	123.8	1737	2306	3459
6	D-I-m4.5-SL6"	6.00	126.3	1699	1776	2682
7	D-I-m6-SL1.5"	1.50	125.8	1077	1894	2465
8	D-I-m6-SL3.25"	3.25	122.0	1113	1524	2357
9	D-I-m6-SL6"	6.00	122.5	554	989	1144

Table 20. Physical properties of concrete with masonry material B and CSA cement

	Mix	Slump, in.	Un. Wt., pcf	$f'_{c,3}$, psi	$f'_{c,7}$, psi	$f'_{c,28}$, psi
1	B-II-m3-SL1.5"	1.50	129.9	2843	3447	3762
2	B-II-m4.5-SL1"	1.00	131.7	2426	2590	3157
3	B-II-m6-SL1.25"	1.25	126.1	1630	1746	1923

Table 21. Physical properties of concrete with masonry material D and CSA cement

	Mix	Slump, in.	Un. Wt., pcf	$f'_{c,3}$, psi	$f'_{c,7}$, psi	$f'_{c,28}$, psi
1	D-II-m3-SL2"	2.00	130.6	3825	4163	4382
2	D-II-m3-SL6.5"	6.50	130.1	4891	4961	5486
3	D-II-m4.5-SL1.5"	1.50	130.9	3720	3819	3869
4	D-II-m6-SL2"	2.00	126.1	1979	1891	1980

Table 22. Physical properties of concrete with masonry material B and portland cement with phosphate

	Mix	Slump, in.	Un. Wt., pcf	$f'_{c,3}$, psi	$f'_{c,7}$, psi	$f'_{c,28}$, psi
1	B-III-m3-SL3"	3.00	131.7	2642	3796	4801
2	B-III-m4.5-SL3.25"	3.25	128.6	1888	2673	3542
3	B-III-m6-SL4"	4.00	118.4	573	900	1418

Table 23. Physical properties of concrete with masonry material D and portland cement with phosphate

	Mix	Slump, in.	Un. Wt., pcf	$f'_{c,3}$, psi	$f'_{c,7}$, psi	$f'_{c,28}$, psi
1	D-III-m3-SL3.75"	3.75	130.8	3484	4558	5962
2	D-III-m4.5-SL3.5"	3.50	126.6	1957	2906	3704
3	D-III-m6-SL3.5"	3.50	125.2	1002	1386	2298

Figure 16 and Figure 17 show that the 28-day compressive strength of the concrete increases with the amount of cement (cement factor, C) or decreases with a/c.

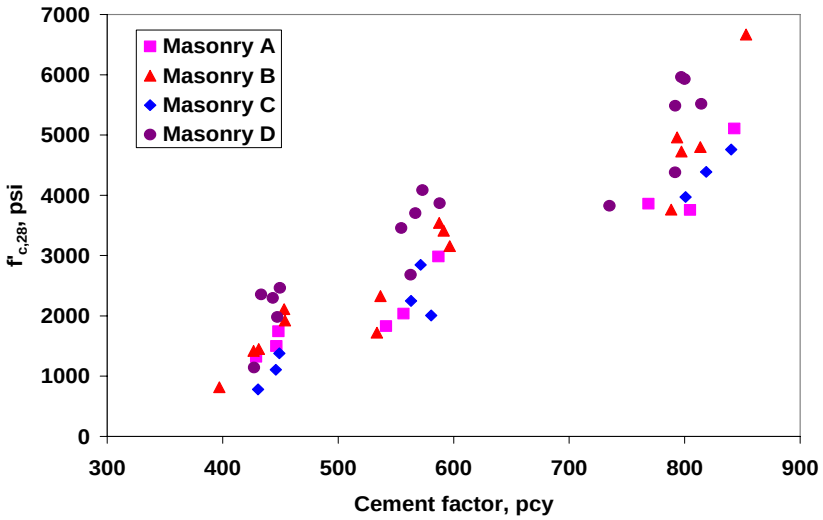


Figure 16. Effect of cement content on compressive strength

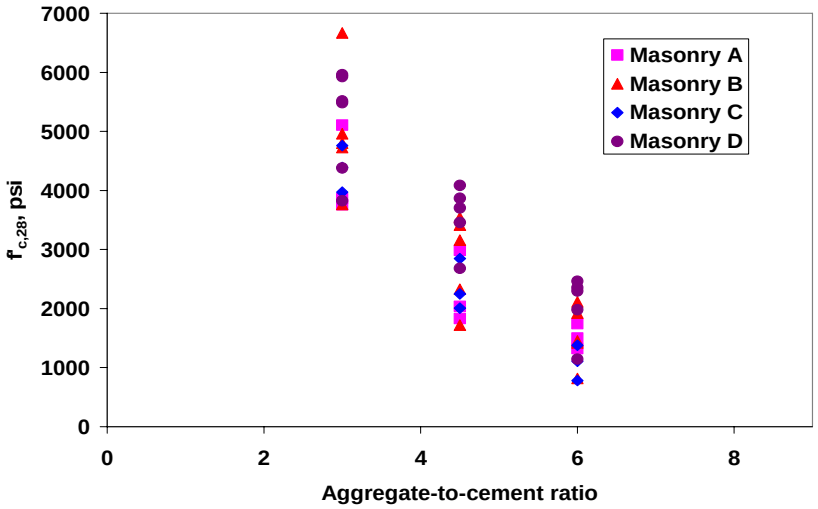


Figure 17. Effect of a/c on compressive strength

For a given recycled aggregate, Figure 18 shows that the 28-day compressive strength also decreases with the w/c. This is in agreement with the well-known Abrams' law of the relationship between w/c and strength of conventional concrete (Neville 1996). Reduced w/c generally provides concrete with a denser and stronger cement paste and a better bond between the paste and aggregate particles, thus improving concrete strength. For a given w/c, the order of strength, from the highest to the lowest, is concrete made with masonry D, B, C, and A. In addition to mixture proportion, the concrete strength is also influenced by the aggregate characteristics, such as strength, gradation, and particle shapes.

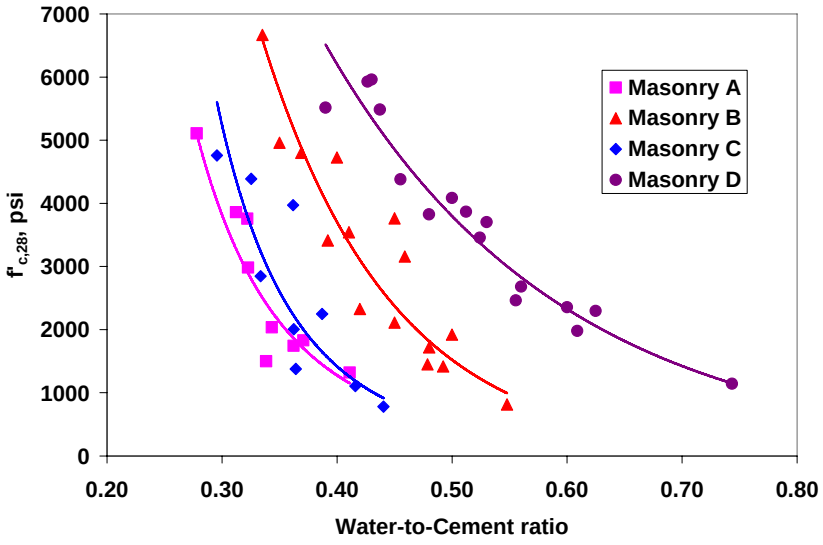


Figure 18. Effect of w/c on compressive strength

An analysis was also performed to compare the unit weight and the 28-day compressive strength of concrete. The results (Figure 19) show that, regardless the amount of cement and w/c, concrete compressive strength generally increased with the unit weight of the concrete. It was noted that for a given mix proportion, concrete made with CSA cement provided higher compressive strength, especially at the early ages, than the corresponding concrete made with portland cement. However, the water demand of the concrete usually increased when CSA cement was used.

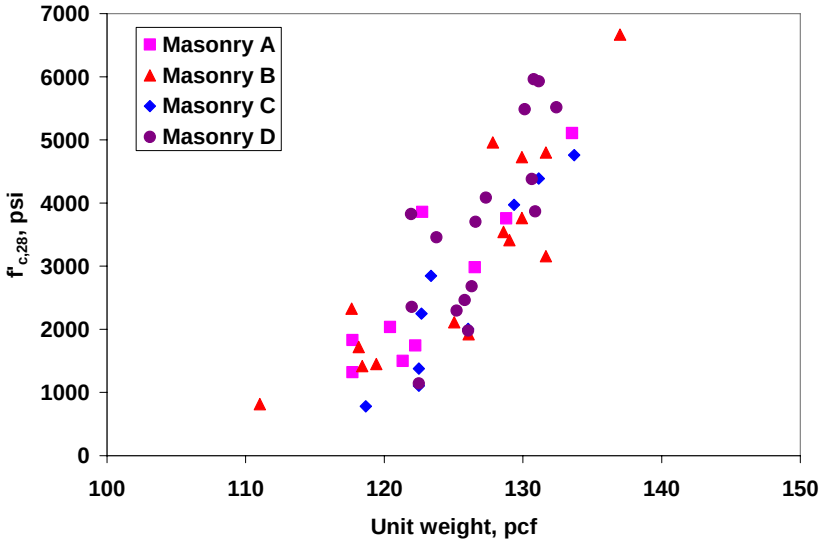
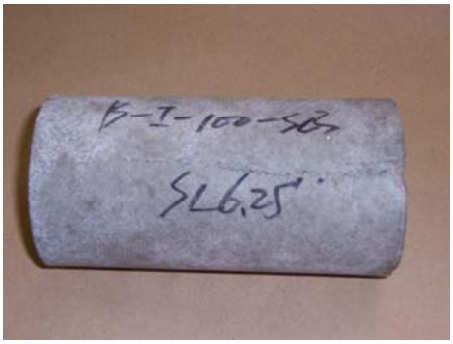


Figure 19. Effect of unit weight on concrete compressive strength



(a) Cylinder with sufficient paste (Mix B-I-m3-SL6.25")

(b) Cylinder with honeycomb (Mix C-I-m4.5-SL4")

Figure 20. Samples with good or bad compaction

It was also observed that, due to the high void content between the recycled aggregate particles, concrete made with masonry C or D (see Table 5) required more cement paste to fill the voids. Honeycombing occurred in the concrete if the cement content was not sufficient (Figure 20), which significantly reduced concrete strength. Therefore, it is recommended to combine natural aggregate with the recycled masonry aggregate if the void content of a recycled aggregate is high (> 42%). Such a combination can also improve the aggregate gradation. The study of combined aggregate was not covered in this project due to the time limit.

4.4 Lead Content and Leachability of Concrete

TCLP lead, total lead, and pH were determined for the 50 mixes prepared in this study. The detailed test results are summarized in Table 24 through Table 31.

Table 24. Lead content and leachability of concrete with masonry material A and portland cement

	Mix	pH, 1:1	TCLP pH	TCLP Pb, mg/L	Total Pb, g/Kg
1	A-I-m3-SL1.75"	11.72	11.05	0.42	19.64
2	A-I-m3-SL4"	11.42	11.43	0.32	16.14
3	A-I-m3-SL6"	11.60	11.16	0.30	15.99
4	A-I-m4.5-SL2"	11.40	10.61	0.32	17.12
5	A-I-m4.5-SL4"	11.48	11.27	0.27	16.02
6	A-I-m4.5-SL6"	11.54	11.36	0.49	15.95
7	A-I-m6-SL1.75"	11.55	10.78	0.06	21.40
8	A-I-m6-SL3"	11.55	10.69	0.05	20.59
9	A-I-m6-SL6.25"	11.65	10.41	0.38	17.26
10	A-I-m3-SL8.25"	11.49	11.30	0.97	15.66

Table 25. Lead content and leachability of concrete with masonry material B and portland cement

	Mix	pH, 1:1	TCLP pH	TCLP Pb, mg/L	Total Pb, g/Kg
1	B-I-m3-SL1"	11.60	11.01	1.16	8.37
2	B-I-m3-SL3.5"	11.54	11.41	2.19	10.35
3	B-I-m3-SL6.25"	11.36	11.19	0.49	9.09
4	B-I-m4.5-SL1.75"	11.78	11.07	0.35	9.04
5	B-I-m4.5-SL4"	11.34	11.33	1.08	8.50
6	B-I-m4.5-SL6.5"	11.54	10.87	1.20	10.78
7	B-I-m6-SL2"	11.89	10.85	0.25	10.11
8	B-I-m6-SL3.5"	11.57	11.25	1.27	10.76
9	B-I-m6-SL6.75"	11.32	10.89	1.10	10.82

Table 26. Lead content and leachability of concrete with masonry material C and portland cement

	Mix	pH, 1:1	TCLP pH	TCLP Pb, mg/L	Total Pb, g/Kg
1	C-I-m3-SL1.5"	11.59	10.91	0.75	8.87
2	C-I-m3-SL3.88"	11.40	10.96	1.16	8.02
3	C-I-m3-SL6"	11.63	11.23	1.09	7.57
4	C-I-m4.5-SL1.75"	11.36	10.22	0.27	7.61
5	C-I-m4.5-SL4"	11.64	10.60	0.94	8.68
6	C-I-m4.5-SL6.5"	11.46	10.57	0.44	7.50
7	C-I-m6-SL2"	11.64	8.04	2.41	9.67
8	C-I-m6-SL4"	11.73	9.68	1.36	9.99
9	C-I-m6-SL6.63"	11.57	9.79	1.18	9.17

Table 27. Lead content and leachability of concrete with masonry material D and portland cement

	Mix	pH, 1:1	TCLP pH	TCLP Pb, mg/L	Total Pb, g/Kg
1	D-I-m3-SL2"	12.01	11.00	0.83	4.19
2	D-I-m3-SL3.75"	11.52	11.15	0.16	4.42
3	D-I-m3-SL6.25"	11.76	10.98	0.76	5.24
4	D-I-m4.5-SL1"	11.35	11.46	0.95	5.02
5	D-I-m4.5-SL3.5"	11.90	10.40	0.63	5.51
6	D-I-m4.5-SL6"	12.02	9.75	0.58	4.19
7	D-I-m6-SL1.5"	12.02	7.33	**6.14**	6.30
8	D-I-m6-SL3.25"	11.90	8.86	1.43	6.24
9	D-I-m6-SL6"	12.01	6.41	**33.00**	5.51

Table 28. Lead content and leachability of concrete with masonry material B and CSA cement

	Mix	pH, 1:1	TCLP pH	TCLP Pb, mg/L	Total Pb, g/Kg
1	B-II-m3-SL1.5"	10.70	10.29	0.22	7.94
2	B-II-m4.5-SL1"	10.78	10.40	0.32	8.88
3	B-II-m6-SL1.25"	11.21	10.54	0.37	11.13

Table 29. Lead content and leachability of concrete with masonry material D and CSA cement

	Mix	pH, 1:1	TCLP pH	TCLP Pb, mg/L	Total Pb, g/Kg
1	D-II-m3-SL2"	10.20	5.78	**91.9**	4.70
2	D-II-m3-SL6.5"	10.52	10.01	0.16	4.88
3	D-II-m4.5-SL1.5"	10.36	9.56	0.10	5.35
4	D-II-m6-SL2"	9.95	5.41	**123**	4.96

Table 30. Lead content and leachability of concrete with masonry material B and portland cement with phosphate

	Mix	pH, 1:1	TCLP pH	TCLP Pb, mg/L	Total Pb, g/Kg
1	B-III-m3-SL3"	11.68	11.27	2.20	10.55
2	B-III-m4.5-SL3.25"	11.71	11.20	1.21	9.74
3	B-III-m6-SL4"	11.79	11.05	2.06	10.86

Table 31. Lead content and leachability of concrete with masonry material D and portland cement with phosphate

	Mix	pH, 1:1	TCLP pH	TCLP Pb, mg/L	Total Pb, g/Kg
1	D-III-m3-SL3.75"	11.68	11.15	0.65	4.84
2	D-III-m4.5-SL3.5"	11.33	10.4	0.72	6.36
3	D-III-m6-SL3.5"	11.27	8.98	1.71	6.17

As shown in Figure 21, the TCLP Pb value is controlled by the final pH value of the TCLP extract. Because of the high alkalinity of the cement hydration products, the TCLP extract pH values for most of the mixes were higher than 9, and the concentration of lead in those TCLP extracts was less than 1 mg/L, which is lower than the level of 5 mg Pb/L for the toxicity characteristic as specified in RCRA. According to the results, as shown in Table 27 and Table 29, four concrete mixes made with masonry D showed TCLP Pb values higher than 5 mg Pb/L, the hazardous waste threshold value. This may be attributed to the low acid neutralizing capacity of this clay brick masonry material. As pointed out in Section 4.1.2, the pH values of unpainted and painted clay brick materials, especially masonry D, were relatively low when compared with those of unpainted concrete block materials. A mix design with higher cement content or the

addition of alkaline materials such as a highly alkaline cement may increase the alkalinity of the concrete and reduce the TCLP Pb value.

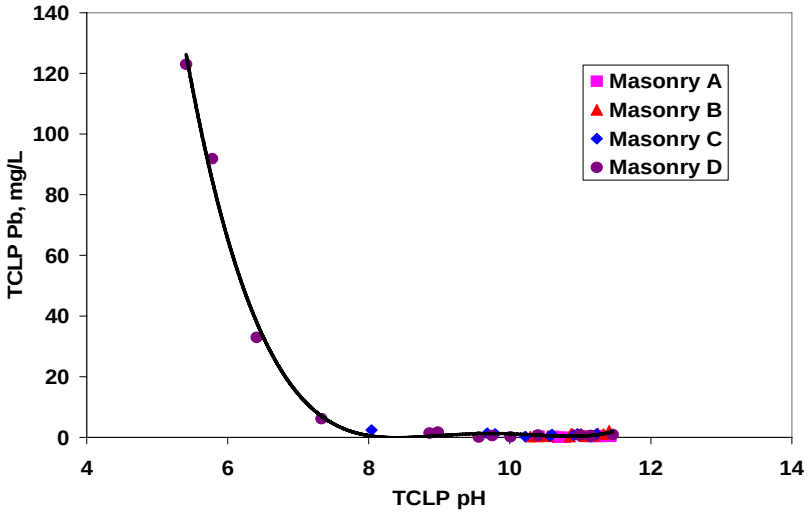
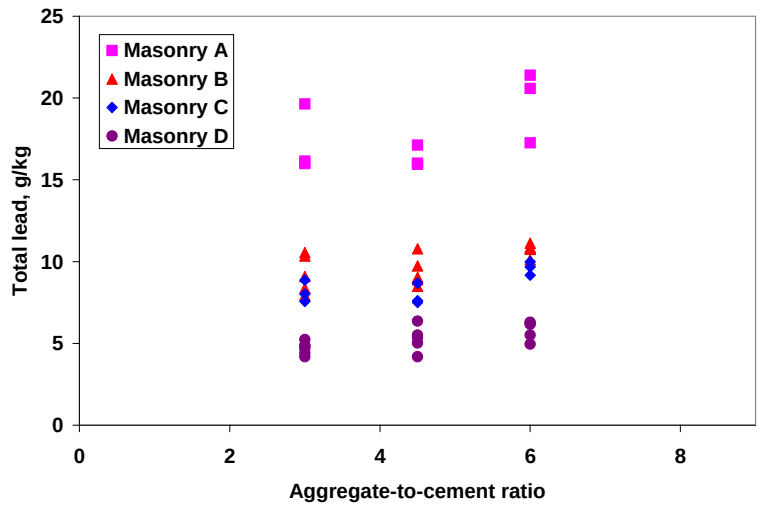
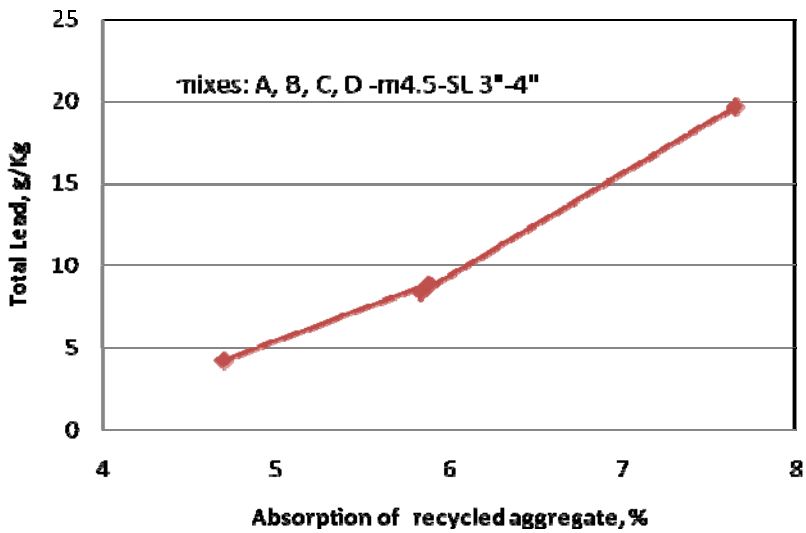


Figure 21. TCLP pH vs. TCLP Pb value

As shown in Figure 22 (a), the total lead of these mixes varied from 4.19 to 21.40 g/Kg, depending on the type of masonry material and the mix proportions of the concrete. Figure 22 (b) illustrates that the total lead of the concrete mixes made with portland cement and having approximately the same slump value increased with the absorption of the recycled aggregate. Similar trends were also found for the concrete mixes having different slump values. Due to the higher absorption of the concrete block, the total lead content of masonry materials A and B was higher than that of the clay brick (masonry materials C and D).



(a) Effect of a/c



(b) Effect of aggregate absorption

Figure 22. Effects of aggregate content and absorption on total lead in concrete

The results also showed that while total lead generally increased with the aggregate to cement ratio, the variability of the total lead concentrations was relatively high. Some mixes had total lead concentrations exceeding the total lead found in the recycled aggregate. This is likely due to the impracticality of withdrawing statistically equivalent portions of the larger stock of recycled aggregate both for preparing the concrete mixes and for chemical analysis. Because LBP was concentrated on the surfaces of the painted bricks and blocks, the crushed, recycled aggregates were highly inhomogeneous materials. It was not technically feasible for the investigators to withdraw statistically representative quantities of material from the storage barrels containing

approximately 500 lb of material. However, this problem did not influence the conclusions of the study because the individual test cylinders could be carefully split for chemical analysis and characterized with good statistical confidence (Appendix A).

As previously stated, the sequestration of lead in basic lead carbonate depends on the pH within the environment of the concrete. The investigators measured the pH value of the concrete mixtures, and the results (Figure 23) indicated that although there was no clear trend of the effect of aggregate content or type on the pH values, all concrete mixes made with portland cement had pH values between 11.32 and 12.02, and the mixes made with CSA cement had pH values between 9.95 and 11.21. Lead was effectively sequestered in these concrete mixes and would not be mobilized if these mixes were used in applications exposed to environmental conditions commonly encountered in the field.

It was also noted that there was no relationship between the total lead and TCLP lead.

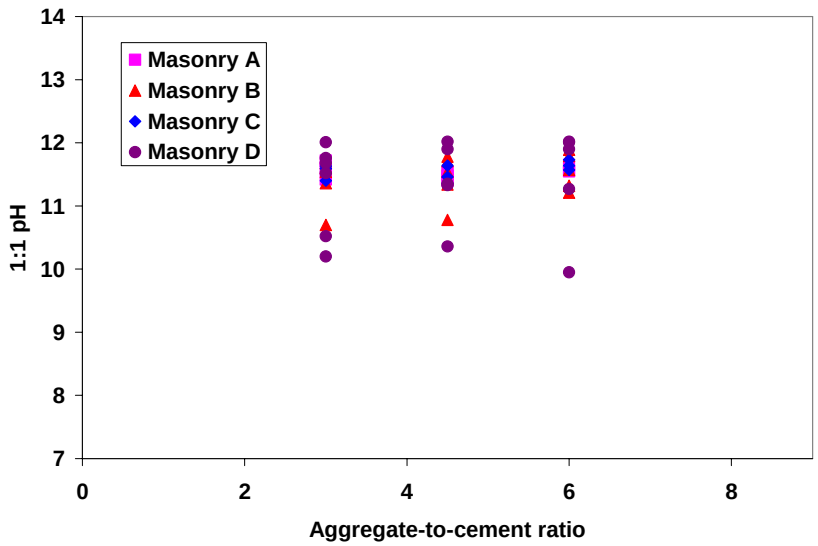


Figure 23. pH value vs. aggregate to cement ratio

Concrete with high soluble alkali content generally has a higher pH value than concrete with low soluble alkali. Since pH values were determined for all of the concrete mixes (Table 24 through Table 27) and the almost of the pH values measured were less than 12.4, the commonly-accepted threshold for damaging alkali-silica reaction to occur in concrete, the present study did not focus on the measurements of soluble alkali content. Only four concrete samples were selected for the soluble alkali test because of the limited budget and time available for the project. Two of the samples were made with recycled concrete block aggregate (A and B) and the other two with recycled clay brick aggregate (C and D). These concrete mixes had a/c of 4.5 and slump of 3” to 4”. Table 32 shows the test results. As seen in the table, the four selected concrete samples, with commonly used mix proportions, all had total soluble alkali content much lower than the limit (3kg/m^3 or approximately 0.13%), above which the damaging alkali-silica reaction may occur in concrete. There was no significant difference in total soluble alkali between the concretes made

with recycled clay brick or concrete block aggregates. The pH values and total soluble alkali content of the concretes studied in the present project indicate that there may be no special concern on the alkali-silica reaction of the concrete made with the recycled LBP-contaminated masonry materials. More soluble alkali tests may be conducted in future to confirm the present findings.

Table 32 Water-soluble alkali analysis results

Mix	pH* (1:1)	Na_2O (weight %)	K_2O (weight %)	Total Alkali (weight %)
A-I-m4.5-SL4”	11.48	0.02	0.03	0.04
B-I-m4.5-SL4”	11.34	0.02	0.03	0.04
C-I-m4.5-SL4”	11.64	0.02	0.02	0.03
D-I-m4.5-SL3.5”	11.90	0.03	0.04	0.06

* see Table 24 through Table 27 for the pH values

4.5 Statistical Analysis

A statistical analysis was performed to study the effects of materials and mix design parameters on concrete properties. Linear regression with multiple parameters including a/c, w/c, type of masonry materials, and type of cement was used to predict the 3-, 7-, and 28-day compressive strength, pH value, TCLP lead, and total lead of different mixes. The prediction of different factors is shown in Figure 24.

The results showed that masonry B and masonry D resulted in concrete with higher strengths compared to masonry materials A and C. Concrete made with concrete blocks (masonry A and B) showed higher total lead contents compared to concrete made with clay brick (masonry C and D), which is consistent with the total lead content in the crushed masonry materials.

CSA cement provided concrete with higher early-age compressive strength but did not show an obvious effect on 28-day strength. Concrete made with CSA cement had lower pH values and higher TCLP lead concentrations than concrete made with portland cement, with or without phosphate addition.

Addition of 5% phosphate in portland cement did not significantly change the TCLP lead concentrations and total lead in the concrete. It is believed that if highly insoluble hydroxypyromorphite [$Pb_5(PO_4)_3OH$] was formed in the concrete system through the lead-phosphate reaction, it would have sequestered lead from the highly acidic conditions of the total lead test. This might have suggested a means for rendering LBP-contaminated masonry non-hazardous under California law. This reaction, however, did not occur in the present study. The concentrations of phosphate added ranged from 31% to 62% of the amounts needed to stoichiometrically convert the lead in the concrete to hydroxypyromorphite but did not result in proportionate reductions in detectable total lead.

Mixture proportions significantly affected concrete compressive strength. Both higher a/c and higher w/c resulted in lower concrete strengths. However, they did not show obvious effects on pH value or TCLP lead concentrations. Total lead concentrations slightly increased with a/c or m and slightly decreased with w/c.

In summary, the above results imply that, with appropriate design, concrete made with recycled, LBP-contaminated aggregates has physical properties that are satisfactory for a variety of useful purposes, including roadways, parking lots, and foundations. Lead in the LBP-contaminated aggregate can be effectively sequestered in concrete. Although the recycled aggregate may have some toxic characteristics, properly designed concrete made with the aggregate will not have the toxicity characteristic for lead (i.e., TCLP lead less than 5mg/L) and would not be considered as hazardous waste under the RCRA.

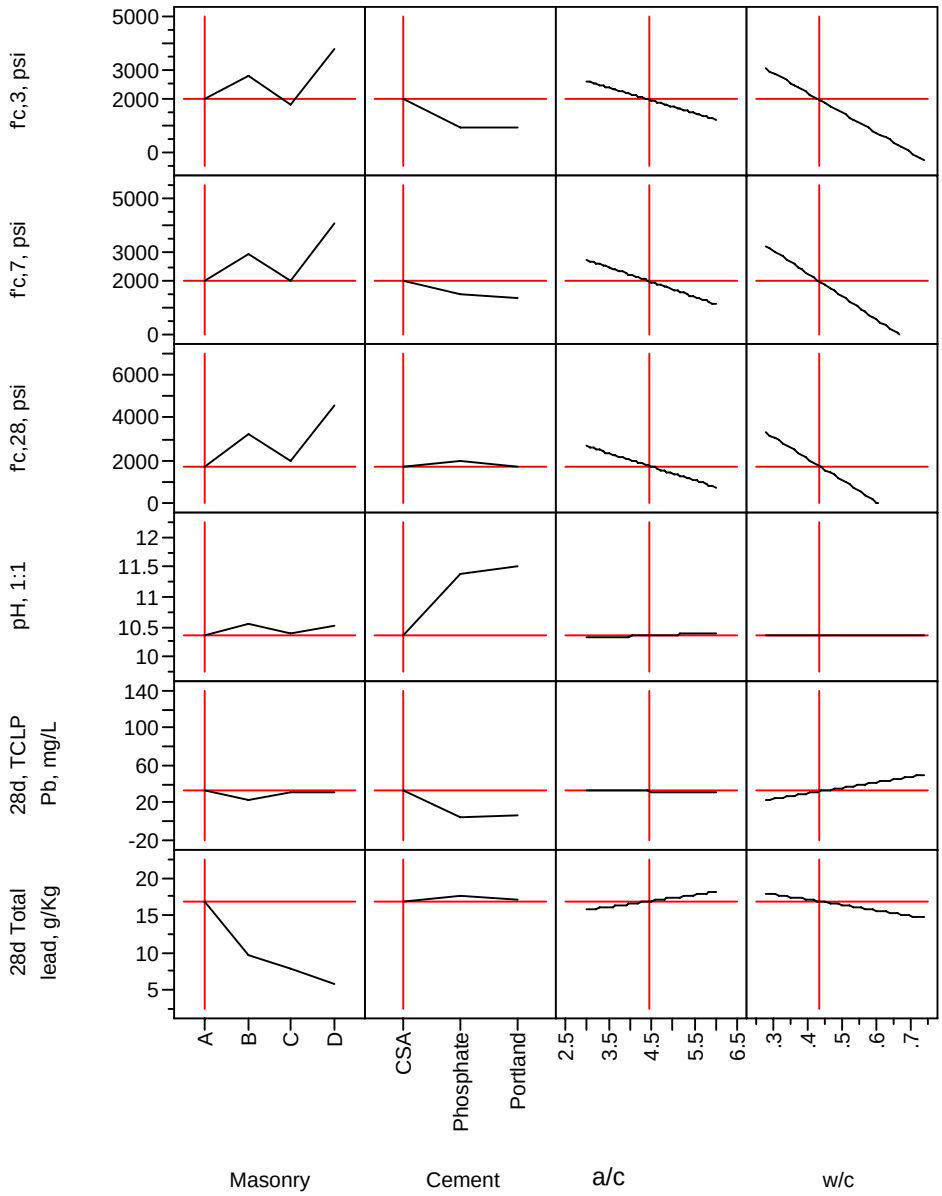


Figure 24. Prediction profiler of concrete properties

4.6 Mix Design Nomograph Development

In the present study, concrete mix design nomographs were developed for concrete made with each type of recycled, LBP-contaminated aggregate and portland cement, and for concrete made with selected recycled aggregate with CSA cement and with portland cement plus phosphate additions. Using the mix design nomographs, proper mix proportions can be selected for the desired workability and strength.

In a concrete mix design nomograph, three correlations—Abrams' law, Lyse's law, and Molinari's law—are generally used (Levy and Helene 2004, Monteiro et al. 1993).

Abrams' law correlates the compressive strength of concrete with the w/c as:

$$f'_c = \frac{k_1}{k_2^{\,w/c}} \qquad \textbf{Equation 1}$$

Where k_1, and k_2 are constants depending on the materials used.

Lyse's law correlates the w/c with the a/c (by weight) as:

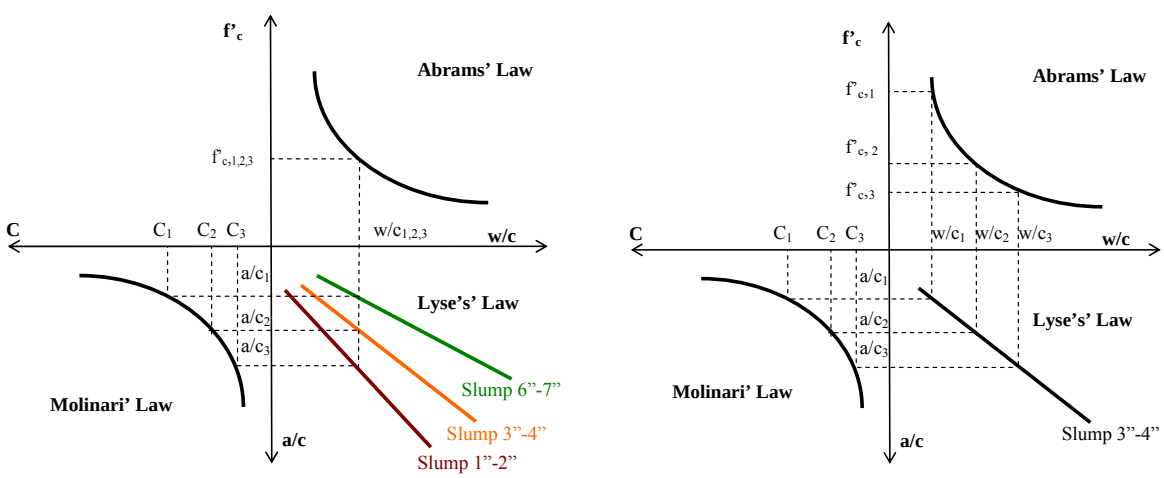
$$m = k_3(w/c) + k_4 \qquad \textbf{Equation 2}$$

Where m is the a/c, k_3, and k_4 are constants depending on the materials used.

Molinari's law correlates the cement content and a/c as:

$$C = \frac{1000}{k_5 m + k_6} \qquad \textbf{Equation 3}$$

Where C is the cement content, k_5, and k_6 are constants depending on the materials used.



(a) for different workability (b) for different strength

Figure 25. Uses of mix design nomograph

Two examples of mix design nomographs are shown in Figure 25. Each mix design nomograph should be developed from a series of proportions of concrete mixtures made with different w/c and a/c for a given aggregate. After a nomograph is developed for particular concrete materials, it can be used for designing new concrete mixtures with different compressive strength and workability (slump) requirements. As shown in Figure 25, the use of a concrete mix design nomograph includes three steps. First, according to the required compressive strength ($f'_{c,1,2,3}$), the w/c for concrete mixtures ($w/c_{1,2,3}$) can be determined through Abram's Law. Second, based on the w/c selected above and the required workability (slump) level, the a/c or $m_{1,2,3}$ can be further determined through Lyse's Law. Finally, the cement content ($C_{1,2,3}$) can be determined based on the Molinari's Law from the a/c. The concrete mix design can therefore be determined based on the three parameters: w/c, a/c, and cement content.

As shown in Figure 26 through Figure 33, for a given w/c, different mix proportions can be used to obtain different workability levels. On the other hand, for a given workability level, w/c and a/c or m can be selected to obtain concrete with a desired compressive strength.

The coefficients k_1 to k_6 in Equations 1–3 can be determined by a series of tests with the same materials and different mix designs. In this study, eight sets of nomographs with different masonry materials and cement combinations have been developed based on the 50 designed and tested mixes. They include four sets of nomographs for concrete made with masonry A, B, C, and D and portland cement at three different workability levels; two sets of nomographs for concrete made with masonry B and D and CSA cement at a single workability level; and two sets of nomographs for concrete made with masonry B and D with portland cement plus a 5% of calcium hydrogen phosphate ($CaHPO_4$) addition at a single workability level. All the nomographs (Figure 26 through Figure 33) showed similar trends to nomographs for recycled aggregate published in the literature (Levy and Helene 2004).

The mix design nomographs developed in this study can help field engineers select the proper mix proportion parameters to meet specified concrete mix design criteria. Concrete with desirable compressive strengths and workability levels can be designed using LBP-contaminated recycled aggregates. While these concrete mixes might have high concentrations of total lead (up to 2.2% in this study), they would not have a toxicity characteristic for lead and would not be classified as hazardous wastes under RCRA.

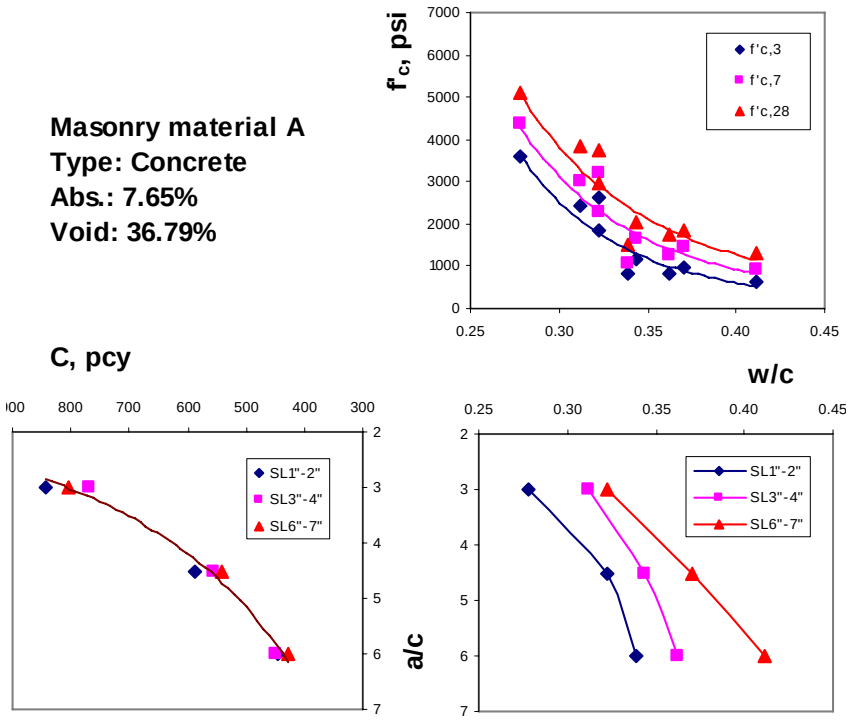


Figure 26. Mix design nomograph for concrete with masonry material A and portland cement

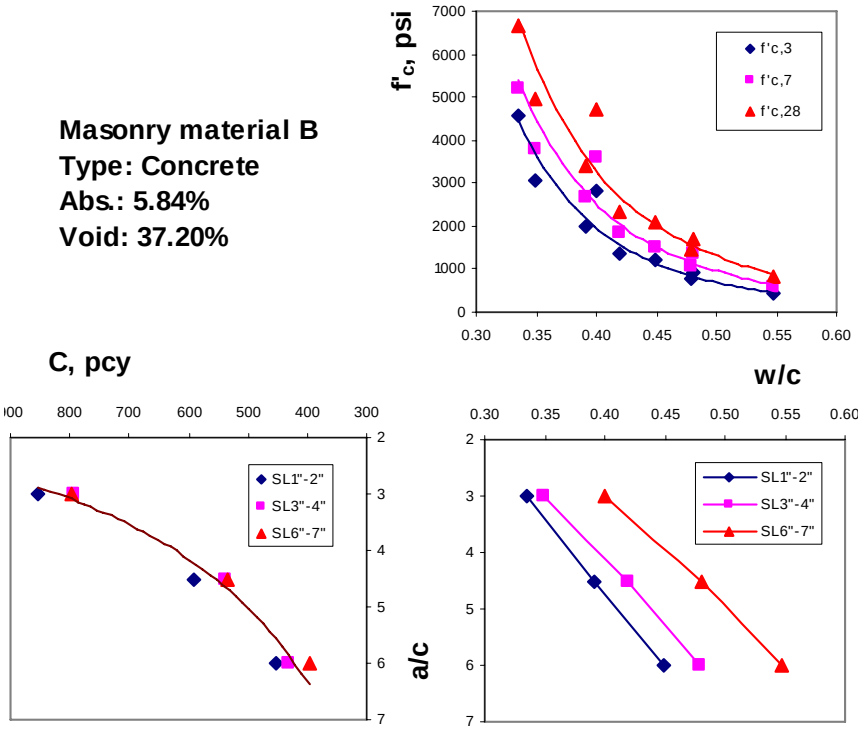


Figure 27. Mix design nomograph for concrete with masonry material B and portland cement

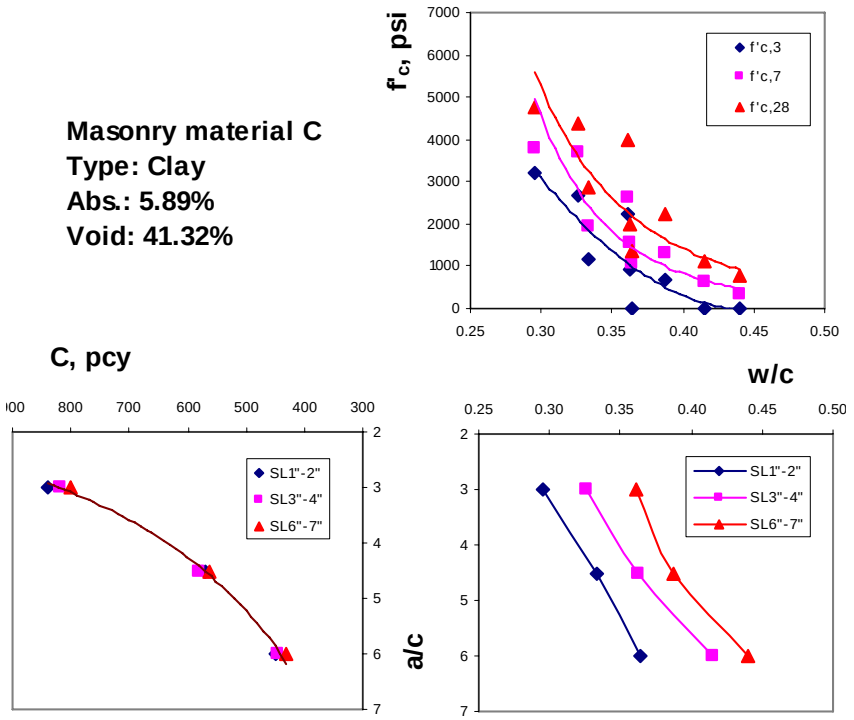


Figure 28. Mix design nomograph for concrete with masonry material C and portland cement (Note: Three mixes with no 3-day strength, was not able to be demolded at 3 days)

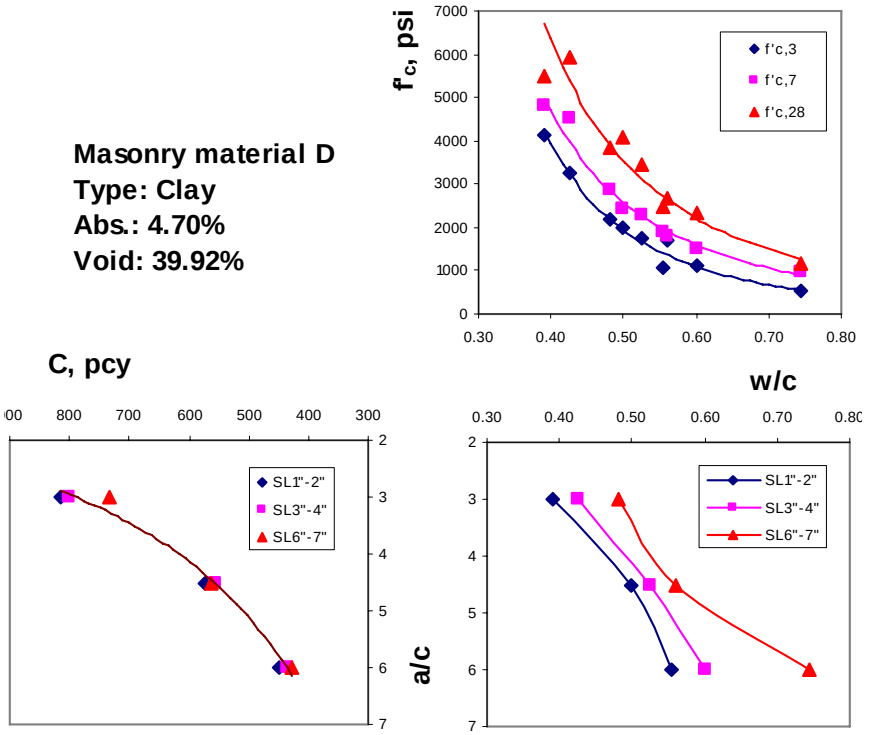


Figure 29. Mix design nomograph for concrete with masonry material D and portland cement

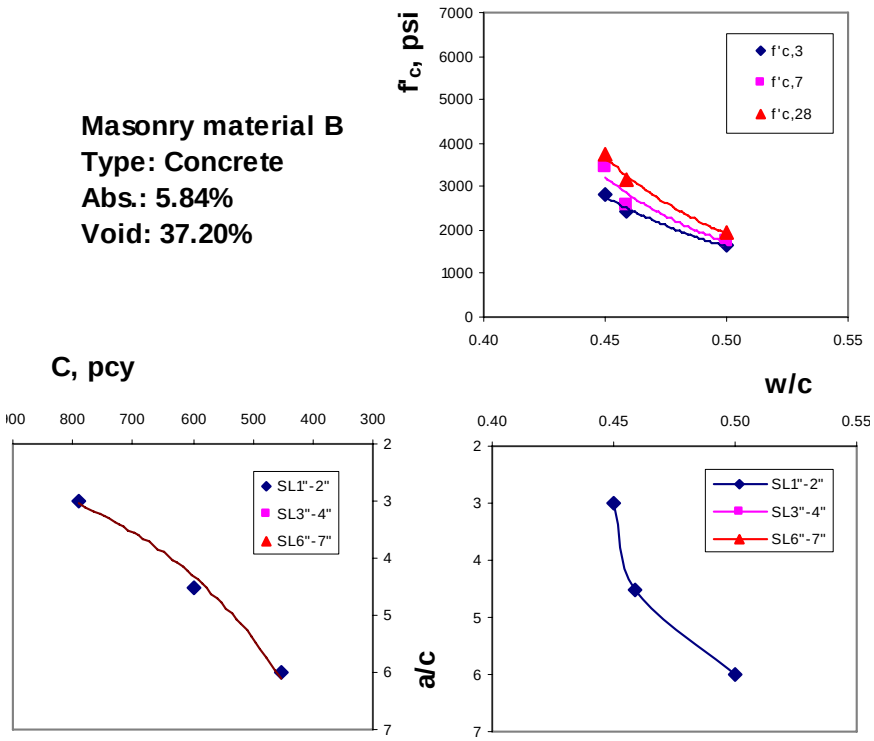


Figure 30. Mix design nomograph for concrete with masonry material B and CSA cement

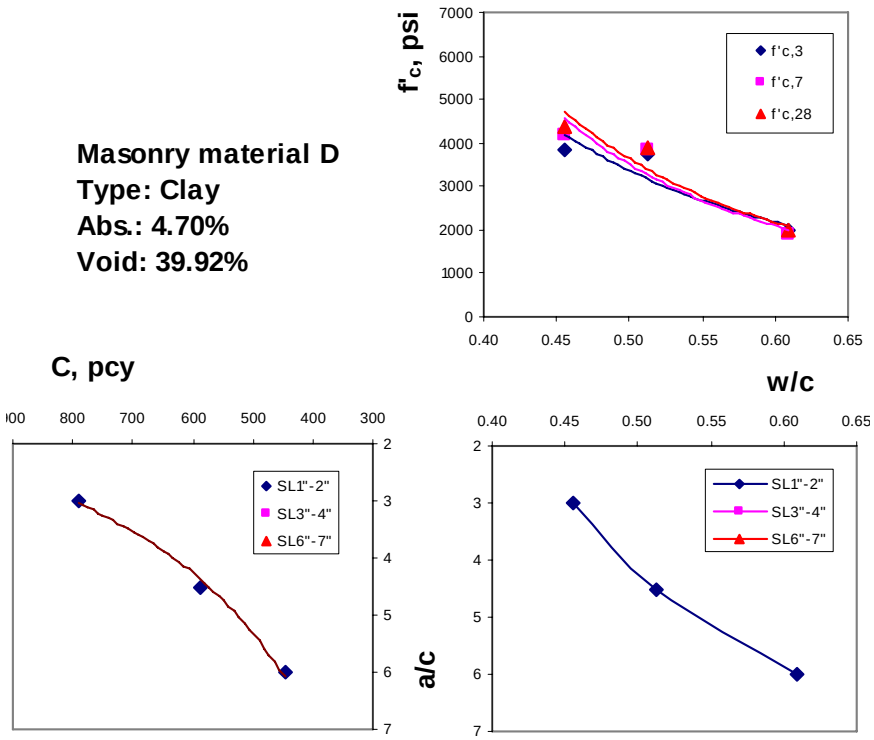


Figure 31. Mix design nomograph for concrete with masonry material D and CSA cement

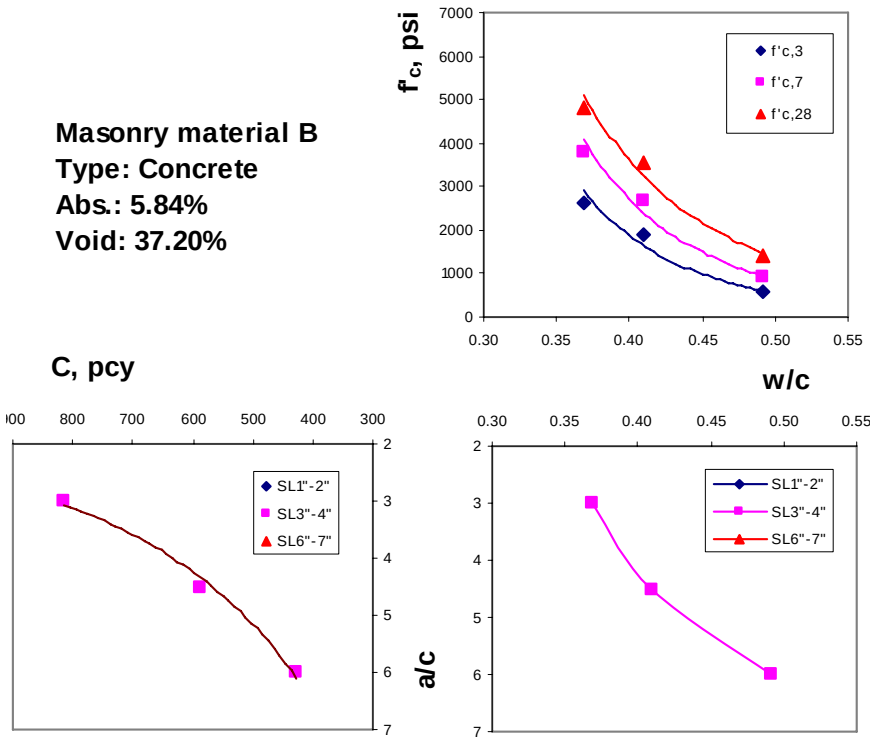


Figure 32. Mix design nomograph for concrete with masonry material B and portland cement with 5% Phosphate

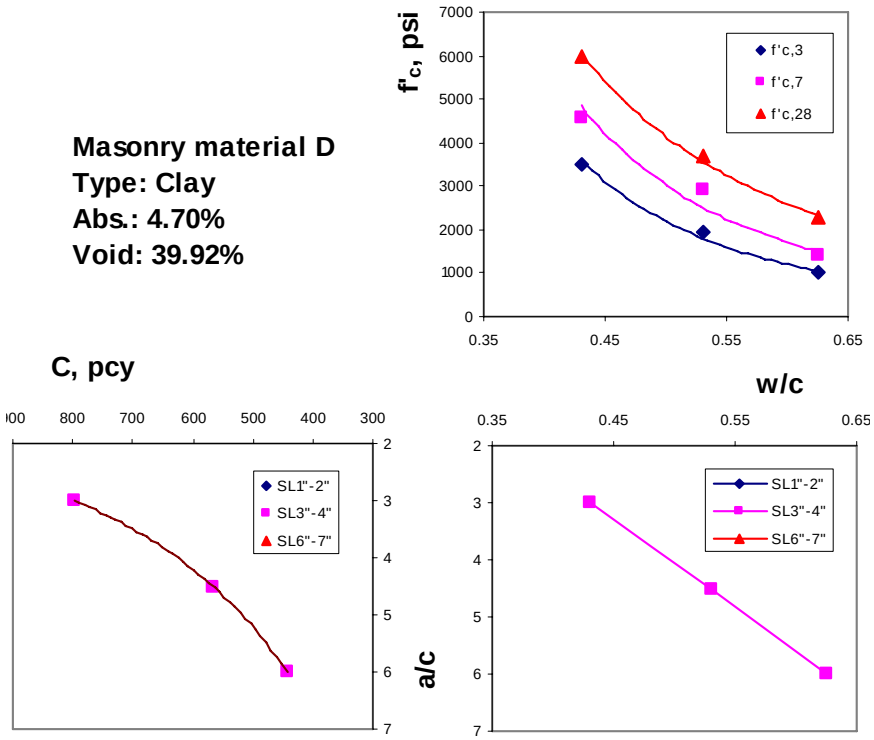


Figure 33. Mix design nomograph for concrete with masonry material D and portland cement with 5% Phosphate

5. DURABILITY OF RECYCLED AGGREGATE

Due to the limitation of time and funding, the study of concrete durability, such as shrinkage cracking, carbonation, alkali-silica reaction, and freezing-thawing resistance was not included in this study. The section below presents a summary of the literature on this subject. Research has indicated that compressive strength is usually reduced with increasing recycled aggregate content (Desai and Limbachiya 2006, Mandal et al. 2002), which was confirmed by the results from the present study. Flexural strength and modulus of elasticity indicated negligible differences with recycled aggregate in the mixes (Desai and Limbachiya 2006, Dhir et al. 2004, Sagoe-Crentsil et al. 2001) or a slight decrease (Mandal et al. 2002, Salem et al. 2003). It was also found that the ultimate shrinkage and creep strains generally increase with recycled aggregate content in the concrete, which is usually due to the lower aggregate modulus and increased proportions of cement content in concrete mixes (Desai and Limbachiya 2006, Mandal et al. 2002, Shayan and Xu 2003, Sagoe-Crentsil et al. 2001).

Mandal et al. (2002) and Desai and Limbachiya (2006) indicated that the durability of recycled-aggregate concrete is equal or slightly inferior to that of natural aggregate concrete due to the relatively high porosity and permeability of recycled aggregate. The reduction in durability was usually greater with increased recycled aggregate content. However, some researchers also showed that the durability of recycled aggregate can be improved by partially replacing cement with fly ash (Mandal et al. 2002) or by using a two-stage mixing approach to improve the pore structure and interfacial transition zone (Tam and Tam 2007).

Permeability and absorption was found to increase with recycled aggregate content (Desai and Limbachiya 2006, Mandal et al. 2002) and the increase is proportional when the recycled aggregate content is higher than 30% (Anon 2005). Other researchers stated that the increase in permeability and absorption with recycled aggregate is very small and can be neglected (Sagoe-Crentsil et al. 2001, Shayan and Xu 2003). Chloride penetration of concrete with recycled aggregate was found to be similar to that of concrete with natural aggregate (Shayan and Xu 2003, Anon 2005). The carbonation depth for concrete with recycled aggregate was found to be only slightly different from concrete with natural aggregate (Ridzuan et al. 2005, Shayan and Xu 2003, Sagoe-Crentsil et al. 2001), or reduced when recycled aggregate was higher than 30% (Desai and Limbachiya 2006; Dhir et al. 2004, Anon 2005). The freezing-thawing resistance of concrete mixtures with recycled aggregate was generally found to be similar to those with natural aggregate (Desai and Limbachiya 2006, Dhir et al. 2004). However, some research found lower freeze-thaw resistance due to the relatively high absorption of recycled aggregate (Salem et al. 2003). Abrasion resistance was usually slightly decreased when recycled aggregates were used (Desai and Limbachiya 2006; Dhir et al. 2004, Sagoe-Crentsil et al. 2001). Sulfate exposure resistance was found to be either slightly lower than (Mandal et al. 2002, Shayan and Xu 2003, Anon 2005) or comparable to those with natural aggregate (Ridzuan et al. 2005). Some research indicated that the resistance of concrete to sulfate exposure can decrease due to increased linear expansion of materials (Desai and Limbachiya 2006; Dhir et al. 2004). Research showed that each material should be tested individually regarding the alkali-silica reaction (Shayan and Xu 2003). However, minimal risk exists provided that the aggregate meets the specifications in BS 8500-2 Clause 5.2.6 (Anon 2005). Other research showed that oxygen permeability decreases

and chloride conductivity and water sorptivity increases with increasing proportions of recycled aggregate (Olorunsogo and Padayachee 2002).

6. COST ANALYSIS

6.1 Literature Survey

The investigators contacted the engineer who was in charge of the deconstruction of a 12-story student dormitory at Iowa State University in 2005. The investigators learned that the cost for a general deconstruction mainly includes soft elements (LBP if any, doors, windows, roofs, etc.) removal, structure demolition, and waste material recycling or disposal. If the waste masonry materials are recycled as aggregate, costs for sieving and grading the recycled aggregate are expected. If the waste masonry materials are disposed, costs for material deposal and new material purchase for new construction are expected.

Depending on the size of the recycling facility, entry into the aggregates recycling business requires a capital investment between $4.40 and $8.80 per metric ton of annual capacity (Wilburn and Goonan, 1998). Processing costs for recycling of aggregates range from $2.76 to $6.61 per metric ton, as well as other expenses, also depending on the size of the operation with larger operations distributing costs over more units of output. Prices for the various aggregate products made from recycled concrete range between $1.00 and $18.00 per metric ton and vary from region to region (USGS 1999). The highest prices are in the southern United States where there is a lack of good quality of nature aggregate. Considering the cost for old concrete removal and disposal, some states have estimated a saving up to 60% resulting from using recycled aggregate versus buying new aggregate (Wilburn and Goonan, 1998).

In addition to the economic benefits mentioned above, a significant amount of money can also be saved by using LBP-contaminated masonry materials in construction instead of costly removal and disposal of the LBP. As summarized in Section 1.1, the commonly used LBP removal methods are mechanical methods (sanding or blasting equipped with vacuum and HEPA filtration), heat methods (hot air guns operating at temperatures below 1100°F), chemical methods (on-site or off-site chemical stripping), encapsulation, and whole component replacement. Rough costs for each of these technologies are presented in Table 33.

Table 33. Comparative costs for LBP removal (adopted from ESTCP 1999)

Technology for LBP removal	Range $/ft^2	Average $/ft^2
Thermal Spray Vitrification (Projected)	3.50 - 9.50	5.00
Abrasive Blasting	5.00 - 18.00	8.00
Wet Abrasive Blasting	5.00 - 20.00	12.00
Vacuum Blasting	4.00 - 20.00	10.00
Water Blasting	4.00 - 20.00	13.00
Water Blasting with Abrasive Injection	4.00 - 19.00	9.00
Power Tool Cleaning To Bare Metal	5.00 - 15.00	7.00

A detailed economic analysis of the wet abrasive blasting process used for LBP removal is reported by Hock and Edwards-Daniels (2001). Three methods were included in their study: 1) wet abrasive blasting (Torbo®) method alone, 2) wet abrasive blasting (Torbo®) with an abrasive lead-stabilizer additive (Blastox®), and 3) wet abrasive blasting (Torbo®) on a surface prepared with a lead-stabilizer coating (PreTox® 2000 Fast Dry). Analysis showed that the cost for removing LBP from existing brick structures was approximately \$1.25/ft^2 at a removal rate of roughly 120 ft^2/hour. The disposal cost was about \$0.29/ft^2 (\$250/ton) for a hazardous waste, and only 0.04/ft^2 (\$35/ton) for a non-hazardous material. The whole LBP removal process is not only costly but also time consuming.

Another economic analysis study was performed by ESTCP (1999) for the Thermal Spray Vitrification (TSV) process used to remove LBP from two bridges and two aircraft hangars. The projected cost range for the TSV process was from \$3.50 to \$9.50/ft^2, with a typical average cost of approximately \$5.00/ft^2, including a \$0.10/ft^2 to \$0.20/ft^2 cost for hazardous waste disposal and a \$0.05/ft^2 to \$0.025/ft^2 cost for non-hazardous waste disposal. The detailed cost analysis from this study can be found in Appendix C (Table 43 and Table 44).

6.2 Disposal-Avoidance Savings

To further understand the cost savings from the use of LBP-contaminated clay brick or concrete block masonry as recycled aggregate, rather than disposal of them as waste, an economic analysis of deconstruction of three differing sizes of hypothetical LBP-contaminated masonry buildings is presented below:

It was assumed that the three hypothetical buildings had a floor area of 3,000, 18,000, and 96,000 ft^2 and a LBP-contaminated interior wall surface of 13,000, 33,000, and 104,000 ft^2, respectively (Table 34). These hypothetical buildings may not necessarily represent common architectural designs but, rather, to be a workable means for comparing possible disposal costs. Three different disposal scenarios were considered in this comparison analysis, and they were:

(I) Disposal in a construction waste landfill;
(II) Disposal in a secure (hazardous waste) landfill; and
(III) LBP removal prior to disposal in a construction waste landfill.

The cost factors used to compute the savings for the disposal scenarios described above are presented in

Table 35.

Table 34. Hypothetical buildings

			Building A	Building B	Building C
a	Story of building		4	3	2
b	Story high, ft		10	10	10
c	Building width, ft		120	60	30
d	Building length, ft		200	100	50
e	Building floor area, ft^2 (e=a×c×d)		96,000	18,000	3,000
f	Internal wall length, ft/story		1,000	400	250
g	Internal wall thickness, in	Concrete block	8	8	8
		Clay brick	6	6	6
h	Internal wall total area, ft^2 (h=a×b×f)		40,000	12,000	5,000
i	Internal wall total volume, ft^3 (i=h×g/12)	Concrete block	26,667	8,000	3,333
		Clay brick	20,000	6,000	2,500
j	External wall length, ft/storey		600	300	150
k	External wall thickness, in		12	12	12
l	External wall total area, ft^2 (l=a×b×j)		24,000	9,000	3,000
m	External wall total volume, ft^3 (m=l×k/12)		24,000	9,000	3,000
n	Internal/External wall unit weight, pcf	Concrete block	115	115	115
		Clay brick	130	130	130
o	Internal wall total weight, ton (o=i×n/2000)	Concrete block	1,533	460	192
		Clay brick	1,300	390	163
p	External wall total weight, ton (p=m×n/2000)	Concrete block	1,380	518	173
		Clay brick	1,560	585	195
q	Total LBP-contaminated interior wall surface, ft^2 (q=2h+l)		104,000	33,000	13,000
r	Total LBP-contaminated masonry, ton (r=o+p)	Concrete block	2,913	978	364
		Clay brick	2,860	975	358

To simplify the cost analysis, cost components such as labor, equipment, and transportation that are common to all scenarios were not included. The waste disposal avoidance savings for disposal Scenarios I, II, and III are presented in Tables 35, 36, 37, respectively. Recycling results in the largest savings in jurisdictions that have the strictest regulatory environment such as California, where LBP-contaminated deconstruction waste is considered hazardous waste that must be disposed in a secure landfill. The cost analysis presented here indicates that recycling masonry as aggregate could result in savings in the range of \$7.75 to \$31.58 per ft^2 of deconstructed building (Scenario II) (Table 36) in such jurisdictions. The cost analysis further indicated that removal of LBP and disposal in a non-secure landfill (Scenario III) (Table 37) was not cost effective relative to Scenario II (disposal in a secure landfill). Disposal-avoidance savings are about half an order of magnitude less (\$1.35 to \$5.48) in jurisdictions such as Iowa, where LBP-contaminated waste is not considered hazardous waste and is disposed in construction waste landfills (Scenario I) (Table 36).

Table 35. Cost savings components

	Cost analysis parameters*		Building A	Building B	Building C
s	Cost for LBP removal, $/ft^2		9.00	9.00	9.00
t	Non-hazardous disposal cost, $/ton		35	35	35
u	Hazardous waste disposal cost, $/ton		250	250	250
v	Aggregate for concrete mix, $/ton		10.15	10.15	10.15
w	Total cost for LBP removal, $ (w=s×q)		936,000	297,000	117,000
x	Total non-hazardous waste disposal cost, $ (x=t×r)	Concrete block	101,967	34,213	12,746
		Clay brick	100,100	34,125	12,513
y	Total hazardous waste disposal cost, $ (y=u×r)	Concrete block	728,333	244,375	91,042
		Clay brick	715,000	243,750	89,375
z	Equivalent amount of natural aggregate, $ (z=v×r)	Concrete block	29,570	9,922	3,696
		Clay brick	29,029	9,896	3,629

* Includes components imported from Table 34. Cost factors may vary with different time or location of project.

Table 36. Cost savings due to recycling: Scenario I, construction waste landfill avoidance

	Cost/saving*		Building A	Building B	Building C
α–I	Disposal cost, $ (α–I=x)	Concrete block	101,967	34,213	12,746
		Clay brick	100,100	34,125	12,513
β–I	Savings from avoided disposal, $ (β–I=x+z)	Concrete block	131,537	44,134	16,442
		Clay brick	129,129	44,021	16,141
χ–I	Unit savings from avoided disposal, $/ft^2 (χ–I=(x+z)/e)	Concrete block	1.37	2.45	5.48
		Clay brick	1.35	2.45	5.38

* Includes components imported from Table 34 and

Table 35.

Table 37. Cost savings due to recycling: Scenario II, secure landfill avoidance

	Cost/saving*		Building A	Building B	Building C
α–II	Disposal cost, $ (α–II=y)	Concrete block	728,333	244,375	91,042
		Clay brick	715,000	243,750	89,375
β–II	Savings from avoided disposal, $ (β–II=y+z)	Concrete block	757,904	254,297	94,738
		Clay brick	744,029	253,646	93,004
χ–II	Unit savings from avoided disposal, $/ft^2 (χ–II=(y+z)/e)	Concrete block	7.89	14.13	31.58
		Clay brick	7.75	14.09	31.00

* Includes components imported from Table 34 and

Table 35.

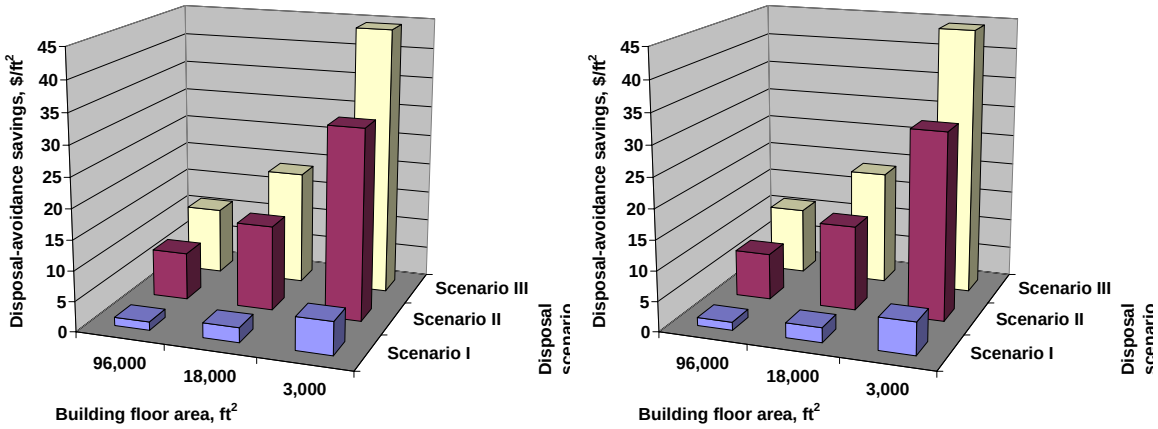
Table 38. Cost savings due to recycling: Scenario III, construction waste landfill and LBP removal avoidance

	Cost/saving*		Building A	Building B	Building C
α–III	Disposal & LBP removal cost, $ (α–III=x+w)	Concrete block	1,037,967	331,213	129,746
		Clay brick	1,036,100	331,125	129,513
β–III	Savings from avoided disposal, $ (β–III=x+w+z)	Concrete block	1,067,537	341,134	133,442
		Clay brick	1,065,129	341,021	133,141
χ–III	Unit savings from avoided disposal, $/ft^2 (χ–III=(x+w+z)/e)	Concrete block	11.12	18.95	44.48
		Clay brick	11.10	18.95	44.38

* Includes components imported from Table 34 and

Table 35.

For all disposal scenarios described above, the unit cost savings resulting from recycling are larger for smaller buildings and slightly larger for concrete block masonry than for clay brick masonry (Figure 34). The bulk of the savings are landfill avoidance savings. Savings due to avoiding purchasing natural aggregate area are a minor portion of the total savings.



(a) Concrete block masonry **(b) Clay brick masonry**

Figure 34. Disposal-avoidance savings

It is noted that LBP-contaminated masonry meets the criteria defined in the California Code of Regulations (CCR) for a recyclable material (California 2007). This means that such a hazardous waste is capable of being recycled (CCR § 66260.10) if it can be considered either:

(1) A spent material, which "is any material that has been used and as a result of contamination can no longer serve the purpose for which it was produced without processing"; or
(2) "A material that is contaminated to such an extent that it can no longer be used for the purpose for which it was originally purchased or manufactured";
(3) Or both of the above.

Special requirements for recyclable materials are given in the 22 CCR § 66261.6.

LBP-contaminated masonry meets the criteria given in 22 CCR § 66261.6(a) (6) for exemption from regulation under California standards and is specifically regulated under the U.S. Code of Federal Regulations (CFR) (GPO Access 2007). The recycling of LBP-contaminated masonry would be subject to regulation under the following parts of 40 CFR:

§ 262 Standards for generators of hazardous waste
§ 263 Standards for transporters of hazardous waste
§ 264 Standards for storage, treatment, and disposal of hazardous waste
§§ 124 and 270 Hazardous waste permits

Because it is likely that LBP-contaminated masonry would be stored for some time before reuse as recycled aggregate, the requirements for waste piles (40 CFR § 264 Subpart L – Waste Piles) are worth noting here. In general, Subpart L regulates waste piles in a manner that prevents the release of contamination to the environment by surface runoff, leaching into groundwater, or wind dispersion. Exemption from the detailed regulations for open waste piles is provided if the waste pile is inside or under a structure that accomplishes the same environmental protections (§ 264.250(c)).

The investigators believe that use of deconstructed LBP-contaminated masonry materials as recycled aggregate in concrete, can significantly reduce the deconstruction cost. Cost savings can result from eliminating LBP removal and waste material deposal, avoiding use of secure landfills, avoiding the time and equipment required for sieving and re-grading recycled aggregate, and reducing natural aggregate consumption.

7. SUMMARY AND CONCLUSIONS

A variety of concrete mixes were made with four aggregates recycled from different lead-contaminated masonry materials, three types of cements, three different aggregate-to-cement ratios, and water-to-cement ratios ranging from 0.28 to 0.74. The physical properties and lead leachability of the recycled aggregates were characterized. The concrete workability, compressive strength, and lead sequestration were evaluated. Eight mix design nomographs were developed. A cost analysis was also conducted for three hypothetical buildings under three different disposal scenarios.

The following conclusions can be made based on the results of the study:

1. *Characteristics of the Recycled, Lead-contaminated Aggregate* – The original concrete block and clay brick masonry had compressive strengths of approximately 3,000–4,700 psi and 10,700–13,700 psi, respectively. Compared with conventional concrete aggregates, the aggregates recycled from both concrete blocks and clay bricks are generally coarser and had lower specific gravity, higher absorption, and a higher volume of voids between the aggregate particles. Due to the low acid neutralizing capacity, as suggested by the pH values of the raw materials, the aggregates recycled from LBP-clay brick masonry had the toxicity characteristic for lead. These aggregates, recycled from LBP-clay brick masonry, also had a significant amount of flat particles.
2. *Lead Sequestering in Concrete* - Test results showed that most concrete samples studied had TCLP-Pb concentrations less than 5mg/L and, therefore, would not be considered as hazardous wastes under RCRA, although a few did exceed the RCRA limit. Lead in the LBP-contaminated, recycled aggregate was sequestered in concrete due to the high alkalinity of portland cement. Concrete samples made with LBP-contaminated clay brick (masonry D) with a high aggregate/cement ratio (a/c or m = 6, rather than commonly used a/c or m = 4) had the toxicity characteristic for leads. No clear relationship was observed between the TCLP and total lead test values. The total lead measured in concrete clearly increased with the amount and water absorption of the aggregate in the concrete.
3. *Concrete Mix Design* - Well-designed and manufactured concrete made with recycled, lead-contaminated aggregate can meet workability and strength requirements for concrete constructions and can abate the lead hazard in recycled aggregates. The mix design nomographs developed in the present study can be easily used by field engineers to ensure the proper selection of mixture proportions. The method for mix design nomograph development can be easily adapted for different aggregates recycled from different field deconstruction projects.
4. *Concrete Properties* - Desirable workability of concrete mixtures, with slump ranging from 1 to 7 inches, can be achieved with the recycled aggregates through proper mixture proportioning such as selecting appropriate w/c and a/c. (Note: Use of a water reducing agent was not included in the present study.) The 3-day compressive strengths of the concrete made with various recycled concrete materials and mixture proportions ranged from 417 psi to 4,891 psi; 7-day compressive strengths ranged from 358 psi to 5,188 psi; and 28-day compressive strengths ranged from 782 psi to 6,666 psi. Concrete with such workability range and 28-day compressive strength higher than 3,000 psi can be used satisfactorily for a variety of constructions, including roadways, parking lots, and foundations.
5. *Effect of Cement and Additives* - Use of CSA cement significantly increased concrete strength at early ages (3 and 7 days) but had a little effect on the 28-day compressive strength. The CSA cement was less alkaline than portland cement and the concrete made with CSA cement had lower pH values than the corresponding concrete made with portland cement, thus being less effective for sequestering lead in the concrete. For one mixture proportion studied, the CSA concrete had the toxicity characteristic for lead, whereas the equivalent portland cement concrete did not. Theoretically, phosphate could react with lead to form hydroxypyromorphite, thus resulting in sequestration of lead. However, such a reaction did not occur in the present study and the addition of 5%

phosphate had no significant effect on apparent total lead content, lead leachability, or compressive strength.

6. *Cost Analysis* - The cost analysis for three hypothetical buildings and three different disposal scenarios indicated that the savings from using the LBP-contaminated masonry materials as recycled aggregate in concrete could range approximately from $\$8/ft^2$ to $\$45/ft^2$, depending on the size of the deconstruction project and the applicable environmental protection regulations. Cost savings may result from eliminating LBP removal and waste material disposal, minimizing use of secure landfills, limiting the time and equipment required for sieving and re-grading recycled aggregate, and reducing natural aggregate consumption for concrete construction.

8. FUTURE WORK

The investigators believe that the following issues are critical for implementation of the present research and they should be addressed in the future study:

1. The present research results have shown that some recycled aggregates had less desirable gradation and much higher voids between the aggregate particles than conventional concrete aggregate. Crushed clay brick had a large portion of flat particles. These deficiencies of aggregates significantly influenced concrete workability, strength, and/or cost. One way to overcome this problem is to sieve and recombine the recycled aggregate, which is generally costly and time consuming. Another effective way to conquer the problem and to improve concrete performance is to use a combination of natural aggregate and recycled masonry materials in concrete. Further study is necessary to better design concrete with a combination of natural and recycled aggregates.
2. The present research focused on aggregate characterization, concrete mix design for workability and strength, and lead sequestration. According to the literature, concrete made with recycled aggregate often has a potential durability problem. Properties such as drying shrinkage, permeability, and freezing-thawing resistance should be investigated for concrete made with LBP-contaminated masonry materials. The effects of supplemental cementitious materials and chemical admixtures on the concrete properties should also be studied.
3. Due to the limited time available for this study, only six mixes were prepared using calcium hydrogen phosphate additions at levels of 5% of the weight of cement. A systematic study of the levels of the phosphate addition that might result in conversion of basic lead carbonate to pyromorphite could result in discovery of a means to sequester lead so strongly that the resulting concrete would not be considered hazardous waste in California. Commercial phosphate cement should be included in future studies.
4. During the early stage of the present project, the investigators contacted the U.S. Army Corps of Engineers and tried to obtain LBP-contaminated masonry materials from field deconstruction projects. However, no such materials could be located. In the late stages of this project Scott Air Force Base (IL) contacted the investigators regarding possible collaboration in a demolition project involving LBP-contaminated masonry materials. Unfortunately, the demolition schedule was not sufficiently flexible to accommodate a

satisfactory field trial. The investigators believe that the concept of the present study has been proven in the laboratory. A field trial involving an application using portland cement concrete made with LBP-contaminated, recycled aggregate from a deconstruction project is now the appropriate next step for transferring this technology to routine use.

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APPENDIX

Appendix A: Quality Assurance Data for Total Lead and pH

Total Lead

To evaluate the reliability of the total lead test, a 1% total-lead fortified matrix blank was prepared gravimetrically by first combining basic lead carbonate with powdered, unpainted concrete block A to prepare a 10% lead standard, then combining the 10% standard with powdered, unpainted concrete block A to prepare the 1% (0.9996%) lead standard. Materials were mixed for five minutes using a Spex Mixer/Mill (Spex Industries, Metuchen, NJ) with a plastic ball for a mixing pestle.

Table 39. 1% lead matrix check standard

Date	g Pb/Kg	% recovery
Theoretical	9.996	100.00
9/11/2007	10.920	109.24%
9/17/07 Rep1	10.406	104.10%
9/17/07 Rep2	10.296	103.00%
9/17/07 Rep3	11.225	112.29%
10/4/2007	10.974	109.78%
10/26/07 Rep 1	10.228	102.32%
10/26/07 Rep 2	10.390	103.94%
10/30/2007	10.181	101.85%
10/31/2007	10.137	101.41%
11/27/2007	10.042	100.46%
mean	10.480	104.84%
standard deviation	0.4086	4.09%
rel. std. dev.	3.90%	3.90%

A total of 10 repetitions in six different analytical batches were performed on this 1% total-lead fortified matrix blank. As shown in Table 39, this test method quantitatively recovered basic-lead-carbonate lead with good reproducibility. The ASTM C114 digestion was a satisfactory alternative to the EPA SW 846 digestion.

To further evaluate the reliability of the total lead test on concrete samples, paired duplicates (duplicate analyses of single, shatterboxed 1/16 splits of whole lab samples) were selected and run with eight analytical batches. As shown in Table 40, the average absolute difference of the total lead of these seven batches was 0.194 g/Kg, which was less than 3% of the mean value. These results indicated that this total lead test procedure was satisfactory for the needs of this study.

Table 40. Total lead duplicates

Sample ID	g Pb/Kg Rep 1	g Pb/Kg Rep 2	Abs Diff, g/Kg	Diff % of mean
0913-4 28d	5.140	4.770	0.370	7.47%
0912-1 28d	10.591	10.513	0.078	0.74%
0906-4 28d	9.367	8.967	0.400	4.36%
0912-4 7d	5.075	5.153	0.078	1.53%
0515-3 28d	4.467	4.368	0.099	2.24%
0508-2 28d	21.279	21.519	0.240	1.12%
0503-3 28d	7.446	7.537	0.091	1.21%
0827-3	6.276	5.619	0.657	11.05%
mean			0.252	3.71%
UWL			0.407	6.00%
UCL			0.484	7.15%

pH

Paired duplicate pH tests (duplicate analyses of single, shatterboxed 1/16 splits of whole lab samples) were performed on five concrete mixes in order to evaluate the reproducibility of the measurements. As shown in Table 40, the average absolute difference of the duplicate pH measurements in five analytical batches was 0.08, which was less than 1% the mean value. These results indicated that the pH test measurements were satisfactory for the needs of this study.

Table 41. pH duplicates

Sample ID	pH Rep 1	pH Rep 2	Abs Diff, pH	Diff % of mean
0905-2	11.32	11.36	0.04	0.4%
0910-3	11.63	11.65	0.02	0.2%
0912-4	11.64	11.73	0.09	0.8%
0913-1	11.27	11.39	0.12	1.1%
0913-3	10.25	10.14	0.11	1.1%
mean			0.08	0.7%
UWL			0.13	1.1%
UCL			0.15	1.4%

Appendix B: Total Lead Change over Different Ages (Concrete with Portland Cement with 5% Phosphate)

Based on calculations, the amount of phosphorous added (cement: $CaHPO_4$ = 1:0.05) was 65% to 32% of the 5:3 stoichiometric ratio of Pb:P in hydroxypyromorphite, $Pb_5(PO_4)_3OH$ (for one set of mixes, that is). Hence, complete conversion of basic lead carbonate to hydroxypyromorphite was not expected, should such a reaction occur at all. The concentrations of total lead in the original mix (by calculation) and the 7-day and 28-day specimens (by measurement) were compared (Table 42). There was no obvious trend in the total lead concentrations in the selected specimens upon aging from 7 to 28 days. Statistical analysis of matched pairs of the 7-day and 28-day total lead test results showed a very high correlation value (0.97) and a p-value of 0.92, which indicated that there was no significant change of total lead content in the concrete mixes within the 28-day period.

Table 42. Total lead change in concrete made with portland cement with phosphate over different ages

Sample ID	7 day Total Pb, g/Kg	28 day Total Pb, g/Kg
B-III-m3-SL3"	10.78	10.55
B-III-m4.5-SL3.25"	9.19	9.74
B-III-m6-SL4"	10.53	10.86
D-III-m3-SL3.75"	5.08	4.84
D-III-m4.5-SL3.5"	4.85	6.36
D-III-m6-SL3.5"	5.30	6.17

Appendix C: Cost Analysis for LBP Removal Process

Table 43. Cost analysis for removal of LBP from brick substrate (adopted from Hock and Edwards-Daniels 2001)

Cost Factors	Torbo® without Stabilization Technology	Torbo® with Stabilization Technology	
		Blastox® (30% Blend)	PreTox 2000 (40-mil wet thickness)
Capital Facilities[a]	$7.14/site hour	$7.14/site hour	$7.14/site hour
Equipment Rental[b]	$30.00/site hour	$30.00/site hour	$30.00/site hour
Labor[c]	$46.00/site hour	$46.00/site hour	$46.00/site hour
Consumables[d]	$16.28/site hour	$16.38/site hour	$16.75/site hour
Environmental Testing[e]	$49.00/site hour	$49.00/site hour	$49.00/site hour
Subtotal	$148.42/site hour	$148.52/site hour	$148.93/site hour
Removal Rate	119 ft^2/hour	119 ft^2/hour	121 ft^2/hour
Removal Cost	$1.25/$ft^2$	$1.25/$ft^2$	$1.23/$ft^2$
Disposal Cost[f]	$0.29/$ft^2$ ($250/ton)	$0.29/$ft^2$ ($250/ton)	$0.29/$ft^2$ ($250/ton)
Total Cost	$1.54/sq ft	$1.54/sq ft	$1.52/sq ft
Non-Hazardous Disposal	N/A	$0.04/$ft^2$ ($35/ton)	$0.04/$ft^2$ ($35/ton)
Non-Hazardous Total Cost	N/A	$1.29/$ft^2$	$1.27/$ft^2$

[a] Capital rates of recovery are from actual contractor costs and DEH government cost estimate detail sheets. Costs for investment are amortized over 7 years for depreciation, and assume a 2000 hour site year.

[b] Includes construction fork lifts for handling of materials, man lifts for site access, and PreTox 2000 spray application equipment (as applicable).

[c] Site personnel labor cost. Labor is quoted from actual contractor costs or derived from government estimate sheets.

[d] Consumables are based on items used up in the demonstration. Blastox®: 46 (100-lb) bags of abrasive (mineral sand and 15% Blastox® additive) were used resulting in 2.33 lb of abrasive mixture per ft^2 of surface area blasted. PreTox 2000: 46 (100-lb) bags of abrasive (mineral sand) were used to remove 40 mil (wet) thickness application of PreTox 2000 resulting in 2.56 lb of abrasive per ft^2 of surface area blasted. The application of 40 mil (wet) thickness on 1,1796 ft^2 required ten 5-gallon containers of PreTox 2000.

[e] Environmental testing includes air monitoring (11 personal and 34 site perimeter), TCLP (12 abrasive media debris), and XRF ($50/site hour).

[f] Actual transportation and disposal costs.

Table 44. Cost analysis for TSV process (for 1,000 ft^2 application) (adopted from ESTCP 1999)

CAPITAL COSTS	
Thermal Spray Gun	$550
Powder Feeder	$1,550
Flow Meters, Air Filter	$300
Hoses and Miscellaneous Fittings	$200
EQUIPMENT TOTAL	$2,600

OPERATIONAL COSTS (for 1,000 ft^2 application)								
PAINT REMOVAL PRODUCTION RATE (mils-ft^2/hr)	Rate ($)		Hours		Cost			
	Bridge	Hangar	Bridge	Hangar	Bridge	Bridge	Hangar	Hangar
					300[1]	600[2]	700[3]	1,000[4]
ACTIVITY								
STARTUP								
Foreman	$27.43	$25	8	8	$219	$219	$200	$200
Laborer	$24.62	$21	8	8	$197	$197	$168	$168
Collection of Glass					$100	$100	$100	$100
Activity Subtotal					$516	$516	$468	$468
TSV PROCESS								
Labor								
Foreman	$27.43	$25	40[2]	39[3]		$1,097	$975	
	$27.43	$25	80[1]	27[4]	$2,194			$675
Painter	$24.62	$23	34[2]	0[3]		$837	$0	
	$24.62	$23	68[1]	0[4]	$1,674			$0
Laborer	$22.73	$21	8[2]	8[3]		$182	$168	
	$22.73	$21	32[1]	6[4]	$727			$126
Materials								
Glass Powder					$1,500	$500	$500	$500
Utilities					$400	$200	$200	$200
Miscellaneous					$100	$100	$100	$100
Equipment Depreciation (10 yr., 60%)					$10	$10	$10	$10
Consumables					$350	$350	$175	$175
Monitoring					$400	$400	$250	$250
Waste Transportation					$100	$100	$125	$125
Non-Hazardous Waste Disposal					$50	$25	$0	$0
Hazardous Waste Disposal					$100	$100	$200	$200
Activity Subtotal					$7,605	$3,901	$2,703	$2,361
DEMOBILIZATION								
Foreman	$27.43	$25	8	8	$219	$219	$200	$200
Laborer	$22.73	$21	8	8	$182	$182	$168	$168
Activity Subtotal					$401	$401	$368	$368
SUB-TOTAL					$8,522	$4,818	$3,539	$3,197
OVERHEAD/PROFIT (10%)					$852	$482	$354	$320
TOTAL COST (1,000 ft^2)					$9,374	$5,300	$3,893	$3,517
COST/ft^2					$9.37	$5.30	$3.89	$3.52

NOTES:
1. Lower bound (extrapolated from actual demonstration production rate for bridge)
2. Based on actual demonstration production rate for bridge
3. Based on actual demonstration production rate for hangar door
4. Upper bound (extrapolated from actual demonstration production rate for hangar door)