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Final Scientific Report for the Period September 1, 2008-August 31, 2010

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Executive Summary

This report describes work conducted on the Building Materials Reclamation Program for the period of September 2008 to August 2010. The goals of the project included selecting materials from the local construction and demolition (C&D) waste stream and developing economically viable reprocessing, reuse or recycling schemes to divert them from landfill storage. Educational resources as well as conceptual designs and engineering feasibility demonstrations were provided for various aspects of the work.

The project was divided into two distinct phases: Research and Engineering Feasibility and Dissemination. In the Research Phase, a literature review was initiated and data collection commenced, an advisory panel was organized, and research was conducted to evaluate high volume C&D materials for nontraditional use; five materials were selected for more detailed investigations. In the Engineering Feasibility and Dissemination Phase, a conceptual study for a regional (Mecklenburg and surrounding counties) collection and sorting facility was performed, an engineering feasibility project to demonstrate the viability of recycling or reuse schemes was created, the literature review was extended and completed, and pedagogical materials were developed.

Over the two-year duration of the project, all of the tasks and subtasks outlined in the original project proposal have been completed. The Final Progress Report, which briefly describes actual project accomplishments versus the tasks/subtasks of the original project proposal, is included in Appendix A of this report.

This report describes the scientific/technical aspects (hypotheses, research/testing, and findings) of six subprojects that investigated five common C&D materials. Table 1 summarizes the six subprojects, including the C&D material studied and the graduate student and the faculty advisor on each subproject.

Table 1. The six subprojects of the Building Materials Reclamation Program

Subproject Subject	C&D Material	Graduate Student	Faculty Advisor
1) Ground gypsum: carbon sequestration, soil amendment (full-scale studies)	Gypsum wallboard	Fabien Besnard ¹	Dr. Helene Hilger
2) Ground gypsum: carbon sequestration, soil amendment (bench studies)	Gypsum wallboard	Rebecca Turner ²	Dr. Helene Hilger
3) Reclaimed structural steel beams	Structural steel	Madeleine Grimmer ²	Dr. Shenen Chen
4) Geopolymer concrete (GC)	Fly ash	Brett Tempest ¹	Dr. Janos Gergely
5) RAC w/ crushed brick aggregate	Brick masonry rubble	Tara Cavalline ¹	Dr. David Weggel
6) RAC w/ crushed concrete aggregate	Concrete rubble	Adam Alvey ²	Dr. David Weggel

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Table of Contents

Acknowledgement.....	2
Disclaimer.....	2
Executive Summary.....	3
Subprojects 1&2) Waste Gypsum Wallboard as a Soil Amendment and Carbon Sequestration (Full-Scale Studies (Outdoors) and Bench Studies (Indoors)).....	9
Overview of C&D Waste.....	9
Processed Construction and Demolition Waste Materials.....	10
Drywall.....	12
Gypsum Wallboard Problem.....	12
Gypsum Wallboard Collection.....	13
Waste Gypsum Wallboard Uses.....	13
References.....	16
Research Introduction: Subprojects 1&2.....	18
Germination Effects.....	18
Lettuce.....	19
Cucumber.....	20
Wheat.....	21
Canola.....	22
Soil Amendment for Biofuel Crop.....	24
Canola.....	24
Bench-scale.....	24
Field tests.....	27
Erosion Control Experiment.....	29
Carbon Sequestration.....	32
Artificial Root Exudate Experiments.....	33
Field Simulation.....	35
First Crop Cycle Evaluation.....	36
Discussion.....	38
Conclusion.....	40
References.....	41
Subproject 3) Reclaimed Structural Members: Investigations of Reused Structural Steel.....	42
Introduction and Literature Review.....	42
Strategies in Structural Steel Reclamation and Production.....	43
Literature Review: Studies on Reclaimed Steel Uses.....	46
Design for Deconstruction.....	48
Integrated Design Process.....	48
Experimental Studies.....	48
Demonstration Design: Multi-Span Bridge.....	55
References.....	58
Subproject 4) Investigations of Geopolymer Concrete.....	59
Background and Literature Review.....	59
Experimental Work.....	62

Development of Concrete Mixtures.....	62
Durability Testing.....	66
Flexural Tests.....	69
Mild Steel Reinforced Beams.....	70
Prestressed Concrete Beams.....	73
Conclusions and Recommendations for Further Study.....	75
References.....	76
Subproject 5) Recycled Aggregate Concrete with Crushed Recycled Brick Masonry Aggregate.....	77
Introduction and Literature Review.....	77
Brick Used as Aggregate in Cementitious Materials.....	77
Studies on Brick Aggregate Concrete.....	79
Recycled Brick Masonry Aggregate Concrete.....	81
Characterization of Whole Brick and Tile.....	85
Characterization of Crushed Brick Masonry Aggregate.....	86
Development of Concrete Mixture Designs and Testing.....	89
Future Work.....	93
References.....	95
Subproject 6) Recycled Aggregate Concrete with Crushed Recycled Concrete Aggregate.....	96
Background: Portland Cement Concrete with RCA.....	96
Portland Cement Concrete with RCA: Mix Design.....	97
Portland Cement Concrete with RCA: Compression Strength.....	98
Portland Cement Concrete with RCA: Tensile Strengths.....	99
Portland Cement Concrete with RCA: Flexural Behavior.....	101
Strength Testing of Recycled Concrete Aggregate.....	104
References.....	106
Appendix A.....	107

List of Figures

Figure 1. C&D waste in perspective.....	9
Figure 2. Composition of construction and demolition waste in the state of North Carolina in 1998.....	10
Figure 3. Petri dishes randomly distributed prior to the start of the experiment.....	19
Figure 4. Lettuce germination scores.....	20
Figure 5. Cucumber germination scores.....	21
Figure 6. Wheat germination scores.....	22
Figure 7. Canola germination scores.....	23
Figure 8. Canola seed germinated after spending 72 hours in a dark 25°C oven.....	23
Figure 9. Evaluation of the number of leaves per plant 16 days after seeding.....	25
Figure 10. Evaluation of the number of leaves per plant 25 days after seeding.....	26
Figure 11. Visual comparison of replicate control; and C-amended plants (600 kg sulfur/ha) at Day 28.....	26
Figure 12. Dry root mass of canola after 200 d in pots.....	27
Figure 13: Example of a plot on April 20.....	28
Figure 14. Mass of 1000 seeds.....	29
Figure 15. Mass of 15 roots.....	29
Figure 16. Grass experiment, May 20 th	30
Figure 17. Accumulated grass height.....	31
Figure 18. Accumulated biomass weight.....	31
Figure 19. Root Coverage.....	32
Figure 20. Artificial root exudates applied to gypsum-amended soil and incubated in test tubes for 7 weeks.....	34
Figure 21. Typical CaCO ₃ concentrations by depth in tube.....	35
Figure 22. Wheat stem length.....	37
Figure 23. Kernels per plant.....	37
Figure 24. Weight of 100 seeds.....	38
Figure 25. Virgin steel production phases.....	44
Figure 26. Recycled steel production phases.....	44
Figure 27. Mixed steel production phases.....	44
Figure 28. Component reuse phases.....	45
Figure 29. Whole building reuse.....	45
Figure 30. Full-scale flexural test set-up for Group A and B beams.....	50
Figure 31. Full-scale flexural test set-up for Group C beams.....	50
Figure 32. Coupon test: stress versus strain for Group A beams.....	51
Figure 33. Coupon test: stress versus strain for Group B beams.....	51
Figure 34. Coupon test: stress versus strain for Group C beams.....	52
Figure 35. Beam flexural tests: stress versus strain (Group A and B beams).....	53
Figure 36. Beam flexural tests: stress versus strain (Group C beams).....	53
Figure 37. Demonstration pedestrian bridge design: Group A and B beams.....	56
Figure 38. Demonstration pedestrian bridge design: Group C beams.....	57
Figure 39. Compressive strength development with aging and curing time.....	65
Figure 40. Creep specimen loading apparatus.....	67
Figure 41. GCC and PCC creep compared to the range of ultimate creep values for Portland cement concrete.....	68
Figure 42. Comparison of shrinkage in PCC-1, GCC-2 and GCC-R specimens.....	68
Figure 43. Adding materials to mixing truck.....	70
Figure 44. Placement and size of reinforcing steel in GCC-2-B2, PCC-1-B3, and GCC-R-B4.....	71

Figure 45. Beam loading and support geometry.....	71
Figure 46. Mild steel reinforced beam loaded in the test frame.....	72
Figure 47. Comparison of load vs. mid-span deflection for four beams tested.....	72
Figure 48. Reinforcing steel placement and beam cross section for prestressed beams.....	74
Figure 49. Prestressed beam test set-up.....	74
Figure 50. Load deflection curves for prestressed beams plotted together.....	75
Figure 51. Cafeteria at Idlewild Elementary School prior to demolition.....	82
Figure 52. Demolition of the brick masonry walls at Idlewild Elementary School.....	82
Figure 53. Partially-demolished brick masonry wall at Idlewild Elementary School.....	83
Figure 54. Demolished brick masonry aggregate from Idlewild Elementary School being loaded for transport to D. H. Griffin Co.'s crushing and grading operation.....	83
Figure 55. The crushing and grading operations of D. H. Griffin Co., located in Charlotte, North Carolina.....	84
Figure 56. Demolished brick masonry wall from Idlewild Elementary School awaiting crushing and grading at D. H. Griffin Co.....	84
Figure 57. After being crushed and graded, recycled brick masonry aggregate from Idlewild Elementary School walls comes off of the conveyors, where it was subsequently shoveled into barrels and transported to UNC Charlotte laboratories.....	85
Figure 58. Whole brick and clay tile after being subjected to ASTM C67 testing.....	86
Figure 59. Recycled brick masonry aggregate material from Idlewild Elementary School.....	89
Figure 60. SSRC-Compressive strength as a function of aggregate replacement percentage.....	99
Figure 61. CRC-Compressive strength as a function of aggregate replacement percentage.....	99
Figure 62. Splitting tensile and MOR specimens.....	100
Figure 63. Beam specimens (a) loading conditions, (b) rebar location and dimensions, (c) displacement measurement locations.....	102
Figure 64. Applied load versus midspan deflection (all beam specimens).....	103
Figure 65. Post-test photos of beams showing crack patterns.....	104
Figure 66. Apparatus for aggregate crush test.....	105
Figure 67. Aggregate crush test (a) test in progress (b) crushed aggregate specimen.....	106

List of Tables

Table 1. The six subprojects of the Building Materials Reclamation Program.....	3
Table 2. Bench-scale soil amendment doses.....	24
Table 3. Canola field planting doses of virgin ground conventional drywall.....	28
Table 4. Grass bench-scale test amendment doses.....	30
Table 5. Root exudate composition from literature and as prepared for ARE.....	33
Table 6. CaCO ₃ concentrations at different drywall doses and application rates.....	35
Table 7. Carbon sequestration treatments.....	36
Table 8. Beam specimens.....	48
Table 9. Steel beam properties: Groups A and B.....	49
Table 10. Steel beam properties: Group C.....	49
Table 11. Group A and Group B coupon test results.....	52
Table 12. Group C coupon test results.....	52
Table 13. Flexural test results for Group A and B beams.....	54
Table 14. Flexural test results for Group C beams.....	54
Table 15. Maximum load and shear resistance for Group A and B beams.....	54
Table 16. Maximum load and shear resistance for Group C beams.....	55
Table 17. Flexural test deflections for Group A and B beams.....	55
Table 18. Flexural test deflections for Group C beams.....	55
Table 19. Hypothetical pedestrian bridge design values (all beam groups).....	57
Table 20. Calculated design moment values for Group A and B beams.....	57
Table 21. Calculated design moment values for Group C beams.....	58
Table 22. Mixing proportions lb/yd ³ (kg/m ³).....	63
Table 23. Number of cylinders made for each aging and curing regimen.....	63
Table 24. Results of compression and tension tests.....	64
Table 25. Mixing proportions for GCC containing recycled aggregate, lb/yd ³ (kg/m ³).....	66
Table 26. Compressive strength results for GCC mixes containing recycled aggregate, psi (MPa).....	66
Table 27. Concrete details and compressive strength at time of testing.....	69
Table 28. Reinforcing steel schedule for GCC-2-B2, PCC-1-B3 and GCC-R-B4.....	70
Table 29. Ratio of observed to predicted cracking moment and ultimate moment.....	73
Table 30. Reinforcing steel schedule for prestressed beams, in (cm).....	73
Table 31. Computed ultimate moment values, kip-in (kN-m).....	75
Table 32. Characterization of whole brick and tile.....	85
Table 33. Test methods used for characterization of crushed brick masonry aggregate.....	87
Table 34. Results of characterization testing of recycled aggregates from Idlewild Elementary School demolition waste, shown with characteristics of a locally-manufactured lightweight aggregate and a local normal weight natural aggregate.....	87
Table 35. Results of ASTM C136 sieve analysis testing of recycled brick masonry aggregate and recycled concrete aggregate produced from Idlewild Elementary School demolition waste.....	88
Table 36. Composition of the recycled brick masonry aggregate produced from Idlewild Elementary School demolition waste.....	88
Table 37. Mixture development for brick masonry aggregate concrete.....	90
Table 38. Test methods used to determine fresh and hardened properties of recycled brick masonry aggregate concrete.....	92
Table 39. Hardened properties of recycled brick masonry aggregate concrete.....	93
Table 40. Mix design.....	98
Table 41. Strength test results.....	101

Subprojects 1&2) Waste Gypsum Wallboard as a Soil Amendment and Carbon Sequestration (Full-Scale Studies (Outdoors) and Bench Studies (Indoors)) (Graduate students: Fabien Besnard and Rebecca Turner; Advisor: Dr. Helene Hilger)

Overview of C&D Waste

In 2003 approximately 170 million tons of waste were generated in the United States (US EPA, 2009). Waste analyses show that close to one third of the total waste stream is construction and demolition (C&D) waste (Figure 1). This is typical of most industrialized nations, where as much as 50% of the waste stream is from C&D (Schachmayer et al. 2001).

Figure 1. C&D waste in perspective; a diagram depicting the various classifications of construction and demolition waste as shown in the United States Environmental Protection Agency (1998).

C&D wastes are wastes produced during construction, demolition, and renovation of roads and structures like buildings and bridges. Each state defines the wastes included among the C&D waste stream. In North Carolina it is described as “solid waste resulting from construction, remodeling, repair, or demolition operations on pavement, buildings, or other structures, not including inert debris, land-clearing debris, or yard debris” (US EPA 1998).

Curro (1991) describes the nature of C&D wastes according to their sources and the means by which they are obtained. The categories include: (i) interior construction waste; (ii) interior demolition waste; (iii) exterior construction waste; and (iv) exterior demolition waste. Interior construction wastes are by-products of indoor construction and would include cardboard, wood crates, wood and metal stud trimmings, wire scraps, pipe scraps, gypsum wallboard leftovers, pieces of carpet, tiles, temporary construction materials, dust, and other general trash.

Interior demolition waste would be generated during interior renovations or removal operations. This waste stream would include materials such as gypsum wallboard, wood studs, steel studs, doors, lighting fixtures, wires, plumbing fixtures, pipes, ceiling tiles, furniture, carpeting, dust, and general trash. While interior demolition waste is generated more frequently, it is not the largest source of wastes among the sub-categories (Curro 1991).

Exterior construction waste includes: pallets, damaged or cut concrete blocks, damaged or cut bricks, soil pipes, conduit pipes, roofing materials, siding materials, soil, landscaping materials, and temporary construction materials. By contrast, exterior demolition waste is generated during the dismantling, deconstruction, or demolition of buildings or other structures and includes large pieces of concrete,

masonry walls, siding materials, roofing materials, wooden frame walls, windows, doors, soil pipe, conduit pipes, and pavement sections. Exterior demolition waste most likely generates the largest quantities of weight compared to all the other C&D waste classifications.

Taken together the various sources of C&D waste yield a waste stream that is largely comprised of concrete, asphalt, wood, metal, cardboard, plastic, soil and drywall; see Figure 2 (Townsend et al. 2001). Although efforts to recover, reuse, or reprocess C&D wastes have been on-going, interest in capturing rather than landfilling C&D wastes has heightened in recent years. The drivers for such activity are resource depletion predictions and available landfill capacity.

Figure 2. Composition of construction and demolition waste in the state of North Carolina in 1998 (NCDENR 1998).

Processed Construction and Demolition Waste Materials

Materials that are currently processed and reused include: wood, cardboard and paper, concrete, asphalt, bricks, drywall, plastic, low grade soil, and metals (steel and non ferrous). Wood is most commonly ground into chips and used for boiler fuel, landscaping bark (where they may be dyed), or soil amendment (Curro 1991). Contaminants in wood chips can include, paint, metals, and plastics, which can be tolerated in most modern wood boilers but are problematic when the wood is used for soil amendment or landscaping (Curro 1991). Cardboard wastes can be recycled, but if they are contaminated by dirt, paint, sealants or moisture, they become less valuable. Concrete, the heaviest C&D waste component, can be processed in an impact crusher and screened. It has the appearance of conventional aggregate except for attached cement debris, but it does not behave as reliably as virgin aggregate. Therefore, it is generally used as base material for sidewalks, driveways, or parking lots but not in structural applications. Testing has shown that concrete made with recycled aggregate is less resistant to impact forces, but its compressive strength can be equal to or greater than that of concrete made with virgin aggregate.

Recycled aggregate has a 10% lower bulk density than natural aggregate. Also, approximately 2.4 times more water absorption occurs in recycled aggregate than in natural aggregate. Due to this greater water absorption, recycled aggregate concrete compressive strengths can be 3% to 16% higher than concrete that uses natural aggregate; but this typically comes at the expense of workability. The reason for this is that a greater portion of the water added to the concrete mix is absorbed by the recycled aggregate,

effectively giving it a lower water-cement ratio. The lower the water-cement ratio, the stronger the compressive strength of the concrete mix (Ridzuan et al. 2005).

Resistance to carbonation and sulfate attacks were also studied for recycled aggregate concrete. In terms of resistance to carbonation, trends observed for conventional concrete were the same for recycled concrete. One trend was: the higher the compressive strength of the concrete, the greater its resistance to carbonation. Since concrete using recycled aggregate can have higher compressive strength than concrete using natural aggregate, concrete using recycled aggregate can also have a higher resistance to carbonation. Experiments have shown that recycled aggregate concrete can also possess a similar resistance to sulfate attack when compared to natural aggregate concrete (Ridzuan et al. 2005).

Processed asphalt pavement is easily recycled in a cradle-to-cradle fashion. The asphalt comes primarily from exterior demolition waste, from projects that involve resurfacing roads. Pavement can be torn up either in sections or with a milling machine. For the most part, hauling costs can be avoided if processed asphalt is treated near a job site. The technology for recycling pavement is advanced enough that a process for both recycling and relaying pavement commonly takes place on site. This form of recycling is called “cold in-place” recycling.

Cold in-place recycled asphalt paving involves using a milling machine, a screening or sizing unit, a mixing unit, and a paver. The milling machine grinds off existing asphalt and passes it on to the screening unit. Usually with computer assistance, the screening unit will then sort the asphalt by size, passing specified amounts to the mixing unit. The mixing unit will then weigh how much asphalt has been placed into it and then adds the correct amount of emulsified liquid asphalt binder to the mix. After the binder has been spread uniformly throughout the mix, the mixer will pass the asphalt to the paver which then reapplies it to the road (Amos 2009). This form of C&D waste recycling is considered on-site or portable recycling.

Given the layout of many C&D waste recycling facilities, bricks are usually processed with concrete and other masonry products. Also, similar to concrete, they are normally limited for use as aggregates for base materials because their mechanical properties, after going through an impact crusher, are unknown. Since concrete and bricks are commonly processed together, they are often crushed to produce a mixed aggregate. In situations where large amounts of brick are readily available, it is worth sorting them separately from the concrete for potential reuse as pavers or landscape stones that have an attractive reddish tint (Curro 1991).

Where C&D waste processing is practiced, it can be screened to generate a low-grade soil substitute that can be used as alternative daily cover (ADC) in landfills. ADC is highly valued in states that do not have access to large amounts of soil or want to reduce the amount of soil dedicated to daily cover. However, this use may become less viable as municipalities press to find alternatives to landfilling (Spencer and Goldstein 2006). If the materials are screened to capture different size fractions, it has been shown that the 0.06 mm-0.125 mm fraction can be reused in new mortar and concrete. When combined with polypropylene fibers to make cement, the resulting product can be even better than using just the fines alone. One research team has speculated that it may be possible to mix the fines with lime and calcinate the mix for reuse in cement (Bianchini et al. 2005).

For some materials or contaminated residuals present in small quantities, it has been shown that they can sometimes be used as a “refuse-derived” fuel (RDF) in an incinerator or boiler, although careful pre-testing is required to ensure there is no hazard associated with emissions and that ash disposal is conducted properly (Curro 1991).

Drywall

Gypsum wallboard is mainly composed of gypsum mineral (calcium sulfate), water, and paper (USG MSDS 2009). A thick layer of gypsum slurry ($\text{CaSO}_4 + 2 \text{H}_2\text{O}$) is sandwiched between two layers of paper, where it is allowed to dry and solidify. Typical drywall is 85% gypsum and 10% cellulose (as paper), with the remainder comprised of starch, glue, and other material specific to the type of wallboard (USG MSDS 2009). In one year, the US sells or uses about 35,500,000 tons of gypsum wallboard. Most (48%) is standard, meaning it is prepared as described above and is ½ inch thick. A smaller fraction (30%) is Type X fire retardant wallboard; and 13% is non-regular wallboard with a thickness ranging from ¼ to 1 inch. The remaining fraction includes wallboard that is used in mobile homes, pre-decorated, veneer based, or moisture resistant (Founie 2006).

Drywall has been heavily used for constructing interior walls for over 40 years (Musick 1992). In 2000 about 1.6 million new homes were built in the US, and most of them used gypsum wallboard (Marvin 2000). In 2006 the world production of gypsum wallboard was estimated at 8 billion square meters. Almost half of this was produced in the US, and the remainder was made in Asia and Western Europe. With the rapid development rates occurring in India and China, it is predicted that production of wallboard will increase substantially in the next decade (Founie 2006).

A review of US construction practices shows that one pound of waste wallboard is generated per square foot of new construction (Recycling Works 1998, Wolkowski 2003); this is equivalent to about 1980 lbs of wasted new drywall for an average home. But construction waste contributes only 64% to C&D drywall waste. Another 14% comes from demolition, 10% from renovation, and 12% from manufacturing (Musick 1992). In Florida, drywall is 5 to 25% of the C&D waste stream (Cordeiro 2006). Further, it will likely be a major component of the C&D waste stream for the foreseeable future.

Gypsum Wallboard Problem

In the 1980s waste gypsum drywall was discarded in landfills as part of the municipal waste stream. However, it became apparent that the moist, anaerobic and organic-rich landfilled waste environment was resulting in hydrogen sulfide (H_2S) emissions (Eq. 1) and metallic sulfide leaching into ground water (Townsend et al. 2001, Musick 1992).

One pound of hydrogen sulfide gas is produced from every four pounds of disposed drywall. At 0.1-10 parts per million (ppm) the gas has a rotten egg odor; above 10 ppm the gas is an irritant to humans; and at 100 ppm it is life threatening (Flynn 1998). Hydrogen sulfide erodes landfill equipment, can be corrosive to gas recovery equipment, and increases SO_x production from flares (Heguy and Bogner 2005). The potential for subsurface migration is also significant, as the gas is very explosive (Flynn 1998).

While drywall contains little heavy metal contamination (Marvin 2000), its manipulation yields dust, and in some cases, such as in the use of Type X drywall, inhalation of the dust can be hazardous (Townsend et al. 2001). Type X drywall (fire resistant) contains fiberglass and other chemicals like chelating agents, water dispersants, and asphalt wax emulsions (Musick 1992). While waste gypsum drywall is used as a soil amendment for corn, there are concerns about using Type X for agriculture (Burger 1993). However, Wolkowski and Crosby (2001) showed that crushed Type X wallboard mixed with soil did not have a negative impact on earthworms.

In addition to being one of the more problematic C&D wastes, drywall is a less marketable waste, and the feasibility of recovering it is largely driven by economics (Cordeiro 2006). The costs incentives to divert it from landfills are driven by factors such as: tipping fees, transportation costs, collection costs, separation costs, processing costs, comparable product costs, the cost of raw gypsum, and the stakeholders' motivations (Cochran 2003, Townsend et al. 2001, Marvin 2000). In some states the cost of raw, mined gypsum is so low that it is cheaper to landfill the used gypsum than to reclaim it. In certain cases, where tipping fees are very low, it is more expensive to collect and process waste drywall than to create a value-added product from it (Musick 1992).

Some building certification programs incentivize contractors to sort C&D wastes on-site, making it more likely that they will use recycling centers than landfills (Cordeiro 2006). In Florida, a service industry has grown up that comes to the construction site to remove drywall or several fractions of C&D waste. These industries have improved the economics of drywall capture (Townsend et al. 2001).

Gypsum Wallboard Collection

When the recycling or reuse of gypsum wallboard is economically feasible, the starting point of all operations is the collection process. On some construction sites stationary compactors can be installed. These closed compactors can box more than twice the amount of waste gypsum wallboard than conventional open containers, and they protect the wallboard from rain. In this case, the number of pulls to empty the containers can compete with the low tipping fees of landfilling (Recycling Works 1998).

Waste gypsum wallboard can be removed either at the job site or at a management facility where all C&D wastes are collected. Collecting gypsum wallboard at the job site requires more work (separation of waste on site by workers) but results in less contamination (Cochran 2003). After collection and grinding, trommel screens have proven most effective for separating the paper from the gypsum (Townsend et al. 2001, Cochran 2003). The end product of most processes is crushed gypsum. Crushed gypsum can be used as an alternative to raw gypsum (Cochran 2003). Since raw gypsum is used in a wide variety of processes, there is the potential for many "second lives" for waste gypsum wallboard.

Waste Gypsum Wallboard Uses

There are many market opportunities for waste wallboard since it can be used as an alternative to raw gypsum. Raw gypsum is used for home gardening, golf course maintenance, spill absorbents in industry, animal waste management, cat litter, horticulture, city parks and recreational facilities, and forestry and mine reclamation (Recycling Works 1998, Nature's Way Resources 2009). If the product is pure enough, it can be used for industrial applications such as the production of food, glass, paper, and pharmaceuticals (Founie 2006). It can also be used as an ingredient in the manufacture of new drywall (recycling wallboard), Portland cement, absorbents, plasters, agricultural supplements and fertilizer additives, in greenhouse industries, and for soil composting and animal production facilities (for its moisture- and odor-absorbent characteristics) (Cordeiro 2006, Wyatt and Goodman 1992). Townsend et al. (2001) suggested that gypsum from wallboard could also be used as a road construction material instead of raw gypsum. Waste gypsum wallboard can also be donated to nonprofit organizations to build affordable houses (when the wallboard sheets are either half size or larger). The half sheet can even be resold for small projects. The ground gypsum can be used to mark athletic fields, to help mushroom growth, for lowering turbidity in water treatment, and to facilitate sodium leaching on the road side (when roads receive a lot of salt during winter months) (Marvin 2000). The purity of the final product (the amount of contamination) often determines the potential reuse options for ground waste wallboard. If it contains paper, it will be adequate for use as a soil amendment for agriculture purposes but not pure enough for food production and pharmaceutical uses. In the following paragraphs, several realistic options for the reuse of waste gypsum wallboard will be discussed in detail.

In some parts of the US, the most feasible market for the reuse of gypsum wallboard is to recycle it into new wallboard (Townsend et al. 2001). In this case the crushed gypsum particles should be less than ½ inch and the product should be low in contamination (moisture and paper) (Cochran 2003). If the gypsum is pure enough, it is blended with raw gypsum and used to produce new wallboard. Some manufacturers already produce new gypsum wallboard containing 7 to 33% of gypsum from recycled gypsum wallboard (Musick 1992). The paper layer can be recycled and reused in the fabrication of gypsum wallboard (Musick 1992), or used in the fabrication of classic paper (Cordeiro 2006). The economic feasibility of recycling gypsum wallboard depends mainly on the regional demand for gypsum wallboard relative to the cost of the raw materials (Marvin 2000).

As raw gypsum is an ingredient of new cement for controlling set time, gypsum from waste gypsum wallboard may be used instead. The crushed gypsum must have a low paper and moisture content (Marvin 2000, Cochran 2003) and gypsum particles must be less than ½ inch in size (Cordeiro 2006).

Waste gypsum wallboard, alone or in combination with wood chips, has been tried as a litter material for animals, especially for chickens and cows. It has been shown that litter of this type can reduce animal foot problems and increase udder health of cows (Marvin 2000). Wyatt and Goodman (1992) showed that crushed wallboard gypsum used as a base and to-dressed with wood shavings (to avoid dust production) was a good litter material for broilers because of gypsum's capacity to absorb and release moisture. There is no evidence of negative animal health effects from gypsum litter amendments. Wolkowski and Crosby (2001) noticed that earthworms living in a gypsum-amended soil were no more impacted than earthworms living in a control soil.

In cases where calcium and sulfur amendments are needed, crushed gypsum wallboard can be a beneficial addition to compost (Musick 1992). The gypsum does not have to be low in paper content, since paper will also easily decompose. However, because some sections of compost can become anaerobic, the process must be monitored for hydrogen sulfide emissions (Marvin 2000).

Using crushed gypsum as a soil amendment is an obvious reuse option, since raw gypsum is already heavily used as a soil amendment to provide nutrients to plants. The wallboard needs to be crushed to a particle size of about 1/8 inch (Cordeiro 2006), but high levels of paper content can be tolerated (Cochran 2003). Burger (1993) pulverized regular construction drywall as a soil amendment on a corn field. He observed about 25% more yield from the corn as compared to his control field without a gypsum amendment. Moreover, the pulverized wallboard performed as well as the conventional agricultural gypsum. Wolkowski (2003) observed no difference in the performance of alfalfa crops in soil with amended crushed wallboard when compared to conventional agricultural gypsum. Wolkowski also observed that crushed wallboard had the same impact on potato yield as regular gypsum fertilizer. Scott et al. (1993) did not observe an increase of yield when gypsum was applied to watermelon. However, the amount of calcium in the watermelon increased, indicating that gypsum was an adequate source of calcium for watermelon. Overall, gypsum as a soil amendment results in an increased yield for several crops (Sumner 1993), including alliums, almonds, barley, citrus, coffee, cranberries, desert salt grass, ginseng, grapes, lawns, marsh vegetation, papaw, peanuts, tomatoes, raspberries, sugarcane, cabbage, broccoli, cauliflower, radishes, turnips, kale, onions, and wheat (Nature's Way Resources 2009, Townsend et al. 2001).

Gypsum can function as both a soil conditioner and a fertilizer. It conditions the soil by decreasing the bulk density (making it lighter) and increasing water drainage (Nadler and Magaritz 1986; Marvin 2000; US Gypsum 2009). It has the ability to flocculate the clay in some soils, creating more large pores for

infiltration of air and water. In poorly draining soils where salts and other nutrients tend to accumulate, it can decrease swelling and cracking, which thereby aids seed emergence (Sumner 1993; US Gypsum 2009). Gypsum is a useful source of calcium in some high pH arid soils, where lime use is not appropriate (Wolkowski 2003). It has also been shown to help with slope stabilization (Founie 2006).

When soil calcium is needed, both lime and gypsum can be used. Gypsum is often preferred when the aim is to apply supplement to the subsoil, because gypsum is the more soluble of the two amendments. Calcium, in the form of gypsum applied to the soil's surface, is shown to migrate into the subsoil (Toma et al. 2005) as opposed to calcium from lime that stays on the surface. Liu and Hue (2001) showed that only 7.6% of calcium applied as lime moved beyond 10 cm of depth, whereas 60% of calcium applied as gypsum moved beyond 10 cm of depth. Rhue and Kamprath (1973) have observed that the movement of sulfur into the subsurface depends on the soil type. In a sandy soil there is more movement than in a clayey soil. Toma et al. (2005) found gypsum as deep as 80 cm below the surface in andisol after 16 years of surface treatment, and the gypsum was still having a beneficial impact on the subsoil acidity.

Gypsum, with surface application, can have beneficial effects on the entire soil profile. In the case of a vegetated soil, gypsum enhances plants and plant roots. Gypsum is a basic source of calcium and sulfur. When these nutrients reach the subsoil, the subsoil has a greater hydraulic conductivity, reducing the resistance to root penetration and allowing the root to proliferate (Block 2000, Sumner 1993, Wong and Ho 1991). This allows the roots to take up nutrients more easily, especially nitrogen for young plants (US Gypsum 2009). Moreover, calcium and sulfur are essential nutrients for plants. Plants need calcium for cell division and the cellular membrane (Wolkowski 2003). Calcium improves fruit quality and prevents plant diseases (US Gypsum 2009). Certain plants, such as alfalfa, need sulfur for the creation of amino acids. Sulfur is also a component of certain plant vitamins and enzymes (Wolkowski 2003). Essential micro-nutrients such as boron and magnesium can also be found in gypsum wallboard, further benefitting plants (Wolkowski 2003). Gypsum has the potential to balance micro-nutrients in plants like iron, zinc, manganese and copper (US Gypsum 2009).

In soil with a high aluminum content (especially Al^{3+}), which makes the soil acidic, gypsum has the potential to lessen the toxicity of aluminum, converting toxic aluminum to a neutral molecule (Block 2000). Aluminum concentrations in the soil solution and on soil exchange sites reduce the activity of Al^{3+} (Smith et al. 1994). Wong and Ho (1993) experimented with gypsum as a soil amendment for the revegetation of red mud with grass. Red mud is a soil residue from the aluminum industry, containing a significant amount of aluminum. The red mud was amended with different rates of gypsum and included sewage sludge. They concluded that although the gypsum amendment required a long period of stabilization before normal plant growth, gypsum combined with sewage sludge was an effective means to revegetate red mud (Wong and Ho 1993). The combination of gypsum and sewage sludge improved the soil structure and hydraulic properties of red mud. It also allowed the leaching of salt and reduced the sodium concentration of the red mud. Moreover, the gypsum provided magnesium, which was necessary for the grass growth (Wong and Ho 1993). Sumner (1993) and Toma et al. (2005) suggest that gypsum improvements to crop yields is likely due to both an increase in the Ca^{2+} nutrient and the detoxification effect of Al^{3+} in the soil. Both improve root proliferation and water availability to crops.

A simple surface application of gypsum can increase the exchangeable calcium (Toma et al. 2005, Liu and Hue 2001) and sulfate (Nadler and Magaritz 1986) in a soil profile. Exchangeable calcium through the entire profile can be observed due to the high solubility of gypsum (0.264 g/100ml) (Musson et al. 2008). As the exchangeable calcium increases, exchangeable Al decreases. It has been observed that the addition of gypsum to soil could decrease the exchangeable Al from 10 to 20 % (Liu and Hue 2001). Calcium has the same effect on exchangeable sodium (Nadler and Magaritz 1986), exchangeable

potassium, and exchangeable magnesium (Burger 1993, Sumner 1993). As a result, these chemicals are released in the soil solution and then leach as sulfate ions moving down the soil profile (Liu and Hue 2001). The leaching of Al^{3+} and Na^+ is beneficial when they are present in high concentrations (red mud, sodic soil). However, it can have a negative impact when essential plant nutrients like potassium and magnesium are leaching. In this case, crushed wallboard amendments would reduce the available potassium and magnesium available to plants, resulting in the need for potassium/magnesium fertilizer to balance their loss in the soil (Burger 1993). Wolkowski (2003) suggests limiting application rates for sandy soil and silt loam soil (2 Mg/ha and 5 Mg/ha, respectively) to once every three to four years to avoid magnesium loss while still providing sulfate.

As gypsum is composed of calcium (Ca^{2+}) and sulfate (SO_4^{2-}), there is a legitimate concern of lowered soil pH through formation of sulfuric acid (H_2SO_4). However, some studies observed no pH modification of the soil after a gypsum amendment (Burger 1993, Smith et al. 1994, Scott et al. 1993), while other studies observed a slight decrease in pH ranging from 0.2 to 0.7 when substantial amounts of gypsum were applied to the soil (Wolkowski 2003, Wolkowski 2000, Liu and Hue 2001). Wong and Ho (1993) observed a significant decrease of 2 pH units in their red mud. However, the initial pH of the red mud was already high (10.6). A similar observation has been made for sodic soils, where the initial pH of 9.0 dropped to 7.8 after the addition of gypsum (US Gypsum 2009). The formation of sulfuric acid was not the reason for the pH decrease, it was instead the release of hydrogen ions previously attached to the clay surface and replaced by Ca^{2+} ions (Wolkowski 2003).

A primary concern about the agricultural use of gypsum wallboard is that, in many states, crushed wallboard is considered construction debris; therefore, a permit is required to apply crushed gypsum on soils. Another concern is that, if crushed gypsum is applied on the soil's surface, the fine particles might blow away under strong winds (Wolkowski 2003). Marvin (2000) also notes that the increase of leaching after gypsum application could lead to phosphate, magnesium, and sodium losses to the crop plants.

In some cases where collection costs, transportation costs, and processing costs are too expensive to compete with landfill tipping fees, crushed gypsum wallboard can be used as a soil amendment at the construction site. The crushed gypsum wallboard can be applied to the land (often grass or crops) surrounding the site. Marvin (2000) suggests that the pulverized wallboard should be evenly spread on a soil with good drainage and aeration (to avoid production of hydrogen sulfide near an inhabited structure). This practice requires a portable grinder and a small applicator, adding to the processing cost (Cochran 2003). However, the elimination of collection and transportation costs offset some increased processing costs. This method, if approved, (since a permit is likely required) can reduce operator costs and landfill space demands. Similar processes for other C&D wastes have already been performed, such as processing waste wood into mulch and using it as soil erosion barriers or as improvements to walkways for construction workers and equipment (Block 2000).

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Research Introduction: Subprojects 1&2

This research is a multi-faceted study aimed at evaluating waste virgin drywall as a soil amendment but also as one of the main components of a passive carbon sequestration system. While it is well known that gypsum (CaSO_4) (the main component of drywall) has value as a soil amendment (USDA 2006), this study aimed to examine (i) germination effects of various drywall products treated for mold inhibition or fire retardation; (ii) use of waste virgin drywall as a soil amendment for biodiesel crops; (iii) the feasibility of using ground waste virgin drywall as a soil amendment for erosion control grass on the construction site where it was generated; and (iv) the feasibility of an environmental system composed of ground drywall and plants for passive carbon sequestration. Carbon sequestration was included in this research because of a study published by D. Manning (Manning 2008), who showed that in the presence of excess calcium, derivatives of carbon-rich plant root exudates could combine with calcium to form calcium carbonate (CaCO_3), an insoluble precipitate. The result is that carbon dioxide, originally taken up by the plant, makes its way into the soil after being incorporated into various exudate constituents, and then it ultimately remains sequestered in the soil as a relatively insoluble precipitate.

Germination Effects

The purpose of the toxicity tests was to evaluate the potential toxicity of three types of drywall on the germination of four seed types. The drywall types used were commercially available as: a conventional drywall (USG Sheetrock® Gypsum Panel), a fire retardant drywall (National Gypsum's Gypsum Board Gold Bond XP Fire Retardant ½"), and a mold, mildew, and moisture resistant drywall (National Gypsum, Mold, Mildew and Moisture Resistant ½"). Abbreviations for each drywall were used for labeling during the experiment, with: "C" the conventional drywall, "F" the fire retardant drywall, and "M" the mold, mildew, and moisture resistant drywall. The four seed types tested in germination tests and bench scale experiments were: lettuce (Grand Rapids, Ferry-Morse), cucumber (Straight Eight, Ferry-Morse), wheat (NC05-20814, NC State, Raleigh), and canola (Dwarf Essex Rape Seed, Wammock Farm Service, Inc.). Lettuce and cucumber seeds were tested because of their germination sensitivity; they are commonly used in toxicity tests (EPA 1996). Wheat and canola were used because they are commonly

cultivated in North Carolina. Wheat is a commercial crop and canola is a crop being tested as a source of virgin oil for biodiesel production.

The germination test procedure evaluated germination rate and root elongation of seeds exposed to different concentrations of dissolved ground drywall solution (Wang et al. 2001). Solutions were prepared by pouring 400 mL of deionized water (DI) over 10 g of ground drywall and stirring for 24 h. The solution was allowed to settle for 24 h before removing the supernatant. The supernatant was considered to be the highest concentration (saturated concentration) and became the stock solution for dilutions. Subsamples were diluted 10, 100 and 1000 fold for use in testing. Seeds were tested in Petri dishes lined with a #1 Whatman filter, and 10 uniform seeds of the same species were placed in each dish. A 5 mL portion of drywall solution was applied to each dish, with (DI) used as a control solution. Triplicate tests of each drywall solution and controls were prepared. The dishes were incubated in a constant temperature chamber at 25°C in the dark for 72 h. They were randomly distributed in the oven to control for any uneven heat effects (Figure 3). The effect of each drywall solution on seed germination was evaluated by comparing the germination score (GS) of each trial. The GS was calculated by

Figure 3. Petri dishes randomly distributed prior to the start of the experiment.

multiplying the average root length by the germination rate. Germination rate was the number of seeds germinated in 72 h. Positive germination was defined as appearance of a root more than 5 mm long. Germination experiments were repeated three times for each seed type.

Lettuce

Lettuce is typically recommended in toxicity tests due to its high sensitivity to chemicals (EPA 1996). While it was anticipated that the treated drywall types F and M might inhibit germination, all drywall types stimulated germination relative to the controls (Figure 4). Increasing drywall doses increased germination rates. However, the amount of stimulation differed among the drywall types. The highest C dose yielded germination scores (GS) nearly double those of controls and well above the GS of the highest concentration of F and M drywall types. The highest F and M doses increased GS to about 125% of the control GS. A close examination of the germination results showed that increases in GS were due to increases in root length and not to differences in germination rates. This suggests that any amendments in F and M type drywall are not affecting seed germination but do result in more growth stimulation than would occur in their absence.

Figure 4. Lettuce germination scores. $n=9$, and standard error bars are shown. Significant differences were found at $p < 0.05$ ($\mu^2 = 0.467$, power = 1). α : statistically higher than any other treatments; β : statistically higher than Control, C-1000x, F-1000x, M-1000x; γ : statistically higher than F-1000x, M-1000x; δ : statistically higher than M-1000x.

Cucumber

Unlike lettuce, cucumber GS were not stimulated by drywall amendments (Figure 5). At the highest dilutions, drywall addition did not impact GS relative to controls, but at the 10-fold dilution strength, the M drywall caused inhibition that was significant ($p < 0.05$) relative to the controls and weaker strength C and F drywall doses. At full strength doses, all drywall types inhibited GS relative to controls, with the GS of the highest concentration of M drywall measuring half that of the controls. Inhibition by the full strength M drywall solution on cucumber GS was significantly greater ($p < 0.05$) than that of C. Similar to the lettuce response, however, the impacts of the drywall on GS was via changes in root lengths and not changes in germination rates.

Figure 5. Cucumber germination scores. $n=9$, and standard error bars are shown. Significant differences were found at $p<0.05$ ($\mu^2 = 0.419$, power=1). α : statistically lower than every treatment except C-1x; β : statistically lower than Control, C-1000x, F-1000x, M-1000x, C-100x, F-100x, M-100x, C-10x, F-10x; γ : statistically lower than control, C-1000x, F-1000x, C-100x, F-100x.

Wheat

Wheat seeds were subjected to the GS protocol because they were relevant to carbon sequestration testing in this study (Figure 6). The trend of drywall effects on wheat GS were much like those of the cucumber seeds, with the highest M drywall dose yielding significantly lower ($p<0.05$) GS than any other treatment or the controls. Interestingly, C doses at 100-fold dilution strength significantly ($p<0.05$) stimulated GS relative to controls and the full strength C dose. Likewise, the 100-fold dilution of F drywall showed stimulatory effects relative to controls and other dosages. At full strength, the C and F drywall treatments were inhibitory relative to the controls.

Figure 6. Wheat germination scores. $n=9$, and standard error bars are shown. Significant differences were found at $p<0.05$ ($\mu^2 = 0.383$, power=1). α : statistically lower than every treatment; β : statistically lower than C-1000x, F-1000x, C-100x, F-100x, F-10x; γ : statistically lower than C-100x, F-100x; δ : statistically higher than Control, C-x, F-x, M-x; ϵ : statistically higher than Control, M-1000x, M-100x, C-10x, C-x, F-x, M-x.

Canola

Canola is an oil-seed crop that is known to have a special need for sulfur (Scherer 2001). Like the lettuce seeds, its germination scores were enhanced by dosing with drywall solutions (Figures 7 and 8). Full strength conventional, fire-retardant, and mildew-resistant drywall solutions scores were not significantly different from one another, but all had more than double the GS of the controls and were significantly different ($p<0.05$) from GS associated with the 1000 fold dilution doses. The full strength conventional drywall solution GS was also significantly higher ($p<0.05$) than the GS of seeds dosed with 100-fold dilutions of drywall of all types. The GS of seeds dosed with full strength fire-retardant and mildew resistant drywall solutions likewise differed significantly ($p<0.05$) from seeds dosed with 100-fold dilutions of fire-retardant and mildew resistant drywall, but they did not differ significantly from the GS of the 100-fold dilution of conventional drywall. All 10-fold dilution drywall samples also resulted in significantly higher ($p<0.05$) GS than the controls, and the 100-fold dilution of conventional drywall outperformed the same strength doses of 100-R and 100-M solutions. Although the stimulatory effects of the F and M type drywall materials were not as robust as that of conventional drywall, all types enhanced the GS of canola seeds. Interestingly, this was the only treatment where higher GS were due not only to root elongation but also to higher germination rates by seeds exposed to the drywall.

Figure 7. Canola germination scores. $n=9$, and standard error bars are shown. Significant differences were found at $p<0.05$ ($\mu^2 = 0.601$, power=1). α : statistically higher than Control, C-1000x, F-1000x, M-1000x, C-100x F-100x, M-100x; β : statistically higher than Control, C-1000x, F-1000x, M-1000x, F-100x, M-100x; γ : statistically higher than Control, C-1000x, F-1000x, M-1000x, F-100x; δ : statistically higher than F-1000x.

Figure 8. Canola seed germinated after spending 72 hours in a dark 25°C oven.

In summary, when germination scores (GS) were assessed for four kinds of plant seeds (lettuce, cucumber, wheat, and canola) to test the potential toxicity of three different types of virgin drywall (conventional, fire retardant and mold, mildew and moisture resistant), the following results were obtained: Ground drywall amendment at high dose had a negative impact on the GS of wheat and cucumber. For both seeds, the M drywall amendment resulted in the lowest GS. In contrast, lettuce and canola responded positively to ground drywall solutions. Conventional drywall amendment resulted in the best GS for both species.

Soil Amendment for Biofuel Crop

Canola

Because canola seeds showed the highest positive response to drywall amendments in the germination score assessment, and because canola crops are increasingly used for U.S. bio-fuel production (Atkinson et al. 2006), subsequent bench-scale and field experiments were conducted using this plant.

Bench-scale

The bench-scale experiment was designed to test the three drywall types used in the germination score tests on the early growth of canola plants. Sixty five one-gallon pots were filled with a mix of topsoil and potting soil (Organic Valley, Scott and Timberline at a ratio of 4/2/1). Each test dosage of ground virgin drywall was added to five replicate pots and then mixed with the soil (Table 2). The controls received no wallboard amendment. Five canola seeds (Dwarf Essex Rape Seed) were planted in each pot on April 26, 2010. After 16 d, the pots were fertilized with 1.327 g of 20-20-20 fertilizer (Jack's Classic All Purpose) dissolved in 378 ml of DI water. The pots were placed in direct sunlight from day 1 to day 65 and then moved to a more shaded location to reduce sun damage to the leaves. A second dose of fertilizer (0.277 g per pot) was applied on Day 149 and the plants were thinned to three per pot.

Table 2. Bench-scale soil amendment doses

Drywall dose (kg drywall/ha)	Drywall dose (kg sulfur/ha)	Drywall dose per pot (g)
500	99	0.91
1,500	298	2.74
3,000	596	5.48
4,500	893	8.21

The trial was terminated on Day 186. Photographs and data on the number of leaves per plant were taken regularly throughout the trial. At the end of the experiment, each plant was carefully removed, and the roots were dried (100°C, 24 h) and weighed. The treatments were statistically compared using analysis of variance (ANOVA) and the least significant difference (LSD) statistical tests. The first leaf count was performed on Day 16. The results paralleled those of the germination score test, with plants receiving drywall amendment showing significantly ($p < 0.05$) higher leaf counts than controls (Figure 9). Pots receiving C type drywall generally outperformed those receiving R or M type amendment. The pots receiving a drywall dose equivalent of 600 kg sulfur/ha showed peak leaf numbers and only the 300 kg sulfur/ha dose of M type drywall approached the stimulatory capacity of C-type drywall.

Figure 9. Evaluation of the number of leaves per plant 16 days after seeding. $n=5$, and standard error bars are shown. Significant differences were found at $p<0.05$ ($\mu^2 = 0.738$, power=1). α : statistically higher than control, C-100, F-100, F-300, F-600, F-900, M-100, M-600, M-900; β : statistically higher than control, C-100, F-100, F-300, F-600, M-100, M-600, M-900; γ : statistically higher than control, M-600, M-900.

The pattern of optimum doses within a drywall type varied, with the highest doses of C and F being stimulatory, but the highest dose of M yielding leaf counts similar to controls. F-type drywall tests showed increased stimulation of leaf production with increasing dose, although its impacts at maximum dosage was lower than the best dosage trials of type R and M drywall. The M drywall optimum dose was 300 kg of sulfur/ha, which was significantly ($p<0.05$) higher than the control.

The second leaf count was performed on Day 25, and the treatment differences were less pronounced. Every dosage of the C drywall resulted in a significantly ($p<0.05$) higher number of leaves per plant than on the controls (Figure 10). Consistent with the first leaf count, the optimum dose of C type drywall was 600 kg of sulfur/ha, and the F type drywall doses produced the smallest increase in leaves per plant relative to the controls. However, the highest dose of M drywall resulted in the lowest leaves per plant count apart from the control. The F drywall amendment resulted in higher number of leaves per plant for each treatment, but only the highest dose (900 kg sulfur/ha) was significantly higher ($p<0.05$) than the control. M drywall amendments resulted in an increase of the number of leaves per plant reaching a significantly ($p<0.05$) higher number of leaves for the 300 kg of sulfur/ha amendment. After the second leaf count, cabbage worms became a problem, and although they were ultimately brought under control (using a garlic/onion spray), it was decided that their damage to the plants compromised any future leaf count data.

Overall, the drywall amendments resulted in a greater number of leaves per plant relative to controls, especially for the C drywall. Further, by visual inspection, it was clear that C drywall amended plants were more robust and had larger leaves (Figure 11).

Figure 10. Evaluation of the number of leaves per plant 25 days after seeding. $n=5$, and standard error bars are shown. Significant differences were found at $p<0.05$ ($\mu^2 = 0.599$, power=1). α : statistically higher than control, C-100, F-100, F-300, F-600, F-900, M-100, M-600, M-900; β : statistically higher than control, F-300, F-600, F-900, M-100, M-600, M-900; γ : statistically lower than C-100, C-300, C-600, C-900, F-100, F-300, F-600, F-900, M-100, M-300; δ : statistically lower than C-100, C-300, C-600, C-900, F-100, F-600, M-100, M-300.

Figure 11. Visual comparison of replicate control (top) and C-amended plants (600 kg sulfur/ha) (bottom) at Day 28.

On Day 200 roots from each plant were collected, dried for 24 h at 100°C, and weighed (Figure 12). ANOVA and LSD statistical tests revealed that the C drywall treatments of 300 and 900 kg sulfur/ha had significantly ($p<0.05$) more root mass than controls and most of the F drywall amendments. Only the M

drywall dose of 300 kg sulfur/ha yielded root masses significantly ($p<0.05$) higher than that of control plants.

Figure 12. Dry root mass of canola after 200 d in pots. $n=5$, and standard error bars are shown. Significant differences were found at $p<0.05$ ($\mu^2 = 0.211$, power=0.994). α : statistically higher than control, C-100, C-600, F-100, F-300, F-600, F-900, M-100, M-600, M-900; β : statistically higher than control, F-100, F-600, F-900, M-600, M-900; γ : statistically higher than control, C-100, F-100, F-300, F-600, F-900, M-100, M-600, M-900.

Field tests

Field tests began in November 2009, with canola seed planted on two sites where the soil was amended with ground conventional drywall. One site in Huntersville, NC is owned by Charlotte Mecklenburg Utilities (CMU); the other site in Newton, NC is part of the Catawba County EcoComplex. Unfortunately, the Newton site did not fare well in unseasonably cold weather during the 2009/2010 winter. A decision to abandon the crop was made in late winter. The experiment is being repeated with a fall 2010 canola crop, but no data are available yet, as the crop is dormant.

The field trial at the Huntersville location was part of a larger biofuel production project, and a small portion of the planting was used for the experiments described here. The field was prepared, fertilized and seeded by a professional farmer. Soil preparation and liming were completed on October 7, 2010, fertilizer (18-24-0) was added on October 23, 2010, and the canola seeds were planted on November 5, 2010. Ground virgin drywall amendment (USG Sheetrock® Gypsum Panel) was surface applied two days after planting. Four doses of ground conventional drywall plus no-drywall controls were planted in randomly distributed replicates of four for a total of 20 plots (Table 3). Each plot was bordered by a one meter buffer.

Table 3. Canola field planting doses of virgin ground
conventional drywall

Treatment	kg sulfur/ha	kg sulfur/m ²	Drywall per plot (g)
Control	0	0	0
C250	250	0.025	631.5
C500	500	0.050	1263
C750	750	0.075	1895
C1000	1,000	0.100	2526

As with the Newton site, plants at the Huntersville site suffered from cold damage, with nearly 30% of the crop lost to an unusually early frost. Moreover, during the months of March, April, and May, the yield was greatly reduced by deer grazing at the time the plants were flowering (Figure 13). Several deer-proofing remedies were employed, but none was entirely successful. As a result, of the 70% remaining after frost damage, only 10% of the crop was healthy enough for experimental analysis. The assessment of treatment effects was done by measuring root dry biomass and seed weight. For seed measurement, 15 plants per plot were harvested (except in cases where only 10 healthy plants remained after deer damage) on June 4, 2010 (Day 182). The weight of 1000 seeds was measured for each treatment. Root mass was measured as described in the pot experiment protocol. The seed and root mass data were analyzed using ANOVA and LSD statistical tests. There were no significant differences in the seed weight and root mass of plants in treatments and control plots (Figures 14 and 15). However, the powers of the experiments were only 0.53 and 0.23 respectively, which means that there was about a 47% and 77% chance to make a type II error on the ANOVA test, the chance to miss a significant difference. As a result, the findings are considered essentially inconclusive.

Figure 13: Example of a plot on April 20. Only few flowers have bloomed and will most likely be eaten by deer in the coming weeks.

Figure 14. Mass of 1000 seeds. $n=4$, and standard error bars are shown. ($\mu^2 = 0.231$, Power=0.526).

Figure 15. Mass of 15 roots. $n=4$, and standard error bars are shown. ($\mu^2 = 0.127$, Power=0.232).

Erosion Control Experiment

The purpose of this experiment was to evaluate the feasibility of grinding waste virgin drywall on a construction site and using it as a soil amendment to enhance erosion control plantings. Grinding the material on site would eliminate the need to transport the waste to a landfill or collection site. Pot experiments were conducted using three types of drywall and fescue grass.

Three types of drywall were tested: a regular drywall (USG Sheetrock® Gypsum Panel); a fire retardant drywall (National Gypsum Board Gold Bond, XP, fire retardant ½”), and a mold, mildew, and moisture resistant drywall (National Gypsum, Mold, Mildew and Moisture Resistant ½”). Each drywall type was applied at four different doses (Table 4). The experimental designed used 52 one-gallon pots filled with a mix of topsoil and potting soil (Organic Valley, Scott and Timberline at a ratio of 4/2/1). The ground gypsum drywall was mixed thoroughly with the soil before filling the pots, and control pots received soil and seed only. Each treatment was replicated four times. Commercial grass seed (Tall fescue, Smart Seed Pennington Seed) was sown at a rate of 0.712 g per pot on April 23, 2010. The pots were fertilized with 0.531 g of 20-20-20 fertilizer (Jack’s Classic All Purpose) dissolved in 75 ml of DI water. The pots were maintained in a sunny outdoor location and watered every day that no rain occurred (Figure 16).

Table 4. Grass bench-scale test amendment doses

Drywall dose (kg drywall/ha)	Drywall dose (kg sulfur/ha)	Dose of drywall per pot (g)
1,000	199	1.82
4,000	796	7.30
8,000	1,591	14.59
10,000	1,989	22.25

Figure 16. Grass experiment, May 20th.

Over the course of the experiment, grass height, grass biomass production, and root coverage were monitored. The grass height was measured every 14 d. The height of the tallest grass strand in each pot was recorded. After each height measurement, the grass was trimmed to 640 mm, a height recommended for conventional lawn maintenance. The grass clippings were dried for 2 h at 100°C and then weighed. Both height and biomass accumulation data were compared among treatment using ANOVA and LSD statistical tests (Figures 17 and 18). The experiment was terminated on Day 89. The soil and grass plug were removed as a single unit from each pot, and the bottom root coverage was assessed as follows: five pots were presented to each of four examiners. Each examiner was instructed to rank the pots on a five-point scale, with one being extensive root coverage and five being minimal root coverage. The rankings in five-pot units of comparison were repeated until all the pots were ranked. The rankings for each pot were compiled, and an overall score was given to each treatment (Figure 19).

Figure 17. Accumulated grass height. Standard error bars are represented on the graph for $n=4$. The following significances are for $p<0.10$ ($\mu^2 = 0.323$, Power=0.761) α : statistically higher than C-800, C-2000, F-200, F-800, F-1600, M-200, M-800, M-1600, and M-2000, β : statistically higher than F-800 and M-200.

Figure 18. Accumulated biomass weight. Standard error bars are represented on the graph for $n=4$. The following significances are for $p<0.10$ ($\mu^2 = 0.218$, Power=0.545). α : statistically higher C-2000, F-200, M-200, M-1600.

Figure 19. Root Coverage. Standard error bars are represented on the graph for $n=4$. The following significances are for $p<0.10$ ($\mu^2 = 0.521$, Power=0.948). α : statistically lower than Control, C-200, C-800, F-200, F-1600, M-200, M-800, β : statistically lower than C-200, C-800, F-200, F-1600, M-200, M-800, γ : statistically lower than C-200, C-800, F-1600, M-200, M-800. δ : statistically lower than F-1600, M-200. Control is significantly lower than F-1600.

The gypsum amendment did not significantly inhibit grass height or biomass accumulation relative to controls (Figures 17 and 18), although among the treatments a few were significantly better ($p<0.01$) than others, suggesting some minor drywall stimulatory effects. There was no evidence that the fire-retardant and mildew-resistant drywall products were problematic. The biomass data were much more variable than grass height, so that although the data show some trend toward drywall inhibition, the statistics were not robust enough to reveal differences. Nevertheless, visible inspection showed that grass in the control pots looked thicker and more robust than pots amended with drywall. There were no significant inhibitory effects on root coverage in treatment pots relative to controls, and in fact, root coverage in pots with the highest doses of ground wallboard was significantly ($p<0.01$) greater than in the lower doses and controls. The direction of trends with root growth did not track with those of height and biomass, which suggests that the drywall may lead to plants shifting from investment in surface growth to investment in below-ground development.

Carbon Sequestration

Two experimental approaches to investigating the potential of drywall to contribute to carbon sequestration were used. In the first, an artificial root exudate was prepared and dosed to soil. In addition to providing organic carbon for reaction with the drywall CaSO_4 , the solution simulated rainfall. After a controlled amount of rainfall was applied, the soil was tested for CaCO_3 formation. In the second approach, a series of experiments was designed to evaluate the passive carbon sequestration potential of an environmental system made of plants growing in soil amended with ground waste virgin drywall. The calcium-rich soil created by adding ground drywall should enhance reactions between the plant root exudates or their degradation products and readily available calcium to form calcium carbonate precipitate. Because the source of carbon in the root exudates is carbon atoms from atmospheric carbon dioxide, the formation of calcium carbonate in the soil is considered a passive form of carbon sequestration. Each of these approaches is described in the sections below.

Artificial Root Exudate Experiments

Published qualitative descriptions of wheat exudates (Rovira 1969) and quantitative descriptions of corn exudates (Krafczyk et al. 1984) were used to create an artificial root exudate (ARE). The most predominant compounds in the corn exudate that were also common to the wheat exudate were used to make the ARE. They included oxalic, malic and citric acids, glucose and fructose; see Table 5. The ARE solution was made three-fold more concentrated than naturally occurring exudates to optimize the likelihood that if the phenomenon was occurring, the experimental protocol would reveal it. A high (11.7%) and low (1.7% by weight) CaSO_4 dose were tested. Each trial used four replicate test tubes, with each containing 10 g of soil (Blue Max Materials, Garden Mix, Charlotte, NC). The soil was mixed and clumps were pressed out to create more uniform particle size and ensure that there were no large air spaces within the soil in the tubes.

In the first trial, ARE was applied to soil in the tubes at a rate of 4 mL/wk for 17 weeks to simulate a total of 84 cm (33 in) of rainfall. After application, the test tubes remained at room temperature and open to the air to allow drying, as would occur under natural conditions. The aim of the protocol was to keep the soil moist but prevent it from becoming waterlogged or from producing leachate. In a second trial, ARE was applied at a rate of 7 mL/wk for 10 weeks to again simulate 84 cm of rain (Figure 20).

Table 5. Root exudate composition from literature and as prepared for ARE

Wheat Exudates [#]		Corn Exudates [§]		Artificial Root Exudates [‡]	
Organic Acids	Sugars	Content	Conc. (mg/L)	Contents	Conc. (mg/L)
Oxalic	Glucose	Oxalic Acid	29.31	Oxalic Acid	87.9
Malic	Fructose	Malic Acid	3.87	Malic Acid	11.6
Acetic	Maltose	Citric Acid	6.89	Citric Acid	20.7
Propionic	Galactose	Fumaric Acid	57.4	Glucose	317
Butyric	Ribose	Succinic Acid	4.60	Fructose	105
Valeric	Xylose	Benzoic Acid	2.88		
Citric	Rhamnose	Glucose	105.85		
Succinic	Arabinose	Fructose	35.07		
Fumaric	Raffinose	Arabinose	41.26		
Glycolic	Oligosaccharides	Sucrose	22.86		

[#]Rovira 1969; [§]Krafczyk 1983; [‡]ARE solution used in these experiments.

Figure 20. Artificial root exudates applied to gypsum-amended soil and incubated in test tubes for 7 weeks.

At the end of the dosing cycles, the soil was extracted from the tubes in 10 layers and assayed for gypsum (CaSO_4) and calcium carbonate (CaCO_3) using thermal gravimetric analysis (TGA). The first layer extracted was the top layer, so that the bottom layer was layer ten. Each layer was placed in a separate sample pan for TGA analysis. A Thermal Analyzer Q 500 TGA (New Castle, Delaware) was used. The balance purge gas flow was set to 90 mL/min, and the sample purge gas flow rate was set to 60 mL/min. Samples and standards were tested from 20°C to at least 925°C. The ramping rate was set to 20°C per minute until 400°C was reached, and then the ramping rate was reduced to a level that varied between 5-10°C/min. It was confirmed that for these experiments the same accuracy was achieved at these two ramping rates, and when ramping rate differences occurred, it was between tubes and not between layers of a given tube. Control soil samples dosed with CaSO_4 and CaCO_3 were used to identify the temperature profile associated with gypsum and calcium carbonate. Calcium carbonate was detected as a combustion peak between 600°C and 800°C.

The results of the analyses for CaCO_3 showed that the top layer in every tube was always high compared to the other layers; concentrations in the subsequent layers varied, with no discernable trend (Figure 21). The top layer was neglected from subsequent calculations, based on the assumption that CaCO_3 formation in this layer may have been due to atmospheric CO_2 dissolution in soil pore water and then reacted to form CaCO_3 . The concentration of CaCO_3 in each soil layer (in mg CaCO_3 /g) was multiplied by the mass of each soil layer to yield the CaCO_3 present in each layer.

Figure 21. Typical CaCO₃ concentrations by depth in tube.

The total mass in the nine bottom soil layers was then calculated for each tube and divided by the total soil in the bottom nine layers. The values derived for each tube were averaged among the four replicates (Table 6). There was high variability among the replicate tubes. Differences between the CaCO₃ measured in the low drywall dose tubes and the controls (with DI water only) were not statistically significant, nor were differences between the low and high loading rates. However, at the high drywall dose, differences between the treatment and control tubes were significant at the $p < 0.05$.

Table 6. CaCO₃ concentrations at different drywall doses and application rates

% CaSO ₄ (wgt/wgt)	mg CaCO ₃ /g of soil Mean $\pm$ std. error	
	4mL/wk	7mL/wk
0.00%	1.00 $\pm$ 0.69	0.63 $\pm$ 0.19
1.17%	2.36 $\pm$ 0.81	1.96 $\pm$ 0.69
11.7%	15.36 $\pm$ 5.92	6.39 $\pm$ 1.32

Field Simulation

For the controlled field simulation of a plant soil system under controlled rainfall, wheat plants were used because their exudates have been characterized in the literature (Ryan et al. 2001) and because hydroponic experiments done as part of this study confirmed their exudation. Ten different doses of drywall amendment were tested (Table 7). Because CaCO₃ precipitation is enhanced at high concentration and high pH (MacAdam and Parsons 2004), seeds were planted in chambers that allowed them to be grown outdoors but shielded them from natural rainfall. They were provided with varying amounts of measurable irrigation: 71 cm (28 in/y) and 84 cm (33 in/y).

Table 7. Carbon sequestration treatments

Treatment	Watering level (in/y)	Drywall (kg/m ²)	Concrete fines dose (% by weight of soil)
1 (control)	33	0	0
2	33	0.48	0
3	33	0.96	0
4	33	1.92	0
5	33	0.96	3%
6	33	1.92	3%
7 (control)	28	0	0
8	28	0.96	0
9	28	0.96	3%
10	28	1.92	0

Ground virgin drywall was prepared by grinding commercial conventional drywall (USG Sheetrock® Gypsum Panel) in a laboratory mill (Thomas-Wiley, Laboratory Mill, Model 4, Thomas Scientific USA). The pH was raised by 1 unit by adding concrete fines (D.H. Griffin Grading and Crushing) to the soil mix. Laboratory pre-trials suggested that an addition of 3% by weight of concrete fines in the soil was enough to increase the pH by 1 unit. The chambers were 1.2 m tall and 0.3 m diameter cardboard tubes filled with an engineered garden soil (a premium soil blend consisting of screened topsoil, creek sand, & compost from Blue Max Materials, Charlotte, NC), and all treatments were tested in triplicate.

A series of plantings was conducted in order to provide long-term plant exudates secretion in the soil and optimize the likelihood of CaCO₃ formation. Ground drywall was applied at the start of each new crop planting. The first and third plantings were wheat, and the second planting was corn. For the first wheat planting, twenty five wheat seeds (NC05-20814, NCSU, Raleigh, NC) were planted in each tube. Seeds were germinated (placed between two damp sheets of paper towel in the dark at 25°C) in the laboratory in October 2009 and then planted in a bed of vermiculite, perlite and peat moss (1:1:4) in the tube three days later (Day 1). The ground virgin drywall amendment was applied on Day 1. The wheat was harvested on Day 198. On July 2, 2010, a crop of corn was started. Two inches of top soil (The Scotts Company LLC) and additional ground drywall amendment doses were applied to each planting container. Four corn seeds (dwarf open pollinated corn, Athens Seed Co., Inc. Watkinsville, GA.) were planted in each container on Day 244. The first three seeds to germinate were allowed to grow, and the fourth was thinned out. The corn plants were harvested on Day 327. In mid-November 2010, the second wheat planting was undertaken using the same methods previously described. The formation of CaCO₃ will be monitored at the end on the third rotation.

First Crop Cycle Evaluation

Although it was not the purpose of the carbon sequestration experiments to evaluate above-ground plant effects, some data was collected to assess the effects of the drywall amendment on the plants. The straw length, number of kernels per plants, and the mass of 100 kernels were evaluated for each of the ten treatments. In every case, the lowest and highest doses of gypsum yielded plants with characteristics similar to controls, while the mid-range dose (0.96 kg gypsum/m²) significantly ($p < 0.01$) improved the stem length, number of kernels per plant, and the seed mass (Figures 22-24). Seed production was 25% higher and seed mass 15% greater at this medium dose.

Figure 22. Wheat stem length. Standard error bars are represented on the graph for n=3. The following significances are for $p < 0.10$ ($\mu^2 = 0.538$, power=0.898). α : statistically higher than control.

Figure 23. Kernels per plant. Standard error bars are represented on the graph for n=3. The following significances are for $p < 0.10$ ($\mu^2 = 0.330$, Power=0.385) α : statistically higher than control.

Figure 24. Weight of 100 seeds. Standard error bars are represented on the graph for $n=3$. The following significances are for $p < 0.1$ ($\mu^2 = 0.319$, Power=0.514) α : statistically higher than control.

Discussion

The use of gypsum-based drywall as a soil amendment here was a natural extension of documented gypsum use in agriculture (Olson 2000). Ground virgin drywall is composed of 85% to 90% gypsum (MSDS 2011). Gypsum enhances soil qualities and delivers calcium and sulfate, both of which are known plant supplements (USDA 2006). Plants need calcium for cell walls and membrane health (White and Broadley 2003), and sulfur is a constituent of protein and essential for N metabolism (Scherer 2001). In addition to these nutrients, pulverized drywall also provides magnesium, phosphorus, potassium and barium (Burger 1993). With an average of about 2000 lbs of virgin drywall discarded for every 2000 sq ft home built, such agricultural applications could convert what is a problematic waste stream in landfills, due to H_2S production, to a value-added commodity for crops. However, with a variety of amended drywall products available to retard fire or resist moisture, mold, and mildew, it is no longer possible to assume that a mix of virgin waste wallboard contains a simple blend of gypsum and paper.

The germination studies showed that plant seed types vary in their response to the presence of various drywall products during germination. While lettuce and canola root growth and canola germination were stimulated by dissolved conventional drywall, cucumber and wheat seed responses were negative. It is well known that certain plants such as lettuce and canola have a specific need for sulfur. Thompson and Kosab (1939) showed that lettuce seeds were “awakened” from their dormant stage faster in a solution with sulfur than in a solution without sulfur. It is also known that canola is a plant that has a high sulfur requirement (Scherer 2001). In the field, canola yield and shoots increased significantly when exposed to a gypsum amendment (Brennan et al. 2007).

There was some enhanced cucumber root growth at low conventional drywall doses, which was likely due to the fact that cucumber is a high consumer of calcium (Ingestad 1972). In cases where cucumber root growth inhibition was evident, it may have been due to cucumber seed’s sensitivity to high salinity (Papadopoulos 1994). Wheat has a relatively low S requirement (Scherer 2001), which likely explains why it did not show the same response as lettuce and canola. Brennan et al. (2007) observed that wheat shoot growth was not stimulated by gypsum, although the grain size increased by about 25%. The fact that some of the most pronounced inhibitory responses were to drywall with resistance to mold and mildew suggests that this may be the results of whatever amendments or treatments are added to give drywall these resistance properties.

The material safety data sheets (MSDS) of the drywalls tested in the germination test and bench-scale experiments do not cite any potential harmful effects from the products on aquatic life (MSDS 2009, 2009, 2011). However, the germination tests showed that fire retardant drywall and especially mold, mildew, and moisture retardant drywall had a negative impact on GS of lettuce, cucumber and wheat. The MSDS sheets for the fire retardant drywall (MSDS 2009, 2011) show that these products contain fiber glass (about 1%) and ethylene vinyl acetate polymer (about 2%, acting as glue). Even if these constituents do not have a recorded impact on living organisms, they are constituents in greater proportion than in conventional drywall, making them the likely source of the mild toxicity observed.

The MSDS of the mold, mildew, and moisture resistant drywall tested (MSDS 2009) mentions that there are less than 1% of additives in the drywall, but the additives are not described. The MSDS of another brand of mold resistant drywall (MSDS 2011) mentions that sodium pyrithione (about 2%) is added to mold resistant drywall. Sodium pyrithione is used to control mold, mildew, fungi, yeast, algae and bacteria, and it is highly toxic to aquatic organisms at high concentration. It is very water soluble and so could have easily been absorbed by the seeds (ARCH 2008). Ground mold, mildew, and moisture resistant drywall amendment significantly affected each seed type except canola. It is possible that the high stimulation of root growth by the sulfur overshadowed any toxic effects of the M drywall on canola seeds.

The results of the bench-scale experiments with canola confirmed some of the observations from the germination study. However, while in the germination tests, all types of drywall increasingly enhanced GS with increasing dose, the pot studies showed less positive effects from F and M drywall relative to the conventional type. The conventional drywall amendment significantly resulted in a higher number and larger leaves than the other drywalls. The root weight of plants was also enhanced more by conventional drywall than by most F and M doses. The overall stimulatory effect of the conventional drywall on plant vigor is consistent with studies that document the high S requirement of canola (Scherer 2001). Swan et al. (1986) observed significantly higher yield of canola when it was exposed to gypsum in a growth chamber study. Interestingly, Warman and Sampson (1994) did not observe any difference in yield between canola amended with gypsum (9.3 and 37.2 mg S/kg soil) and the control in a growth chamber. However, he observed an increase in S uptake.

The findings that conventional drywall can stimulate early growth of canola is significant to crop survival. A faster growth of the canola plant is an important asset to handle the winter temperature. Canola plants need to be exposed to the cold winter to be able to flower in the spring (vernalization) (Wright 2010). However, an extreme cold event can permanently damage the plants. The more developed the plants are before the winter, the better they will handle cold temperatures. The fact that not all drywall types can be relied upon to stimulate enhanced growth is a disappointing finding, because it suggests that careful sorting of waste wallboard will be necessary if this value-added property of conventional wallboard is to be exploited.

It was extremely unfortunate that the cold weather vulnerability of young canola plants (as described above) along with deer grazing caused so much crop loss in the field study. The plant samples collected showed no significant differences between treatment and controls, but the plants were so compromised that it is hard to have confidence in the data. Fortunately, the experiment is being repeated (Fall 2010) with a crop planted in a new and more protected location. Presently, the crop is healthy, and it is hoped that it will yield valuable (more valid) data in the spring and summer of 2011. Bora (1997) and Ahmad et al. (2005) observed a significant increase of seed yield, seed oil content and oil yield on a canola field amended with 40 kg sulfur/ha.

The experiments with artificial root exudate (ARE) did show some accumulation of CaCO_3 in tubes with soil containing the higher of two drywall-to-soil doses tested. The increased retention time offered by the slower of the two loading rates did not have an effect on CaCO_3 formation. When the drywall dose used in these tests is converted to a field application rate, it would be equivalent to 58 t sulfur/ha which is well above the typical agricultural doses recommended in the literature. Therefore, sequestration rates occurring during normal agricultural activity in regions of the country where rainfall is in the range tested here or below is likely negligible. To accomplish sequestration at the drywall doses used here, a subset of high CaSO_4 -tolerant plants would need to be identified, and it is not likely that a case could be made for taking agricultural soil out of service for this purpose. It may be possible to put previously contaminated soil into service if appropriately tolerant plants were identified or organic matter susceptible to decay was applied.

Wheat germination studies and wheat that was grown as part of a carbon sequestration assessment showed that conventional drywall did not influence the wheat GS but did have positive effects on plant growth. As the dose of ground drywall increased, the stem length, number of seed per flower, and the seed weight of wheat plants increased. The optimum dose from our testing protocol was about 1 kg of ground gypsum wallboard / m^2 (1 t/ha). This dose resulted in 8% longer stem growth, 25% more seed per flower, and 15% heavier seeds. These findings are consistent with other studies where gypsum amendments resulted in increased wheat yield (Caires et al. 2002); (Brennan et al. 2007). Rashid et al. (2008) applied 2.5 t gypsum / ha and found a 46% increase in wheat grain yield. The germination test did not show such a promising effect on wheat but this is in line with the Brennan et al. study (2007) that observed an increase of wheat yield by 25% but no increase of shoot biomass when exposed to a gypsum amendment in a pot study.

The pot studies, in which the tolerance of fescue grass to conventional drywall was tested, aimed to assess the feasibility of grinding waste virgin wallboard on a construction site and applying it to grass planted for erosion control. If the grass showed good tolerance for the gypsum, this method would eliminate the cost of moving the waste drywall off site. The results of this experiment showed that the use of ground drywall in this way may not be the best use of waste virgin drywall. While at a high drywall dose the root coverage is slightly better than the control and could enhance erosion control, the grass was not as visually attractive as the control grass. The thickness and the height of the grass were negatively affected by any gypsum wallboard amendment. The poorer top growth found here is not consistent with trends seen in other studies where gypsum amendments increased clipping weight for fescue grass, Kentucky blue, and bent grass (SoilSolutions). The enhanced root growth reported here is in accordance with prior reports.

Conclusion

Two phases of experiments have been described. The first part of Phase I aimed at evaluating ground virgin drywall as a soil amendment for biodiesel crops and grass (erosion control); the second part of Phase I examined the potential plant toxicity of three types of drywall marketed. Phase II focused on the potential to incorporate ground gypsum wallboard into a passive carbon sequestration system. Results of most Phase II experiments are reported here, although some remain on-going.

Overall the germination tests showed that (i) canola biodiesel crop survival and yield are enhanced by a ground waste drywall amendment that can be derived by sorting C&D waste at a construction site and diverting virgin drywall from the landfill; (ii) ground drywall affects different types of seeds differently and should not be used unless pre-tested for effects on early plant root growth; and (iii) amended drywall such as fire retardant drywall and especially mold, mildew, and moisture retardant drywall can be

detrimental to plants, with the effect likely due to the chemicals embedded in the paper part of the drywall.

Taken together, the results show that diversion of waste drywall from landfills for some targeted uses where high impacts can be achieved is feasible. Both federal and state governments are launching and aggressively supporting initiatives to move the U.S. vehicle fleet to liquid biofuels within the next few decades. The amount of waste drywall generated during construction together with the impact of its disposal in landfills makes its diversion for biofuel production an appealing option, because the cost of the feedstock is the critical variable in making biofuel production cost-feasible. Likewise, the ability to retain waste drywall on a construction site and put it to use for erosion control is a valuable addition to the now limited set of options for managing this material. If erosion control grass is temporary, then a strong root system with adequate, although perhaps less aesthetic, top growth could serve well until a final grass cover is established. Since gypsum is known to move downward through the soil fairly rapidly, it may be diluted out of the soil by the time a permanent grass planting occurs.

The harvest of the second field crop of canola combined with the dismantling and analysis of the field soil columns for carbon sequestration impacts will provide valuable information to complement what is reported here. Additional studies with artificial root exudate are also underway, so that a more complete assessment of the potential sequestration impacts of drywall soil amendments can be accomplished. The results will be disseminated in upcoming papers reporting on the findings of this research. Further, more details will be included in the doctoral dissertation of Fabien Besnard and the MS thesis of Rebecca Turner.

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Subproject 3) Reclaimed Structural Members: Investigations of Reused Structural Steel (Graduate student: Madeleine Grimmer; Advisor: Dr. Shen Chen)

Introduction and Literature Review

Through experimental and analytical research, this subproject investigates the feasibility of reusing structural steel elements in new construction projects after being obtained from demolition. The work presented here is divided into two distinct phases. The first phase consists of a comprehensive literature review and feasibility study of regional construction waste cyclical flows. The second phase involves an engineering feasibility structure to demonstrate a preliminary design using reclaimed structural steel. Actual structural steel members (beams) were obtained from a demolition site and a demolition scrap yard and were tested to determine their load carrying capacity and other performance measures. The test results are used to establish a “reduction factor” to be used in the demonstration design. The reduction factor accounts for uncertainties associated with strength and stiffness properties of the reclaimed structural steel elements. The preliminary design of multiple-span bridges is performed to demonstrate this design change when using reclaimed structural steel. A basic, yet practical, life cycle analysis (LCA) was performed at

the end of the study to demonstrate the viability of reclaimed steel applications and to compare the use of reclaimed structural steel to that of virgin steel.

In 2008, an estimated 3.5 million tons of construction and demolition waste was disposed of in North Carolina landfills (North Carolina RBAC, 2010). This represents approximately 31% of landfill waste contributions for 2008. With tipping fees in North Carolina ranging from \$35/ton for Mecklenburg County to \$65/ton for Dare County, reusing construction materials, such as steel (which is heavy and can cost much more to dispose of than other common construction materials), could potentially be an environmentally conscious and economically viable option. If North Carolina recovers the 31% of the construction and demolition waste annually disposed in its landfills, it would result in a potential cost avoidance of \$36.8 million based on the Mecklenburg County disposal rate of \$35/ton (North Carolina RBAC, 2010).

Currently almost 98% of structural steel used in construction is derived from recycled materials or older steel shapes that have been cut and melted down after their service life (Woods, 2007). Recycled steel can offer significant savings in greenhouse gas emissions (GGE) as a result of lower carbon dioxide production from the manufacturing process as compared to primary (or virgin) steel production.

Steel recycling has been practiced in the United States for over 170 years and is vital to conserving energy, landfill space, and raw materials (Spoerl, 2000). The recycling rate of structural beams and plates from 2004 through 2007 was almost 98%, which reflects an increase from an estimate of 85% in 1997 (Fenton 2009). According to Fenton, in 2008 an estimated 65 million tons of steel was recycled in the United States (in steel mills and foundries) as compared to an estimated 99 million tons of raw steel produced during that same year.

Strategies in Structural Steel Reclamation and Production

Reclaimed (reused) steel, unlike recycled steel, does not go through the traditional manufacturing process. Rather, reused steel involves sourcing steel components from old buildings or bridges to be used in new construction with minimal reprocessing. Most alterations consist of cleaning, additional fabrication such as installing shear studs, removing welds, filling in bolt holes, etc. The primary source of carbon emissions results from transporting reclaimed steel with minimal additional emissions required for its fabrication. Although structural steel has a high strength-to-weight ratio, it has a carbon footprint of 1,460 lbs of CO₂ (carbon dioxide) per ton of steel produced (Weisenberger, 2009). The following paragraphs describe five possible steel production scenarios involving different levels of steel reuse.

The basic form of steel production is commonly referred to as virgin steel production, named after the origin of the iron content (Figure 25). Virgin steel production involves the extraction of iron ore from mining activities and transporting it to a refinery where it is melted down in a blast furnace (usually by the basic oxygen process). The material is processed further and commonly rolled into structural shapes. The steel elements are then designed and fabricated for use in a structure (service). After service the members are transported to a landfill. The arrows represent transportation phases of the process, as shown in Figure 25.

Figure 25. Virgin steel production phases.

Another scenario is recycled steel production (Figure 26), which does not involve mining iron ore but relies only on using scrap steel as the primary feedstock in the steel making process. Pure recycled steel production is a process where the structural steel produced is composed of 100% reclaimed structural steel from other uses. The electric arc furnace is used in the production of recycled steel products (Hyde and Engel, 2000).

Figure 26. Recycled steel production phases.

A popular scenario is called mixed steel production; it includes both virgin and recycled steel inputs to the material production process (Figure 27). Once the steel has come to the end of its service life, it is recovered, reprocessed, and sent back to the foundry to be reprocessed with virgin steel material, or it is simply sent to the landfill.

Figure 27. Mixed steel production phases.

Component reuse is a process that involves one or more elements being removed from a dismantled structure and being used in a new or existing structure. Reclaimed structural steel (or salvaged structural steel) is said to have “secondary life” or “secondary service”. Comparatively, this process has the potential to require the least amount of energy input (Figure 28).

Figure 28. Component reuse phases.

Existing buildings can offer opportunities for adaptive reuse and community redevelopment. Many older buildings can be reconditioned to modern requirements. This either refers to redesign of the building and renovation or completely deconstructing the building. Whole building reuse (Figure 29) can offer significant potential cost savings because the material needed to construct or change a structure is already provided.

Figure 29. Whole building reuse.

There are many benefits to reusing structural steel elements: natural resources that would have been used to make virgin steel are conserved; it follows that carbon-based emissions released into the atmosphere are reduced; and the material is diverted from potential landfill disposal. Using reclaimed steel when appropriate can contribute to environmentally wise engineering decisions and sustainable design.

Ultimately the potential sustainability of structural steel can be summarized by the following attributes:

- Some steel buildings could be easily deconstructed, enabling the reuse of steel members in other applications.
- Compared to monolithic building components made of concrete or masonry, steel can maintain its configuration if properly deconstructed.
- Once the reclaimed steel member has been used in a new construction project minimal additional, if any, ongoing maintenance is required.
- Steel-framed buildings are durable and have long life spans, which can allow for: easy integration of mechanical systems, lower floor-to-floor heights, reduced building volume, and lower energy consumption.
- There is an existing high demand for steel scrap and steel components, which ensure future reuse and recycling applications of steel structures.

The price of reclaimed steel can vary greatly but is generally higher than the scrap steel but lower than that of new steel (Winters-Downey, 2010). Typically, the structural steel material is 25-30% of the total cost of the structural system; the remaining 70%-75% of the cost is due to fabrication and erection. Since the cost of fabrication (or alteration) of reclaimed structural steel can be much less than newly fabricated structural steel, a potential 20% or more cost reduction is possible (Melkin, 2010).

There are some disadvantages that currently pose potential problems to designers wishing to use reclaimed structural steel, including:

- The lack of any unifying market that can efficiently and consistently supply sources of reclaimed steel.
- The use of reclaimed structural steel is further complicated by the lack of an authoritative agency (or institution) that can properly regulate quality standards.
- The AISC code and the International Building Code (IBC) require reclaimed steel, like virgin steel, to meet established ASTM material standards for grade, chemical composition and type of shape and thicknesses of that shape. While there are many ASTM standard tests that can be used to determine geometric and mechanical properties, there is no guidance to selecting the most efficient and inexpensive test method.
- Potential contamination due to lead paint is a concern when selecting reclaimed structural steel elements. Removal of paint on a salvageable item by sand-blasting or hand stripping is preferred but can be labor-intensive and incurs additional costs.
- Major economic issues are associated with the coordination of locating a supply of salvageable steel and providing appropriate storage conditions for that steel within the scope of the construction project. The steel must be sourced, stored, and accurately accessed for damage within the overall project life cycle (Webster, 2002).
- A designer must establish a range of acceptable bay sizes and floor-to-floor heights that permit the use of the available reclaimed structural steel elements with minimal refabrication.
- Weldability and age of the steel are also a concern. Many older forms of structural steel, such as cast and wrought iron, are nearly impossible to weld. As a general rule, all steel produced before 1923 should be checked for weldability by metallurgical test or not considered for reuse all together (Newman, 2001).

Literature Review: Studies on Reclaimed Steel Uses

A study done in Italy (Bonoli et al., 2004) on the recycling of inert waste from construction, demolition and industrial activity, further emphasized the need to promote construction and demolition waste recycling despite prevailing industry attitudes. The study largely focused on concrete aggregate reclamation and the recycling and reuse of construction waste materials in new construction. Bonoli et al. (2004) called attention to the need for legislation that requires a methodical approach to adopting sustainable construction practices. The study did not specify a methodology or practice of reusing structural steel components rather than other materials such as rock, concrete, asphalt wood and plaster. It did offer an approach to using steel slag waste from foundries as a material that could be used in pavement construction and soil slope stability. Use of steel slag as a soil amendment for vegetated embankments was suggested in a study done in the United Kingdom by Lewis, et al. 2003.

Two studies performed independently by Fujita and Iwata (2008) and Gorgolewski (2006) proposed the development of an online database for reusable steel members that could track the cyclical process through design, fabrication, construction, maintenance, demolition, and storage. Fujita and Iwata (2008) proposed the creation of a central database of reusable members that would be properly stored and

registered to be efficiently sold and distributed within a regional industry. Also, the origin of the steel members would be known, since it would be a requirement of registration into the online database; thus the issue of unknown virgin material properties (i.e. grade of steel, chemical composition, etc.) would be reduced. This would help minimize legal concerns faced by scrap yards, which tend to be skeptical of releasing information about where steel members originated.

The Fujita and Iwata study evaluated coupon specimens cut from reclaimed steel I-beams to identify their corresponding tensile yield strengths and percent elongations. Chemical tests were also performed to determine the chemical composition of the steel, which can also be used to identify material grade. The compilation of the study's results was compared to the standards for newly-manufactured rolled members. Fujita and Iwata found that reclaimed steel members evaluated by visual inspection, mechanical property tests, chemical component tests, and degradation inspection met the requirements of the Japanese Industrial Standards (JIP), which is equivalent to the U.S.'s American Institute of Steel Construction (AISC). A comparison of dismantling practices of structures showed that steel members obtained through unscrewing high strength bolts or obtained by gas torch cutting revealed members of nearly identical quality. They concluded the study by promoting dismantling practices to minimize damage done to reusable members and encouraging a reuse system to establish an efficient industry. The study suggested the process of "designing for deconstruction".

Gorgolewski (2006) presented the most comparable study to the present research. He examined eight construction projects that required the reuse and recycling of structural steel in the construction and demolition processes. In addition to these case studies, Gorgolewski also briefly described other case studies that reused structural steel components in Canadian construction projects. A survey was conducted for seven sectors of the steel construction industry by using a list of questions which were summarized in the work (Gorgolewski, 2006). The responses to the survey indicated that steel fabricators and erectors had "some sense of what would be required" to indicate structural integrity. Mechanical laboratory testing of coupons (or standard mill steel samples cut from the reclaimed steel member) and chemical testing were the most cited methods by designers to determine material properties of the steel. It was also found that some fabricators understood that knowing the age of the steel and the availability of old technical documents would make steel identification more realistic. The responses generated from engineers and architects concluded the need for a central information source (or organization) that would be capable of storing and organizing reusable members with accurate descriptive images; this could potentially improve bidding accuracy by fabrication contractors. Designers also cited that tax incentives and emission savings could be offered to greatly increase the potential for reclaimed steel use.

Although the study did not specify that physical testing should be performed to identify the structural integrity of the components that were reused, it reemphasize that the practice of reusing steel must be interactive and precise in order for it to be cost effect. The study did not address the concern of how to establish unknown structural properties of the reclaimed steel.

Knowing the age of the building from which steel was salvaged is helpful in identifying viable members for reuse (Webster, 2002). Appearance can also serve as a guide (Beckmann, 1995). In the article entitled "Reclaimed Structural Steel and LEED Credit MR 3 – Material Reuses", published by Modern Steel Construction (MSC), an example of a private engineering firm specifying its independent requirements for using reclaimed structural steel was presented (Winters-Downey, 2010). The company suggests that salvaged structural steel be called out on the design drawings as SSS and that it be clouded for emphasis. SSS members should not include welds, riveted or bolted splices along the length of the member, and should not contain areas of accelerated localized corrosion.

Design for Deconstruction

The goal of designing for deconstruction is to consider the end-of-life management of a building material in the beginning phase of design to minimize the consumption of raw materials. The capturing of materials removed from a building's demolition or renovation, to be reused in construction projects, reduces the overall environmental impact of a building's materials. Engineers and designers can practice design for deconstruction by designing buildings that facilitate adaptation and renovation (Hood et al., 2006). Design for deconstruction involves specifying deconstruction characteristics of a building structure in order to determine the future recycle potentials of a building, for its components and materials. Certain performance indicators can be identified that give a measure of deconstructability and reusability of a building. These indicators can be as simple as using welds instead of bolt holes (if possible) or as complicated as illustrating the complete deconstruction procedure of each steel member in the deconstruction of the structure (Durmisevic and Brouwer, 2002).

There are many resources available to assist designers and engineers in designing for deconstruction. The state of California and the Integrated Waste Management Board (IWMB) jointly created a manual on designing for deconstruction, which provides a basic framework for designers and engineers attempting to design for deconstruction along with an example of a building that was designed for deconstruction (IWMB, 2001). The IWMB of California introduced an executive order by the governor in August 2000 establishing sustainable building as a primary goal for state construction and tasking the State and Consumer Services Agency with its implementation.

Integrated Design Process

The term "integrated design" refers to a design process that asks all the stakeholders of the building community and the technical planning, design, and construction teams to look at the project's objectives, building materials, systems, and assemble them from many different perspectives (Prowler, 2009). Integrated design ensures that communication is effectively executed through all stages of planning, design, and construction. At an early stage each design objective is identified, along with specific project goals that are coordinated with the interdependent design and implementation phases. Design charrettes, which are focused collaborative brainstorming sessions amongst stakeholders and project participants, have become widely accepted as a means to create an integrated design process.

Experimental Studies

Five reclaimed structural steel I-beams were obtained from demolition waste sites. The beams were divided into two groups based on their origin. Two of the beams originally purchased were later cut into two different beams with matching lengths. Full-scale flexural tests were performed on the beams. Tensile tests were performed on coupon specimens cut from the remains of the steel member. Table 8 summarizes the length of each beam as tested and the assigned designations of the beam groups.

Table 8. Beam specimens

Group	Origin	Shape	Beam	Length
A - B	FOILS Scrap Yard	W 14 x 34	A1	12' - 0" (365.8 cm)
			A2	
			B1	
			B2	
C	Demolished Idewild Elementary School	W 10 x 22	C1	9' - 4" (283.5cm)
			C2	
			C3	

The beams in Groups “A and B” were originally two beams, each of 25 ft in length. The beams were purchased for \$422.00, which is approximately 25 cents per lb. The beams from “Group C” were obtained directly from the local demolition of Idlewild Elementary school, located in Charlotte, North Carolina. The beams were donated to the research project by DH Griffin company. The company informed the research group that under ordinary circumstances the beams would most likely be sold to a scrap dealer to be remelted into new structural shapes. Tables 9 and 10 display the section properties of the beams in Groups A and B and Group C, respectively. The cross sectional area of the steel shape is denoted by A , and D is the depth of the section. The width of the flange is denoted by b_f , the thickness of the flange is denoted by t_f , and the thickness of the web is denoted by t_w . The section modulus is represented by S_x , the plastic section modulus is represented by Z_x , and the moment of inertia about the x-axis for the section is given by I_x . The appropriate AISC shape designations were determined using the measurements in the tables and were verified by AISC Table 1-1 for structural I-shapes (AISC, 2005).

Table 9. Steel beam properties: Groups A and B

W 14 x 34					
D	=	14.0 in	A	=	10.0 in ²
b_f	=	6.80 in	S_x	=	48.6 in ³
t_f	=	0.50 in	Z_x	=	54.6 in ³
t_w	=	0.30 in	I_x	=	340 in ⁴

Table 10. Steel beam properties: Group C

W 10 x 22					
D	=	10.2 in	A	=	6.49 in ²
b_f	=	5.75 in	S_x	=	23.2 in ³
t_f	=	0.36 in	Z_x	=	26.0 in ³
t_w	=	0.24 in	I_x	=	118 in ⁴

Before the full-scale flexural experiment was designed, the beams were surveyed by visual inspection for excess flange deformities, altered geometry, existing weld plates, bolt holes, web stiffeners, and other issues that would not be present for virgin steel members.

The full-scale flexural tests were performed with each beam simply-supported and loaded at the 1/3 points. The load, deflections, and strains were measured with, respectively, a pressure transducer connected to a hydraulic cylinder, cable wire potentiometers (or “wire pots”, DT), and strain gages (SG). Figure 30 displays the loading conditions, wire pots, and strain gauge locations for the Group A and B beams. The arrows indicate the point loads applied to the top flange of the beam. Figure 31 shows a similar diagram for Group C beams.

Figure 30. Full-scale flexural test set-up for Group A and B beams.

Figure 31. Full-scale flexural test set-up for Group C beams.

The greatest challenge to designing with reclaimed structural steel is adequately identifying important material and member parameters. The influence of time with respect to dimension changes, strength

(grade) changes, and deterioration mechanisms such as: fatigue, corrosion, erosion, weathering and marine growth, can greatly impact a structural steel member (Melchers, 1999). The following plots present the results of the steel coupon tests. Figure 32 shows the stress-strain curves obtained from tensile tests performed on coupon specimens cut from Group A beams. Figure 33 presents the stress-strain curves obtained from Group B beams, and Figure 34 presents the most representative stress-strain curve obtained from Group C beams.

Figure 32. Coupon test: stress versus strain for Group A beams.

Figure 33. Coupon test: stress versus strain for Group B beams.

Table 11 presents the calculated Young's modulus (E), the yield stress (F_y), and ultimate stress (F_u) from Group A and B coupons. The yield stress was determined using the 0.2% offset method as described in ASTM E8 (ASTM E8-09). Table 12 displays the same material properties determined from Group C coupons.

Figure 34. Coupon test: stress versus strain for Group C beams.

Table 11. Group A and Group B coupon test results

Coupon	E ksi (kN/mm ²)	F _y ksi (N/mm ²)	F _u ksi (N/mm ²)
A1	27,944 (193)	53.6 (370)	69.7 (481)
A2	28,771 (198)	56.2 (387)	71.7 (494)
A3	32,203 (222)	53.7 (370)	69.8 (481)
B1	34,220 (236)	52.7 (363)	69.4 (478)
B2	34,197 (236)	54.4 (375)	71.8 (495)
Average	31,467 (217)	54.1 (373)	70.5 (486)

Table 12. Group C coupon test results

Beam	E ksi (kN/mm ²)	F _y ksi (N/mm ²)	F _u ksi (N/mm ²)
C1	29,807 (205.5)	38.8 (271)	61.3 (422)
C2	28,917 (199.4)	37.9 (265)	61.4 (423)
C3	25,208 (173.8)	34.5 (241)	57.2 (394)
C4	29,329 (202.2)	38.0 (265)	62.1 (428)
Average	2,8315 (195.2)	37.3 (261)	60.5 (417)

The coupon tests indicate that the beams from Groups A and B are ASTM grade A50, which has a minimum yield strength of 50 ksi and a minimum ultimate strength of 65 ksi. The coupons cut from the Group B beams indicate that the steel is ASTM grade A36, which has a minimum yield strength of 36 ksi and a minimum ultimate strength of 58-80 ksi.

When compared to the coupon tests, the full-scale flexural load tests demonstrated larger deviations in beam performance. Figure 35 displays the extreme fiber tensile stress versus the extreme fiber tensile

strain at midspan for Group A and B beams. Figure 36 displays the extreme fiber tensile stress versus the extreme fiber tensile strain at midspan for Group C beams.

Figure 35. Beam flexural tests: stress versus strain (Group A and B beams).

Figure 36. Beam flexural tests: stress versus strain (Group C beams).

The yield stress was determined using the 0.20% offset method, as specified by ASTM E8. Table 13 displays the results of the full-scale flexural tests for the Group A and B beams. Table 14 displays the results for the full-scale flexural tests for the Group C beams. The coefficient of variance (COV) in the tables was determined as the ratio of the standard deviation to the mean (average).

Table 13. Flexural test results for Group A and B beams

Beam	Max Moment k-in (kN-mm)	Yield Stress ksi (N/mm ²)	Max Stress ksi (N/mm ²)
A1	2882.0 (325.9)	47.9 (330.5)	59.3 (409.2)
A2	2848.0 (322.1)	52.9 (365.0)	58.6 (404.3)
B1	2678.0 (302.9)	44.3 (305.7)	55.1 (380.2)
B2	3124.0 (353.3)	45.4 (313.3)	64.3 (443.7)
Average	2883.0 (326.1)	47.6 (328.6)	59.3 (409.3)
Standard Deviation	159.2	3.3	3.3
COV	0.055	0.070	0.055

Table 14. Flexural test results for Group C beams

Beam	Max Moment k-in (kN-mm)	Yield ksi (N/mm ²)
C1	822.0 (93.0)	35.4 (244.3)
C2	641.0 (72.5)	27.6 (190.4)
C3	919.9 (104.0)	39.6 (273.2)
Average	794.3 (89.8)	34.2 (236.0)
Standard Deviation	115.5	4.9
COV	0.145	0.145

The maximum shear resistance was determined from the full-scale flexural test and using loading equations from Table 3-23 of the AISC manual. Tables 15 and 16 present the maximum shear and load applied to the beams calculated from the results of the large scale flexural experiment.

Table 15. Maximum load and shear resistance for Group A and B beams

Beam	Max Shear kip (kN)	Load kip (kN)
A1	144.1 (641.0)	72.1 (320.7)
A2	142.4 (633.4)	71.2 (316.7)
B1	133.9 (595.6)	66.9 (297.6)
B2	156.2 (694.8)	78.1 (347.4)
Average	144.2 (641.2)	72.1 (320.6)
Standard Deviation	8.0	4.0
COV	0.055	0.006

Table 16. Maximum load and shear resistance for Group C beams

Beam	Max Shear kip (kN)	Load kip (kN)
C1	38.7 (172.0)	19.3 (86.0)
C2	45.4 (201.9)	22.7 (101.0)
C3	64.4 (286.5)	32.2 (143.2)
Average	49.5 (220.1)	24.7 (110.1)
Standard Deviation	10.9	48.5
COV	0.220	0.220

Tables 17 and 18 display the beam deflections for Group A and B and Group C beams, respectively.

Table 17. Flexural test deflections for Group A and B beams

Beam	Yield in (cm)	Max in (cm)	Permanent Set in (cm)
A1	0.50 (1.27)	1.48 (3.76)	0.94 (2.39)
A2	0.39 (0.99)	1.66 (4.22)	0.89 (2.26)
B1	0.49 (1.24)	1.88 (4.78)	1.53 (3.89)
B2	0.42 (1.06)	2.48 (6.29)	1.92 (4.88)
Average	0.45 (1.14)	1.88 (4.76)	1.32 (3.35)
Standard Deviation	0.05	0.38	0.43
COV	0.103	0.201	0.324

Table 18. Flexural test deflections for Group C beams

Beam	Yield in (cm)	Max in (cm)	Permanent Set in (cm)
C1	0.25 (0.64)	0.42 (1.07)	0.13 (0.33)
C2	0.45 (1.14)	0.53 (1.34)	0.2 (0.51)
C3	0.49 (1.25)	0.6 (1.52)	0.39 (0.99)
Average	0.40 (1.01)	0.52 (1.31)	0.24 (0.61)
Standard Deviation	0.10	0.07	0.11
COV	0.265	0.143	0.458

Demonstration Design: Multi-Span Bridge

The pedestrian bridge design was based approximately on the length of the beam members used in this study and the material properties (i.e. yield stress) determined from coupon testing. For this reason, the length of the bridge span designed with beams from Groups A and B was 12 feet, whereas the length of

the bridge span using Group C beams was 8 feet. The bridge design does not consider other typical bridge components such as the concrete decking, foundations, railings, etc. However, the presence of typical bridge components was considered only for calculating dead loads applied to the bridge girders. The beams were considered simply-supported beams with a uniformly distributed load. Typical sidewalk loading as specified by AASHTO (2003) was applied to the bridge beams. The minimum design uniform load for pedestrian railings is 50 pounds per linear foot (AASHTO, 2003).

Figure 37 is a simplified elevation and section of a hypothetical pedestrian bridge using Group A and B beams. Figure 38 is a simplified elevation of a hypothetical pedestrian bridge using Group C beams.

Figure 37. Demonstration pedestrian bridge design: Group A and B beams.

Figure 38. Demonstration pedestrian bridge design: Group C beams.

The maximum design shear, moment, and deflection values for the hypothetical pedestrian bridge were calculated using Case 1 of the AISC code in Table 3-23 (AISC, 2005); the results are presented in Table 19.

Table 19. Hypothetical pedestrian bridge design values (all beam groups)

	ASTM Material	Beam Span ft (m)	ω k/in (N/m)	(V)b kip (N)	(M _{max})b k-in (N-mm)	(Δ max)b in (mm)
Beams AB	Grade 50.	12 (3.7)	0.05 (8.4)	3.4 (15.1)	122.1 (13.8)	0.03 (0.66)
Beams C	Grade 36.	8 (2.4)	0.03 (5.2)	1.4 (6.3)	33.9 (3.8)	0 (0.02)

Tables 20 and 21 summarize, respectively, for Group A and B beams and Group C beams the calculated plastic moment capacities, the nominal moment capacities, and the design moment capacities for virgin steel, along with the reduced reclaimed steel design approach.

Table 20. Calculated design moment values for Group A and B beams

	M_{px} Plastic (Yielding) k-in (N-mm)	M_n Nominal (LTB) k-in (N-mm)	$\Phi_b M_n$ LRFD k-in (N-mm)	M_n/Ω_b ASD k-in (N-mm)
Reclaimed Structural Steel	2593.5 (293.0)	2403.5 (271.56)	2196.7 (2482)	1493.9 (168.8)
Virgin Steel	2730.0 (308.4)	2584.4 (292.0)	2325.0 (262.8)	1547.4 (174.8)

Table 21. Calculated design moment values for Group C beams

	M_{px}		M_n		$\Phi_b M_n$		M_n/Ω_b	
W 10 x 22	Plastic (Yielding)		Nominal (LTB)		LRFD		ASD	
	k-in (N-mm)		k-in (N-mm)		k-in (N-mm)		k-in (N-mm)	
Reclaimed Structural Steel	(800.3)	(90.4)	840.9	(95.0)	747.5	(84.4)	542.0	(61.2)
Virgin Steel	936.0	(105.7)	983.6	(111.1)	885.2	(100.0)	589.0	(66.5)

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Subproject 4) Investigations of Geopolymer Concrete (Graduate student: Brett Tempest; Advisor: Dr. Janos Gergely)

Background and Literature Review

Concrete is a versatile construction material in frequent use throughout the United States. Although its components are derived from plentiful quarry sources, the production of Portland cement is becoming an unattractive industrial process as concern mounts over energy use and greenhouse gas production. In order to produce Portland cement, limestone is heated in a kiln until CaCO_3 is reduced to CaO . This results in the release of one molecule of CO_2 for every molecule of CaO produced, as well as an assortment of greenhouse gasses generated by the combustion of fuels used to heat the kiln. In total, 0.8 tons of CO_2 are released for every ton of cement produced (Gartner 2004). The manufacture of cement accounts for at least 7% of worldwide greenhouse gas generation on an annual basis (Chindaprasirt, Chareerat et al. 2007).

Two strategies to reduce the energy and greenhouse gas intensiveness of concrete use are to seek alternate energy sources for heat generation during cement manufacture and to reduce the quantity of cement required to mix concrete of various strength. For instance, waste solvents and tires have been used in place of oil and natural gas in the kilns. Research and practice have also shown that up to 20% of the cement can be replaced by the pozzolan, fly ash.

While the use of fly ash as a pozzolan represents a major stride towards "green" concrete, the energy intensiveness of Portland cement remains a major impediment to true sustainability. As acceptance of global climate change grows, the motives for reducing greenhouse gas emission are becoming imperatives for businesses. Limits to greenhouse gas production in the form of economic penalties are already appearing on the regulatory horizons for industrial emitters. However, despite the problems with Portland cement, concrete has an institutionalized role in economical construction and does incorporate many positive environmental features such as durability, recycleability and thermal mass.

A different type of binder, called geopolymer, can serve as the cementitious agent in concrete in place of Portland cement. The term "geopolymer" was instituted by Davidovits (1991) following research into inorganic-polymer technologies for industrial applications. Geopolymers are formed when aluminosilicates dissolve in a strong base, reorganize and precipitate in a hardened state (Davidovits 1991; Duxson, Fernández-Jiménez et al. 2007). They can have properties very similar to Portland cement when formed under suitable conditions (Sofi, van Deventer et al. 2007). Geopolymers have been manufactured from industrial wastes, such as blast furnace slag, for more than 60 years and are also often referred to as alkali-activated cements or inorganic polymer cements (Duxson, Fernández-Jiménez et al. 2007). Many researchers have produced geopolymer paste with kaolinite and metakaolinite as a source material of aluminates and silicates (Alonso and Palomo 2001; Xu and van Deventer 2002). Construction silt and

industrial waste products have also been successfully used (Lampris, Lupo et al. 2009). Slavik et al. (2008) produced geopolymer material that attained structural strength with coal bottom ash and demonstrated its durability with freeze-thaw tests as well as wet-dry tests. However, the bulk of research into the use of industrial waste in geopolymer cements has centered on pulverized fuel ash or fly ash due to its wide and plentiful availability (Palomo, Grutzeck et al. 1999; Roy 1999; Buchwald and Schulz 2005; Sun 2005; Duxson, Fernández-Jiménez et al. 2007; Duxson, Provis et al. 2007; Jo, Park et al. 2007; van Deventer, Provis et al. 2007; Andini, Cioffi et al. 2008).

Of the more than 70 million tons of fly ash produced in the United States in 2006, much less than half was used; the remainder entered the waste stream. The southeast alone produced more than 30 million tons (American Coal Ash Association 2007). Landfilling fly ash has been shown to have negative environmental consequences, including leaching toxic compounds and heavy metals into groundwater. The use of fly ash as an aluminosilicate source material for geopolymer gives rise to many environmental benefits. Not only does it eliminate the pollution problems associated with Portland cement production, it relieves the burden of safely disposing of fly ash (Roy 1999).

The reaction of aluminosilicate materials in alkaline environments gives rise to the geopolymeric cements under consideration in this subproject. The basic conceptual model of the geopolymerization process is a series of three phases, which are (Glukhovsky 1959):

- 1) Dissolution: the aluminosilicate material is dissolved in an alkaline solution
- 2) Reorientation: the liberated silicate and aluminate monomers form short aluminosilicate oligomers
- 3) Solidification: the three-dimensional geopolymer matrix becomes rigid during a reaction that frequently requires the addition of heat

When geopolymer is generated for the purpose of producing concrete it is mixed with aggregates before the hardening phase initiates. The necessity of geopolymer cements to proceed through these three reaction phases requires a slightly different concrete mixing technique than is typical for Portland cement concrete. Frequently this indicates that the cements are produced by combining a dry aluminosilicate source material (fly ash) with a pre-mixed activating solution containing alkalinity and supplementary soluble silicate. The cement is mixed with aggregates, formed, and finally cured under elevated temperature conditions (Hardjito and Rangan 2005). The sustainability benefits of geopolymer cement concretes (GCC) are related to its use of the waste material, fly ash. By incorporating the fly ash into the concrete, the dual environmental challenges of landfilling the ash and reducing the amount of Portland cement-related greenhouse gas emissions are addressed. One means of improving the sustainability farther is by the incorporation of recycled material for aggregate. Demolition rubble comprises 8% of the construction and demolition waste produced in Mecklenburg County, North Carolina. In 2005, this equaled more than 31,000 tons (Mecklenburg County Land Use and Environmental Services Agency 2006).

When demolition rubble is diverted from the landfill, its current uses are largely restricted to low-grade, non-structural applications such as road sub-base and erosion control. While researchers have used RCA to manufacture structural strength concretes, there have been problems associated with the high water absorption capacity and interrupted interfacial transition zone of reclaimed aggregates (Topçu and Sengel 2004; Tu, Chen et al. 2006). These challenges might not have the same impacts in geopolymer concretes due to the absence of hydration processes and the ability of geopolymer to bond with Portland cement mortar.

RCA is used in concrete in order to reduce the natural resource demands of concrete production as well as to create an outlet for a large waste stream. The aggregates are produced by crushing pieces of concrete that are generated from demolition projects. This sort of demolition work is often aligned with large-scale material disposal undertakings. Examples include clean-up in the aftermath of earthquakes and other natural disasters as well as wrecking large facilities like the Stapleton Airport in Denver, Colorado. Elias-Ozkan suggests that municipalities can control the quantities of concrete rubble destined for landfills or unsuitable dumping grounds by more tightly controlling the issuance of demolition permits (Elias-Ozkan 2001). The opportunities for reclaiming material for aggregate in this manner could include production of aggregates on-site in the case of demolition-rebuild projects (Elias-Ozkan 2001). Doing so would reduce the energy required for transporting construction materials to the site and would control the source content.

The crushed pieces may be regraded in order to produce material suitable for use in concrete. However, there are other quality issues related to using a material of such variable consistency. Oikonomou surveyed the current state of RCA knowledge and determined that industrial and municipal requirements for greater use include a control system for collection and sorting of demolition waste, greater public support, more technical studies, and development of specifications (Oikonomou 2005). While there are preliminary documents published by RILEM and BRE, Oikonomou categorizes the information required for the safe and sustainable use of RCA as:

- 1) Historical data on the make-up of antiquated concretes
- 2) Physical characteristics: presence of contaminants, water absorption, specific gravity
- 3) Mechanical characteristics: abrasion, degradation
- 4) Environmental characteristics: leaching potential

Although the original, virgin aggregates might be visible, between 25 and 60% of volume occupied by a single RCA particle is the mortar paste that remains adhered (Tu, Chen et al. 2006). The presence of this paste affects the performance and characteristics of the aggregate in several ways. The absorption capacity of recycled aggregates tends to be higher and can require larger amounts of water to achieve adequate workability (Topçu and Sengel 2004). Hydration might also be delayed as a result of the absorption capacity. The workability of the mix is also affected by the greater angularity of RCA.

Tam et al. conducted research whereby the cement mortar was removed from the aggregate particles by treating them with acidic solutions (Tam, Tam et al. 2007). The acid attacks the CaO in the mortar and was found to be effective at reducing some of the negative physical characteristics of the RCA surrounding absorption capacity and affected surface at the interfacial zone. The process was determined to be cost effective when the benefits of waste diversion from the landfill were included (Tam, Tam et al. 2007).

The impact of RCA use on compressive strength has been well researched. In general, researchers have found that compressive strength decreases as the ratio of recycled aggregate to virgin aggregate increases. Topcu and Sengel created concrete specimens with target strengths of 2300 psi and 2900 psi (15.9 MPa - 20.0 MPa) and then replaced virgin aggregates with RCA at the rate of 30, 50, 70 and 100% (Topçu and Sengel 2004). The specimens were subjected to compressive testing, freeze-thaw cycling and flexural testing. It was found that the compressive strength decreased with the addition of RCA. However, the freeze-thaw cycling had little effect on the flexural or compressive strength of the specimens (Topçu and Sengel 2004).

Tu et al. explored the use of RCA in high performance concrete (HPC). The research group tested concretes in strength ranges suitable for structural applications (3,000-6,000 psi) (20.7-41.4 MPa) that had been created with either recycled coarse or recycled coarse and fine aggregates. It was determined that, while a strength reduction of 20-30% could be expected due to aggregate replacement, the durability of the concrete matrix and its ability to protect steel from chloride intrusion was suitable for reinforced, structural applications (Tu, Chen et al. 2006).

The challenges to maintaining stringent mechanical performance standards while using RCA in concrete mixes have been overcome by adapting either the batching process or reducing the proportion of recycled material. Tam et al. (2005) have adapted the mixing process into two stages- the first to coat the aggregate in a rich cement slurry, and the second to complete the addition of mixing water. The author found that this technique filled microcracks along the interfacial transition zone and also allowed fresh paste to reach the surface of the mineral aggregate. The problem of high water absorption capacity in RCA has been addressed by simple techniques such as presoaking aggregates prior to batching (American Concrete Pavement Association 2009).

State departments of transportation as well as national-level agencies, such as the National Cooperative Highway Research Program (NCHRP), National Ready Mix Concrete Association (NRMCA), the American Concrete Pavement Association (ACPA), and the Federal Highway Administration (FHWA) have produced guidance on the implementation of projects that permit or encourage recycled concrete aggregates in new PCC applications.

Control of concrete quality when RCA is used is achieved via several strategies that are given in state department of transportation materials specifications or in the guidance published by the previously listed agencies. These strategies include the following major themes:

- 1) Limitation to the quantity of RCA in the concrete
- 2) Preparation and handling guidelines
- 3) Limits to the source of acceptable materials
- 4) Restrictions on the type of elements permitted to contain RCA
- 5) Characterization requirements

Experimental Work

Geopolymer cements were used to create concrete having compressive strength in the range of 5,000 to 12,000 psi (34-83 MPa) with either purely virgin aggregates or with an aggregate mixture containing a proportion of recycled aggregates. The mechanical properties of these concretes were evaluated to determine the compressive, tensile, and elastic behaviors. Durability tests were also performed to assess creep and shrinkage characteristics. Prestressed and mild steel reinforced beams were made with the geopolymer cement concrete (GCC) and were tested to failure. The results of these flexural tests were used to confirm the applicability of traditional concrete design criteria and techniques. Each of these research phases is summarized in the following sections. A full report of this research is available in "Engineering Characterization of Waste Derived Geopolymer Cement Concrete for Structural Applications" (Tempest 2010).

Development of Concrete Mixtures

Three 1.5 ft³ (0.04 m³) batches of geopolymer concrete were made in the lab with the proportions given in Table 22. The primary difference in the mix designs is the quantity of NaOH and silica fume included in the activating solution. For Mix #1 and #2, 60 3"x6" (76mmx152mm) cylinders were made. 18 cylinders

were made for Mix # 3. Mixing was performed in a 3ft³ (0.08 m³) rotary mixer. Procedures for creating the cylinders followed ASTM C192 (ASTM 2007). For consistency, the step of vibrating all the cylinders for one minute after rodding was added.

Table 22. Mixing proportions lb/yd³ (kg/m³)

Mix #	1	2	3
Fly Ash	834 (495)	798 (474)	766 (455)
Water	274 (163)	274 (163)	274 (163)
NaOH	83 (49.5)	103 (61.6)	122 (72.7)
Silica Fume	62 (37.1)	77 (46.2)	91 (54.5)
Fine Aggregate	1336 (793)	1336 (793)	1336 (793)
Coarse Aggregate	1336 (793)	1336 (793)	1336 (793)

The cylinders were aged and cured according to the schedule presented in Table 23. The aging process occurred under ambient conditions in the structures lab at UNC Charlotte. After the cylinders were consolidated, the 0-hour aging batch was placed directly in the 167°F (75°C) curing oven. The other cylinders were left out in the lab and added to the oven after either 24 or 48 hours of aging. Cylinders were demolded immediately after they were removed from the oven and were stacked on a pallet under ambient conditions in the lab until testing on the 28th day. From each batch and curing group, three cylinders were tested in compression in accordance with ASTM C39.

Table 23. Number of cylinders made for each aging and curing regimen

Aging	Curing	
	24 hours	48 hours
0 hours	10	10
24 hours	10	10
48 hours	10	10

The compression tests revealed that the material strength ranged from a minimum of 4,700 psi to a maximum of 9,800 psi (32-68 MPa). The results show that strength development is related to all three variables that were manipulated in this experiment: activator concentration, aging time, and curing time. These results verify trends found by other researchers as well as provide insight into their interrelation.

The average mix strength was highest for the Mix #2 group and lowest for the Mix #3 group. Thus, strength seemed to improve when the alkalinity of the activating solution was increased from 10% NaOH/fly ash to 13% NaOH/fly ash, but declined when the alkalinity was further increased to 16% NaOH/fly ash. Despite these general trends with strength development related to the alkalinity of the activating solution, there is an important influence from the aging and curing schedule.

The results presented in Table 24 show two main trends in strength development for the aging and curing routines used in this course of experiments. Increasing aging time from 0 to 2 days improved the 28-day compressive strength in all cases. Increased curing time at 167° F (75° C) also improved the 28-day

strength in all cases. These results are illustrated in Figure 39. For the Mix 1 specimens, high temperature curing for an additional day improved the compressive strength an average of 12%. For these same specimens, the impact of additional aging was an average of 6% increase in compressive strength. For the Mix 2 specimens, the effect of additional high temperature curing time was an average compressive strength increase of 13%. The impact of additional aging time on these specimens was an increase of strength by 8% on average. Mix #3 showed the greatest improvement in strength with both increased aging time and 24 hours of curing. However, the maximum strength was achieved for Mix #2.

Table 24. Results of compression and tension tests

Mix #	Aging Time (days)	Curing Time (hours)	f'_c psi, (MPa)	f_t psi, (MPa)
1	0	24	5,302 (37)	474 (3.3)
1	0	48	6,010 (41)	558 (3.9)
1	1	24	5,915 (41)	420 (2.9)
1	1	48	6,465 (45)	544 (3.8)
1	2	24	5,939 (41)	485 (3.3)
1	2	48	6,978 (48)	550 (3.8)
2	0	24	7,356 (51)	708 (4.9)
2	0	48	7,983 (55)	764 (5.3)
2	1	24	7,732 (53)	555 (3.8)
2	1	48	9,308 (64)	696 (4.8)
2	2	24	8,287 (57)	879 (6.1)
2	2	48	9,787 (67)	851 (5.9)
3	0	24	4,708 (32)	
3	0	48	6,336 (44)	
3	1	24	6,171 (43)	
3	1	48	6,780 (47)	
3	2	24	7,926 (55)	
3	2	48	8,094 (56)

Figure 39. Compressive strength development with aging and curing time.

Recycled aggregates collected from the demolition project case study were incorporated at various rates into the Mix #1 described above. Concrete cylinders were prepared from the recycled aggregate mixes and were tested after 7 and 28 days. Two sets of cylinders were made using the mix designs given in Table 25. Thus, two batches representing each virgin aggregate replacement ratio was mixed two times. The cylinders were aged for two days and then cured at 167°F (75°C) for two days. The cylinders were tested in compression using ASTM C39 procedures at cylinder ages of 7 days and 28 days (ASTM 2005). The results of the compression test are provided in Table 26. The strength ranged from 4,997 psi (34.5 MPa) to 7,290 psi (50.3 MPa) at 7 days. 28-day cylinder strengths ranged from 5,310 psi (36.6 MPa) to 8,359 psi (57.6 MPa). All mix designs showed an increase in compressive strength between the 7th and 28th day.

Table 25. Mixing proportions for GCC containing recycled aggregate, lb/yd³ (kg/m³)

Component	Virgin Aggregate Replacement Ratio						
	100%	80%	50%	40%	30%	20%	10%
Fly Ash	815 (484)	815 (484)	815 (484)	815 (484)	815 (484)	815 (484)	815 (484)
Water	268 (160)	268 (160)	268 (160)	268 (160)	268 (160)	268 (160)	268 (160)
NaOH	82 (48)	82 (48)	82 (48)	82 (48)	82 (48)	82 (48)	82 (48)
Silica Fume	61 (36)	61 (36)	61 (36)	61 (36)	61 (36)	61 (36)	61 (36)
Fine Aggregate	1304 (774)	1304 (774)	1304 (774)	1304 (774)	1304 (774)	1304 (774)	1304 (774)
Coarse Aggregate	0 (0)	261 (155)	652 (387)	783 (464)	913 (542)	1044 (619)	1174 (697)
Recycled Coarse Aggregate	1305 (774)	1044 (619)	652 (387)	522 (310)	391 (232)	261 (155)	131 (77)

Table 26. Compressive strength results for GCC mixes containing recycled aggregate, psi (MPa)

	Virgin Aggregate Replacement Ratio						
	100%	80%	50%	40%	30%	20%	10%
Batch 1, 7-Day	5,490 (37.9)	4,997 (34.5)	6,388 (44)	6,964 (48)	5,218 (36)	4,607 (31.8)	6,771 (46.7)
Batch 1, 28-Day	6,336 (43.7)	6,220 (42.9)	7,505 (51.7)	8,127 (56)	5,310 (36.6)	6,111 (42.1)	7,570 (52.2)
Batch 2, 7-Day	6,715 (46.3)	6,157 (42.5)	7,290 (50.3)	6,694 (46.2)	6,657 (45.9)	6,517 (44.9)	7,163 (49.4)
Batch 2, 28-Day	7,209 (49.7)	6,677 (46)	8,359 (57.6)	7,310 (50.4)	7,318 (50.5)	7,324 (50.5)	7,938 (54.7)

The results from the concrete mixtures with only virgin aggregates as well as the two sets of GCC mixed with recycled aggregates indicate that it is possible to develop compressive strength suitable for structural applications while using significant proportions of recycled aggregates. All replacement ratios from 10% through 100% provided concrete with greater than 6,000 psi (41.4 MPa) at 28 days. For strength development purposes, the optimal quantity of recycled aggregate to replace, as determined by this study, is between 40 and 50% by weight.

Durability Testing

Durability specimens were manufactured with GC containing 45% RCA by mass of the coarse aggregates as well as GCC with 100% virgin aggregates and the PCC control concrete. The RCA used originated from the Idlewild demolition case study described in previous reports. The durability specimens include prisms to measure concrete shrinkage and 15 cm x 30 cm cylindrical specimens to measure creep under sustained compressive loads.

The test set-up for the creep specimens is shown in Figure 40. The apparatus maintains a constant load of 35,000 lb (156 kN) on the concrete cylinders, and strain is measured at discrete time intervals.

Figure 40. Creep specimen loading apparatus.

Strain was measured using a demountable strain gage over the course of 200 days. Figure 41 shows that C_u , the ratio of elastic strains and creep strains, for the GCC appears to be less than 1.0. The range defined by $C_u=1.30$ and $C_u=4.15$ on the charts denotes the typical range of ultimate strain for Portland cement concrete. The GCC is well outside the lower end of this range. This indicates that the creep behavior of GCC is significantly improved over the expected behavior of PCC.

Figure 41. GCC and PCC creep compared to the range of ultimate creep values for Portland cement concrete.

Data was available for 224 days of post-curing shrinkage for PCC and GCC-2. However, data only extend 56 days for the GCC-R batch. Figure 42 illustrates the increase in shrinkage strain with time. The largest shrinkage strains were found in the PCC mix. Shrinkage increased rapidly between day 0 and day 28. The strains appear to be approaching $700 \times 10^{-6} \%$, which is within the typical range for Portland cement concrete. Moist-cured Portland cement concrete has an average ultimate strain of $800 \times 10^{-6} \%$. GCC-R approaches an upper value of 270×10^{-6} at 56 days. Although the test duration was shorter than for GCC-2, it appears that the ultimate shrinkage will be higher for the concrete containing recycled aggregates. This indicates that the recycled aggregates have made some impact on the shrinkage characteristics of the concrete.

Figure 42. Comparison of shrinkage in PCC-1, GCC-2 and GCC-R specimens.

Geopolymer cement concretes with and without recycled aggregates showed lower strains at each time increment than Portland cement concrete. Shrinkage strains in the PCC batch were more than 200% of the strains found in both geopolymer materials. For the ultimate shrinkage strain $(\epsilon_{sh})_u$ the data do appear to approach an asymptote. For PCC the shrinkage strains appear to approach 700×10^{-6} in/in (mm/mm), which is typical for moist-cured Portland cement materials. For the GCC-2 batch, the limit appears that it will be in the range of 300×10^{-6} in/in (mm/mm). The results of the shrinkage and creep tests indicate that geopolymer cement concretes with and without recycled aggregates are promising candidates for precast and prestressed applications where volume changes can result in significant performance degradation.

It is important to note that the test procedure is only set-up to measure shrinkage in the GCC that occurred after high temperature curing. However, it will be important to understand and predict any volume changes that occur in the GCC as it undergoes the aging process and the high-temperature curing process. These changes could be attributable to both the action of water evaporation from pore spaces in the GCC as well as to the formation of polymeric bonds during the hardening phase. A technique to measure these strains would need to account for the thermal expansion that occurs during elevated temperature curing.

Flexural Tests

A series of four mild-steel reinforced beams and three prestressed beams was prepared using accepted reinforced concrete design and construction practice. In the mild-steel reinforced series, three of the four beams were prepared with GCC either containing virgin aggregates or a combination of RCA and virgin aggregates. The fourth beam was a control, having PCC and virgin aggregates. The prestressed beams included one having GCC with virgin aggregates, one having GCC with RCA, and one with the PCC control mix. More specific details for each mix are provided in the Table 27. The concrete was truck-mixed and placed using conventional technology as shown in Figure 43.

Table 27. Concrete details and compressive strength at time of testing

Concrete Mix	Characteristic	Compressive Strength, psi (MPa)
GCC-1	First batch of geopolymer cement concrete with virgin aggregates	11,000 (75.8)
GCC-2	Second batch of geopolymer cement concrete with virgin aggregates	11,900 (82.0)
PCC-1	Portland cement concrete	12,500 (86.2)
GCC-R	Geopolymer cement concrete with 45% recycled aggregates	9,200 (63.4)

Figure 43. Adding materials to mixing truck.

Mild Steel Reinforced Beams

One beam was poured of each of the concrete mixtures presented in Table 27. The beams had reinforcement details as shown in Table 28 and Figure 44. Once cured, the beams were supported and loaded as shown in Figures 45 and 46. Equal loads were applied at the 1/3-span points. Displacements were measured at the beam centerline as well as directly under the loading points. The load was applied through a deep steel spreader beam and was generated with a hydraulic cylinder mounted to the load-frame as shown in the photo.

The beams prepared with GCC exhibited load deflection behavior typical of beams created with PCC. Material properties determined from tests of GCC specimens, were used in conjunction with reinforced concrete design formulas and methods to predict the performance of the reinforced and prestressed GCC beams. Overall, there was very good correlation between the predicted and observed results as measured by the deflection predictions, cracking moment predictions, and ultimate moment predictions. Figure 47 compares the performance of the GCC beams and the PCC control beam. The beam containing recycled aggregates, GCC-R-B4, performed nearly identically to the PCC control beam, PCC-1-B3. The beam containing geopolymers cement with virgin aggregates achieved significantly higher deflection prior to failure than the PCC control.

Table 28. Reinforcing steel schedule for GCC-2-B2, PCC-1-B3 and GCC-R-B4

Bar Type	Grade	Diameter	Dimension					
			1	2	3	4	5	6
A	60	0.5 (12.7)		140 (3,560)				
B	60	0.375 (9.5)	4.5 (114)	5.0 (127)	9 (229)	5 (127)	9 (229)	4.5 (114)

Figure 44. Placement and size of reinforcing steel in GCC-2-B2, PCC-1-B3, and GCC-R-B4.

Figure 45. Beam loading and support geometry.

Figure 46. Mild steel reinforced beam loaded in the test frame.

Figure 47. Comparison of load vs. mid-span deflection for four beams tested.

In order to verify the applicability of existing design procedures, the prevailing concrete design guideline, ACI 318, was used to predict the ultimate load capacity of the mild steel reinforced beams. The average ratio of predicted to observed performance was 1.34. This indicates that the design provisions are slightly conservative in predicting the performance of GCC beams. However, since the beams were underreinforced, calculated results are typically found to be conservative. The predicted and observed moment capacity for each of the beams is given in Table 29. The close agreement of the capacity predictions with the observed performance indicates that the existing design formulations for reinforced concrete may be applied to GCC beams.

Table 29. Ratio of observed to predicted cracking moment and ultimate moment kip-in, (kN-m)

<i>Beam</i>	M_n (<i>observed</i>)	M_n (<i>predicted</i>)	$\frac{M_n (observed)}{M_n (calculated)}$
GCC-1-B1	600 (68)	423 (47.8)	1.42
GCC-2-B2	760 (85.9)	567 (64.1)	1.34
PCC-1-B3	670 (75.7)	568 (64.2)	1.18
GCC-R-B4	682 (77.0)	540 (61.0)	1.26

Prestressed Concrete Beams

Three prestressed concrete beams were prepared with reinforcing details as shown in Table 30 and Figure 48. As with the mild steel reinforced beams, each prestressed beam featured a different concrete mix, as described in Table 27. Using the test set-up shown in Figure 49, the beams were loaded until they failed. Load was generated by a hydraulic jack attached to a manually controlled hydraulic pump. The load application was monotonic and proceeded at a rate of 3,000 lb/sec (13 kN/sec) during the linear portions of the load-deflection history.

The load-deflection behavior of the prestressed beams is shown in Figure 50. All three beams exhibited similar behavior up to the point of concrete crushing, which occurred at loads of approximately 90,000 lb (400 kN). The beam strength anticipated by accepted design equations provided in ACI 318 was very similar to the failure loads recorded during the load tests. The predicted strength and observed strength for each of the three beams is given in Table 31. The average ratio of predicted to observed moment capacity was 1.03.

Table 30. Reinforcing steel schedule for prestressed beams, in (cm)

Bar Type	Grade	Diameter	Dimension					
			1	2	3	4	5	6
A	60	0.5 (1.27)		212 (538)				
B	60	0.375 (.95)	4.5 (114)	8.0 (20)	16 (41)	8 (20)	16 (41)	4.5 (11)
C	270	0.5 (1.27)		216 (549)

Figure 48. Reinforcing steel placement and beam cross section for prestressed beams.

Figure 49. Prestressed beam test set-up.

Figure 50. Load deflection curves for prestressed beams plotted together.

Table 31. Computed ultimate moment values, kip-in (kN-m).

Beam	M_n (observed)	M_n (predicted)	$\frac{M_n (observed)}{M_n (calculated)}$
GCC-2-P1	3,125 (353)	3,255 (368)	0.96
PCC-1-P2	3,112 (352)	3,350 (378)	0.93
GCC-R-P3	3,124 (353)	2,805 (317)	1.11

Conclusions and Recommendations for Further Study

Geopolymer cement concretes offer an alternative to Portland cement concrete that can provide many of the same structural functions but in a more sustainable fashion by reducing the energy inputs and emissions outputs of the manufacturing process. A series of studies were performed to assess the mechanical performance of geopolymer material test specimens and structural components. These tests have verified the applicability of some design methods for flexural Portland cement concrete components to GCC.

These results indicate that GCC is a feasible material for structural concrete applications. This study has focused on concretes made from only a few batches of source materials and has evaluated the performance of concretes under limited conditions. In order to improve the quality of some of the results, as well as to increase confidence in some of the conclusions, the following are suggested for further study:

- The gradation of aggregates should be optimized more rigorously for the concretes under evaluation. It may be possible to improve the workability and some mechanical characteristics of the concrete by studying the interaction of mortar and aggregate in both the plastic material as well as the cured material.
- Although there was not sufficient data recorded in this study to provide a correlation, it appears that the age of the concrete may have a significant impact on the stress-strain relationship or the ultimate strain. Higher ultimate strains may be found in GCC materials at

later ages. This was evidenced by the very large deflections recorded in the test of the 229 day-old beam GCC-2-B2 prior to reaching its ultimate moment. Mineralogical changes over time might cause such a change in the macro-performance of the material and should be investigated.

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Subproject 5) Recycled Aggregate Concrete with Crushed Recycled Brick Masonry Aggregate
(Graduate student: Tara Cavalline; Advisor: Dr. David C. Weggel)

Introduction and Literature Review

Brick Used as Aggregate in Cementitious Materials

Use of construction and demolition waste in cementitious materials, including the use of brick and recycled brick masonry as aggregates, is far from a novel concept. In Roman times, structures such as buildings and water supply channels were constructed using natural pozzolans and crushed brick (Hansen 1992). The earliest use of crushed brick in cementitious materials using Portland cement occurred in Germany in 1860 (Devenny and Khalaf 1999, Hansen 1992). In Europe, many buildings damaged or destroyed by bombs during World War II included brick masonry. As part of rebuilding the damaged cities in Germany, rubble recycling plants were created, producing crushed brick masonry aggregate that was used in new concrete construction. The crushed brick masonry aggregate produced by these plants was used to construct 175,000 new housing units (Hansen 1992).

After debris from World War II bombing was cleared, bricks were no longer widely used as concrete aggregates in Europe (Khalaf and DeVenny 2004). However, economic conditions and lack of suitable sources of natural aggregates has resulted in brick being used as aggregate in developing nations over the past decades. Use of brick aggregate in concrete has become common in locations where sources of natural aggregate are not available and the cost of importing natural aggregate is prohibitive or politically unfeasible. An example is Bangladesh, where the land primarily consists of a deltaic plain (Mazumder et. al 2006). Here, new bricks are often made and are then subsequently crushed for use as aggregates. However, even in locations such as this, brick aggregate concrete has been limited to "low level uses such as pipe bedding or site fill," and "this is mainly due to impurities in the material, lack of knowledge of its performance in concrete, lack of available standards on the use of recycled aggregates in concrete and high water absorption characteristics of recycled brick aggregates (Khalaf 2006)."

In the United States and in other developed nations, use of recycled brick masonry as aggregate in concrete and other cementitious materials could be economically advantageous in many locales due to the cost and increasingly limited availability of natural aggregate sources. Landfill space would be saved, and the environmental benefits of re-use of an existing waste material would be realized. Brick aggregate concrete mixtures can offer other benefits over natural aggregate concrete as well. Brick aggregate concrete mixtures are lighter than similar normal aggregate concrete mixtures, which can significantly reduce the self-weight of a concrete structure. Khalaf (2006) notes that “by using concrete of low density, smaller sections (for structural members) can be used and consequently the size of foundations can be reduced, representing a financial savings.”

Unfortunately, a number of impediments stand in the way of widespread acceptance and use of recycled brick masonry as aggregate in concrete and other cementitious materials. Lack of knowledge of performance of brick aggregate concrete is the major obstacle for reuse of brick waste (Debeib and Kenai 2008). “Only a small amount of work has been carried out using the types of brick that are commonly used in construction today, and there is little knowledge on the subject in the United Kingdom and other countries (Khalaf 2006).” However, with increased environmental awareness during the past decades and with economic incentives to re-use construction and demolition waste, use of masonry rubble and recycled concrete aggregate is once again receiving attention from the engineering and scientific community.

Robinson et. al (2004) state that factors limiting the reuse of concrete as aggregates (and, it can be presumed, the reuse of demolished brick masonry as aggregates) include “processing costs, quality and performance issues, and lack of large quantities where needed.” Additional complications are caused by contaminants that are often present in the material. Fragments of concrete and timber may be incorporated into the demolition debris, and the fragments of brick inherently include some fractions of attached and detached mortar (Tam and Tam 2006). Demolished brick masonry is often contaminated with plaster and sheetrock, although the increased prevalence of on-site separation of demolition waste is helping this situation.

Performance factors that limit the use of recycled concrete aggregate include specific gravity, absorption, soundness (resistance to environmental conditions such as chemical and physical weathering), gradation (grain-size distribution), and contaminant solubility and the potential for groundwater contamination (Robinson et. al 2004).”

Robinson et. al (2004) also indicate that external factors that influence the limited use of recycled aggregates include “cost, state specifications, and environmental regulations.” Other problems related to the crushing and handling of recycled brick masonry aggregates have been noted, particularly due to the fines generated during crushing. Chen et. al (2003) studied the effects of using both unwashed and washed recycled aggregate in concrete mixtures. Using unwashed recycled aggregates resulted in lower strengths, particularly flexural strength, with a more readily observable effect at lower water/cement ratios.

Given the current economic and social climate, additional research to understand the performance of recycled brick masonry aggregate used in concrete and other cementitious materials is both timely and imperative. Current research by this project team and by other researchers aims to address these concerns by gaining a better understanding of the performance and limitations of recycled aggregates. Through a better technical understanding of the behavior of fresh and hardened concrete made from recycled aggregates, regulatory agencies may develop a comfort level with recycled aggregates, in turn easing restrictions on their use and allowing them to be competitive in the construction market.

Studies on Brick Aggregate Concrete

The earliest published work on recycled brick used in cementitious materials is that of Newman (1946), who performed testing on concrete and mortars made from brick rubble obtained from demolished shelters used during World War II. Newman's brick aggregate concrete mixtures were made (1) using brick as both fine and coarse aggregate, and (2) using brick as coarse aggregate with river sand. Mixtures were created using brick from demolished shelters from eight cities in England, Scotland, and Wales, with water-cement ratios varied from approximately 0.70 to 1.05 in order to maintain a consistent slump. Compressive strengths resulting from these mixtures varied based upon water cement ratio and source of brick aggregate, and ranged from 875 to 5770 psi for mixtures using brick as both fine and coarse aggregate, and from 945 to 5690 psi for mixtures using brick only as coarse aggregate. Other research performed in the 1940s produced brick aggregate concrete with compressive strengths between 15 and 25 MPa (approximately 2175 to 3625 psi) (Hansen 1992), although Khalaf (2006) attributes these low strengths to use of a weaker cement produced during this era or impurities present in the brick aggregates used.

A relatively large gap in time exists between the testing performed on brick aggregate concrete created using World War II rubble and the "next generation" of testing on brick aggregates used in cementitious materials. Khan and Choudhury (1978) present information on typical brick aggregate concrete mixtures used in Bangladesh. Batching processes are described, and information on mechanical properties is presented. Compressive strengths of these mixtures ranged from 3950 to 6260 psi, which is typical of concrete used in many modern structural applications. The authors note that characteristics and quality of the original brick weigh heavily on the performance of recycled brick aggregate, and this quality is dependent on the initial source mineralogy as well as the firing process.

More recent studies related to brick aggregate concrete and mortar typically focus on addressing the workability issues inherent in use of the very porous brick aggregates as well as establishing mixtures that exhibit suitable mechanical properties. A key part of designing brick aggregate concrete and mortar mixtures includes addressing the high water demand. Additional water needs to be added to brick aggregate mixtures in order to provide the required workability, but this often comes at the expense of strength of the hardened concrete or mortar. Researchers have tried to address this issue by either pre-soaking the brick aggregate prior to mixing (Hansen 1992) or by modifying the mixing procedure to ensure that the water used in the mixture has adequate contact time with the cement (Khaloo 1994).

A number of published studies present data on the mechanical properties of brick aggregate concrete (Akhtaruzzaman and Hasnat 1983, Akhtaruzzaman and Hasnat 1986, Schultz and Hendricks 1992, Pakvor et. al 1994, Debeib and Kenai 2008, among others), and to some extent, the durability characteristics of brick aggregate concrete (Litvan and Sereda 1977 and Kibriya and Speare 1996). The mechanical properties and durability characteristics of brick aggregate concrete are often compared to the properties of similar concrete mixtures that contain normal aggregate. Most of the studies perused as part of this literature review investigated the effect of varying percentages of brick aggregate replacement (for both fine and coarse aggregates) on mechanical properties such as compressive strength, tensile strength, flexural strength, and modulus of elasticity of brick aggregate concrete and mortar.

By the turn of the century, mixture proportioning for brick aggregate concrete had progressed to a point where mixtures of acceptable strength and early age performance characteristics were being produced quite readily. For example, a study by Levy and Helene (2004) concluded that "concrete made with recycled aggregates (20%, 50%, and 100% replacement) from old masonry or from old concrete can have the same fresh workability and can achieve the same compressive strength of concrete made by natural aggregates in the range of 20 to 40 MPa at 28-days. Padmini et al. (2001) tested brick aggregate concrete

mixtures generated using a five-factor factorial design in order to isolate the characteristics most influential in governing the compressive strength of the concrete. It was found that cement content, moisture content of the brick aggregate (pre-soaked vs. not pre-soaked), and strength of the brick aggregate had the most influence on compressive strength, while sand content and aggregate size had minimal influence. It is noted that cement content had a significantly greater influence on compressive strength than the any of the other four factors. Subsequently, additional testing was done to further explore the effects of variation of the three parameters deemed most influential (listed above) on compressive, flexural, and splitting tensile strengths. Data obtained was used to create relationship curves that could be used as guidelines for developing new mixture designs for brick aggregate concrete based on the ACI 211.2 procedure for structural lightweight aggregate concrete.

Cachim (2009) performed a study on the mechanical properties of brick aggregate concrete made using replacements of natural coarse aggregates with brick aggregates at levels of 15% and 30%. Natural sands were used for all mixtures. The brick aggregate used by Cachim was obtained from construction waste, although the mortar content is not discussed. Cachim (2009) tested the aggregates to determine the initial absorption capacity, measuring absorption percentages for the first 2 minutes and 5 minutes, in order to determine “a curve of the evolution of the water absorption with time.” He found that at least 75% of total water absorption by the brick aggregates occurred within the first 2 minutes, while at least 91% of the total water absorption by the brick aggregates occurred within the first 5 minutes. Cachim used this information to establish a mixing protocol that included addition of a percentage of the total absorption of the brick aggregates in order to ensure that “aggregates absorbed part of the water and that the pores were at least partly saturated” prior to adding cement. This was done in lieu of soaking the aggregates, as has been done many previous studies.

Cachim’s (2009) results showed reductions in compressive strengths for the brick aggregate concretes that were similar to the findings of de Brito et al. (2005) and Akhtaruzzaman and Hasnat (1983), although Cachim states that “the attained strength showed that crushed bricks can be used to substitute natural aggregate in concrete (24.5 to 38.5 MPa (approximately 3550 to 5580 psi) at 28 days) for percentages from about 15% to 20%. Cachim indicates that the saturated brick aggregates provide a measure of internal curing due to the water available to facilitate hydration after the mixture has used up the readily available mix water. Cachim concludes “Thus, the moderate use of saturated bricks in concrete act as a self-curing agent for concrete... The correct balance between the reduced strength of crushed brick aggregates and its effectiveness as a self curing agent is the key point to use them as aggregates in concrete.”

The influence of mortar attached to the brick aggregate on the fresh and hardened properties of brick aggregate concrete has been studied by relatively few. Attached mortar is a source of sulfate (Newman 1946, de Juan and Gutierrez 2009), and significantly influences the absorption of the brick aggregate. The role of the mortar fraction in recycled brick aggregates needs to be further defined in order to make brick aggregate concrete a viable construction material. De Juan and Gutierrez (2009) provided relationships between mortar content and aggregate fraction size, mortar content and absorption, mortar content and sulfate content, and mortar content and abrasion resistance. This study did not, however, link the mortar content to test results of other mechanical or durability properties.

More recent studies have focused on improving basic brick aggregate concrete mixtures with modern technologies utilized in other conventional Portland cement concrete mixtures. Jankovic (2002) performed testing on brick aggregate concrete that included varying dosage levels of polymer admixture. Results from her study indicate that increasing levels of polymer admixture generally result in increases in compressive and flexural strength, while reducing the modulus of elasticity. The polymer-modified brick

aggregate concrete mixtures also had lower absorptions, displayed greater creep, and reduced shrinkage. Other studies have been performed on the use of brick fines in concrete mixtures. Corinaldesi et al. (2002) explored the use of crushed brick as fine aggregate, as well as the use of brick fines obtained from the crushing process, in mortar. In these mixtures, polypropylene and stainless steel fibers were added to explore the effects on compressive strength, flexural strength, bond strength and shrinkage. Stainless steel fibers provided improved mechanical properties, while the polypropylene fibers did not have beneficial effects. It was concluded that in many circumstances, the cost of addition of fibers would be offset by the lower cost of brick aggregates. Corinaldesi and Moriconi (2004) performed additional studies on the use of brick aggregates in normal concrete mixtures as well as the addition of brick fines to self-consolidating concrete. Both types of mixtures developed as part of this study were deemed to have acceptable performance according to the authors.

Despite the difficulties encountered in producing brick aggregate concrete with suitable workability, very few studies attempted to use water-reducing or superplasticizing admixtures. One exception is a study by Khalaf (2006) in which brick aggregate concrete was made using coarse aggregates made from crushed new bricks that did not include a mortar fraction or impurities that would be found in demolished brick rubble. A superplasticizing admixture was used to assist in achieving suitable workability and to assist in maintaining the desired water to cement ratios for the mixtures (which varied from 0.55 to 0.7, relatively high for modern-day concrete). Khalaf attempted to understand and refine the mixing procedure for brick aggregate concrete during his study (2006). For mixtures that did not use superplasticizing admixtures, the author indicated that the brick aggregate was pre-wet prior to mixing in order to minimize initial absorption of the mix water. Khalaf's targeted compressive strengths of the mixtures at 28-days were 43 MPa (approximately 6235 psi) and 50 MPa (approximately 7250 psi), which are significantly higher than the compressive strengths targeted in many earlier studies, and are consistent with the design strengths of many structural concrete mixtures used today.

Interest in pozzolanic qualities of brick (Barronio and Binda 1997) has driven some recent research. Zakaria and Cabrera (1996) found that, compared to the normal aggregate concrete control samples, brick aggregate concrete at early ages (less than 7 days) had relatively lower compressive strengths. But at later ages, compressive strengths for the brick aggregate concrete had relatively higher compressive strengths. Zakaria and Cabrera indicate that this finding is in agreement with researchers in Germany (Schulz and Hendricks 1992), who "attributed this to the pozzolanic effect of the finely ground portion of the burnt brick." Khatib (2005) studied brick aggregate concrete mixtures prepared using crushed brick to replace fine aggregate. Brick aggregate was obtained from demolished structures, so it is likely that some fraction consisted of mortar. He found that with regards to compressive strength, the mixture prepared with the 25% brick aggregate replacement had the same 90-day strength as the 28-day strength, even though at 28-days the ratio was 0.84. Khatib attributes the strength gain between 28 and 90 days to pozzolanic effects provided by the brick fine aggregate. He concludes that "replacing (sand) in concrete with fine CB (crushed brick) does not cause substantial reduction in long-term strength even at high replacement levels. With up to 50% replacement, the long-term strength is similar to that of the control, whereas at 100% replacement, a reduction of only less than 10% occurs. Khatib (2005) also found that increased percentages of brick aggregate result in lower shrinkage.

Recycled Brick Masonry Aggregate Concrete

Concrete mixtures of varying strength and workability were developed using crushed brick masonry as a replacement for normal weight coarse aggregate. In order to obtain the 'cleanest' demolished brick masonry that can be achieved via readily employable source separation techniques for this study, the crushed brick masonry aggregate was made from brick masonry obtained from a single demolition site, Idlewild Elementary School in Charlotte, North Carolina.

Impurities in the brick masonry aggregate were minimized by ensuring that components such as sheetrock, acoustical tile, roof material, and other interior building components were removed prior to demolition of the brick masonry walls. The demolition contractor, D. H. Griffin Co., utilized the “top down” demolition sequence in which the concrete slab-on-grade was allowed to remain in place while other building components were sequentially demolished from the roof down. This facilitated separation of building components on a “clean” surface as they were demolished, and the brick masonry was removed with minimal contamination from other building components. The brick masonry that was used in this study was monitored by UNC Charlotte personnel during the demolition process, during loading and transport to a local crushing yard, and during transport to UNC Charlotte laboratories.

Figure 51. Cafeteria at Idlewild Elementary School prior to demolition. Walls are mainly clay brick, with clay tile comprising the lower portion of some walls.

Figure 52. Demolition of the brick masonry walls at Idlewild Elementary School. The concrete slab-on-grade was left in place while the brick masonry walls were demolished, facilitating a “clean” working surface for separation and collection of the demolished brick masonry as well as other recycled building materials.

Figure 53. Partially-demolished brick masonry wall at Idlewild Elementary School.

Figure 54. Demolished brick masonry aggregate from Idlewild Elementary School being loaded for transport to D. H. Griffin Co.'s crushing and grading operation.

Figure 55. The crushing and grading operations of D. H. Griffin Co., located in Charlotte, North Carolina.

Figure 56. Demolished brick masonry wall from Idlewild Elementary School awaiting crushing and grading at D. H. Griffin Co.

Figure 57. After being crushed and graded, recycled brick masonry aggregate from Idlewild Elementary School walls comes off of the conveyors, where it was subsequently shoveled into barrels and transported to UNC Charlotte laboratories.

Characterization of Whole Brick and Tile

Prior to transport to the crushing and grading facility, samples of whole brick and whole clay tile were obtained from the demolished rubble in order to determine properties in accordance with ASTM C67, “Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile.” The whole brick and whole clay tile samples were taken to UNC Charlotte’s laboratories, where most of the attached mortar was removed by mechanical means. Tests to determine the compressive strength, modulus of rupture, absorption, and initial suction were performed, and the results are summarized in Table 32.

Table 32. Characterization of whole brick and tile

	Brick	Clay Tile
Compressive Strength (psi)	9752	11805
Modulus of Rupture (psi)	2010	1070
Absorption (%) (24-hr soak procedure)	8.5	4.0
Suction (g) (gain in weight corrected to basis of 30 in ²)	4.0	0.9

Figure 58. Whole brick and clay tile after being subjected to ASTM C67 testing.

Characterization of Crushed Brick Masonry Aggregate

The crushed brick masonry aggregate produced at D. H. Griffin Co. was mechanically separated into three gradations: AASHTO M43 #78, AASHTO M43 #67, and smaller size material that may have a gradation similar to an ASTM C33 sand. For this study, the crushed brick masonry aggregate used was the material mechanically separated into the AASHTO M43 #78 gradation (nominal size $\frac{1}{2}$ " to No. 8). The crushing operation generates fine material that clings to the aggregates. These fines were not washed off of the recycled brick masonry aggregate at D. H. Griffin Co.'s facility. However, this fine material was washed from the recycled brick masonry aggregate when it was taken to UNC Charlotte's laboratories, prior to testing.

Relevant ASTM standard test methods were used to determine properties of the crushed brick masonry aggregate, including absorption, specific gravity, bulk density, gradation, and abrasion resistance. The ASTM methods listed in Table 33 were used. A summary of test results for the crushed brick masonry aggregate is shown in Table 34, along with test results for the recycled concrete aggregate produced from the slab-on-grade at Idlewild Elementary School. Published data for a locally quarried natural normal weight aggregate and for a locally manufactured lightweight aggregate are also shown for comparison.

Table 33. Test methods used for characterization of crushed brick masonry aggregate

Characteristic	Method of Testing
Unit weight and specific gravity	ASTM C29 “Standard Test Method for Bulk Density (“Unit Weight”) and Voids in Aggregate.”
Absorption	ASTM C127, “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate.”
Gradation	ASTM C136 “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.”
Abrasion resistance	ASTM C131 “Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.”

Table 34. Results of characterization testing of recycled aggregates from Idlewild Elementary School demolition waste, shown with characteristics of a locally-manufactured lightweight aggregate and a local normal weight natural aggregate

	Recycled Brick Masonry Aggregate	Locally Manufactured Lightweight Aggregate	Recycled Concrete Aggregate	Locally Quarried Normal weight Natural Aggregate
	Idlewild Elementary School	Stalite	Idlewild Elementary School	Martin Marietta Quarry
Specific Gravity (at Saturated Surface Dry Condition)	2.19	1.53	N/A	2.84
Absorption	12.2	6.0	7.6	0.34
Abrasion (Gradation C)	43.1	25 to 28	N/A	17.2
Loose Bulk Density (Unit Weight, Dry) (lb/ft³)	60.9	50	80.0	95.9

*Note: All data is for ½ inch nominal maximum size material (AASHTO M43 #78 gradation, typical)

It can be seen from Table 34 that the crushed brick masonry aggregate produced from the Idlewild Elementary School has a loose bulk density (ASTM C 29 shoveling procedure) that is approximately 2/3 that of a locally quarried normal weight natural aggregate (typically used in concrete). The absorption of the recycled brick masonry aggregate is far greater than that of both the local normal weight natural aggregate and is almost twice that of the recycled concrete aggregate produced from the Idlewild Elementary School material. The absorption of the crushed brick masonry aggregate is also roughly twice that of a locally manufactured lightweight aggregate (Stalite). Properties of the brick masonry aggregate were also compared to ASTM C330, “Standard Specification for Lightweight Aggregates for Structural Concrete” in order to select the proper mixture design procedure and to better understand the potential performance of this material in concrete mixtures. It is noted that the bulk density of the material is

slightly higher than the upper limit for maximum dry loose bulk density specified by ASTM C330, which is 55 lb/ft³.

The ASTM C 136 sieve analysis test results of the AASHTO M43 #78 recycled brick masonry aggregate material is shown in Table 35, along with the sieve analysis results of the recycled concrete aggregate and the acceptable range for AASHTO M43 #78 gradation material. It is noted that, although both the recycled brick masonry aggregate and the recycled concrete aggregate met AASHTO M43 requirements for most sieve sizes, the percentage of material passing the 3/8 sieve (retained on the No. 4 sieve) was slightly higher than the acceptable range. Discussions with D. H. Griffin Co. personnel indicated that when they periodically discover that material is not meeting the required gradation, the sorting process utilized in the crushing and grading operation is modified slightly to bring the gradation of the material produced back into specification.

Table 35. Results of ASTM C136 sieve analysis testing of recycled brick masonry aggregate and recycled concrete aggregate produced from Idlewild Elementary School demolition waste

Sieve Opening (in.)	% of Material Finer		
	Recycled Brick Masonry Aggregate	Recycled Concrete Aggregate	AASHTO M43 #78 Acceptable Range
3/4	100	100	100
1/2	99.8	100	90-100
3/8	85.1	85	40-75
No. 4	19.5	14	5-25
No. 8	0.8	3	0-10
Pan	0	0	---

The recycled brick masonry aggregate produced from the Idlewild Elementary School demolition waste was largely comprised of three components: clay brick, clay tile, and mortar; see Table 36. Three representative samples of the recycled brick masonry aggregate were obtained using a sample splitter. Each sample was sorted by component by hand, and measurements of relative proportion by weight and by volume were obtained. Of particular interest is the amount of mortar present in the aggregate (almost 1/3 by weight and by volume), which while presumably influencing the performance of the recycled brick masonry aggregate in concrete mixtures, is largely ignored in virtually all published studies on this topic. Although the “top-down” demolition sequence utilized at Idlewild Elementary School was largely successful in preventing most contaminants from being incorporated into the crushed brick masonry aggregate, it was evident from visual observations that some debris other than clay brick, clay tile, and mortar was present in the material.

Table 36. Composition of the recycled brick masonry aggregate produced from Idlewild Elementary School demolition waste

Material	% by weight	% by volume
clay brick	64.5	63.9
clay tile	2.1	1.9
Mortar	30.1	31.6
other (rock, porcelain, lightweight debris)	3.3	2.6

Figure 59. Recycled brick masonry aggregate material from Idlewild Elementary School.

Development of Concrete Mixture Designs and Testing

Due to the high absorption of the brick masonry aggregate, mixture designs were developed in accordance with ACI 211.2, “Standard Practice for Selecting Proportions for Structural Lightweight Concrete.” Issues addressed in development of mixture designs included the high absorption and angularity of the brick masonry aggregate, which made achieving the desired workability (slump) difficult without the use of water-reducing admixtures. The recycled brick masonry aggregate was saturated for at least 24 hours prior to batching, and damp towels were used to bring the moisture content of the brick masonry aggregate to saturated surface dry (SSD) condition prior to batching. Admixtures typically used by ready-mixed concrete suppliers were used to assist in obtaining the desired workability while simultaneously increasing strength by reducing water content. A summary of concrete mixtures batched as part of this study, along with compressive strength test results, is shown in Table 37.

Several initial concrete mixtures exhibiting acceptable workability and compressive strength were successfully developed and tested during October, November, and December 2009. These mixtures are identified in Table 37 as BAC 1.0, BAC 2.0, BAC 2.1, BAC 2.2, BAC 2.3, and BAC 3.0. The compressive strengths of several of these early mixtures were higher than anticipated using the ACI 211.2 design procedures. Therefore, in keeping with the sustainability focus of this project, these mixture designs were subsequently modified with the goal of achieving the target strengths at lower cement contents (BAC 4.0 through BAC 4.6).

Test data from the trial mixtures of brick masonry aggregate concrete batched during late 2009 led to the identification of mixture proportions for four baseline mixtures (BAC 5.0, BAC 6.0, BAC 6.1, and BAC 6.2). These four baseline mixtures were batched in January 2010. Three of the four baseline mixtures included a high range water reducing admixture (BAC 6.0, BAC 6.1, and BAC 6.2), while the fourth baseline mixture (BAC 5.0) did not include a water reducing admixture. This mixture did, however, have the same cement content as one of the other three mixtures in order to identify the amount of water that would be needed to achieve similar workability without the aid of chemical admixtures. The proportions of these mixtures were selected to produce 28-day compressive strengths which, including the overdesign requirements outlined by the American Concrete Institute (ACI) in ACI 318 “Building Code Requirements for Structural Concrete,” would be representative of commercially available 4000 psi, 5000

psi, and 6000 psi mixtures. Without a history of performance data, 4000 psi, 5000 psi, and 6000 psi mixtures must reach 28-day compressive strengths of 5200 psi, 6200 psi, and 7300 psi, respectively.

For each of these batches, fresh properties including slump and air content were measured. Testing was also performed to determine the following hardened properties: compressive strength, modulus of elasticity, Poisson's ratio, splitting tensile strength, modulus of rupture, and equilibrium density. Specimens were tested at ages of 3-days, 7-days, 14-days, 28-days, and 90-days. ASTM test procedures used for testing of fresh and hardened concrete properties are listed in Table 38.

Results of fresh property tests (slump and air content) for each of the batches are shown in Table 37. The targeted slump range (with use of water-reducing admixture) was between 4 and 8 inches, which was typically achievable using water-reducing admixtures. Saturation of the recycled brick masonry aggregate prior to batching was critical in ensuring that the aggregate did not absorb an excessive amount of the mix water. Adequate workability would not have been achieved without pre-soaking the aggregates. The high-range water reducer provided the desired slump within low ranges of manufacturer's recommended dosages, and was utilized in most mixtures.

The targeted air content was between 4 and 8 percent, which is typical of most air-entrained concrete mixtures used in structural and pavement applications. This was readily achievable using an air-entraining admixture. It is noted that, due to the high porosity of the recycled brick masonry aggregate, the gravimetric method of determining the air content of the fresh concrete (ASTM C138) was utilized. The gravimetric method of air content testing is recommended for lightweight aggregates due to the fact that the pressure method of determining air content (ASTM C231) can give false readings due to the voids in the porous aggregates.

Table 37. Mixture development for brick masonry aggregate concrete

	BAC 1.0	BAC 2.0	BAC 2.1	BAC 2.2	BAC 2.3	BAC 3.0
	10/20/2009	10/28/2009	11/2/2009	11/2/2009	11/2/2009	11/16/2009
Coarse Aggregate (lb/yd ³)	1178.6	1052	1052	1052	1052	1178.6
Sand (lb/yd ³)	1149.4	1281	1281	1281	1281	1417
Cement (lb/yd ³)	812.5	677	677	677	677	600
Water (lb/yd ³)	316	301.2	320.1	262.1	237.3	291
w/c ratio	0.39	0.44	0.47	0.39	0.35	0.49
Air Entraining Admixture (oz)	472	605	500	500	500	446
Mid-Range Water Reducing Admixture (oz)	0	0	0	1944	0	0
High-Range Water Reducing Admixture (oz)	0	0	0	0	1304	0
Slump	7	3.5	7.5	5	10	4.5
Air content	4.5	5	6.5	7	7.25	5.5
3-day compressive strength (psi)	3895	2668	3097	1804	5337	2378
7-day compressive strength (psi)	4692	3146	3903	2107	6197	3128
28-day compressive strength (psi)	6067	4117	4726	2480	6962	3642
90-day compressive strength (psi)	6813	---	4995	2746	7574	4292

Table 37 (cont.). Mixture development for brick masonry aggregate concrete

	BAC 4.0	BAC 4.1	BAC 4.2	BAC 4.3	BAC 4.4	BAC 4.5
	12/7/2009	12/7/2009	12/7/2009	12/14/2009	12/14/2009	12/17/2009
Coarse Aggregate (lb/yd ³)	1178.6	1178.6	1178.6	1178.6	1178.6	1178.6
Sand (lb/yd ³)	1284	1284	1284	1355.7	1427.6	1254
Cement (lb/yd ³)	675	675	675	625	575	725
Water (lb/yd ³)	260.2	281.8	211.6	197.4	186.9	291.5
w/c ratio	0.39	0.42	0.31	0.32	0.33	0.4
Air Entraining Admixture (oz)	500	500	405	500	351	513
Mid-Range Water Reducing Admixture (oz)	0	0	0	0	0	0
High-Range Water Reducing Admixture (oz)	0	0	1080	810	675	0
Slump	8	3.5	7	7	6	5
Air content	5.5	7	7	8	5.5	6.5
3-day compressive strength (psi)	2200	3491	5722	4084	2642	2872
7-day compressive strength (psi)	2513	3979	6249	4712	3297	3339
28-day compressive strength (psi)	3515	5167	7858	5304	3484	4518
90-day compressive strength (psi)	3831	5575	7879	5360	3803	4992

Table 37 (cont.). Mixture development for brick masonry aggregate concrete

	BAC 4.6	BAC 5.0	BAC 6.0	BAC 6.1	BAC 6.2
	12/17/2009	1/22/2010	1/24/2010	1/26/2010	1/29/2010
Coarse Aggregate (lb/yd ³)	1178.6	1178.6	1178.6	1178.6	1178.6
Sand (lb/yd ³)	1185	1296	1296	1356	1428.3
Cement (lb/yd ³)	775	675	675	625	575
Water (lb/yd ³)	299.4	292	216	200	183.6
w/c ratio	0.39	0.43	0.32	0.32	0.32
Air Entraining Admixture (oz)	513	405	486	405	405
Mid-Range Water Reducing Admixture (oz)	0	0	0	0	0
High-Range Water Reducing Admixture (oz)	0	0	1080	864	864
Slump	4.5	6	5.5	6	3.5
Air content	5.5	5.5	7.5	8	6.5
3-day compressive strength (psi)	2821	2139	4559	3684	4508
7-day compressive strength (psi)	3323	2858	6182	4074	5283
28-day compressive strength (psi)	4306	3675	6497	5307	6450
90-day compressive strength (psi)	4870	3872	6903	5362	7343

Table 38. Test methods used to determine fresh and hardened properties of recycled brick masonry aggregate concrete

	Property	Method of Testing
Fresh Properties	Slump	ASTM C43 “Standard Test Method for Slump of Hydraulic-Cement Concrete.”
	Air content	ASTM C138 “Standard Test Method for Density, (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete.”
Hardened Properties	Compressive strength	ASTM C39 “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.”
	Modulus of elasticity and poisson’s ratio	ASTM C469 “Standard Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression.”
	Splitting tensile strength	ASTM C496 “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.”
	Flexural strength (modulus of rupture)	ASTM C78 “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading).”

Test results for hardened properties of the baseline mixtures of the recycled brick masonry aggregate concrete (BAC 5.0, BAC 6.0, BAC 6.1, and BAC 6.2) are shown in Table 39. Overall, the test results indicate that concrete mixtures batched using coarse aggregate produced from the brick masonry obtained from the case study site have fresh and hardened properties that are typically acceptable for use in a number of structural and paving applications. Values for compressive strength for the baseline mixtures indicate that concrete strengths typical of structural and pavement mixtures (4000 to 6000 psi) can be achieved at reasonable cement contents (less than 700 pounds per cubic yard). Mixtures with relatively low cement contents (on the order of 500 to 600 pounds per cubic yard) were also capable of developing suitable compressive and flexural strengths. Values for modulus of elasticity and Poisson’s ratio are typical of conventional normal weight and lightweight concrete mixtures utilized in structural and paving applications.

Table 39. Hardened properties of recycled brick masonry aggregate concrete

	BAC 5.0	BAC 6.0	BAC 6.1	BAC 6.2
3-day compressive strength (psi)	2139	4559	3684	4508
7-day compressive strength (psi)	2858	6182	4074	5283
28-day compressive strength (psi)	3675	6497	5307	6450
90-day compressive strength (psi)	3872	6903	5362	7343
3-day modulus of elasticity (psi)	2,200,000	3,340,000	3,120,000	3,600,000
7-day modulus of elasticity (psi)	2,753,000	3,977,000	3,467,000	3,430,000
28-day modulus of elasticity (psi)	2,783,000	3,840,000	3,563,000	3,903,000
90-day modulus of elasticity (psi)	2,905,000	3,960,000	3,645,000	3,875,000
3-day Poisson's ratio	0.18	0.16	0.18	0.19
7-day Poisson's ratio	0.21	0.17	0.21	0.14
28-day Poisson's ratio	0.18	0.16	0.17	0.16
90-day Poisson's ratio	0.17	0.18	0.18	0.17
7-day flexural strength (modulus of rupture) (psi)	519	797	730	716
28-day splitting tensile strength (psi)	320	439	484	387

Future Work

Additional work will be performed after close of the project to better understand performance capabilities of the recycled brick masonry aggregate and the recycled brick masonry aggregate concrete. The supply of coarse aggregate material produced from the crushed recycled brick masonry from the case study site has now been exhausted. However, a fairly large quantity of the resulting fine aggregate (sand) is still available. Future work may include batching and testing of mortar mixtures using this fine aggregate material. Studies on the possible pozzolanic activity of the material may be performed.

Members of the project team anticipate performing additional testing on the recycled brick masonry aggregate to characterize its shape and texture. A small amount of the recycled brick masonry aggregate produced from the Idlewild Elementary School demolition debris has been set aside, and it is anticipated that ASTM D4791, "Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate" and ASTM D3398, "Standard Test Method for Index of Aggregate Particle Shape and Texture" will be performed on this material. Additionally, testing using a scanning electron microscope (SEM) with energy-dispersive x-ray (EDX) capabilities is planned. Information on the microstructural composition of the recycled brick masonry aggregate, as well as its chemical composition, will be obtained.

It was noted that, when replicate samples are tested, the brick masonry aggregate concrete appears to have more variability in the test results than concrete produced with traditional coarse aggregate. This was not quantified, as companion mixtures using other natural or manmade lightweight aggregates were not prepared and tested as part of this work. Additional analysis of the data will include a statistical analysis of this apparent increased variability of the baseline mixtures (BAC 5.0, BAC 6.1, BAC 6.2, and BAC 6.3), its possible effects on concrete quality, and possible implications regarding widespread use of this material in commercial applications.

Members of the project team are working with D. H. Griffin Co. to obtain more recycled brick masonry aggregate from another demolition site. The current downturn in the economy has resulted in a general slowdown of construction activities, and as of December 2010, a suitable demolition site capable of producing a suitable quantity of “clean” brick masonry aggregate was not yet identified. It is anticipated that construction (and subsequently, demolition) activity in the Charlotte region will increase in Spring 2011, and more recycled brick masonry aggregate will then become available.

Once a suitable demolition site is identified and additional recycled brick masonry aggregate is obtained, it is anticipated that a number of tests previously performed on the Idlewild Elementary School material will be repeated. Whole brick/tile and aggregate characterization tests will be performed, and a series of recycled brick masonry aggregate concrete mixtures will be batched. It is anticipated that the fresh and hardened property tests performed on the recycled brick aggregate concrete containing material from the new source will include the same tests performed on concrete produced using the Idlewild Elementary School material (outlined in Table 38). Additional tests on mechanical properties that will be performed include tests for drying shrinkage and creep behavior. Testing to evaluate the durability performance of the recycled brick masonry aggregate will also be performed. It is anticipated that durability testing will include freeze-thaw resistance, sulfate resistance, chloride permeability, surface resistivity, and air and water permeability. Focus will be placed on understanding the potentially increased variability in the material by applying the appropriate statistical methods on a larger number of replicates for each test.

D. H. Griffin Co. has also offered to construct a test pavement comprised of recycled brick masonry aggregate concrete so that members of the project team can evaluate the in situ performance of the material in service conditions. It is planned that the test pavement will be constructed on the premises of D. H. Griffin Co.’s crushing and grading operations in Charlotte, North Carolina. The test pavement will be constructed in the drive lanes utilized by the incoming and outgoing trucks, in line with the weigh scales serving the facility. At its proposed location, the test pavement should receive significant traffic loading in a relatively short period of time. Data on the trucks traversing the pavement (both axle spacing and weights) will be readily available from the scales, providing valuable insight into the loads experienced by the pavement. Currently, members of the project team are working on designing the thickness of the test pavement and are identifying possible means of instrumenting the test pavement and/or subgrade with sensors to obtain performance data. As part of the evaluation of the test pavement, drilled core samples will also be obtained for petrographic observation and mechanical property testing.

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Subproject 6) Recycled Aggregate Concrete with Crushed Recycled Concrete Aggregate
(Graduate student: Adam Alvey; Advisor: Dr. David C. Weggel)

Background: Portland Cement Concrete with RCA

With the growing push towards greener and economical development (sustainable development) the construction and demolition industry should embrace or develop better methods to reduce the environmental impact of demolition and new construction projects. This can be accomplished by reducing construction and demolition waste through reusing or recycling as much of that waste as possible. For example, concrete elements such as: slabs, beams, walls, and columns can be collected and crushed with the resulting rubble being used as aggregate for new concrete.

This research focuses on evaluating whether crushed concrete can effectively be used as the coarse aggregate in structural concrete applications. The testing performed on the recycled aggregate concrete (RAC) goes beyond standard compression and tensile tests that may be adequate for pavements and curbing, since the goal is to produce RAC members sufficient for structural applications. The compressive strength, tensile strength, modulus of rupture, and flexural performance of the RAC was evaluated, and the results were used to design full-scale girders for a small pedestrian bridge.

Portland Cement Concrete with RCA: Mix Design

When mixing fresh concrete using RCA, it is necessary to take into account the material differences between RCA and virgin (natural) granite aggregate; granite is a commonly-occurring natural aggregate in many parts of the country. Since the RCA is more porous, it tends to absorb more water during mixing than when using virgin aggregates. The water absorption of the recycled aggregates has been found to be approximately three times that of natural aggregates (Rakshvir and Barai, 2006). As a method of managing the increased water absorption during mixing, it is recommended to presoak the aggregate for 24 hours to create a saturated surface dry (SSD) condition and then to adjust the mixing water (Khalaf and DeVenny, 2004). Water reducing admixtures could also be utilized during mixing. A different mixing procedure was suggested by Vivian et al. (2007) that could be utilized to minimize the potentially detrimental effects of RCA on the concrete mixing process by improving the interfacial zone between the aggregate and cement during mixing.

The higher absorption of RCA can negatively affect the workability of concrete, as the aggregate pulls water from the mix and the free water in the cement paste is reduced, which reduces the slump and overall workability of the concrete. This effect can be minimized by increasing the mixing water, presoaking the aggregates to an SSD condition, or using water reducing admixtures (Rakshvir and Barai, 2006). In a study by Poon et al. (2004) it was found that if the recycled aggregates are used in an SSD state, the replacement of virgin aggregates by recycled aggregates in any percentage results only in a small change in the initial slump and workability of the concrete. Another contributor to the reduced workability is the increased angularity and coarseness of RCA. It is suggested by Lamond (2002) that the reduced workability caused by the angularity and coarseness of the aggregate could be controlled by including more fine aggregates in the concrete mix.

Recycled concrete aggregates also have a lower gross density than virgin granite aggregates. This becomes an issue when attempting to proportion the virgin versus recycled aggregates in a mix. In order to maintain a consistent volume of coarse aggregate in a mix when using both RCA and virgin aggregates, it is necessary to calculate the equivalent volume mass of each aggregate to maintain an “equivalent” mix design (Lamond, 2002).

Considering the findings reported in the literature, batch mixes were designed for a target compressive strength. Two different types of RCA were tested: a general demolition waste which contained crushed concrete, brick, CMU block, and other waste (labeled as CRC) and a source-separated crushed concrete taken from the floor slab of Idlewild Elementary School (labeled as SSRC). Two groups of batches, each using one type of reclaimed aggregate, had the following

RCA contents by volume: 0% (the control), 10%, 20%, 30%, 40%, 50%, 80%, and 100%. The mixes were designed for a minimum compressive strength of 6000 psi and a slump of 3". All coarse aggregates were used in an SSD state to minimize the effect of the recycled aggregate's higher absorption; the mixing water was adjusted based on the absorption of the RCAs. From these batch mixes, 3" cylinders were made for compressive strength testing at 7, 14, and 28 days. The mix design for each batch of concrete (including the virgin aggregate control) was identical as shown in Table 40.

Table 40. Mix design

Percentage of Aggregate Replacement	0	10	20	30	40	50	80	100
Cement (lb/yd ³)	938	938	938	938	938	938	938	938
Virgin Aggregate (lb/yd ³)	1625	1463	1300	1138	975	813	325	0
Recycled Aggregate (lb/yd ³)	0	147	293	440	587	733	1173	1466
Fine Aggregate - Sand (lb/yd ³)	972	972	972	972	972	972	972	972
Water (lb/yd ³)	384	384	384	384	384	384	384	384

Portland Cement Concrete with RCA: Compression Strength

Previous research that investigated the effects of RCA on the compressive strength of concrete has produced somewhat conflicting results. For instance, it has been stated by Li (2008) that the compressive strengths of concrete made using RCA have been shown to be notably less than those using virgin aggregates. As virgin coarse aggregate was replaced with RCA the compressive strength was shown to decrease, and when all coarse aggregate was RCA the reduction in compressive strength was between 12% and 20%. However, when only 20% of the coarse aggregate was replaced, the strength reduction was negligible (Li, 2008). Rakshvir and Barai (2006) further investigated the effects of RCA on Portland cement concrete's compressive strength. They concluded that only when the replacement of coarse virgin aggregate with RCA reached 50% was there a noticeable loss in the compressive strength of the concrete. However, even at 100% RCA replacement, the loss in compressive strength was only between 5% and 15%, and the concrete still met design requirements. Sagoe-Crentsil et al. (2001) found that there was no significant difference between the strength of Portland cement concretes as a function of aggregate type (recycled versus virgin aggregates). The reported reduction in compressive strength was typical of concretes made using laboratory-crushed recycled concrete as the coarse aggregate, but this was not found to be the case when using recycled concrete aggregates crushed in the field.

The results of the compressive strength tests, based on the mix design shown in Table 40, are shown in Figures 60 and 61. The figures show that every concrete mix met the minimum specifications of the mix design (the 6000 psi target strength) regardless of the level of aggregate replacement; however, for the higher percentages of aggregate replacement (greater than 40%), the minimum acceptable strength level was approached. The figures also show that above the 40% coarse aggregate replacement, a notable consistent decrease in the compressive strength is observed relative to the control. The trends observed in these figures led to modulus of rupture (MOR) and tensile strength testing of mixes with coarse aggregate replacement of: 0%, 40%, and 100%.

Figure 60. SSRC-Compressive strength as a function of aggregate replacement percentage.

Figure 61. CRC-Compressive strength as a function of aggregate replacement percentage.

Portland Cement Concrete with RCA: Tensile Strengths

Ge & Zeng (2004) determined that the splitting tensile strength of concrete decreases as the RCA percentage increases, amounting in a reduction of 40% for concrete with 100% RCA. Sagoe-Crentsil et al. (2001) found that there was no notable reduction in the ratio of splitting tensile strength to compressive strength when the RCA percentage varied; further, the splitting tensile-

to-compressive strength ratio of recycled aggregate concretes were comparable to those of conventional concretes (made with natural aggregates). It was concluded that, since using recycled concrete aggregates had no detrimental effect on the tensile strength, good bond characteristics between the recycled aggregate and the mortar matrix likely exist. Therefore the failure mechanism of recycled aggregate concrete specimens would be expected to be similar to that of the normal Portland cement concrete.

Five sets of three beams were constructed in order to determine the affects of recycled aggregates on the modulus of rupture (bending tensile strength). These small beam specimens had a 6"-square cross section and were 20" long (to be tested with an 18" clear span). The first set of specimens served as the control; that is, 100% virgin (granite) coarse aggregate was used. The second set of specimens used 100% CRC (recycled) coarse aggregate; the third set of specimens used 100% SSRC (recycled) coarse aggregate. The fourth and fifth sets used 40% coarse RCA, using the CRC and SSRC sources, respectively.

Companion 3"-diameter cylinders were poured alongside each set of MOR specimens; the cylinders were tested at 7, 14, and 28 days to determine the variation in compressive strength with time. At 28 days the MOR beams were tested following the procedure given in *ASTM C78* (2010) for determining modulus of rupture. Splitting tension tests were performed on the corresponding 3" cylinders. The 28-day compression tests were performed using both 3" and 4" diameter cylinders to investigate potential size effects on strength. Figure 62 shows representative MOR beam and cylinder specimens after pouring, after curing, and after testing.

Figure 62. Splitting tensile and MOR specimens.

The averaged results of the compressive and tensile strengths are shown in Table 41. The data show that, while the use of coarse RCA has only a small effect on the splitting tensile strength, its effect on the modulus of rupture has considerably more variance. The splitting tensile strengths were all within 15% of the control (VGA), while the modulus of rupture varied by up to 35% relative to the control.

Table 41. Strength test results

Aggregate Type	Compressive Strength	Splitting Tensile Strength	Modulus of Rupture
	(psi)	(psi)	(psi)
VGA	8429	474	1192
SSRC 40%	7994	447	787
SSRC 100%	7148	449	914
CRC 40%	8541	411	979
CRC 100%	8532	456	806

Portland Cement Concrete with RCA: Flexural Behavior

In order to demonstrate the adequacy of RAC for use in structural applications, it is necessary to investigate whether members made of this material can be designed using current design procedures (following the ACI code) while performing as expected. As a result, steel-reinforced RAC beams (girders) were designed, constructed, and tested in the UNC Charlotte structures lab. The beams were tested, and the applied load, deflections, and strains were measured in order to assess the beam's flexural behavior. The beam's moment capacity and its load-deflection behavior were determined from experimental results; further, the beam's nominal flexural capacity was compared to the strength-based design calculations given in ACI 318-08 (ACI Committee 318, 2008).

A total of three beams, each of a different concrete material but identical in configuration, were constructed and tested; see Figure 63. The first beam was the control, which used 100% virgin (granite) coarse aggregate. The second and third beams used, respectively, 100% SSRC and CRC coarse RCAs. The beams were designed following ACI 318-08. Each beam's cross-section was 7" wide and 10" deep, using 3 #4 rebars for the flexural reinforcement along the bottom face; see Figure 63b. Stirrups were placed at 8" on center along the length of each 12' beam. Each beam had a clear span of 10' and was loaded at the third points, producing a region of constant moment between the two applied loads. All three beam specimens were tested to failure.

(a)

(b)

(c)

Figure 63. Beam specimens (a) loading conditions, (b) rebar location and dimensions, (c) displacement measurement locations.

Figure 64. Applied load versus midspan deflection (all beam specimens).

Figure 64 shows some of the results obtained when testing the beams to failure; overlay plots of load versus midspan deflection are provided for each beam. Replacing the coarse aggregate with recycled material was shown to have little to no effect on the flexural behavior of these reinforced concrete beams (made with Portland cement). Overlooking the erratic displacement shown in the plot of Beam 2 (caused by a faulty displacement transducer as verified by the third point transducers), all three beams displaced almost identically as a function of applied load. During testing, cracks were marked on the beams as shown for all beams in Figure 65; there was no appreciable difference in the general crack patterns or loads corresponding to crack occurrence among the three beam specimens. A detailed analysis of the results will be reported in Mr. Alvey's MS thesis.

Figure 65. Post-test photos of beams showing crack patterns.

Strength Testing of Recycled Concrete Aggregate

Samples of the virgin granite and recycled concrete aggregates have been tested following the guidelines in *ASTM C131, the Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine* (2006). These tests revealed that both recycled aggregate samples were within the stated ASTM requirements for the abrasion resistance of aggregates used in concrete.

In an effort to gain insight on the aggregates' crushing strength and relate the findings to possible strength limitations for quality recycled aggregates used in the construction of structural members, the literature was researched resulting in the possibility of using the testing procedures found in British standards: *Tests for mechanical and physical properties of aggregates, Methods for the determination of resistance to fragmentation* (BS EN 1097-2:1998, 1998). The test procedure in this British standard could be used as an alternative to the Los Angeles Abrasion test when indirectly determining the crushing values of the aggregate.

UNC Charlotte researchers have independently developed a simple test apparatus in an effort to more directly measure aggregate crushing strength; testing has been completed on the three aggregate types. This test crushes a 6-inch deep sample of aggregate in a 6-inch diameter cylinder,

measuring applied loading and average deformation simultaneously. Figure 66 is a diagram of the apparatus used for these tests; Figure 67 includes photos during and after an aggregate crush test.

Figure 66. Apparatus for aggregate crush test.

The results were analyzed for both load-controlled and displacement-controlled tests. It is theorized that the load-deflection curve (or a derivative of it) of the aggregate crush test could be used to more directly estimate the compressive strength of a recycled aggregate (or at least provide another indirect measure of aggregate suitability). Using the resulting compressive strength and the law of mixtures, it may be possible to predict whether an aggregate has suitable strength for use as the coarse aggregate in a concrete of desired strength. Establishing a standard for the minimum strength of suitable recycled aggregate, using a simple test procedure, may make structural applications of concrete using recycled aggregates more accepted. This additional work will be reported in Mr. Alvey's MS thesis.

Figure 67. Aggregate crush test (a) test in progress (b) crushed aggregate specimen.

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Appendix A:

FINAL PROGRESS REPORT

Project Title: BUILDING MATERIALS RECLAMATION PROGRAM

**Final Progress Report for the Period September 1, 2008-August 31, 2010
DOE Project # DE-FG26-08NT01982**

Submitted by

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Executive Summary

This report describes work conducted on the Building Materials Reclamation Program for the period of September 2008 to August 2010. The goals of the project included selecting materials from the local construction and demolition (C&D) waste stream and developing economically viable reprocessing, reuse or recycling schemes to divert them from landfill storage. Educational resources as well as conceptual designs and engineering feasibility demonstrations were provided for various aspects of the work.

Approach

The project was divided into two distinct phases: Research and Engineering Feasibility and Dissemination. In the Research Phase, a literature review was initiated and data collection commenced, an advisory panel was organized, and research was conducted to evaluate high volume C&D materials for nontraditional use; five materials were selected for more detailed investigations. In the Engineering Feasibility and Dissemination Phase, a conceptual study for a regional (Mecklenburg and surrounding counties) collection and sorting facility was performed, an engineering feasibility project to demonstrate the viability of recycling or reuse schemes was created, the literature review was extended and completed, and pedagogical materials were developed.

Over the two-year duration of the project, all of the following tasks (and subtasks) have been completed, as outlined in the original project proposal.

Phase 1 – Research

Task 1.0 Data Collection and Literature Review: Compile necessary background information to begin project.

Subtask 1.1 Research Partner Organization: Work with industrial partners MRR Southern, a North Carolina based C&D waste handler, and BP Barber, a civil engineering firm with offices in Charlotte and throughout the Southeast, to create a regional database of C&D waste streams. Perform a market analysis to evaluate the regional demand for salvaged and reprocessed materials (SRM).

This subtask has been completed for C&D waste used as recycled aggregates in concrete as detailed in “Construction and Demolition Waste used as Recycled Aggregates in Concrete: Solutions for Increasing the Marketability of Recycled Aggregate Concrete” by Brett Tempest, Tara Cavalline, Janos Gergely, and David Weggel, presented at the *2010 Concrete Sustainability Conference*, National Ready Mixed Concrete Association, Tempe, AZ, April 13-15, 2010. This task has also been completed conceptually for other C&D materials, as reported in the reviews in the Final Scientific Report.

Subtask 1.2 Literature Review: Conduct a literature review and summarize the status of the most abundant and environmentally challenging C&D waste materials with respect to recyclability and marketability. Focus on non-traditional end uses that would be feasible nationally and regionally, and consider potential environmental impacts of various uses.

This subtask has been completed. A Google site called C&D Waste Team was created as a literature repository, where all four faculty and the six graduate students (three Ph.D. students and three M.S. students) working on this project posted technical references. Extensive literature reviews are included in the Final Scientific Report and in the graduate students’ dissertations and theses.

Task 2.0 Organization of Advisory Panel: Establish an Advisory Panel to guide the activities of the research program.

Subtask 2.1 Recruit panel members: Identify important entities in the community that could influence, produce, or benefit from C&D waste or SRMs and incorporate them into an Advisory Panel. Members might include:

- wrecking companies
- contractors
- landfill operators
- local professional organizations
- representatives from the community college system
- Mecklenburg County Land Use and Environmental Services Agency

The Advisory Panel (AP) for this project was comprised of eight external professionals with expertise in C&D waste, public works, or a closely related area. These individuals are listed below.

- Mr. Scott Brown, Brown and Caldwell (formerly of BP Barber)
- Mr. Dan Moore, MRR Southern, LLC
- Mr. Geoffrey C. Burdick, P.E., Project Manager, Solid Waste Engineering Land Use & Environmental Services Agency
- Mr. Ray Maxwell, Gaston County Public Works
- Mr. Bob Young, Plant Manager, US GreenFiber, LLC
- Dr. Eli Stav, Director of Technical Development, National Gypsum Company
- Dr. Jeff Ramsdell, Associate Professor, Appalachian State University
- Mr. Frank Reed, Director of Stores, Habitat for Humanity Charlotte

Subtask 2.2 Meet with members: Establish a meeting schedule that will allow the Advisory Panel to effectively guide the Research Team in its activities.

This subtask has been completed. Faculty and graduate students on the Research Team were consistently in contact with one or more of the Advisory Panel members, most notably Dan Moore and Scott Brown. Furthermore, the support of the D.H. Griffin companies (i.e. D.H. Griffin Grading & Crushing, LLC and D.H. Griffin Infrastructure, LLC) was instrumental to the subprojects that involved reclaimed steel and recycled aggregates.

Subtask 2.3 Continue relationships with panel members: Use the panel members to assist with dissemination of information and technology transfer following completion of the study.

This subtask will continue beyond the completion of this project as more information is disseminated and technological developments are transferred through future journal publications, formal/informal presentations, and discussions with panel members. Further, the relationships formed between UNC Charlotte faculty and Advisory Panel members and the D.H. Griffin companies will likely lead to future collaborations on new sustainability projects.

Task 3.0 Material Selection: Select several materials for more detailed investigation and experimentation.

Subtask 3.1 Decision Matrix: Create a decision matrix to judge which of the more problematic materials have the highest potential for sustainable and cost-effective recycling nationally and regionally. Examples of high volume materials include gypsum wallboard, CCA-treated wood, asphalt shingles, crushed concrete rubble.

This subtask has been completed. Five materials were selected for detailed investigation and experimentation: gypsum wallboard, *reclaimed* structural steel, two types of recycled aggregate (crushed rubble) for recycled aggregate concretes (RAC) – crushed concrete aggregate and crushed brick aggregate, and fly ash used to produce a geopolymers concrete. The subject matter of the six specific subprojects, including the type of C&D material, the lead graduate student on the project, and the faculty advisor, are provided in the table below.

Subproject Subject	C&D Material	Graduate Student	Faculty Advisor
1) Ground gypsum: carbon sequestration, soil amendment (full-scale studies)	Gypsum wallboard	Fabien Besnard ¹	Dr. Helene Hilger
2) Ground gypsum: carbon sequestration, soil amendment (bench studies)	Gypsum wallboard	Rebecca Turner ²	Dr. Helene Hilger
3) Reclaimed structural steel beams	Structural steel	Madeleine Grimmer ²	Dr. Shenen Chen
4) Geopolymer concrete (GC)	Fly ash	Brett Tempest ¹	Dr. Janos Gergely
5) RAC w/ crushed brick aggregate	Brick masonry rubble	Tara Cavalline ¹	Dr. David Weggel
6) RAC w/ crushed concrete aggregate	Concrete rubble	Adam Alvey ²	Dr. David Weggel

¹Working towards the degree of Ph.D.

²Working towards the degree of M.S.

Subtask 3.2 Experimentation: Design and conduct laboratory studies that target the most promising applications that could significantly advance the likelihood that such materials could become more marketable.

This subtask has been completed. A brief summary of the progress during the duration of the project (the Building Materials Reclamation Program) is provided below for each of the six subprojects. More details are reported in the Final Scientific Report and in the graduate students' dissertations and theses.

Subprojects 1&2) Waste Gypsum Wallboard as a Soil Amendment and Carbon Sequestration (Full-Scale Studies (Outdoors) and Bench Studies (Indoors)) (Graduate students: Fabien Besnard and Rebecca Turner; Advisor: Dr. Helene Hilger)

Two phases of experiments have been conducted. The first part of Phase I aimed at evaluating ground virgin drywall as a soil amendment for biodiesel crops and grass (erosion control); the second part of Phase I examined the potential plant toxicity of three types of drywall available on the market. Phase II focuses on the potential to incorporate ground gypsum wallboard into a passive carbon sequestration system. While most of the experiments performed in the first part were completed, the experiments of the second part continue.

Overall the germination tests showed that (i) canola biodiesel crop survival and yield are enhanced by a ground waste drywall amendment that can be derived by sorting C&D waste at a construction site and diverting virgin drywall from the landfill; (ii) ground drywall affects different types of seeds differently and should not be used unless pre-tested for effects on early plant root growth; and (iii) amended drywall such as fire retardant drywall and especially mold, mildew, and moisture retardant drywall can be detrimental to plants, with the effect likely due to the chemicals embedded in the paper part of the drywall.

Taken together, the results show that diversion of waste drywall from landfills for some targeted uses where high impacts can be achieved is feasible. Both federal and state governments are

launching and aggressively supporting initiatives to move the U.S. vehicle fleet to liquid biofuels within the next few decades. The amount of waste drywall generated during construction together with the impact of its disposal in landfills makes its diversion for biofuel production an appealing option, because the cost of the feedstock is the critical variable in making biofuel production cost-feasible. Likewise, the ability to retain waste drywall on a construction site and put it to use for erosion control is a valuable addition to the now limited set of options for managing this material. If erosion control grass is temporary, then a strong root system with adequate, although perhaps less aesthetic, top growth should serve well until a final grass cover is established. Since gypsum is known to move downward through the soil fairly rapidly, it should be diluted out of the soil by the time a permanent grass planting occurs.

The harvest of the second field crop of canola combined with the dismantling and analysis of the field soil columns for carbon sequestration impacts will provide valuable information to complement what is reported here. Additional studies with artificial root exudate are also underway, so that a more complete assessment of the potential sequestration impacts of drywall soil amendments can be accomplished. The results will be disseminated in upcoming papers reporting on the findings of this research. Further, more details will be included in the doctoral dissertation of Fabien Besnard and the MS thesis of Rebecca Turner.

Subproject 3) Reclaimed Structural Members: Investigations of Reused Structural Steel (Graduate student: Madeleine Grimmer; Advisor: Dr. Shenen Chen)

Through experimental and analytical research, this subproject investigates the feasibility of reusing structural steel elements in new construction projects after being obtained from demolition. The work presented here is divided into two distinct phases. The first phase consists of a comprehensive literature review and feasibility study of regional construction waste cyclical flows. The second phase involves an engineering feasibility structure to demonstrate a preliminary design using reclaimed structural steel. Actual structural steel members (beams) were obtained from a demolition site and a demolition scrap yard and were tested to determine their load carrying capacity and other performance measures. The test results are used to establish a “reduction factor” to be used in the demonstration design. The reduction factor accounts for uncertainties associated with strength and stiffness properties of the reclaimed structural steel elements. For example, for Group A and B beams under flexure, a material reduction factor of 0.94 is suggested; and for Group C beams a material reduction factor of 0.84 is suggested. The preliminary design of multiple-span bridges is performed to demonstrate this design change when using reclaimed structural steel. A basic, yet practical, life cycle analysis (LCA) was performed at the end of the study to demonstrate the viability of reclaimed steel applications and to compare the use of reclaimed structural steel to that of virgin steel.

Subproject 4) Investigations of Geopolymer Concrete (Graduate student: Brett Tempest; Advisor: Dr. Janos Gergely)

Geopolymer cement concretes offer an alternative to Portland cement concrete that can provide many of the same structural functions but in a more sustainable fashion by reducing the energy inputs and emissions outputs of the manufacturing process. A series of studies were performed to assess the mechanical performance of geopolymer material test specimens and structural components. These tests have verified the applicability of some design methods for flexural Portland cement concrete components to GCC.

These results indicate that GCC is a feasible material for structural concrete applications. This study has focused on concretes made from only a few batches of source materials and has evaluated the performance of concretes under limited conditions. In order to improve the quality of some of the results, as well as to increase confidence in some of the conclusions, the following are suggested for further study:

- The gradation of aggregates should be optimized more rigorously for the concretes under evaluation. It may be possible to improve the workability and some mechanical characteristics of the concrete by studying the interaction of mortar and aggregate in both the plastic material as well as the cured material.
- Although there was not sufficient data recorded in this study to provide a correlation, it appears that the age of the concrete may have a significant impact on the stress-strain relationship or the ultimate strain. Higher ultimate strains may be found in GCC materials at later ages. This was evidenced by the very large deflections recorded in the test of the 229 day-old beam GCC-2-B2 prior to reaching its ultimate moment. Mineralogical changes over time might cause such a change in the macro-performance of the material and should be investigated.

Subproject 5) Recycled Aggregate Concrete with Crushed Recycled Brick Masonry Aggregate (Graduate student: Tara Cavalline; Advisor: Dr. David C. Weggel)

Several initial concrete mixtures exhibiting acceptable workability and compressive strength were successfully developed and tested during October, November, and December 2009. These mixtures are identified as BAC 1.0, BAC 2.0, BAC 2.1, BAC 2.2, BAC 2.3, and BAC 3.0. The compressive strengths of several of these early mixtures were higher than anticipated using the ACI 211.2 design procedures. Therefore, in keeping with the sustainability focus of this project, these mixture designs were subsequently modified with the goal of achieving the target strengths at lower cement contents (BAC 4.0 through BAC 4.6).

Test data from the trial mixtures of brick masonry aggregate concrete batched during late 2009 led to the identification of mixture proportions for four baseline mixtures (BAC 5.0, BAC 6.0, BAC 6.1, and BAC 6.2). These four baseline mixtures were batched in January 2010. Three of the four baseline mixtures included a high range water reducing admixture (BAC 6.0, BAC 6.1, and BAC 6.2), while the fourth baseline mixture (BAC 5.0) did not include a water reducing admixture. This mixture did, however, have the same cement content as one of the other three mixtures in order to identify the amount of water that would be needed to achieve similar workability without the aid of chemical admixtures. The proportions of these mixtures were selected to produce 28-day compressive strengths which, including the overdesign requirements outlined by the American Concrete Institute (ACI) in ACI 318 “Building Code Requirements for Structural Concrete,” would be representative of commercially available 4000 psi, 5000 psi, and 6000 psi mixtures. Without a history of performance data, 4000 psi, 5000 psi, and 6000 psi mixtures must reach 28-day compressive strengths of 5200 psi, 6200 psi, and 7300 psi, respectively.

For each of these batches, fresh properties including slump and air content were measured. Testing was also performed to determine the following hardened properties: compressive strength, modulus of elasticity, Poisson's ratio, splitting tensile strength, modulus of rupture, and equilibrium density. Specimens were tested at ages of 3-days, 7-days, 14-days, 28-days, and 90-days.

Subproject 6) Recycled Aggregate Concrete with Crushed Recycled Concrete Aggregate (Graduate student: Adam Alvey; Advisor: Dr. David C. Weggel)

This research focuses on evaluating whether crushed concrete can effectively be used as the coarse aggregate in structural concrete applications. The mix design of the recycled aggregate concrete (RAC) developed for this subproject is shown in Table 1. The testing performed on the RAC goes beyond standard compression and tensile tests that may be adequate for pavements and curbing, since the goal is to produce RAC members sufficient for structural applications. The compressive strength, tensile strength, modulus of rupture, and flexural performance of the RAC was evaluated, and the results were used to design full-scale girders for a small pedestrian bridge.

Table 1. Mix design

Percentage of Aggregate Replacement	0	10	20	30	40	50	80	100
Cement (lb/yd ³)	938	938	938	938	938	938	938	938
Virgin Aggregate (lb/yd ³)	1625	1463	1300	1138	975	813	325	0
Recycled Aggregate (lb/yd ³)	0	147	293	440	587	733	1173	1466
Fine Aggregate - Sand (lb/yd ³)	972	972	972	972	972	972	972	972
Water (lb/yd ³)	384	384	384	384	384	384	384	384

The averaged results of the compressive and tensile strengths are shown in Table 2.

Table 2. Strength test results

Aggregate Type	Compressive Strength	Splitting Tensile Strength	Modulus of Rupture
	(psi)	(psi)	(psi)
VGA	8429	474	1192
SSRC 40%	7994	447	787
SSRC 100%	7148	449	914
CRC 40%	8541	411	979
CRC 100%	8532	456	806

Replacing the coarse aggregate with recycled material was shown to have little to no effect on the flexural behavior of the reinforced concrete beams (made with Portland cement). All three beams displaced almost identically as a function of applied load. During testing, cracks were marked on the beams; there was no appreciable difference in the general crack patterns or loads corresponding to crack occurrence among the three beam specimens. These results indicate that RAC has the potential to be used in structural applications. A detailed analysis of the results will be reported in Mr. Alvey's MS thesis.

Phase 2 – Engineering Feasibility and Dissemination

Task 4.0 Regional C&D Facility: Create a preliminary design that could be used to estimate likely costs and transport issues related to the creation of a community or regional scale C&D materials brokerage facility.

This task is complete.

A search was conducted in order to identify existing C&D waste facilities in the Charlotte region and to characterize the types of C&D waste processed at each facility. For purposes of this effort, the “Charlotte region” was limited to the following counties:

- North Carolina: Cabarrus, Catawba, Cleveland, Gaston, Iredell, Lincoln, Mecklenburg, Rowan, Stanly, and Union
- South Carolina: Cherokee, Chester, Lancaster, and York

The search was conducted using websites that included:

- The Directory of Markets for Recyclable Materials, maintained by the Division of Pollution Prevention and Environmental Assistance (DPPEA) of the North Carolina Department of Environment and Natural Resources (DENR) (www.p2pays.org),
- Landfill and Recycling Options, maintained by Cabarrus County (www.cabarruscounty.us/waste/docs/waste_regionalandfillrecyclingoptions.pdf),
- The Center for Waste Minimization, maintained by the South Carolina Department of Health and Environmental Control (SCDEHC) (www.scdhec.gov/environment/admin/CWM/wmindex/), and
- The Recycling Directory, maintained by the South Carolina Department of Commerce (<http://maps.sccommerce.com/resource/recyclingdirectory.aspx>).

A total of 33 businesses involved in C&D waste recycling were identified within the Charlotte region. For each of these facilities, the type(s) of waste recycled (or accepted for processing at other facilities) was identified and tallied. Materials included asphalt pavement, asphalt shingles, carpet, carpet padding, ceiling tiles, concrete and brick, drywall, plastic, roofing material, salvaged building materials, scrap lumber, and vinyl siding. If available, processing capabilities were also identified. Categories included deconstruction services, mixed C&D waste processing, mobile recycling capability for concrete and brick waste, and mobile recycling capability for wood waste. Facilities identified in this review, along with their areas of business, are listed in Table 3.

Table 3.

Summary of Businesses Involved in C&D Waste Recycling Near Charlotte, NC						
No = not listed in NC2pays.org literature as involved with this material/activity						
NL = not listed specifically in other NC/SC database, assumed NO						
	Company	County	Address	City	State	ZIP
1	Griffin Brothers Companies	Mecklenburg	19109 W. Catawba Ave. #200	Cornelius	NC	28031
2	Highway 49 C&D Landfill and Reprocessing Center	Cabarrus	2105 Speedrail Ct.	Concord	NC	28025
3	Russo Dumpster Service, Inc.	Mecklenburg	217 W. 24th St.	Charlotte	NC	28206
4	Rogers Grading	York	4183 Mockingbird Lane	Rock Hill	SC	29730
5	Griffin Brothers Companies	Mecklenburg	15300 Holbrooks Rd.	Huntersville	NC	28078
6	Hawk Sanitation & Recycling, Inc.	Mecklenburg	900 Norris Ave.	Charlotte	NC	28206
7	Boggs Paving, Inc.	Union	2318 Concord Ave.	Monroe	NC	28110
8	Westinghouse Materials	Mecklenburg	911 E. Westinghouse Blvd. (Blue Max)	Charlotte	NC	28273
9	Blue Ridge Recycling, Inc.	Mecklenburg	3811 N. Davidson St.	Charlotte	NC	28205
10	Junk Rescue Company	Mecklenburg	P.O. Box 790042	Charlotte	NC	28206
11	The Linda Construction Co., Inc.	Mecklenburg	1801 N. Tryon St.	Charlotte	NC	28206
12	Sky Recycling, LLC	Mecklenburg	721 North Poplar St. Unit #1 (28202)	Charlotte	NC	28206
13	Carolina Disposal Service, Inc.	Davidson	816 Shady Hanes Rd.	Lexington	NC	27295
14	Applied Abatement Concepts, LLC	Cleveland	120 Wiggins Ln.	Kings Mountain	NC	28086
15	CBC Concrete Crushing & Recycling	Iredell	628 Oak Ridge Farm Hwy	Mooresville	NC	28115
16	McGraw, Inc.	Mecklenburg	11205 Reames Rd.	Charlotte	NC	28269
17	Habitat Charlotte ReStore - Wendover Road	Mecklenburg	1133 N. Wendover Rd.	Charlotte	NC	28211
18	Habitat Charlotte ReStore - Wilkinson Blvd.	Mecklenburg	3326 Wilkinson Blvd.	Charlotte	NC	28208
19	Carolina Gypsum Reclamation	Union	7323 Old Gold Mine Rd.	Marshville	NC	28103
20	RJ Brewer Grinding Services	Mecklenburg	3733 Kidd Lane	Charlotte	NC	28216
21	AEIPLUS, Inc.	Mecklenburg	2128 Eastway Dr.	Charlotte	NC	28205
22	Commercial Plastics Recycling, Inc.	Catawba	721 Shea Rd.	Newton	NC	28658
23	McManus and Son Drum Co. Inc.	Mecklenburg	5631 Racine Ave.	Charlotte	NC	28269
24	Polyreps	Union	2501 Ashcraft Ave.	Monroe	NC	28110
25	Southern Resources, Inc.	Mecklenburg	3826 Raleigh St.	Charlotte	NC	28206
26	Habitat for Humanity of Matthews	Mecklenburg	136 E. Charles St. (28105)	Matthews	NC	28106
27	Habitat for Humanity of Union County	Union	2520 W. Roosevelt Blvd.	Monroe	NC	28110
28	Cadieu Tree Experts	Mecklenburg	1605 Scott Ave.	Charlotte	NC	28203
29	Cool Springs Mulch & Stone	Iredell	130 Marshall Forest Ln.	Statesville	NC	28625
30	Profile Products	Catawba	219 Simpson St. SW	Conover	NC	28613
31	Bowers Fibers, Inc.	Lancaster	3577 Chester Highway	Lancaster	SC	29720
32	Habitat Cabarrus ReStore	Cabarrus	2902 Cannon Blvd.	Kannapolis	NC	28083
33	Cunningham Brick	Davidson	701 N. Main St.	Lexington	NC	27292

Summary of Businesses Involved in C&D Waste Recycling Near Charlotte, NC			
No = not listed in NC2pays.org literature as involved with this material/activity			
NL = not listed specifically in other NC/SC database, assumed NO			
	Company	phone	email
1	Griffin Brothers Companies	704-895-4506	mike@griffinbrothers.com
2	Highway 49 C&D Landfill and Reprocessing Center	704-455-1561	ron@griffinbrothers.com
3	Russo Dumpster Service, Inc.	704-791-4624	b.weeks@russodumpsterserviceinc.com
4	Rogers Grading	803-327-5705	
5	Griffin Brothers Companies	704-875-3367	
6	Hawk Sanitation & Recycling, Inc.	704-376-4295	
7	Boggs Paving, Inc.	704-282-0033	mbatson@boggsdpaving.com
8	Westinghouse Materials	704-821-2426	mike@bluemaxmaterials.com
9	Blue Ridge Recycling, Inc.	704-807-3680	carpetrecycling@gmail.com
10	Junk Rescue Company	800-586-5911	info@junk911.com
11	The Linda Construction Co., Inc.	704-333-7120	gary@lindaconstruction.com
12	Sky Recycling, LLC	980-322-5266	dnoz2004@bellsouth.net
13	Carolina Disposal Service, Inc.	336-731-7777	carolinadisposal@yahoo.com
14	Applied Abatement Concepts, LLC	866-505-6652	georgeculver@hotmail.com
15	CBC Concrete Crushing & Recycling	704-294-0496	info@gogreencbc.com
16	McGraw, Inc.	704-598-6969	
17	Habitat Charlotte ReStore - Wendover Road	704-716-7044	tmurphy@charlotterestore.org
18	Habitat Charlotte ReStore - Wilkinson Blvd.	704-392-4495	jmuse@charlotterestore.org
19	Carolina Gypsum Reclamation	704-624-2077	cgr@griffinbrothers.com
20	RJ Brewer Grinding Services	704-399-5500	
21	AEIPLUS, Inc.	704-536-8321	jin@aeiplus.com
22	Commercial Plastics Recycling, Inc.	828-466-2711	timb@cpinc.net
23	McManus and Son Drum Co. Inc.	704-598-2224	mcmansondrumcoinc@bellsouth.net
24	Polyreps	704-238-9949	recycling@polyreps.com
25	Southern Resources, Inc.	704-342-1696	elisaw@southernresources.com
26	Habitat for Humanity of Matthews	704-847-4266	erin@habitatmatthews.org
27	Habitat for Humanity of Union County	704-296-9414	mreece@unionhabitat.org
28	Cadieu Tree Experts	704-589-2716	dcadieu@hotmail.com
29	Cool Springs Mulch & Stone	704-872-0008	Allen_Sharpe@msn.com
30	Profile Products	828-327-4165	jclark@profileproducts.com
31	Bowers Fibers, Inc.	803-285-8451	amasonjo@bowersfibers.com
32	Habitat Cabarrus ReStore	704-786-4000	
33	Cunningham Brick	704-672-6181	

Table 3. (continued)

Summary of Businesses Involved in C&D Waste Recycling Near Charlotte, NC								
No = not listed in NC p2pays.org literature as involved with this material/activity								
NL = not listed specifically in other NC/SC database, assumed NO								
	Company	mixed C&D processing	asphalt pavement	asphalt shingles	carpet	carpet padding	ceiling tiles	concrete & brick
1	Griffin Brothers Companies	yes	yes	no	no	no	no	yes
2	Highway 49 C&D Landfill and Reprocessing Center	yes	no	no	no	no	no	yes
3	Russo Dumpster Service, Inc.	yes	no	no	no	no	no	yes
4	Rogers Grading	yes	no	no	no	no	no	yes
5	Griffin Brothers Companies	yes	NL	NL	NL	NL	NL	yes
6	Hawk Sanitation & Recycling, Inc.	yes	NL	NL	NL	NL	NL	NL
7	Boggs Paving, Inc.	no	yes	yes	no	no	no	yes
8	Westinghouse Materials	no	yes	no	no	no	no	yes
9	Blue Ridge Recycling, Inc.	no	no	no	yes	yes	no	no
10	Junk Rescue Company	no	no	no	yes	yes	no	yes
11	The Linda Construction Co., Inc.	no	no	no	yes	no	yes	yes
12	Sky Recycling, LLC	no	no	no	no	yes	no	no
13	Carolina Disposal Service, Inc.	no	no	no	no	no	yes	no
14	Applied Abatement Concepts, LLC	no	no	no	no	no	no	yes
15	CBC Concrete Crushing & Recycling	no	no	no	no	no	no	yes
16	McGraw, Inc.	no	no	no	no	no	no	yes
17	Habitat Charlotte ReStore - Wendover Road	no	no	no	no	no	no	no
18	Habitat Charlotte ReStore - Wilkinson Blvd.	no	no	no	no	no	no	no
19	Carolina Gypsum Reclamation	no	no	no	no	no	no	no
20	RJ Brewer Grinding Services	no	no	no	no	no	no	no
21	AEIPLUS, Inc.	no	no	no	no	no	no	no
22	Commercial Plastics Recycling, Inc.	no	no	no	no	no	no	no
23	McManus and Son Drum Co. Inc.	no	no	no	no	no	no	no
24	Polyreps	no	no	no	no	no	no	no
25	Southern Resources, Inc.	no	no	no	no	no	no	no
26	Habitat for Humanity of Matthews	no	no	no	no	no	no	no
27	Habitat for Humanity of Union County	no	no	no	no	no	no	no
28	Cadieu Tree Experts	no	no	no	no	no	no	no
29	Cool Springs Mulch & Stone	no	no	no	no	no	no	no
30	Profile Products	no	no	no	no	no	no	no
31	Bowers Fibers, Inc.	no	no	no	yes	no	no	no
32	Habitat Cabarrus ReStore	no	no	no	no	no	no	no
33	Cunningham Brick	NL	NL	NL	NL	NL	NL	NL

Summary of Businesses Involved in C&D Waste Recycling Near Charlotte, NC								
No = not listed in NC p2pays.org literature as involved with this material/activity								
NL = not listed specifically in other NC/SC database, assumed NO								
	Company	drywall (gypsum)	mobile recyclers concrete & brick	mobile recyclers wood waste	plastic buckets - HDPE	roofing material	salvaged building materials	scrap lumber
1	Griffin Brothers Companies	yes	no	no	no	yes	no	yes
2	Highway 49 C&D Landfill and Reprocessing Center	yes	no	yes	no	no	no	yes
3	Russo Dumpster Service, Inc.	yes	no	no	no	no	no	yes
4	Rogers Grading	no	no	yes	no	no	yes	yes
5	Griffin Brothers Companies	yes	NL	NL	NL	NL	NL	yes
6	Hawk Sanitation & Recycling, Inc.	NL	NL	NL	NL	NL	NL	NL
7	Boggs Paving, Inc.	no	no	no	no	no	no	no
8	Westinghouse Materials	no	no	no	no	no	no	no
9	Blue Ridge Recycling, Inc.	no	no	no	no	no	no	no
10	Junk Rescue Company	no	no	no	yes	no	yes	no
11	The Linda Construction Co., Inc.	yes	no	no	yes	no	yes	yes
12	Sky Recycling, LLC	no	no	no	yes	no	no	no
13	Carolina Disposal Service, Inc.	no	no	no	no	no	no	no
14	Applied Abatement Concepts, LLC	no	yes	no	no	no	no	no
15	CBC Concrete Crushing & Recycling	no	yes	no	no	no	no	no
16	McGraw, Inc.	no	no	no	no	no	no	no
17	Habitat Charlotte ReStore - Wendover Road	no	no	no	no	no	yes	no
18	Habitat Charlotte ReStore - Wilkinson Blvd.	no	no	no	no	no	yes	no
19	Carolina Gypsum Reclamation	yes	no	no	no	no	no	no
20	RJ Brewer Grinding Services	no	no	yes	no	no	no	no
21	AEIPLUS, Inc.	no	no	no	yes	no	no	no
22	Commercial Plastics Recycling, Inc.	no	no	no	yes	no	no	no
23	McManus and Son Drum Co. Inc.	no	no	no	yes	no	no	no
24	Polyreps	no	no	no	yes	no	no	no
25	Southern Resources, Inc.	no	no	no	yes	no	no	no
26	Habitat for Humanity of Matthews	no	no	no	no	no	yes	no
27	Habitat for Humanity of Union County	no	no	no	no	no	yes	no
28	Cadieu Tree Experts	no	no	no	no	no	no	yes
29	Cool Springs Mulch & Stone	no	no	no	no	no	no	yes
30	Profile Products	no	no	no	no	no	no	yes
31	Bowers Fibers, Inc.	no	no	no	no	no	no	no
32	Habitat Cabarrus ReStore	no	no	no	no	no	yes	no
33	Cunningham Brick	NL	yes	NL	NL	NL	NL	NL

A review of this tabular listing of C&D waste-recycling companies suggests that a remarkable array of facilities currently exists, and that a considerable fraction of C&D waste generated in the region is not landfilled. Further, locations within and around the Charlotte metropolitan area where C&D waste can be stored and processed are relatively plentiful, as evidenced by the network of facilities currently registered with North Carolina and South Carolina governmental agencies. Of particular interest for the subject project are five facilities in the Charlotte region that perform processing of mixed C&D waste; see Table 4.

Table 4. Mixed C&D waste processing facilities

Company	County	Address	City	State
Griffin Brothers Companies	Mecklenburg	19109 W. Catawba Ave. #200	Cornelius	NC
Highway 49 C&D Landfill and Reprocessing Center	Cabarrus	2105 Speedrail Ct.	Concord	NC
Russo Dumpster Service, Inc.	Mecklenburg	217 W. 24th St.	Charlotte	NC
Rogers Grading	York	4183 Mockingbird Lane	Rock Hill	SC
Griffin Brothers Companies	Mecklenburg	15300 Holbrooks Rd.	Huntersville	NC
Hawk Sanitation & Recycling, Inc.	Mecklenburg	900 Norris Ave.	Charlotte	NC

After conducting this review, the project team did not deem it appropriate to proceed with the conceptual design of a new C&D waste processing facility as originally proposed. More effort was, therefore, put into detailed scientific/engineering evaluation of alternative uses of high volume C&D materials. Dissemination of the results of these studies will assist existing facility owners and design engineers with making better use of these materials, thus potentially placing them in higher demand. The subsequent growth of existing enterprises (locally and nationally) would suffice to increase the number of jobs available within this market sector without adding the capital expense of new infrastructure. Utilization of these facilities is predominantly driven by market demand (value of the commodity materials), transportation costs (typically related to the distance from the construction/demolition sites to the C&D facility and the mode(s) of available transportation), and tipping fees at local landfills. Reducing these costs can be achieved through effective reuse planning and storage in response to fluctuating market demands, tax credits, subsidies, ordinances, or other means, and would further promote expansion of this industry.

Task 5.0 Engineering Feasibility Project: Create a test structure to show the economic feasibility and environmental benefits of using the materials researched as part of Task 3.0.

Subtask 5.1 Conceptual Design: Conceive of a design for the test structure that features some or all of the materials from Task 3.0.

This subtask has been completed. Three variations of the superstructure (girders) for a 3 m-long pedestrian bridge were designed. The designs were for similar bridge superstructures made from: 1) reclaimed structural steel, 2) geopolymer concrete (GC), and 3) Portland cement concrete with RCA.

Subtask 5.2 Engineered Design: Final design and construction of the structure.

This subtask was completed for each of the three bridge superstructures: 1) the reclaimed structural steel girders, 2) the GC girders, and 3) the Portland cement concrete with RCA girders.

Subtask 5.3 Assessment: Assess some of the key performance characteristics of the structure.

This subtask has been completed. The performance characteristics of the GC girders were reported in Dr. Brett Tempest's dissertation titled "Engineering Characterization of Waste Derived Geopolymer Cement Concrete for Structural Applications", the Subtask 3.2 sections of several quarterly progress reports, and the Final Scientific Report. This subtask has also been completed for the reclaimed structural steel girders and the girders made from Portland cement concrete with RCA, as reported in the Subtask 3.2 sections of several quarterly progress reports and the Final Scientific Report. Finally, detailed reporting of the performance characteristics of the reclaimed structural steel girders and the Portland cement concrete with RCA girders will be included, respectively, in the MS theses of Madeleine Grimmer and Adam Alvey.

Subtask 5.4 Analysis: Estimate the life cycle costs of the structure relative to one using virgin materials.

This subtask has been completed for the GC girders and is reported in Dr. Brett Tempest's dissertation titled "Engineering Characterization of Waste Derived Geopolymer Cement Concrete for Structural Applications".

Subtask 5.5 Evaluation: Evaluate the environmental impacts of the structure relative to a similar one using virgin materials.

This subtask has been completed for the GC girders and is reported in Dr. Brett Tempest's dissertation titled "Engineering Characterization of Waste Derived Geopolymer Cement Concrete for Structural Applications".

Subtask 5.6 Continued Monitoring: Make provisions to monitor the designed structure (e.g. sensors, collection mechanisms) so that, in addition to the baseline monitoring here, subsequent long-term studies of the material performance can be conducted.

This subtask has been completed for the Portland cement concrete with RCA girders as described below. Long-term monitoring will continue for two years beyond the end of the project (August 31, 2010).

The performance of concrete containing recycled aggregate has been evaluated as a part of the research presented in this report. Cylindrical concrete specimens have been used to measure the compressive strength of the material. Further, reinforced concrete beams were prepared in order to demonstrate the behavior of recycled aggregate concrete (RAC) in structural components. This series of experiments has given an indication that recycled aggregate concrete is a viable construction material from a strength perspective. In order to further demonstrate the material,

the research team has established a long-term test that will provide information regarding deformations under sustained dead loads and outdoor environmental conditions. The long-term field test results will be related to performance predictions made following the evaluation of material performance with standard test methods.

The time-dependent deformation of concrete under sustained loads is referred to as creep. In Portland cement concrete, the paste fraction undergoes dimensional changes while the aggregates tend to restrain creep-related deformation. Because much of the reclaimed aggregate consists of the paste fraction from the source monolith, creep may occur at a greater magnitude in RAC. This could present design problems in structures with significant sustained dead loads or in prestressed and post-tensioned applications. The tests described below are intended to evaluate the potential for creep in RAC using a loaded beam situated outdoors for a two-year period as well as loaded concrete cylinders stored under controlled environmental conditions.

Loaded and Exposed Beam

A reinforced RAC beam has been prepared and aged in ambient outdoor conditions for a period of six months. The results of static load testing of an identical beam are available in the research performed by Adam Alvey (Subproject 6). The beam dimensions and reinforcement details are provided in Figures 1 and 2. The beam is situated in an exposed, outdoor location and is instrumented with vibrating wire strain gages at six points along the beam's center line. Two gages are applied at the tension face of the beam, two gages at the uncracked neutral axis, and two gages at the compression face. Static loads are applied with heavy weights at the 1/3 points of the beam's clear span, as shown in Figure 2. The magnitude of the loads was determined such that they produce stresses at the compression face equivalent to 40% of the compressive strength of the concrete material determined by cylinder tests. Deflection, strain, and environmental conditions will be monitored continuously for the first week of exposure, weekly for the following four weeks, and then monthly thereafter for a period of two years.

Environmentally Controlled Tests

The measurement of creep in a controlled laboratory setting is undertaken by preparing concrete cylinders, allowing them to cure for a specified period of time, and then subjecting them to a constant stress that does not exceed the proportional limit for the material. The range typically used is around 40% of the cylinder's compressive strength. For this study a series of three RAC cylinders created from the same batch of concrete used to cast the previously described beam will be instrumented with vibrating wire strain gages and loaded to 40% of their compressive strength. The cylinders will be stored in a loaded condition inside an environmental chamber which maintains 73°F and 50% humidity. Strain in the cylinders will be measured continuously for one week and then daily for a period of two years.

Figure 1. Beam cross section and rebar/stirrup specifications.

Figure 2. Beam dimensions.

Analysis of Results

After the two-year evaluation period, results from the controlled environment testing will be used to determine the creep coefficient associated with the RAC. The creep coefficient will be compared with values from similar strength virgin aggregate concretes to ascertain if the recycled aggregates contribute to increased creep potential. The coefficient will also be used to predict long-term deflection in the beam specimen. The predicted deflection will be compared with the measured deflection from the exposed beam in order to assess the applicability of methods used to estimate creep in virgin aggregate concrete to RAC. While the results of the study will not be sufficient to provide guidance to designers using RAC, they may uncover a research need that requires further attention.

Task 6.0 Pedagogical Development: Develop course modules or a dedicated course on deconstruction and C&D waste management.

A multidisciplinary course entitled “Green Building and Integrative Design,” was offered for architecture and engineering students at UNC Charlotte. Course modules developed by researchers in the Building Materials Reclamation Program were integrated in the class to introduce material salvage and material reuse. This course was first offered in the 2009 fall semester and for a second time in the 2010 fall semester.

Technical Presentations and Publications

- The technical paper titled “Compressive Strength and Embodied Energy Optimization of Fly Ash Based Geopolymer Concrete” by Tempest, Sanusi, Gergely, Ogunro, and Weggel, all UNC Charlotte authors, was submitted to the World of Coal Ash (WOCA) Conference for publication. It was accepted, and Brett Tempest presented it at the WOCA Conference in Lexington, Kentucky on May 4-7, 2009.
- The technical paper titled “Construction and Demolition Waste used as Recycled Aggregates in Concrete: Solutions for Increasing the Marketability of Recycled Aggregate Concrete” by Tempest, Cavalline, Gergely, and Weggel, was submitted to the National Ready Mixed Concrete Association for publication. It was accepted, and Tara Cavalline presented it at the *2010 Concrete Sustainability Conference*, National Ready Mixed Concrete Association, Tempe, Arizona, April 13-15, 2010.
- Mr. Fabien Besnard gave a presentation titled “Evaluation of Waste Virgin Gypsum Wallboard as a Soil Amendment” at the NC SWANA Fall 2010 Conference held in Wilmington, North Carolina, October 20, 2010.