
THE ROLE OF HVFA CONCRETE IN THE SUSTAINABILITY OF THE URBAN BUILT ENVIRONMENT

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ABSTRACT

Although fly-ash as a partial replacement for cement has been utilized for many years, its use has been almost exclusively used in low volume percentages such as 10% or 20% cement replacement. This paper looks at high volume percentage replacements from 40% to 70%. A mini-mix study revealed that 50% and 60% cement replacement percentages were the best candidates for full scale testing. The environmental benefits included a 25% reduction in smog, human health, and fossil fuel reduction compared to the same element built with 100% Portland cement mix. The economic benefits included a 15% capital cost reduction and a 20% life-cycle cost reduction when compared with a 100% Portland cement mix. Full scale testing included a complete mix design in addition to the construction of four concrete infrastructure products. The products built included an alley panel and curb and gutter sections in the City and county of Denver, a precast manhole and lid, and a twin tee prestressed girder. Although cement products are just one of many materials used in the construction of the built environment, its production has a large impact on the environment. Lowering the embodied energy of multiple types of construction materials will have a significant effect on sustainable urban development. Symbiotic recycling of waste material, such as fly ash in concrete, back into the built environment can help reduce materials on the input side and pollution on the output side of the bulk material flow of an urban city.⁴

KEYWORDS

LEED, high volume fly ash concrete, green engineering

INTRODUCTION

Current “green building” guidelines for construction materials establish qualitative environmental goals, relating the distance of transportation of the product instead of the required energy of material extraction and production, termed embodied energy [1]. However, sustainability of the urban built environment requires choosing building materials based on quantitative structural, thermal, environmental and economic criterion. In order to define a construction material as a viable green alternative, an environmental life cycle assessment (LCA) and a life cycle cost (LCC) analysis should be completed in addition to structural and durability testing. However, the time and cost of obtaining the performance data and putting it in the hands of the design engineer is a significant barrier to commercializing sustainable building materials [2].

For the first time in human history, more than 50% of the world's population is currently residing in cities [3]. Populations in many cities in the developing world, e.g., Dhaka in Bangladesh, are increasing at unprecedented rates of more than 6% per year, placing huge demands on urban infrastructure. The use of minerals, including construction materials and metals, account for more than 90 percent by weight of non-food, non-fuel construction materials used in the United States [4]. Thus, the construction industry is likely to be a dominant player in material cycles in the anthroposphere. Concrete dominates the material used in construction both in terms of gross mass of material used as well as the energy consumed and the pollution released from cement manufacture and installation. If the embodied energy of concrete can be reduced without decreasing performance or increas-

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ing cost, significant environmental and economic benefits may be realized [5]. Concrete is primarily comprised of Portland cement, aggregate, and water. Although Portland cement typically only comprises 12 percent of the concrete mass, it accounts for approximately 93 percent of the total embodied energy of concrete* and 6% to 7% of the worldwide CO₂ emissions [6]. The phase I testing presented in this paper documents the procedures undertaken to evaluate if a concrete mix with a high volume fly ash (HVFA) replacement for Portland cement would provide environmental and economic benefits and still achieve the required workability, durability, and strength testing necessary for the design of the foundation and basement walls of structures. The testing included “mini-mixes”, full-scale batch testing, durability tests, and the manufacture of structural products. The products include a precast manhole, the installation of road and curb and gutter panels in the Denver, Colorado area, and a twin tee prestressed girder. Future products include a structural foundation storage shed wall.

A bulk material flow analysis for a Colorado urban city will be proposed as an ongoing Phase II study. Materials to be studied include the HVFA concrete testing presented in this paper in addition to stainless and structural steel, aluminum, aggregates, polyvinyl chloride, asphalt, raw water, and potable water.

HIGH VOLUME FLY ASH CONCRETE

According to a generally accepted definition, high volume fly ash (HVFA) concrete is constituted by a minimum of 50% fly ash, a low water content (130kg/m³), less than 200 kg/m³ cement content, and a low water-cementitious ratio (less than 0.4) [7]. Fly ash from western U.S. modern thermal power plants generally does not require processing prior to being incorporated into concrete and is therefore considered to be an “environmentally free” input material for LCA purposes [8]. When used in concrete, fly ash is a cementitious material that can act as a partial substitution for Portland cement without significantly compromising compressive strength. The pozzolanic properties of a good-quality

fly ash are governed primarily by the mineralogy, low carbon content, high glass content, and 75% or more particles finer than 45 µm [7]. The two main types of fly ash used for concrete additives in the U.S. are ASTM Class F and ASTM Class C. Class F fly ash was used for the laboratory HVFA concrete testing in this study and three of the products. One of the products produced, the prestressed double tee girder, used Class C fly ash.

BARRIERS TO INCORPORATE FLY ASH

There may be a perception among engineers and architects that concrete construction codes are prescriptive in the sense that there is a maximum permissible limit of fly ash that can be specified in a concrete mix. The confusion arises from the governing standards as, for instance, American Standards for Testing Materials (ASTM) C 595 limits the proportion of the pozzolan in the cement to 40 percent by mass while a new, performance-based cement standard ASTM C 1157 [9] does not limit the type and the content of components in the blended cement. The uniform building code generally defers to ASTM C 618 [10] in regards to fly ash content that states that the optimum amount of fly ash or natural pozzolan for any specific project is determined by the required properties of the concrete and other constituents of the concrete and is to be established by testing.

LCA/LCC TESTING OF HVFA CONCRETE

Compressive strength testing of 12 HVFA “mini-mixes” was completed to select promising mixes to carry forward for further full-scale testing. The mini-mixes evaluated substitution of Portland cement with Class F fly ash ranging from 40 to 70 percent by weight (typical concrete mixes contain between zero and 15 percent fly ash). In addition, the proposed HVFA concrete mixes were initially evaluated with LCA/LCC software to evaluate the appropriateness of referring to HVFA concrete as an economically and environmentally friendly concrete.

LCA Testing

The Building for Environmental and Economic Sustainability (BEES) Version 3.0 software is a LCA/LCC

* The assumptions include; cement hauled 80 km (50 miles) to ready-mix plant, aggregate hauled 16 km (10 miles), concrete hauled 8 km (5 miles) to building site. The concrete mix consists of: 297 kg/m³ (500 lb/cy) cement, 831 kg/m³ (1,400 lb/cy) sand, 1187 kg/m³ (2,000 lb/cy) crushed stone, 154 kg/m³ (260 lb/cy) water.

tool containing environmental and economic performance data for nearly 200 products across 23 building elements [8]. The LCA assessment is a “cradle-to-grave” approach that considers raw material acquisition, product manufacture, transportation, installation, operation and maintenance, and ultimately recycling and waste management. For this paper, BEES has been applied to evaluate the effects of the inclusion of Type F fly ash into concrete production. However, only fly ash contents of 0% (100% Portland cement), 15%, 20%, and 35% (for slabs) has been included in the BEES database. Extrapolated for percentages up to 70% was completed. The functional unit for concrete quantities is 0.09 m^2 (1 ft^2) and a product service lifetime of 50 years. The energy requirements for the HVFA materials in BEES are the following:

- Coarse and fine aggregate: BEES conservatively assumes that all aggregate is crushed and the energy assumed for production and an 85 km round-trip to a ready-mix plant is 155 kJ/kg (66.8 Btu/lb).
- Portland cement: BEES data for cement manufacture is based on the average ASTM C150 Type I/II cement [11]. The energy assumed for production (based on a weighted average of manufacturing processes) and a 100 km round-trip to the ready-mix plant is 5,320 kJ/kg (2,280 Btu/lb).
- The transport energy for all materials in concrete production is by truck, consuming 1.18 kJ/kg*km (0.818 Btu/lb*mi).
- There is no energy assigned to fly ash other than 100 km round-trip transport to the ready-mix plant.

The impact assessment evaluated for equivalent CO_2 value using the methodologies of TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) that are based on “midpoint” characterization approaches that reflect the relative potency of the stressors at a common midpoint within the cause-effect chain. Environmental impact categories are generally of two types: (1) the depletion categories, which include abiotic resource depletion, biotic resource depletion, land use, and water use, and (2) the pollution categories, which include ozone depletion, global warming, human toxicology, eco-toxicology, smog formation, acidification, eutrophication, odor, noise, radiation,

and waste heat [12]. The results for the concrete mixes are illustrated against eight environmental impact categories, representing an overall performance for the various fly ash substitution percents, shown on Figure 1.

The BEES output for overall environmental performance indicates substantial indicator reductions for increasing volumes of fly ash as a substitution for Portland cement, particularly the human health and global warming assessments. The overall environmental impact for 35% of the fly ash mix was 11.7% when compared to the 0% (100% Portland cement) mix. This was linearly extrapolated to estimate a 26.6% reduction in environmental performance for a mix with 70% fly ash inclusion. If these scores are each first multiplied by the quantity of functional units to be used in a particular building the environmental impacts may then be compared and can provide insights into selecting building elements.

LCC Testing

The same concrete mixes were evaluated using BEES for a life cycle cost using a real interest rate (discount factor) of 3.5 percent [13]. All expenses for the alternatives during the period of analysis are in base year 2002 dollars. The results are shown on Figure 2. The higher amount of fly ash substitution provided the greatest reduction in lifetime costs. The results indicate a 10.3% reduction in economic performance for the 35% fly ash mix when compared to 0% substitution. This result was linearly extrapolated to estimate a 21.3% reduction for 70% fly ash inclusion.

INITIAL “MINI-MIX” HVFA TRIALS

The “mini-mix” (MM) approach substitutes the ASTM C 128 [14] sand moisture cone for the ASTM C 143 [15] concrete slump cone as a measure of workability. MM tests are mixed in the same proportions as a full-scale mix, but without the coarse aggregates. The process was selected for determining an appropriate HVFA mix as the effect of variables on concrete systems can be rapidly assessed. Twelve MM batches were mixed over a range of 40 to 70 percent Class F fly ash substitution for Portland cement and water reducing admixtures that would produce required early and long-term strengths for potential use as precast and structural items.

The mixes were divided into three ranges of total cementitious content (low-L, medium-M, and high-H).

FIGURE 1. Environmental performance for varying amounts of fly ash substitution.

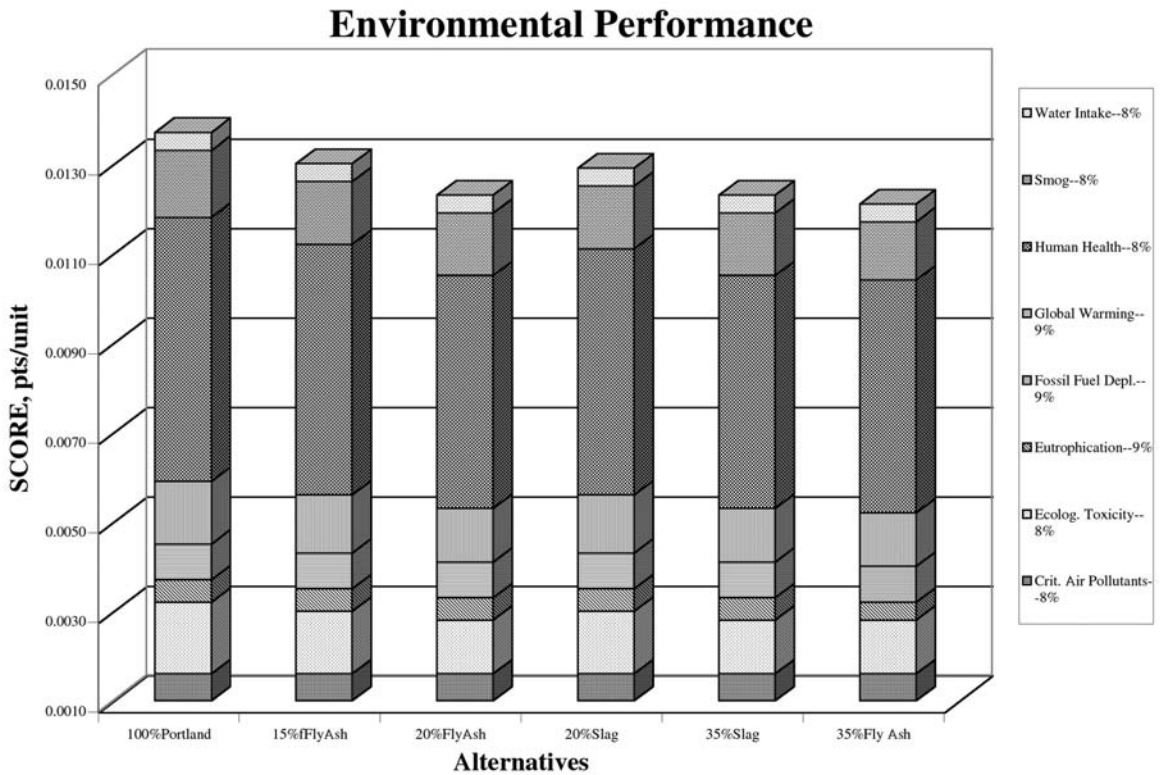
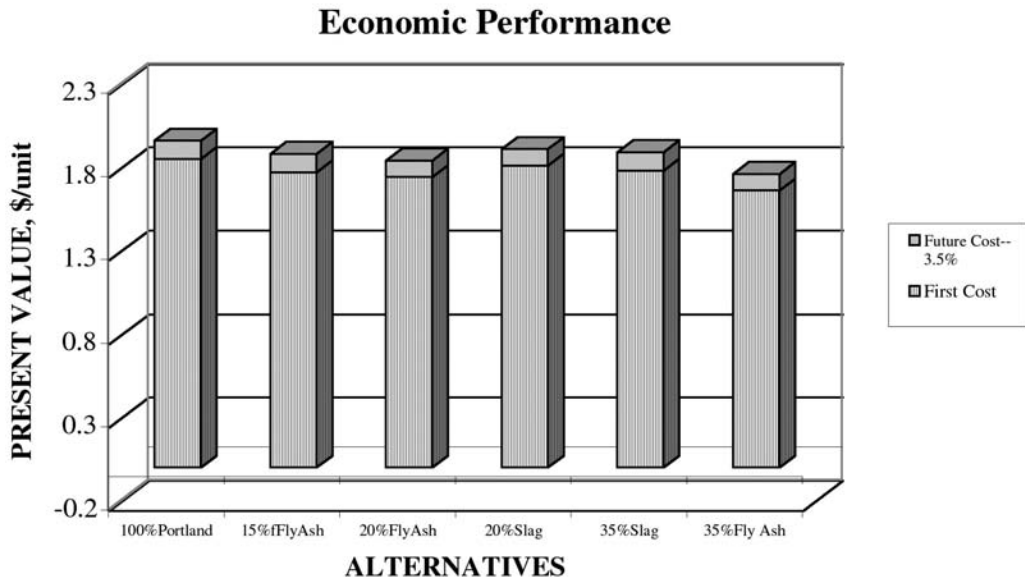


FIGURE 2. Economic performance for varying amounts of fly ash substitution.



The total cementitious material (TCM) for the three sets was 327-kg/m³ (550 pounds per cubic yard) for the low (L), 369-kg/m³ (620 pounds per cubic yard) for the medium (M), and 410-kg/m³ (690 pounds per cubic yard) for the high (H). Each range of cementitious content was further divided into four total fly ash replacement percentages of 40, 50, 60, and 70 (e.g., L70 is a low TCM mix with 70 percent fly ash replacement). The fly ash used in the mix was Class F obtained from the Coal Creek power plant in North Dakota and brought to Colorado by rail. The fly ash particle diameters were 29.09 percent finer than 10 µm and 67 percent finer than 45 µm (per ASTM C 618). In addition, Glenium 3020 HES (now known as Euclid), a water reducing agent (WRA) was added to the mixes. The proportions used in the 12 MM tests are shown in Table 1.

Measuring compressive strength using the MM procedure is conventionally obtained by 50.8-mm by 101.6-mm (2-in by 4-in) cylinders. But due to the number of samples, and that the MM trials were to be a precursor to full-mix design strength and durability trials, 50.8-mm (2-inch) cubes were tested for compressive strength. It was anticipated that the MM strength results would be approximately 20 percent to 30 percent higher than full-scale tests that include the coarse aggregate fraction and are broken in larger cylinders (101.6-mm by 203.2-mm/ 4-inch by 8-inch). The main criteria for selecting which of the MM mixes would be carried on for full-scale testing

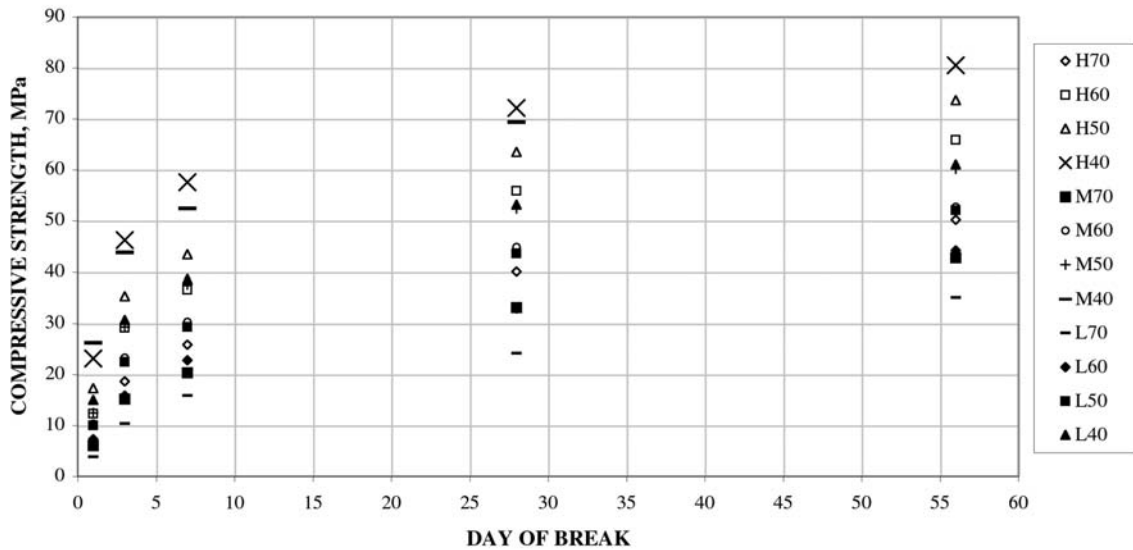
were those with the highest percentage of Portland cement replacement and those that achieved 1-day compressive strengths of 10.35 MPa (1500 psi) for pre-cast work, and 28-day strengths of 27.6 MPa (4000 psi) for structural concrete. The compressive strength test results for the 12 mixes at 1, 3, 7, 28, and 56-day breaks are shown on Figure 3.

The performance of these mixes at early-age strength showed promising results. All of the tests except L70 met the 28-day strength of 27.6 MPa (4000 psi). However, L70, M70, and L60 did not meet the 1-day break strength of 10.35 MPa (1500 psi). Much of the unexpected very high strengths for the passing tests are likely the result of low water cement (w:c) ratios, the use of smaller cylinders, and the lack of non-homogeneity usually found in larger aggregate. At early ages, the fly ash does not provide a chemical strength matrix, but it does act as solid filler and a cement paste hydration site for further strength development. At later ages the fly ash does form additional calcium silicate which results in increasing strength. Although the strengths increase with decreasing fly ash content, it is anticipated that the trend would not continue as a higher w:c would be required to compensate for decreased workability due to the floc associated with higher portland contents. The early-age compressive strength and the high volume of fly ash content led to the selection of four mixes for full scale testing using 101.6-mm by 203.2-mm (4-inch by 8-inch) cylinders.

TABLE 1. Mix proportions for the 12 mini-mixes.

Material	H70 kg/m ³	H60 kg/m ³	H50 kg/m ³	H40 kg/m ³	M70 kg/m ³	M60 kg/m ³	M50 kg/m ³	M40 kg/m ³	L70 kg/m ³	L60 kg/m ³	L50 kg/m ³	L40 kg/m ³
Cement	122.8	163.7	204.7	245.6	110.3	148.3	183.9	220.7	97.9	130.5	163.1	195.8
Fly Ash	286.5	245.6	204.7	163.7	258.1	221.9	183.9	147.1	228.4	195.8	163.1	130.5
WRA	12.3	16.4	20.8	24.6	11.1	14.8	18.3	22.1	9.8	13.1	16.2	19.4
Fine Aggregate	777.0	769.8	765.3	767.4	825.7	821.4	831.4	782.8	854.5	862.9	869.5	868.8
Coarse Aggregate	1071	1094	1083	1082	1070	1074	1063	1102	1072	1072	1061	1059
Water	122.8	115.8	128.6	132.5	118.9	117.8	121.5	124.7	124.6	124.6	122.6	123.6
Air												
Content, %	0.6	0.7	0.6	0.6	0.8	1.2	1.3	1.2	0.6	0.6	1.4	1.7
w:c ratio	0.30	0.28	0.31	0.32	0.32	0.32	0.33	0.33	0.38	0.38	3.80	0.38

Notes: The value represents an equivalent quantity for a full-scale mix. Coarse aggregate not used in mini-mix tests. Computed air content based on gravimetric analysis.

FIGURE 3. Compressive strength test results for the 12 mini-mix batches

FULL-SCALE BATCH TESTS

Four mix designs were chosen for full-scale testing from the MM results. L50 was chosen because its 1-day compressive strength was 10.00 MPa (1450 psi) and a 28-day strength of 43.61 MPa (6325 psi). M50 was selected due to a 1-day compressive strength of 12.41 MPa (1800 psi), and the 28-day compressive strength was 52.40 MPa (7600 psi). H60 mix had a 1-day compressive strength of 12.24 MPa (1775 psi), and a 28-day compressive strength of 55.85 MPa (8100 psi). The H70 mix had a 1-day strength of 6.20 MPa (900 psi), and a 28-day compressive strength of 39.99 MPa (5800 psi).

In addition to the L50, M50, H60 and H70 mixes, two 100 percent Portland cement mixes were included for comparison purposes (L0 and M0). The tests run on all samples included; compressive strength ASTM C 39 [16], slump ASTM C 143 [14], air content ASTM C 231 [17], and temperature ASTM C 1064 [18]. All samples were compared on the basis of a 12.7 cm (5 inch) slump. In addition, two durability tests, freeze/thaw ASTM C666 [19] and sulfate resistance ASTM C1012 [20] were used to evaluate M50, H60, and H70. The proportions used in the full-scale tests are shown in Table 2.

TABLE 2. Mix proportions for the full-scale tests.

Material	H70 kg/m ³	H60 kg/m ³	H0 kg/m ³	M50 kg/m ³	M0 kg/m ³	L50 kg/m ³	L0 kg/m ³
Cement	123.0	164.0	409.0	184.0	368.0	163.0	336.0
Class F Fly Ash	287.0	246.0	0.0	184.0	0.0	163.0	0.0
WRA	0.6	0.79	1.96	0.88	1.76	0.79	1.56
Fine Aggregate	767.0	778.0	663.0	820.0	697.0	857.0	755.0
Coarse Aggregate	1068.0	1068.0	1103.0	1068.0	1103.0	1068.0	1103.0
Water	126.0	128.0	143.0	129.0	146.0	139.0	135.0
Air Content,%	6.1	6.1	5.6	6.5	7.5	1.6	7.5
w:cm ratio	0.31	0.31	0.35	0.35	0.4	0.41	0.4

Laboratory Testing

The mix consistency for slump was maintained between 10 cm to 15 cm (four to six inches) and the mix temperature was maintained between 15.6°C to 26.7°C (60°F to 80°F). The air content was within a reasonable range of 6.5 percent, plus or minus one percent.

The compressive strength test results for the 6 full-scale mixes at 1, 3, 7, 28, and 56-day breaks are shown on Figure 4.

The test results indicate significant differences between the MM compressive strength results and the full-scale mix compressive strength results. The H60 and H70 mixes produced the lowest w:cm values due to the high replacement percentage of Portland. The L50 mix was the only mix not to include air entrainment for comparison purposes. This may explain the relatively higher compressive strength of the full-scale L50 mix when compared to the MO mix with a similar w:cm. H60 performed slightly better than the M50 mix likely due to the higher cementitious content and the lower w:cm.

The 28-day and 56-day compressive strengths were acceptable, and could be used for all structural

and non-structural concrete applications. The one day strengths did not meet our stated criteria of 10.0 MPa for precast work. However, the H60 mix performed well on the three day and seemed a good candidate mix for further evaluation.

Durability tests were conducted on M50, H60, H70 and a control (100 percent Portland). For the freeze-thaw testing, at the time of this paper publication, all of the samples showed no sign of visible deterioration after over 200 cycles of freezing and thawing. For sulfate expansion (ASTM C 1012), the mixes were evaluated to determine the effect of cement substitution by fly ash. The test evaluates the expansion of mortar bars immersed in a sulfate solution. The mortar bars were cured until they reached a compressive strength of 20.0 ± 1.0 MPa (3000 ± 150 psi), as measured before the bars are immersed in sodium sulfate. The curing times ranged from one day for the control to nearly four weeks for the H70 mix. After 123 days, the fly ash mixes generally out-performed the control mix with the H70 mix showing the least expansion. These results are in line with reported lower permeability for HVFA concrete [7]. The results of the sulfate expansion test are shown on Figure 5.

FIGURE 4. Compressive strength test results for the 7 full-scale batches.

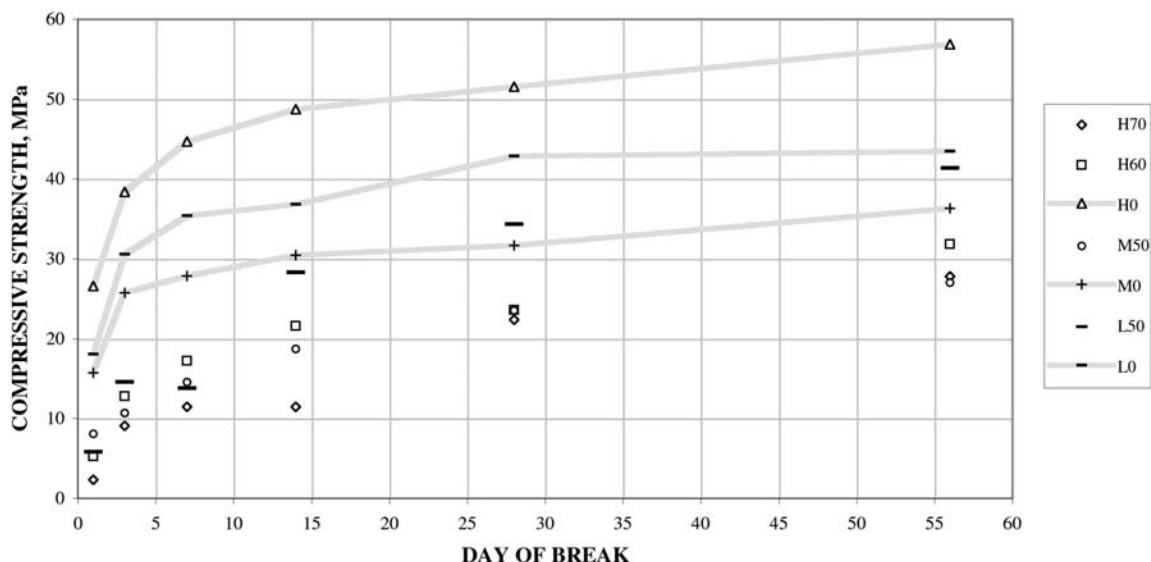
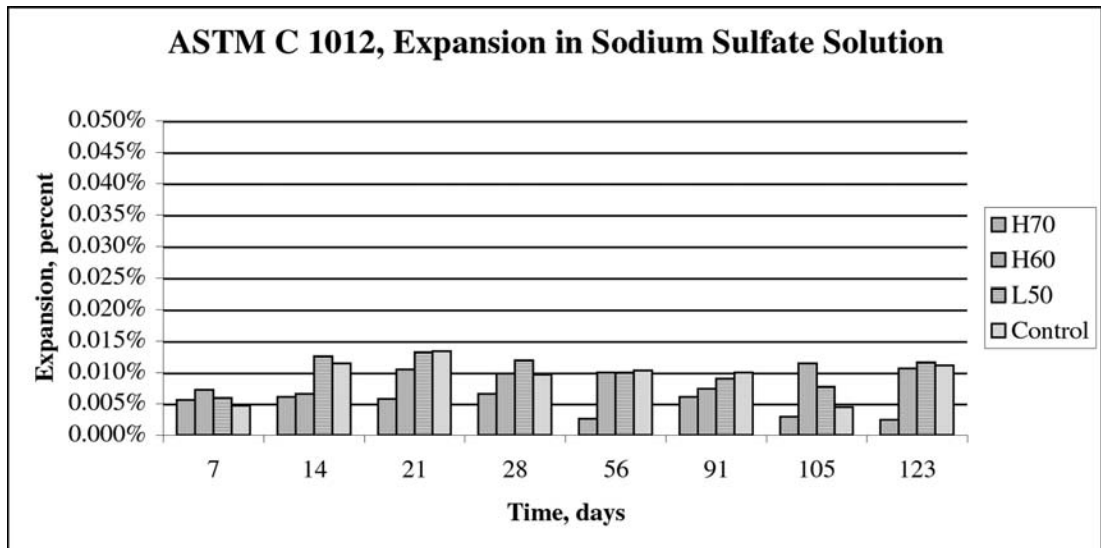


FIGURE 5. Results of sulfate expansion test (ASTM C 1012).



HVFA CONCRETE IN THE BUILT ENVIRONMENT

The primary goal of phase one of this study was to evaluate an HVFA concrete mix that would be readily used in the built environment. Although the durability test results were satisfactory, the relative inconsistencies in the compression testing results indicated further evaluation of HVFA mixes are necessary prior to use in a structural foundation. However, for light structural loading, the H60 mix provided excellent durability results and sufficient strength for use in the field. Therefore the H60 design mix was selected for four field applications to see how readily industry would accept HVFA in the field.

AMCOR Precast Manhole

As part of this study, AMCOR Precast in Littleton, Colorado produced a 1.83 m (72 inch—height and diameter) precast manhole and base section with a 0.255 m (10 inch) thick lid with an access hole using the H60 mix. The final product is shown in Figure 6.

The forms were stripped at one-day without steam curing and the surface texture and appearance were considered to be good by AMCOR. The manhole was designed for AASHTO HS-20 traffic loading and is to be installed at a development project in Fredrick, Colorado in the winter of 2005. The man-

hole included four pipe penetrations, including a 1.22 m (48 inch) hole, and two 0.61 m (24 inch) holes for storm sewer piping (21).

City and County of Denver: Cast-in-Place Alley-Slab and Curb and Gutter

The City and County of Denver Streets Department volunteered to use the H60 mix for an alley panel (placed on November 9, 2004 and located between Fourth and Fifth Street, and Steel and Adams Streets) and curb and gutter sections (placed on March 22, 2005 and located near 17th and Sheridan) on the condition that 28-day compressive strength be 17.24 MPa (2500 psi). For comparison, typical high-early cement mixes were placed next to the H60 panel and curb and gutter sections. These projects were significant in that the HVFA was mixed with ready-mix concrete from a local ready-mix company.

Prior to placing the panel, the contractor unilaterally decided to add a significant amount of superplasticizer to the mix to increase the slump to approximately 18 cm (7 inches). The strengths for the alley panel were independently tested by the City and County of Denver and cylinders were taken at the time of placement. Despite the high slump, the 3-day compressive strength was 21.37 MPa (3100 psi), adequate to open the alley to traffic.

FIGURE 6. H60 precast manhole and lid (AMCOR).



The HVFA concrete required approximately 3 hours from placement to broom finishing, compared to a one hour set for the high-early mix. There was not a discernible color difference between the two mixes. The ready-mix contractor commented that although the set time was longer than typical, he indicated that it would not be a problem when placing large amounts of concrete due to the time on site. Other than the time of initial set, he noted that the HVFA concrete was easier to float off than the high-early strength mix and that he would have no problems using the mix again. The City and County of Denver is planning on installing an H60 slab-on-grade for a salt storage facility and a street panel on 23rd Avenue, an artillery road exposed to de-icing salts in summer 2005.

Rocky Mountain Prestress Plant T-Beam

Rocky Mountain Prestress Plant produced a prestressed structural double-tee girder using the H60 mix. For comparative purposes, the mix was modified to substitute Class C fly ash for Class F and Type III for Type I/II cement. The mix produced very satisfactory compressive strengths, particularly at the day one breaks. The compressive strength test results for the H60 (Type C fly ash, Type III cement) for the slab and double-tee beam at 1, 7, and 28 breaks are shown in Figure 7. The double tee girder was load

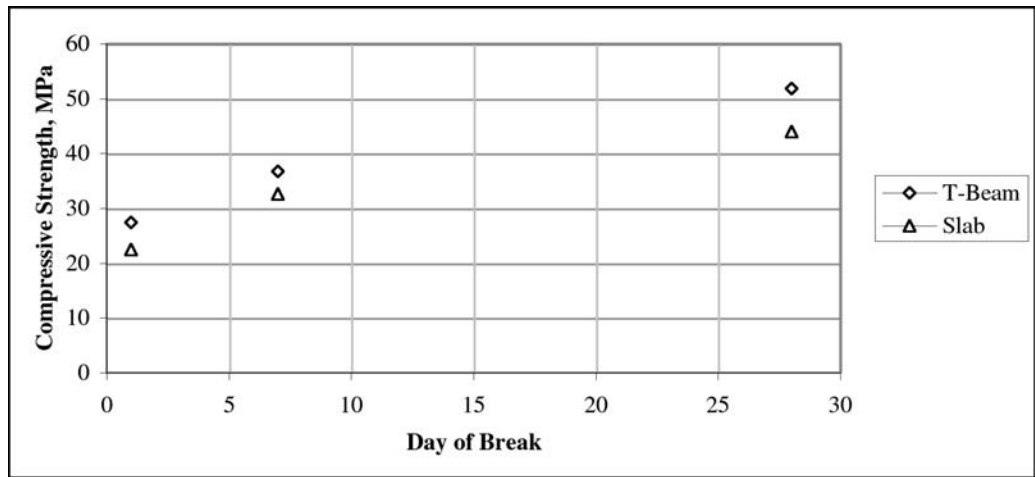
tested following ACI 318-20 "Strength Evaluation of Existing Structures" and performed well [22].

BULK-MATERIAL FLOW ANALYSIS OF THE URBAN BUILT ENVIRONMENT

With nearly half of the world's six billion people living in cities, lowering the embodied energy of construction materials such as concrete, steel, aluminum, asphalt, water, etc. used for the urban built environment will have a significant effect on sustainable urban development. Construction materials are overwhelmingly the largest constituent of net additions to urban infrastructure (net stock). As material stocks grow, so does the potential waste volume and, equally, the potential for recycling old material into new stock.

Materials used by a city for the purposes of building infrastructure either accumulate forming material stocks, removed and replaced during operation and maintenance, or they are released as waste and emissions. Specific materials can be quantified in terms of origin of manufacture, mode of transportation, life span and disposal by a bulk-Material Flow Analysis (bulk-MFA). The associated environmental burden of each material can be characterized from cradle-to-grave analysis using Life Cycle Assessment (LCA) methodology. The materials of an urbanized area in the United States will build upon the ongoing industrial symbiosis investigations completed at

FIGURE 7. Compressive strength test results for the slab and double-tee beam.



the University of Colorado at Denver by identifying waste to value potential within a city infrastructure. An urbanized area is defined by the census bureau as a statistical geographic entity consisting of a central place and adjacent densely settled territory that together contain at least 50,000 people, generally with an overall population density of at least 1,000 people per square mile [23].

Sustainable urban development encompasses quantifying a city's consumption of natural resources and the resulting loss of ecosystems and air and water emissions due to construction and transportation. A tool that could be used by decision-makers to develop long-term environmental goals based on material use reduction, identification of potential symbiotic recycling of waste back into the infrastructure and lower embodied energy material selection would provide the basis for scenario building for policy decisions. Auditing the primary materials used in a city's infrastructure can therefore address several issues: identify materials that are heavily used to scarcity on the input side and the pollution or emission on the output side. This may be very significant for planning sustainable development on national scale or even on global scale.

No major international organization currently collects statistics on energy consumption at the city level and data on energy and material fluxes at the city level are extremely scarce [24]. Most bulk-MFA studies utilize national or large regional databases to identify material usage and scale down to evaluate

per capita material usage on a city scale. For example, a bulk-MFA study of Greater London assumed that 2.6 percent of UK's construction materials are consumed in London. This is because the national database identified that 2.6 percent of construction workers are employed in London [25]. This method of scaling down assumes that material consumption occurs where the materials are manufactured.

Current bulk-MFA methodology uses two systems: Eurostat in Europe and World Resources Institute (WRI) in North America. Both systems are based on statistical information for imports, outputs and domestic extractions. Typically, much of the data is then scaled to evaluate per capita indicators. The bulk-MFA portion of the Phase II study will use data on material used that is directly obtained from the main infrastructure departments. For the purposes of this study, it is proposed to study the urban city of Longmont, Colorado detail based on their 2004 building material usage.

DISCUSSION, CONCLUSIONS, AND FURTHER STUDIES

The LCA/LCC evaluations indicated that HVFA could provide environmental impact and life-cycle cost reductions in the 25 percent to 15 percent range, respectively. The overall environmental performance of a material in BEES does not represent an *absolute* value, rather a proportional difference in *relative* performance of materials [8]. The economic

benefits included an approximate 15% initial cost reduction for HVFA when compared with a 100% Portland cement mix as shown in Table 3.

Although the full-scale strength tests were not conclusive, the strengths and the field installations will ultimately provide empirical data for the designer to recommend higher fly ash content. Long-term testing will be completed on the strength and durability of the street panels and the manhole (observed from the inside at least). Research will continue with evaluating the optimal H60 and L50 mixes. In addition, comparison will be made to similar replacements of Portland cement with Class C fly ash and slag. The testing for Phase II includes the following:

- **Optimal HVFA mix:** A higher fly ash content allows a lower water to cementitious materials ratio (w:cm) thereby leading to an increase in compressive strength. Conversely, the increased substitution of fly ash for Portland cement leads to a reduced compressive strength. The next phase of testing will seek to identify an optimal fly ash and w:cm ratio.
- **Slag:** Slag is another cementitious material that can act as a partial substitution for Portland cement without significantly compromising compressive strength. Slag is a waste product from the steel industry. However, the material is not considered as “environmentally free” as fly ash as quenching and granulating processes are required prior to inclusion in concrete, thereby increasing the embodied energy.
- **Class C Fly Ash:** Class C fly ash has a higher loss-of-ignition (LOI) allowed under ASTM 618 [10] and may be more susceptible to cracking as a result. However, the optimal HVFA Class F mixes will be compared to similar mixes using Class C fly ash.

TABLE 3. Cost per cubic yard for full mix designs.

Mix	Cost, \$
L0	\$41.17
L50	\$34.83
M0	\$44.18
M50	\$36.94
H0	\$47.34
H60	\$37.35
H70	\$35.48

Phase II Bulk Flow Case Study: Longmont, Colorado

A material use audit will be completed for the infrastructure sectors within Longmont, Colorado to identify the total environmental impact of the materials and to identify potential uses for wastes and by-products. The proposed bulk-MFA study, will gather data directly from the department heads and head engineers from the water, wastewater, public works, storm-sewer, and power (Longmont is co-owner of their own fossil fuel power facility) to start a database of actual material purchases for the year 2004. Materials to be audited include concrete, steel, stainless steel, aluminum, aggregates, polyvinyl chloride, asphalt, raw water, and potable water.

Scenarios may be developed to extrapolate the environmental impacts based on current policies and comparisons to alternative policies that provide “targets” for an unspecified year will be completed. The findings of the study will be divided into three tiers of indicators: 1) city level for comparison of Longmont with cities of similar size and form; 2) comparison of environmental impact between the sectors of infrastructure; and 3) indicators that are sector specific.

These data will be evaluated with LCA/LCC software (BEES, Version 3.0 and Athena Environmental Indicator) to evaluate mid-point impacts on a sector-by-sector basis. The LCA software that will be used to analyze environmental impact of infrastructure material use is TEAM [26]. This software accounts for the various energies and emissions during each phase of the Life Cycle Assessment as defined by ISO14040. The model defines each phase as follows:

- **Resource Extraction:** In addition to the actual harvesting, mining or quarrying of a resource, the extraction phase includes the transportation of raw resources to the mill or plant gate which defines the boundary between extraction and manufacturing and impacts to the ecological carrying capacity effects of resource extraction.
- **Manufacturing:** This stage starts with the delivery of raw resources and other materials at the mill or plant gate and ends with the delivery of building products to selected cities.
- **Construction:** The on-site construction activity stage includes energy required for the transportation of equipment to and from the site, concrete form-work, and temporary heating and ventilation.

- **Life Span:** During the life span of the product, periodic maintenance activities such as jetting, patching and replacing are included.
- **Demolition:** The end of a product's life cycle is identified for the final life cycle stage.
- **Recycling/reuse/disposal stages:** ATHENA databases take account of recycled materials coming in as raw material for the manufacturing stage for various products (e.g. fly ash in concrete and steel scrap for steel products).

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