Utilizing Concrete Rubble for Post-Disaster Reconstruction

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Natural and human-induced disasters destroy millions of buildings and infrastructure components while inflicting significant economic loss worldwide. These disasters can create substantial amounts of concrete debris that can be crushed and turned into recycled concrete aggregates (RCA) for use in new concrete mixes. Research exists that states concrete made with 100% RCA can be used for the construction of concrete-framed structures in seismic geographic regions. This paper focuses on the environmental, societal, and economic aspects of utilizing RCA generated on-site for the production of low-income concrete homes in post-disaster situations. This paper utilizes Northern Colorado market research to compare the typical cost breakdown of a cubic yard of 3000 psi structural concrete delivered from a stationary batch plant to the costs of producing a cubic yard of concrete on-site using locally produced RCA. After incorporating the mobilization costs of concrete recycling equipment and a portable concrete batch plant, a cost savings will be experienced once 4043 tons of RCA is generated and utilized for the production of 4492 cubic yards of concrete. Once the break-even point has been achieved, the savings for producing concrete on-site for the production of concrete homes increase by $22.82 per cubic yard of concrete.

Key Words: Disaster Recovery, Recycled Concrete, Concrete Framed Structures

Introduction

This paper identifies several environmental, societal and economic benefits of recycling concrete in disaster areas, while providing a cost comparison of a cubic yard of concrete produced at a typical stationary batch plant versus concrete produced on-site using local concrete rubble as aggregate in the concrete mix. The cost comparison will either support or negate the notion that utilizing on-site concrete rubble for use in new structural concrete mixes provides an economical solution to post-disaster reconstruction efforts. Home owners, contractors, non-profit organizations, disaster relief agencies and governments will be able to apply this research when coordinating rebuilding efforts after natural disasters. The conclusion will provide recommendations and propose future research opportunities for organizations interested in producing low-income concrete homes with recycled concrete aggregates (RCA) generated on-site.

The Sustainable Characteristics of Concrete

Comprised of water, fine and coarse aggregate, and Portland cement concrete accounts for forty percent of all construction and demolition waste (C&D) in Europe (Oikonomou, 2004). As a durable material that gains strength over time, concrete's structural integrity makes it viable for reuse in disaster locations. In fact, reinforced concrete homes constructed with either virgin aggregate or RCA typically do not deteriorate unless affected by specific degradation mechanisms such as sulfate attacks, alkali-aggregate reactions, steel reinforcement corrosion, water infiltration, freeze-thawing, fire, and thermal damage (ACI, 2008). Some of concrete's sustainable characteristics include significant energy savings once in place, minimized life-cycle costs, high insulation values, improved indoor air quality, higher productivity, reduced maintenance costs, post-consumer waste minimization and the availability of raw materials (i.e. water, sand, aggregate) (ECCO, 2008). Even ancient civilizations recognized concrete's sustainable attributes. A tour of Rome, Italy or Athens, Greece demonstrates the viability of concrete as a truly durable, reliable and long-lasting structural material (Delatte, 2001).

Naik (2008) defines a sustainable concrete structure as "one that is constructed so that the total societal impact during its entire life cycle is minimal" (p. 99). Recycling and reusing concrete for reconstruction purposes can assist with a project striving to attain Leadership in Energy and Environmental Design (LEED) Certification (LEED New

Construction v.3.1) based on United States Green Building Council (USGBC) standards. As recognized by the USGBC and Portland Cement Association (PCA), concrete's sustainable properties allow for a variety of reapplication purposes that serve the betterment of humankind. Reaffirmed by the Environmental Council of Concrete Organizations (2008), concrete and cement have remained "reliable and versatile products that continue to pave the way toward an environmentally secure future for successive generations here on Earth" (p. 1). As this paper strongly suggests, building concrete homes constructed with RCA produced on-site can provide durable and reliable shelter for displaced individuals and families who have recently experienced a disaster.

Recycled Concrete and the Environment

Within the last thirty years, the life cycle of concrete has extended beyond manufacturing, placement, demolition, and transporting to the landfill. When ample concrete debris exists, recycling concrete on-site for reuse as RCA in a concrete home would reduce the need for raw aggregate in the concrete mix, may reduce reconstruction time, and can potentially cut reconstruction costs. The production and manufacturing of raw or virgin aggregate ruins the landscape and contributes to the degradation of the environment (Blinker, 1998). Furthermore, recycling concrete on-site for reuse in a fresh concrete mix would decrease the need for transportation. Transporting aggregate and concrete in large diesel trucks increases wear-and-tear on the roads, increases the consumption of raw materials, and increases the amount of CO2 and other harmful emissions released into the atmosphere (Ahmad & Lippiatt, 2004). Utilizing concrete debris as aggregate in structural concrete mixes results in a decrease in the total pollutants emitted during the entire construction process by eliminating the production of raw aggregate and the need to transport pre-mixed concrete to the reconstruction site (PCA, 2009).

Following a disaster, a decision must be made concerning what to do with the construction debris. In underdeveloped or impoverished countries, few designated or regulated landfills exist; therefore, construction debris are often dumped in convenient locations like rivers, drainage-ways or shorelines (Fatta et al., 2003). Recycling and reusing concrete on-site for the production of low-income concrete homes will reduce the amount of building materials dumped into waterways. Low income (simple designed) homes would be defined by area and local custom and in many parts of the world may only be 20'X 20'in dimension; a basic shelter system.

Virgin Aggregate Production vs Concrete

In 2007, Vivian W.Y. Tam from the Griffith School of Engineering in Australia performed a cost and benefit analysis comparing the current method (CM) of generating virgin aggregate to the production of recycled concrete rock or aggregate; the construction recycling method (CRM). During the CM, transportation costs increase as C&D is frequently hauled substantial distances from disaster sites to landfills. The CM of aggregate production and its use in concrete consists of the following: stripping, blasting, stockpiling, sorting, crushing, washing, screening, final production, and selling on the open-market. After a successful transaction, the aggregate must travel from its production site to a ready mix concrete batch plant where it is incorporated in a concrete mix for a specific purpose. Once ready for dispatch, the concrete must be loaded and transported to the disaster site for placement. Because virgin aggregate can be relocated several times before reaching a final destination, using the CM is not economically justifiable in disaster relief situations when other methods exist (Tam, 2007).

During the final product stage, Tam (2007) declares "the benefit gained is the difference between the price of the same quantity produced by the concrete recycling method and the current method" (p. 826). The conclusion of Tam's research states that recycling concrete is more economically beneficial than dumping concrete in landfills and mining for new aggregate, as "recycling concrete can result in considerable savings and eliminate the cost of disposal (as high as US $100/ton)" (CN, 2009, p. 1).

Based on Tam's assessment (2007), a net benefit would be experienced in disaster locations with bountiful concrete debris; therefore, utilizing the CRM to supply aggregate for constructing a low-income concrete home would be increasingly cost beneficial compared to the CM. Referencing Tam's calculations, transforming concrete debris on-site into usable RCA would decrease the amount of C&D dumped in recycling yards at $25.80/ton therefore increasing the net benefit of the CRM. Although Tam's study (2007) does not address the costs of transporting concrete recycling equipment to disaster locations, it can be assumed that these transportation costs would induce a negative cost benefit to the CRM. When specifically applying Tam's research to building concrete homes consisting of RCA, the costs of transporting the aggregate in the concrete have not been assessed. This paper will build on Tam's research and evaluate the costs of using on-site generated RCA in concrete (CRM) versus utilizing virgin aggregate and transporting concrete to a disaster location (CM).

Causes and World Wide Locations of Excess Concrete

In their paper *Concrete Waste in the Global Perspective*, Hansen and Lauritzen (2004) state that natural catastrophes, human induced disasters, and buildings outliving their original purpose often times result in concrete rubble. During the oil boom of the late 1960's and 1970's, the Middle East experienced great wealth which led to substantial construction growth in the Gulf region in the 1970's. Now, these structures are in need of major repairs or replacement because they have reached the end of their design life, were not constructed as designed, or were not properly maintained while in service (Abdelfatah & Tabsh, 2008). War-time conflicts also destroy buildings and infrastructure, often times without warning. Some locations throughout the world with severe building and infrastructure damage resulting from war include the Gaza Strip, Afghanistan, Iraq, the Balkans, East Europe and the Philippines. Stephen McRae of the U.S. Department of Homeland Security (personal communication, March 17, 2009) states that the U.S. Air Force currently has in place portable crushing and screening plants utilized for rapid-response runway reconstruction after bombings and disasters.

Specific locations like India, the Philippines, China, Japan and Mexico are hotbeds for natural disasters, experiencing three to five major natural disasters every year that destroy a multitude of homes, commercial buildings, and infrastructural components (Dilley, 2005). California suffers 3 to 4 billion dollars worth of damage to its infrastructure and buildings annually, while earthquakes cause another 1 to 2 billion dollars worth of damage throughout the rest of the U.S. Due to the frequency of earthquakes, the Los Angeles and San Francisco Bay areas claim 40% of total annualized economic loss nationwide (FEMA, 2009). With substantial economic loss experienced annually throughout the world due to natural and human-induced disasters, multiple opportunities exist to crush concrete debris on-site for reuse in concrete mixes for the immediate production of concrete homes.

Predominant Uses of Recycled Concrete

The predominant applications for RCA utilized by the government and private sector include new concrete generated for pavements, shoulders, median barriers, sidewalks, curbs and gutters, bridge foundations, structural grade concrete, stabilized cement aggregate pavement bases, lean-concrete or econo-crete bases, bituminous concrete, flow-fill and aesthetic design (PCA, 2009). The U.S. Department of Transportation's Federal Highway Administration National Review on RCA (2008) suggests that all states recycle concrete except Alabama, Alaska, Georgia, Maine, Missouri, Montana, New Hampshire, Tennessee and Vermont. As available landfill space decreases and disposal costs increase, more states will consider recycling concrete (CN, 2009). In addition to the reuse of concrete for the previously mentioned horizontal construction applications, a multitude of case studies recommend its application for structural use in vertical construction (i.e. single-story concrete homes); however, skepticism continues to remain a hindrance to the advancement of the concrete industry.

Utilizing RCA for Structural Application

Exploring the structural integrity and strength of newly generated concrete with RCA, Falkner, Sun and Xiao (2005) performed a series of experiments supporting the use of recycled concrete aggregates in concrete framed structures in areas with seismic activity. Using mixes consisting of 0%, 30%, 50% and 100% RCA, seismic performance was tested under a low-frequency cyclic lateral load with constant vertical actions, similar to what would be experienced during an actual earthquake. Utilizing RCA produced from the Shanghai International Airport runway deconstruction material, the researchers determined that increasing the percentage of RCA resulted in a decrease in the general seismic behavior; however, a concrete structure with a high percentage of RCA will still resist an earthquake according to Chinese standard GB 50011-2001 (Falkner, Sun and Xiao 2005).

Some skepticism arises from concrete mixed with RCA due to the high water absorption rate between 3.05% and 9.25%, therefore requiring additional water during the concrete mixing phase which is assumed to result in a decrease of the overall strength of the concrete (Sharma & Singh, 2009). The addition of water should be off-set with the addition of Portland cement. The researchers concluded that even RCA with a water absorption rate of

9.25% still met the minimum American Concrete Institute (ACI) Code 318 requirement of 3000 psi concrete when used in seismic zones (Falkner, Sun, & Xiao, 2005). In fact, the lowest compressive strength of a specimen cast by Falkner, Sun and Xiao (2005) et. al with 100% RCA broke at 21.8 MPa or 3160 psi, supporting the notion that concrete made with RCA can be used in structural application. The researchers' conclusion stresses the importance of quality control by stating that any concrete mix (i.e. with or without RCA) must be designed properly for a structure to withstand an earthquake (Falkner, Sun, & Xiao, 2005). Without a proper concrete mix design, a concrete structure could eventually fail. The mix designs in Table 2 provide a reliable source for re-creation of the test results in a real-world application using similar inputs for the RCA material.

The Need for More Economic Data

Because excessive concrete debris remains a world-wide issue, it is important to continue exploring new uses for concrete. Although most often used for road base, fill, and aesthetic purposes, the above outlined attributes of RCA demonstrate that opportunities exist for utilizing crushed concrete in a structural concrete design mix for a home, even in countries with high levels of seismic activity (Falkner, Sun, & Xiao, 2005). The potential for using RCA is clear; however, little research exists that explores the monetary costs associated with disaster relief efforts in which on-site produced RCA is utilized in concrete mixes for the construction of low-income, cast-in-place concrete homes.

This research assesses the assumption that constructing simple-designed concrete homes with RCA as opposed to virgin aggregate is an economical solution to low-income housing in disaster locations with severe building and infrastructure damage. The basis of this assumption will be supported by two findings:
The literature review; and a unit price cost comparison for a cubic yard of concrete fabricated in the field using locally produced RCA versus the cost per cubic yard of concrete delivered to a disaster site from a stationary concrete batch plant.

Applied Market Research

The majority of market research and information applied in this study, including costs and quantities, was gathered in Northern, Colorado for the purpose of a convenience sample. Utilizing costs and quantities provided by Lafarge of Greeley, the cost breakdown for one cubic yard of delivered 3000 psi structural concrete with 0% RCA can be seen in Table 1.

Table 1 – Cost breakdown of one cubic yard of 3000 psi structural concrete

Input	Unit cost ($/cy)
Cement	$28.00
Coarse aggregate	$13.00
Washed sand	$7.00
Admixture/water	$3.50
Fixed production cost	$13.50
Transportation costs	$25.00
Total	$90.00

(J. Pinello, personal communication, July 6, 2009)

As revealed in Table 1, cement and transportation tend to be the driving cost factors for one cubic yard of 3000 psi structural concrete. Referencing the suggested inputs for concrete produced with 0%, 30%, 50% and 100% RCA, as provided by Falkner, Sun and Xiao (2005) as well as the costs provided by Lafarge of Greeley in Table 1, Table 2 displays the material quantity costs (in U.S. dollars) of one cubic yard of 3000 psi structural concrete.

Table 2 – Material quantity costs of 3000 psi structural concrete

Input	0% RCA	30% RCA	50% RCA	100% RCA
Cement	$28.00	$34.02	$34.02	$35.98
Coarse aggregate	$13.00	$11.35	$10.25	$7.50
Washed sand	$7.00	$6.56	$6.41	$5.86
Admixture/water	$3.50	$3.78	$3.96	$4.34
Final production cost	$13.50	$13.50	$13.50	$13.50
Total	$65.00	$69.21	$68.14	$67.18

Table 2 suggests a total materials cost difference of $2.18 between concrete mixed with 0% RCA versus concrete made 100% RCA. Based on these costs alone, it appears that producing concrete with virgin aggregate would be more cost effective than producing concrete with RCA; however, after adding transportation costs into the equation, producing concrete on-site with locally generated RCA becomes more economical. Because concrete delivery costs equal $25.00 per cubic yard, as shown in Table 1, the maximum cost savings for producing concrete on-site with 100% RCA equals $22.82 per cubic yard.

To accurately compare the costs in Tables 1 and 2 with a cubic yard of concrete produced on-site, crushing equipment and portable concrete batch plant mobilization costs must be included. Market research concluded that concrete recycling equipment mobilization, including break-down costs, would vary between $35,000 and $50,000 depending on distance to subject location, scope of work, size and number of equipment. Once mobilized, RCA is produced in the field at a cost of $7.50 per ton (J. Pinello, personal communication, July 6, 2009). As RCA quantities increase, production costs decrease. The mobilization and break-down cost for a portable concrete batch plant averages approximately $60,000 (L. Glenn, personal communication, July 10, 2009).

Since aggregate and concrete will be generated on-site, the average mobilization costs of the equipment ($42,500 for a concrete recycling plant and $60,000 for a portable concrete ready mix plant) was included to determine the "break-even" point of RCA and concrete production. Based on cost and quantity information provided by Lafarge of Greeley and Falkner, Sun and Xiao (2005), delivering concrete to a disaster location for the construction of low-income concrete homes would be more cost efficient until 4492 cubic yards of concrete made with at least 4043 tons of locally generated RCA can be produced on-site. The breakeven point here is measured in cubic yards and tons of RCA and tells us what volume and tonnages are needed based on local cost data to overcome the additional cost of mobilization of the portable concrete crusher and portable batch plant. To aid with visualization, once approximately 150 - 20 ft. x 20 ft. square concrete homes have been constructed using 4043 tons of RCA, the savings of using RCA over virgin materials increase by $22.82 per cubic yard of concrete.

Conclusions

Because disaster sites often times experience substantial damage to concrete buildings and infrastructure, generating RCA for its utilization in concrete produced on-site provides an economic solution to disaster reconstruction. It is important to note that the "break-even" point of RCA and concrete production assumes all infrastructure and roads are accessible from the stationary ready-mix batch plant to the disaster site. Because earthquakes and other disasters can destroy roads and bridges, transporting ready-mix and other construction equipment via ground may not even be an option; therefore, the costs of transporting equipment via air should be assessed to better understand these incorporated costs. When few transportation and disaster reconstruction options exist, transporting all construction equipment via air provides several social benefits. For example, air transportation assures that the equipment will reach the disaster site simultaneously and without delay. Once the equipment has been mobilized, a decreased timeframe for reconstruction should ensue as local residents rebuild their communities rather than becoming refugees. The use of local labor with outside direction in this rebuilding process may prevent or lower the number of refugees in a post-disaster climate. This social benefit may also outweigh the additional cost of air transport for crushers and batch plants.

Research suggests that the trend in RCA production demonstrates a continued decrease in costs in future markets. From the recordings of a conference in Dundee, Scotland, Lauritzen and Torring (2002) state that recycling concrete will become a normal and more economical practice due to the following main realizations:
An increase in costs of natural aggregates due to a decrease in supply and increased environmental fees and transportation costs;
Higher dump fees due to a lack of landfill space;
An increase in costs of natural aggregates due to a decrease in supply and increased environmental fees and transportation costs; and
A decrease in costs will be realized with the development of more advanced demolition and concrete recycling technology.

In addition to the optimistic viewpoint presented by Lauritzen and Torring (2002), Hansen and Lauritzen (2004) assert that a project recycling and reusing concrete will only be successful upon meeting the following three requirements:
Mandated selected demolition;
Established local processing plants and depots for recycling concrete; and
RCA must be marketed to compete with local natural aggregate.
Because transportation accounts for a high percentage of the cost to the end user, concrete and aggregate-associated costs can be greatly reduced if an abundance of usable concrete rubble exists on or near the site. If a site proves to contain enough reusable concrete, it can be assumed that the most feasible option for timely and economical reconstruction would be to transport all the equipment (i.e. crushers, screens, earth-moving equipment, and a portable, hydraulic concrete batch plant) to the site at the start of deconstruction or immediately following a disaster. Because large-scale disasters have the potential to cause widespread destruction, producing 4043 tons of RCA from concrete debris should not be a difficult task and constructing a simple cast-in-place concrete home in a disaster location can be economically justifiable.

Future Research

The data gathered from this research will be best applied to recycling concrete for the construction of low-income homes in the United States only if an abundance of usable concrete rubble exists on-site (at least 4043 tons of usable RCA); however, the costs can also be used to gauge how this type of reconstruction will equate in locations throughout the world. Since the cost savings for utilizing RCA generated on-site in Greeley, Colorado resulted from reduced transportation needs, the same theory can be applied to other world-wide locations with excess concrete debris. The market for this type of application will most likely be created through humanitarian responses initiated by governments following disasters. Environmental and social responses to disaster relief and reconstruction will also encourage governments to seek alternative disposal methods for concrete debris and new rebuilding techniques. While a private company could potentially experience a profit by transporting all the equipment and materials to the site at the beginning of a project and following the method prescribed in this paper, this initial cost investigation may be best utilized by a non-profit organization. Once logistics, operations, and management procedures and issues have been perfected, the company could potentially restructure and transform into a successful for-profit organization.

While research has been conducted concerning the life-cycle of concrete mixed at a stationary ready mix plant, future research should include a thorough life-cycle analysis of concrete mixed on-site with locally produced RCA. A life-cycle analysis would assist in quantifying the environmental and economic outputs of RCA v. those of natural aggregate. As researchers and construction professionals continue to publish successful case studies and undertake innovative disaster relief projects, the once inconceivable practice of using RCA in the construction of concrete homes will optimistically become a normal and expected routine. If an abundance of concrete exists on-site after a disaster, reusing the concrete as RCA for the production of concrete homes will result in environmental and social benefits, as well as a decrease in construction costs as transportation tends to be a driving cost factor.

References

ACI. *Design Life of Concrete Structures.* Retrieved December 5, 2008, from http://www.concrete.org/FAQ/afmviewfaq.asp?faqid=20

Blinker, R. (1998). Mining and the Natural Environment. *Mining, Environment and Development, UNCTAD.*

Concrete Network. (2009). *Recycling Concrete.* Retrieved May 1, 2009, from http://www.concretenetwork.com/concrete/demolition/recycling_concrete.htm

Delatte, N. (2001). Lessons from Roman Cement and Concrete. *Journal of Professional Issues in Engineering Education and Practice, ASCE, 127*(3), 109-115. Retrieved November 18, 2008, from Civil Engineering Database.

Dilley, M., Chen, R., Deichmann, U., Lerner-Lam, A., Arnold, M., Agwe, J., et al. (2005). *Natural Disaster Hotspots: A Global Risk Analysis*. The World Bank. Retrieved December 5, 2009, from http://www.worldbank.org/

Environmental Council of Concrete Organizations. *Why Concrete?* Retrieved December 5, 2009, from http://www.ecco.org/

Falkner, H., Sun, Y., & Xiao J. (2005). Seismic performance of frame structures with recycled aggregate concrete. *Engineering Structures, 28*(2006), 1-8. Retrieved December 1, 2008, from Science Direct Database.

Fatta, D., Papadopoulos, A., Avramikos, E., Sgourou, E., Moustakas, K., Kourmoussis, F., et al. (2003). Generation and management of construction and demolition waste in Greece—an existing challenge. *Resources, Conservation and Recycling 40* (2003) 81–91. Retrieved July 9, 2009, from Science Direct Database.

Federal Emergency Management Agency. (2009, June 4). *FEMA Prepares New Study of Annualized Earthquake Losses.* Retrieved June 7, 2009, from http://www.fema.gov/plan/prevent/hazus/hz_aelstudy.shtm

Hansen, T.C., & Lauritzen, E.K. (1997). Recycling of Construction and Demolition Waste. Danish Environmental Protection Agency. *Environmental Review, 1997*.

Lauritzen, E.K., & Torring, M. (2002). Total Recycling Opportunities-Tasting the Topics for the Conference Session. *Proceedings of the International Conference on Sustainable Concrete Construction*, Dundee, Scotland, pp. 501-510, 2002.

Naik, T. (2008). Sustainability of Concrete Construction. *Practice Periodical on Structural Design and Construction, ASCE, 13*(2), 98-102. Retrieved November 6, 2008, from Civil Engineering Database.

Oikonomou, N. (2004). Recycled concrete aggregates. *Cement & Concrete Composites 27*(2005), 315-318. Retrieved November 6, 2009, from Science Direct Database.

Portland Cement Association. *Materials: Aggregates.* Retrieved January 29, 2009, from http://www.cement.org/tech/cct_aggregates_recycled.asp

Sharma, P.C., & Singh, S.K. (2009). *Use of Recycled Aggregates in Concrete-A Paradigm Shift*. Retrieved May 21, 2009, from http://www.nbmcw.com/

Tam, V. (2007). Economic comparison of concrete recycling: A case study approach. *Resources, Conservation and Recycling*, *52*(2008), 821-828. Retrieved November 5, 2009, from Science Direct Database.