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Performance and Implementation of Low-Quality Recycled Concrete Aggregate

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Abstract

Our project seeks to greatly reduce the energy required for concrete production by using mostly recycled concrete. The use of recycled concrete aggregate (RCA) is not a new phenomenon, but has not been studied in the context of low-cost disaster reconstruction efforts, which was our focus—specifically, the 2010 earthquake in Haiti.

In our experiments, we sought to replicate the variability in concrete quality that is often found on poorly supervised construction sites. Construction companies in developing nations often add water to cement, which decreases the concrete's final structural strength. Thus, our experiment produced several samples of concrete with a high water to concrete ratios, which we then crushed and turned into RCA to produce new concrete. We tested both our initial concrete samples and the final concrete products for compression and tensile strengths.

From our data, we were able to conclude that RCA is a reasonable low-cost aggregate in the production of concrete structures. Our experimental results suggest that some of the downsides of low quality RCA can be offset by high water absorption in the process of making new concrete.

Finally, we discuss possible implementations of our findings and suggest avenues of future research.

Author's Note

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Keywords: recycled concrete aggregate, sustainable development, internal curing, disaster zone reconstruction

1. Introduction

In January 12, 2010, a 7.3 magnitude earthquake devastated the Republic of Haiti, fatally affecting over 300,000 people, displacing 1.3 million more, and causing over $8 billion in damages, or 120% of the country's GDP only a year before. 55% of the monetary loss could be attributed to infrastructure damage, including an overwhelming 40% that belonged to the housing sector[1]. Given Haiti's limited resources and available materials in the aftermath of the disaster, it follows that reusing the concrete debris might be the most economical and sustainable way to rebuild the cities of Haiti.

Concrete is the most widely used material in construction – comprised of aggregate (usually coarse rocks and fine sand), cement, and water, it is produced through an essentially one-way chemical hydration reaction that causes the cement to bind the aggregate together. The production of concrete requires a vast amount of natural resources, especially for obtaining aggregate, which is the largest component (by volume, and usually by weight as well) of the final concrete mixture. In recent decades, driven by aspirations towards more sustainable construction, there has been a push to replace these traditional aggregate materials with recycled products, such as glass, fly ash, or processed concrete rubble.

Cement, another essential component of concrete, is also the most costly. In addition, it is a significant contributor to the world's CO_2 production[2]. By using recycled concrete aggregate (RCA)[3], we reduce the environmental impact of construction by using less virgin aggregate and eliminating the need to dispose of the concrete debris resulting from earthquake damage and demolition. Applied more broadly, usage of recycled aggregate has the potential to reduce the financial cost of many large-scale infrastructure projects.

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[1] Global Facility for Disaster Reduction and Recovery, *Haiti– 2010– PDNA Estimated the Earthquake Impacts Equivalent to 120% Of GDP,* https://www.gfdrr.org/gfdrr/node/320 (Oct. 15, 2012)

[2] Chemistry World, *The Concrete Conundrum*, http://www.rsc.org/images/Construction_tcm18-114530.pdf (Oct, 15, 2012)

[3] Recycled Concrete Aggregate (RCA) is aggregate made from mechanically processed concrete rubble, where large chunks of rubble are pulverized into pebble-sized pieces suitable for mixing into fresh concrete; no chemicals, additives, or other modifications are involved in this process.

Despite the precision required to produce structurally sound concrete, some unscrupulous contractors will inevitably attempt to cut corners to save on costs. This is particular prevalent in third world countries, where construction sites can be poorly supervised. Construction companies in developing nations often add water to cement, which decreases the concrete's final structural strength. Often, this is to make the concrete more workable and easier to pour, as companies lack access to chemical admixtures that aid the mixing process. Or, cement can be deliberately left over, since companies can sell remaining portions on the black market for extra profit.

The goal of our project was to quantify the effect of recycled aggregate on final concrete compressive strength; in other words, how practical it is to produce high-strength concrete from low-strength aggregate.

2. Investigation

Our research spanned a total of eight months. Phase I consisted of the manufacture of flawed concrete in order to mimic that of Haitian buildings. By systematically replicating unfavorable site mixes, we produced several different samples of low-quality concrete. These samples were then tested for compressive and tensile strengths. In Phase II, these samples were crushed by a crushing machine and used as RCA to create new concrete, which was in turn tested for its compressive strength. Analyses were made to quantify the relationship between the quality of the final concrete product and that of its RCA components.

In the scope of our investigation, we narrowed experiments to structural concrete, since that is the type most vulnerable to earthquake and other forces of nature; non-structural concrete (for example, sidewalk or road surfacing) is less affected by natural disasters.

3. Experiment Design

3.1 Mix Design

In producing our concrete samples, we chose to approach the reduction of cement content and increase of water content separately, since the combination of the two would too rapidly and drastically lower the concrete's quality. Deviating from the control sample, the variable samples each followed decreasing increments of 10% for cement and increasing increments of 5% for water. Each sample would have either a decrease in cement *or* an increase in water—given one, all other mix parameters were held constant.

Our control mix was designed to be non-air-entrained concrete with a nominal maximum coarse aggregate size of ¾" and a slump[4] of no more than 4

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[4] Slump is a measure of the workability of freshly mixed concrete; i.e. how easily it can be poured.

inches[5]. Mix design goals included a volume ratio of 63% aggregate, and a total density of 3960 lbs per cubic yard. Our control mix was predicted to have a ultimate compressive strength of 4000psi.

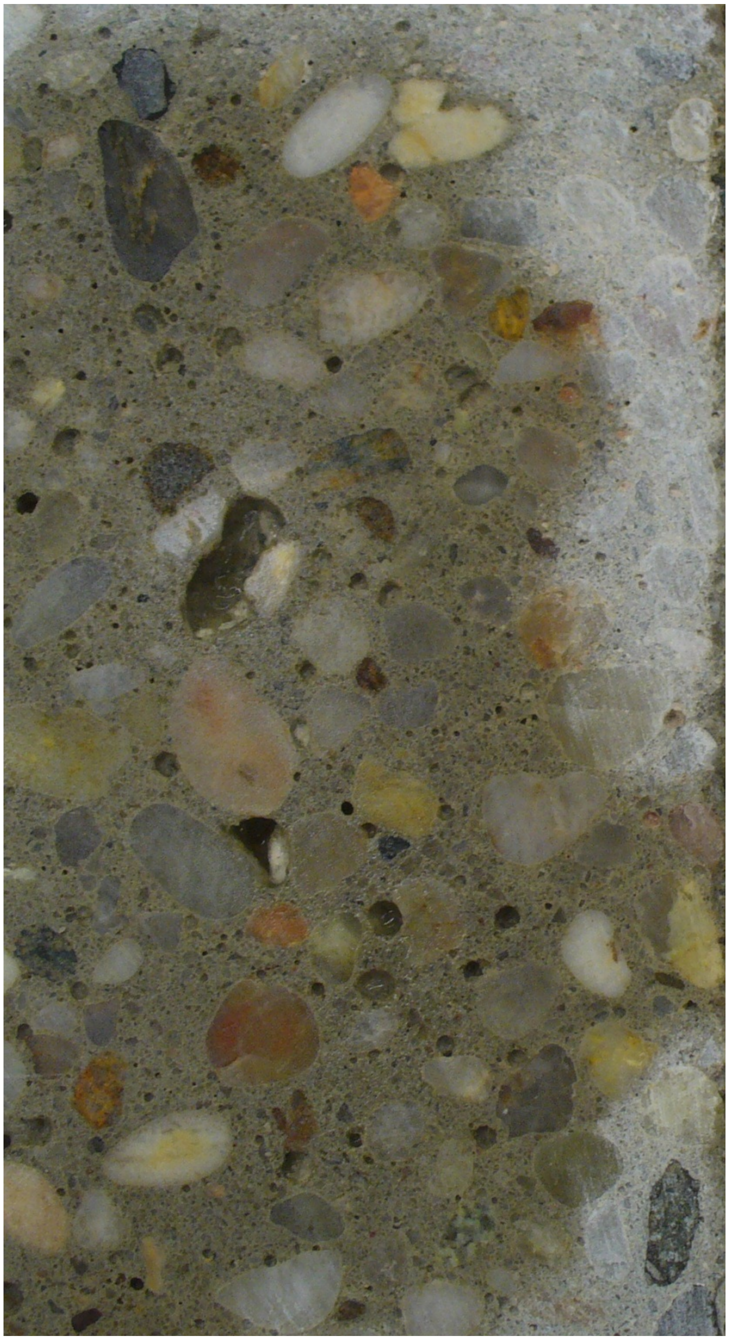

Figure 1: Large cross-section showing the uniform distribution of coarse aggregate in simulated RCA, approximately 3" by 6". Specimen has been wet slightly to make it easier to distinguish quartz aggregate pebbles.

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[5] 4 inches is the specified maximum slump for poured structural load-bearing concrete walls or columns.

3.2 Mix Procedure and Consolidation

Our mix procedure emphasized a uniform dispersal of water, rather than a rigorously defined set of incremental mix proportions. Early mixing observations noted that when following a rigid set of mix proportions, ingredients can cake up once the water is added, resulting in nonuniform dispersal of cement components that were partially segregated even after the full mixing cycle. Therefore, our solution was to visually observe the mixing and add water (while still mixing) until the ingredients appeared uniformly wet before proceeding to add the next round of ingredients. By doing so, we resolved the issue of clumping and aggregate segregation in the mixing bowl.[6] Our specimens were also more uniform in cross-section appearance.

3.3 Strength Evaluation

To evaluate the strength of samples we made, we chose to use a a simple compression test and a splitting tension test. These are the primary testing methods that are used in the commercial development of custom concrete mixes, particularly during the construction of high-rises where quality control of concrete pours is critical to ensuring the final stability of the structure. Although 28-day tests are standard for those quality control tests, we chose to perform 7-day tests, due to our use of Portland Type III cement instead of the Portland Type I cement usually used for structural concrete.

The primary difference between the two is simply the rate of curing. Portland I reaches 95% of its strength in 28 days, and Portland III reaches 95%of its final strength in 7 days. Substituting Portland III for Portland I to speed up experimental testing is an accepted lab practice, and does not significantly affect the conclusions we arrived at.

3.4 Aggregate Selection: Granite vs. Quartz

For our coarse aggregate, we chose to use quartz pebbles instead of the standard granite, as quartz pebbles are more commonly found in beachfront areas such as Haiti.

Quartz aggregate also generally differs from granite aggregate in nominal size (diameter); this is due to differences in quarrying method. Granite comes in large boulders that have to be further fractured, whereas our selected quartz aggregate came in smaller particles the size of river pebbles. Our original plan was to have granite chips of 3/8” to 3/4” in diameter. However, the quartz pebbles had a different particle size distribution, and for practical reasons we decided to use

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[6] Industry contacts informed us that uniform dispersal of concrete components is easily obtained in the commercial mixing process, due to differences in mixing mechanics that arise from economy of scale. Large-scale commercial production can usually obtain uniform ingredient distribution without the high level of scrutiny that we performed in experimental circumstances.

pebbles 3/16” to 1/2" in diameter. This change was slight, and was within the bounds of ASTM guidelines.

	Average Compressive Strength	Average Tensile Strength
Quartz Aggregate, .5 w/c	5209 psi	1774 psi
Granite Aggregate, .5 w/c	5804 psi	1936 psi

Figure 2: Control Sample Strength Comparison

Our findings indicated that the mechanical properties of the two do not differ significantly. The average compressive and tensile strengths of the quartz control were only slightly lower than the granite control sample, and we determined that this was adequately explained by the pebble surface being smoother than that of granite gravel and differences in ambient humidity at the time of mixing.

4. Phase I Data Summary

Batch	Water-Cement Ratio	Total Density (lb/ft^3)	7-Day Compressive Strength (psi)	7-Day Tensile Strength (psi)
A	0.50	4356	5,209.44	443.54
B	0.56	4290	4,429.12	319.81
C	0.63	4224	4,477.66	311.60
D	0.71	4158	3,393.53	321.34
E	0.83	4092	2,779.24	265.05
F	1.00	4026	2,093.44	212.27
G	0.55	4389	4,827.25	292.49
H	0.60	4422	4,362.07	342.07
I	0.58	4405	4,638.06	353.80
J	0.53	4372	4,730.10	373.89

Figure 3: Batch Summary and Compressive Strength Test Results

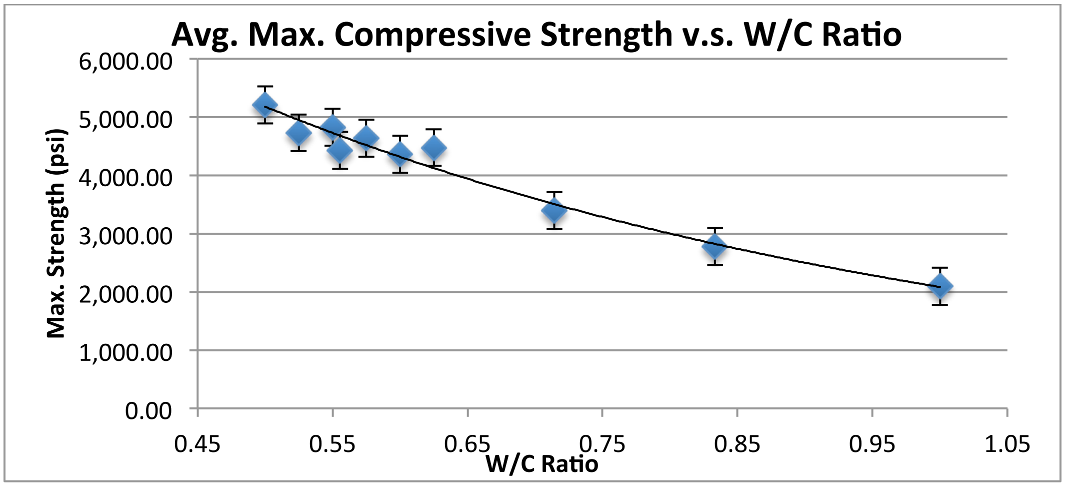

Figure 4: Compressive Strength Results, Stress (psi) vs. w/c Ratio

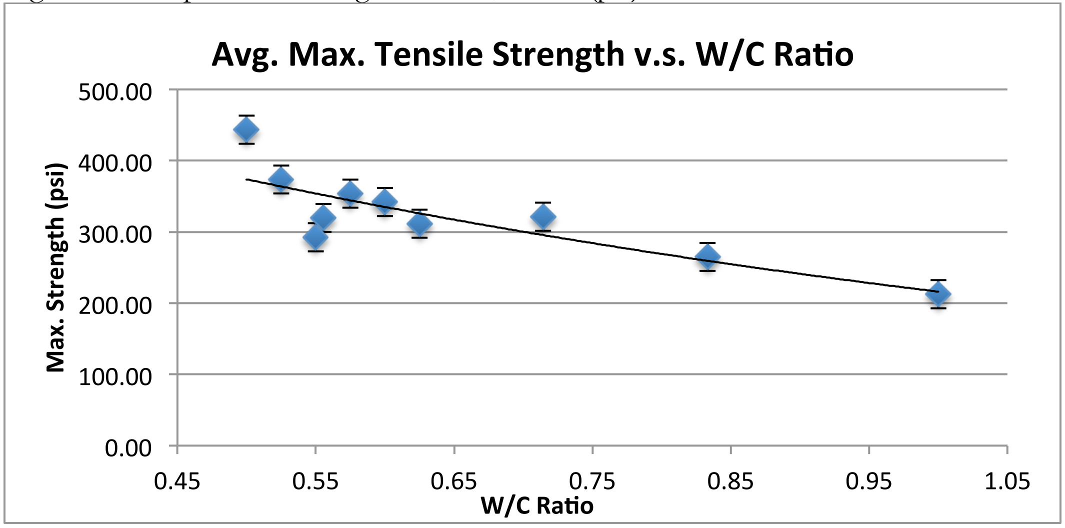

Figure 5: Tensile Strength Results, Stress (psi) vs. w/c Ratio

5. Phase I Analysis

The simulated RCA performed largely as expected. As shown on the graphs, compressive and tensile strengths decreased steeply as the water to cement ratio increased, according to an exponential best-fit correlation. Based on standard error analysis, the individual sample results all fell within 3 standard deviations of the mean. Put simply, it means that our lab-simulated RCA is an appropriate replication of concrete rubble found in real-world demolition sites.

In processing the simulated RCA, care was taken to ensure that the particle size distribution of the RCA approximated the particle size distribution of the virgin aggregate used in Phase I.

6. Phase II - Relationship between RCA strength and Final Concrete Strength

6.1 Phase II: Mix Design and Observations

For the Phase II test plan, we tested one primary variable: the quality of the recycled aggregate. The crushing machine is calibrated to replicate the sieve gradients of the original aggregate set as closely as possible. The Phase I samples were crushed to this setting, with the processed RCA comprising both coarse and fine aggregate. A secondary variable was the w/c ratio.

It was observed that test batches of RCA with .5 or .6 water to cement ratios resulted in mixes that were extremely dry and unworkable. Test batches of .7 and .8 water to cement ratios resulted in mixes that were workable enough to be pursued for measurement and analysis.

We also observed that slump was lowest for the lowest-quality RCA. As detailed in the next section, this is probably due to the higher absorptive properties of lower-quality RCA.

6.3 Phase II Data Analysis

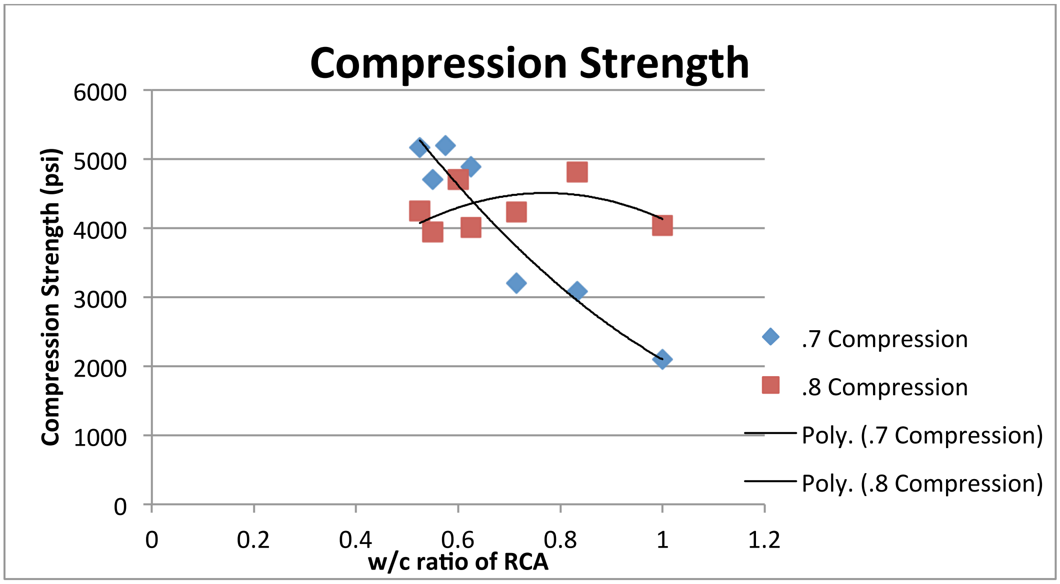

Figure 6: Compressive Strength vs. Original w/c Ratio of RCA

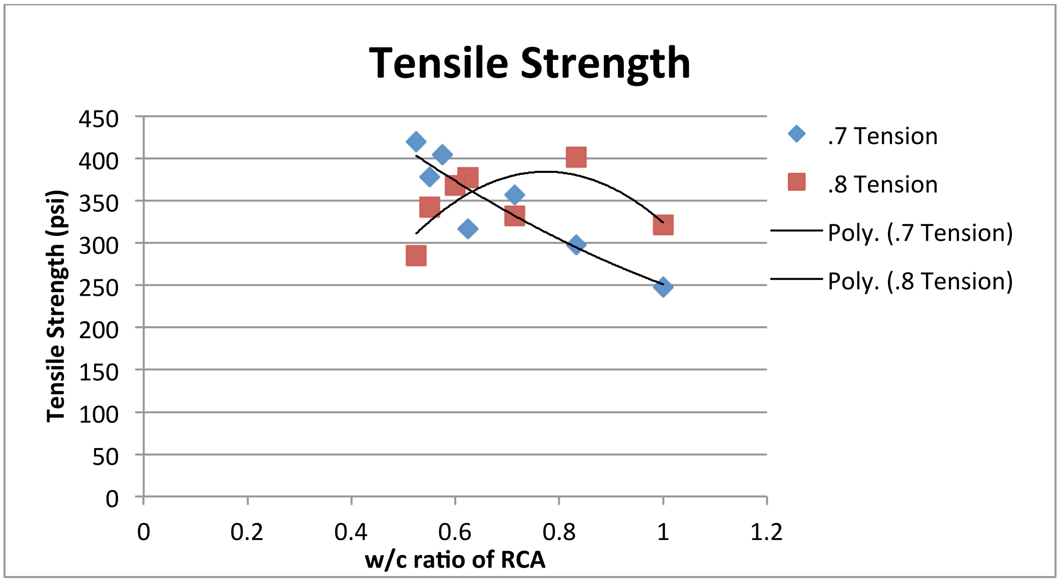

Figure 7: Tensile Strength vs. Original w/c Ratio of RCA

There appears to be two separate peaks for the .7 and .8 w/c ratios. Since the only variable different in the figures above, it seems that the w/c ratio has a balancing effect against the quality of the recycled aggregate. From to the two peaks, we can conclude that lower-quality aggregate will produce concrete of higher strength when the w/c ratio is increased accordingly. Higher-quality RCA performed better at lower w/c ratios than lower-quality RCA.

Another noteworthy phenomenon is the indication that tensile strength of RCA concrete suffers more detrimental effects than compressive strength. Whereas most of the compression test specimens surpassed 4000 psi in compression and were comparable to the control sample, none of the tensile tests reached the threshold of virgin aggregate concrete strengths. Because there was no strong positive or negative correlation, this implies that the strength of the RCA itself is not a significant factor in contributing to tensile strength.

7. Key Conclusions and Proposed Explanations

From our data, we conclude that the quality of the original aggregate is less important than the water to cement ratio. Concrete with a lower water to cement ratio seemed to be more sensitive to the quality of recycled aggregate, indicating that the degree of water absorption was a significant factor in the final strength. This is supported by the absorption tests we performed separately.

7.1 Internal Curing

In order to get a better understanding of the RCA's absorption capacity, we conducted water absorption tests for several recycled and virgin aggregate types, and found that the absorption rate of recycled aggregate is somewhere between 9 – 15 %, while the water absorption rate of quartz and granite aggregate is only between 3 – 4 % and 10%, respectively. This indicates that the absorption capacity of RCA is large enough to produce internal curing[7] within the sample.

Therefore, we conclude that the recycled aggregate absorption capacity is more than three times of normal aggregate, with most of the absorption taking place in the pores of the RCA mortar surrounding the original aggregate. A quick estimate of the high water absorption of recycled aggregate is the significant loss of workability in early mixing of batches with RCA, which became dry even when w/c ratio of 0.6 and 0.7 are used. This amount of water absorbed in early mixing is critical in preventing concrete shrinkage and self-desiccation, as well as being necessary for completion of the concrete hydration process.

We posit that the lower-quality RCA allowed for more water absorption during the mixing process, which meant that hydration of cement could take place internally for a longer period of time; this is confirmed by the higher strength of .8 water to cement ratios with lower-quality RCA.

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[7] "Internal curing has been defined by the American Concrete Institute (ACI) as "supplying water throughout a freshly placed cementitious mixture using reservoirs, via pre-wetted lightweight aggregates, that readily release water as needed for hydration or to replace moisture lost through evaporation or self-desiccation"" – Weiss, Bentz, Schindler, and Luna. *Internal Curing: Constructing More Robust Concrete.* Structure Magazine, January 2012

Figure 8: Tensile fracture plane of .8 w/c ratio specimen made with RCA; the sample on the left had a RCA w/c ratio of about .6, whereas the sample on the right had a RCA w/c ratio of .8

Furthermore, immediately after the tension and compression tests were completed, a color differential was noted in the specimen cross-sections; the interior of the cylinders were a darker gray, surrounded by a 1-cm perimeter of lighter-colored concrete. This color differential was due directly to the presence of moisture, and dissipated quickly after the cross-section was exposed to air. This color differential was much greater in specimens containing lower-quality RCA; this supports the notion that lower-quality RCA results in more internal curing. Figure 8 is a sample comparison of these color differentials.

With this in mind, we conclude that internal curing takes place in concrete produced with RCA, and that the degree of internal curing depends on the quality of the RCA. We also conclude that the negative effects of low-quality RCA can be significantly offset by a higher w/c ratio.

8. On-Site Implementation Options and Construction Approaches

Developing a viable recycled aggregate concrete mix is only the first step towards an ultra-low-cost housing system for Haiti and other disaster-stricken areas. A practical design for a dwelling using the novel material must also be derived. This process is twofold – any design must resist future seismic or hurricane damage, but must also be buildable by local craftsmen with minimal NGO support.

One option calls for the fabrication of concrete masonry blocks using the recycled aggregate concrete. This design has the benefit of being relatively simple to construct without any new training – a distinct advantage in a nation where only 22% of students advance to education above the primary level and literacy is limited[8]. However, using unreinforced masonry units has the disadvantage of low resistance to any tensile loading. This will typically result in cracking and eventual failure at the middle of the wall where the maximum bending moment occurs[9]. Thus, it is necessary to introduce significant reinforcements to the construction if it is to withstand seismic loading. This makes construction much more complicated and expensive, likely making the use of a concrete masonry design less than ideal.

The development of a system consisting of prefabricated concrete wall panels and roof/floor slabs would be a more practical option. Once a system of formworks is devised, the same design could be provided by a sponsoring NGO and used to mass produce dwelling components on-site or at a neighborhood staging location (essentially an open-air factory). Given the small size and basic nature of the dwellings required by Haitian villagers, the wall panels could easily be hoisted into place using a foundation with a specially designed channel by a team of local residents or volunteers. Even lifting a roof slab would only require a hand-powered rudimentary crane. Additionally, reinforcement (always necessary given the low tensile strength of concrete) would be added during the fabrication of the actual panels, making the construction process straight forward. In tropical regions without access to steel rebar, it is possible that bamboo could be substituted, with natural plant fibers adding to the tensile strength – in the end, the actual material used may vary, but reinforcement of some kind will be probably be necessary in seismic regions.

However, the system is not without some challenges. The most critical is developing a structural configuration minimizing the number of connections required between adjoining panels or slabs and the panels and foundation. This is key to the success of the system because the metal or other types of components necessary to connect each element could quickly increase both the cost and complexity of construction. Ideally, all materials would be readily available from local sources or could be fabricated from local materials with minimal skills or training. The ideal structural design could be built by villagers after rudimentary training by volunteer engineers from an NGO and could be summarized by "Ikea"-style

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[8] Suzata, Eriko. 2011. Education in Haiti: An Overview of Trends, Issues, and Plans. World Innovative Summit for Education.

[9] Kelly, Trevor E. 1996. Earthquake Resistance of Unreinforced Masonry Buildings. Paper No. 689. Eleventh World Congress on Earthquake Engineering.

instructional pictures, circumventing the problems associated with widespread illiteracy.

Furthermore, mix procedures would differ from actual lab procedures due to changes in efficiency of scale. For residents in developing nations unfamiliar with mixing instructions, our lab procedure could be simplified to steps as straightforward as: Mix coarse and fine aggregate, then add all the required water, then finally mix in all the cement, further mixing for a period of 5 minutes before pouring.

9. Future Directions

9.1 Beyond Haiti

While there is still certainly need for an affordable and modular housing system on the island, the disaster did occur nearly three years ago. Thus, it will be useful to consider expanding our technology to consider the needs of other disaster areas. Examples to consider include the eastern United States (prone to hurricane damage, especially in the wake of Sandy in October 2012), Japan and the rest of the Pacific "Ring of Fire," and central China (specifically earthquake-prone Sichuan Province).

As we saw, the type of aggregate used in concrete can affect its strength. Thus, it is important to consider what resources different regions have access to as that will determine the composition of the existing mixes that will be found in rubble. Haiti, for example, does not have large granite deposits; rather, the island features volcanic material, silica, and limestone[10]. In relation to the regions we proposed to investigate expansion to, we found that due to limited resources, Japan has a major RCA industry already and some of the rubble may include aggregate that has already been recycled[11]. Additionally, while the US east coast has plentiful granite and other resources, central China offers limited granite and instead features sandstone, gravel, and shale[12]. Because the team has limited knowledge of geology, it may be useful to consult with a geologist at the university for further assistance.

Although our experiment focused on minimal-cost materials and thus did not consider common concrete admixtures, another interesting avenue of research to consider is the possibility of adding a ceramic or glass admixture to the concrete. This admixture could be recycled from ceramic debris on site, and recent research found that adding such an admixture can improve the strength of concrete[13]. In relation to other debris on site, it is also important that we think about the way our aggregate is prepared to ensure an absence of contaminants. Research has shown

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[10] G.J. Draper, J.F. Lewis, G. Gutiérrez, Geologic map of Hispaniola, 1995. http://www.fiu.edu/orgs/caribgeol/hispaniola.html. (16 December 2005).

[11] *Japan Concrete Institute*, 1996-2012, 3 December 2012, http://www.jci-net.or.jp/index-e.shtml.

[12] R.T. Ryder , D.R. Dudley, Z. Sun, Y. Zhang, Y. Qiu, and Z. Guo, "Petroleum Geology of the Sichuan basin/ China," *USGS*, October 1991.

[13] F. Pacheco-Torgal. "Compressive strength and durability properties of ceramic wastes based concrete." *Materials and Structures* 44, no. 1 (2011): 155-167.

that, while not necessarily a detriment to raw strength, brick contaminants can result in increased porosity[14]. This could be a concern in regions experiencing a freeze-thaw cycle.

Finally, especially for Haiti, it is necessary to consider the negative effects of a tropical marine environment and the presence of salts in the air. This is especially vital if our materials are used with conventional steel reinforcement which can corrode if salts penetrate the surrounding concrete[15]. This could become a concern if the amount of aggregate is not adequate to prevent moisture penetration or if the concrete is porous, which might happen in the presence of some contaminants.

Beyond simply researching the qualities of our new material, we believe that we can develop a system that can foster economic development and social entrepreneurship. The RCA industry can be profitable if proper care is taken to set up facilities and transport[16]. We believe that we can find a way to empower people long after an NGO or similar organization leaves the affected area. Rather than simply providing housing, we could help to construct new businesses that process rubble and provide RCA materials for reconstruction. This is precisely the sort of stimulus suffering regions need. With a strong local economy, the recovery process becomes much easier and more complete.

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[14] Jian Yang, Qiang Du, Yiwang Bao. "Concrete with recycled concrete aggregate and crushed clay bricks." *Construction and Building Materials* 25. no. 4 (2011): 1935-1945.

[15] P. Castro, L. Maldonado, R. de Coss. "Study of chloride diffusion as a corrosive agent in reinforced concrete for a tropical marine environment." *Corrosion Science* 35. no. 5-8 (1993): 1557-1562.

[16] USGS, "Recycled Aggregates – Profitable Resource Conservation," 2000