Development of Appropriate and Sustainable Construction Materials

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Executive Summary

Description and Objective of Research: In only 12 years – from 1987 to 1999 – the world's population increased by 20 percent, from 5 to 6 billion. This growth, combined with dramatic increases in per capita resource consumption, contributes to increasingly serious social and environmental problems. These problems will only worsen over the next 50 years as the projected world population nears 9 billion and developing nations become more industrialized.

The overall purpose of Phase I of this design project was to investigate the feasibility of substituting natural pozzolans for Portland cement in the construction of engineering infrastructure in the developing world. The evaluation criteria used in this Phase 1 study included: workability, strength, availability, economic, societal concerns, and environmental impact. In particular "high tech" solutions which are not sustainable on a long-term basis in most of the developing world were forgone, and instead students learned to apply "appropriate technology" – defined as *the use of materials and technology that are culturally, economically, and socially suitable to the area in which they are implemented.*

The use of a natural pozzolans for hydraulic cement began in prehistoric times, and was abandoned for western-based Portland cement concrete technology in the early 1900's. In recent years incorporation of natural pozzolans into engineering materials has been largely supplanted by pozzolans derived from industrial byproducts such as fly ash produced from the burning of pulverized coal, silica fume produced from electric arc furnaces, and ground blast furnace slag.

However, in developing countries, especially those with active or historic volcanism and/or large scale rice production, there are potential large supplies of suitable natural pozzolans. In addition, locally available (and thus cost effective) natural pozzolans may substantially reduce the overall use of Portland cement if simple and reliable field methods can be developed that would judge their suitability for use in concrete.

United Nations Millennium Development Goal Number 1 is to "eradicate extreme poverty and hunger." Since more than a billion people still live on less than US$1 a day, there is a need for low cost and a locally available substitutes for Portland cement. Natural pozzolans will most likely be free to local communities, like sand and gravel currently are. Therefore, if a community obtains materials locally, their labor can usually be considered as an in-kind cost to the project's sponsors. Millennium Development Goal Number 7 is to "ensure environmental sustainability" with a target for year 2015 to reduce by half the proportion of people without access to safe drinking water. Water supply projects are one aspect of engineering infrastructure where natural pozzolans might be used.

Three natural pozzolans were evaluated in our Phase I study; volcanic ash, diatomaceous earth, and rice husk ash.

- A life cycle assessment (LCA) and economic input-output LCA were performed to further determine the environmental impact of manufacturing 1 ton of Portland cement.
- Laboratory tests were performed on different pozzolan-cement mixes to determine issues related to workability and strength.
- An economic and social analysis, focused on the Philippines, was performed to support Phase II plans to construct prototype water storage tanks that contain some percent of natural pozzolan substitution.
- The global economic savings and potential reduction in anthropogenic CO_2 emissions were estimated, assuming, these natural pozzolans were used in water supply projects to serve the one billion people in the word that do not have access to safe drinking water.

Summary of Findings: From 1880 to 1996, the world's annual consumption of Portland cement rose from less then 2 million tons to 1.3 billion tons. Some associated environmental costs include: a) after vehicle and utility emissions, cement manufacturing is the largest industrial producer of CO_2 and accounts for over 50% of all industrial CO_2 emissions; b) for every ton of cement produced, 1 to 1.25 tons of CO_2 are produced; and, c) approximately 3,200 lbs of raw materials is required to manufacture 2,000 lbs of cement.

Two life cycle assessments (LCA), using Simpro software and an economic input-output LCA, performed in this study confirmed the regional and global environmental impact of manufacturing Portland cement. In addition, the results of the LCA showed that the manufacturing life stage contributed the greatest amount of environmental stress (e.g., acid rain potential, ecotoxicity, land use, climate change, and human health respiratory impact) for every environmental impact category evaluated except for the impact on minerals from the life stage of premanufacturing.

The three natural pozzolans were found to have widespread availability on a global basis and furthermore, they may be available to communities at no cost, such as sand and aggregate (i.e., gravel) are currently available.

Extensive compressive strength tests and workability tests that followed established ASTM procedures suggested that two of these pozzolans, volcanic ash and rice husk ash, could be substituted for Portland cement at up to 25% in the manufacture of concrete with no loss in workability or strength. As an example of greater detail for the substitution of volcanic ash for Portland cement, the compressive strengths from the 25%-substitution of volcanic ash produced satisfactory results at both the 7-day and 28-day cylinder breaks, resulting in compressive strength values of over 3,000 psi at 28 days. These values meet standards for strength established by the U.S. construction industry. However, the 50% mix resulted in a compressive strength that was significantly below the controls. The test cylinders also showed an expected strength gain between the 7-day and 28-day breaks which amounted to approximately 1,000 psi. Tests results determined that the physical properties of volcanic ash, such as angularity, surface area, and porosity are similar to Portland cement, which would explain why a standard 0.5 water-to-cement (w/c) ratio could be used for mixing.

Social and economic studies that focused on the Philippines indicated that it is one of many developing countries in need of water, sanitation, and housing infrastructure investment. Since poor people largely depend on physical labor for income, health and education conditions play an important role in poverty and income distribution. Poor living conditions may also adversely affect the growth on human capital formation and therefore the potential for Foreign Direct Investment (FDI). The incidences of health problems, lack of access to safe drinking water and sanitation, education impediments, crime, and instability due to these living conditions create very unattractive investment climates for FDI. Locally available pozzolans would decrease the price of construction materials and can be processed on-site with low-tech training.

Conclusions: As an extension of the overall goals of the project, an investigation was performed to quantify the real-world contributions that the implications of the project could entail. Specifically, the potential economic savings (U.S. dollars) and reduction of CO_2 emissions (tons) were estimated with the assumption that these natural pozzolans would be utilized on a global basis, to their fullest extent as determined in this study's strength tests. It was also assumed that the pozzolans would be applied in the construction of either spring-boxes or gravity fed water systems within the developing world.

United Nations Millennium Development Goal Number 1 is to "eradicate extreme poverty and hunger." Since more than a billion people still live on less than US$1 a day, there is a need for low cost and a locally available substitutes for Portland cement. Natural pozzolans will most likely be free to local communities, like sand and gravel currently are. A second Millennium Development Goal (No. 7) is to "ensure environmental sustainability" with a target for year 2015 to reduce by half the proportion of people without access to safe drinking water.

The results (summarized in Table I.5) suggest that if the natural pozzolans investigated in this study were used to construct spring boxes or gravity fed water systems for the 1 billion people worldwide that do not have access to safe drinking water, $141 to $451 million could be saved if volcanic ash or rice husk ash were substituted for Portland cement at a 25% level, and $37 to $102 million could be saved if diatomaceous earth was substituted for Portland cement at 6.25%.

It was estimated that if natural pozzolans were used to construct spring box water systems for the 1 billion people worldwide that do not have access to safe drinking water, the total anthropogenic CO_2 emissions could decrease 0.95 million tons if volcanic ash or rice husk ash were substituted for Portland cement at a 25% level, and 240,000 if diatomaceous earth was substituted for Portland cement at 6.25%. It was estimated that if natural pozzolans were used to construct gravity fed water systems for the 1 billion people worldwide that do not have access to safe drinking water, the total anthropogenic CO_2 emissions could decrease 3.8 million tons if volcanic ash or rice husk ash were substituted for Portland cement at a 25% level, and 874,000 tons if diatomaceous earth was substituted for Portland cement at 6.25%.

Supplemental Keywords: Concrete, cement, pozzolan, volcanic ash, rice, construction, water supply and sanitation, developing world, appropriate technology, climate change, sustainability

Relevant Web Sites:

- Michigan Tech Sustainable Futures Institute, www.sfi.mtu.edu
- Michigan Tech Master's International Program in Civil & Environmental Engineering, www.cee.mtu.edu/peacecorps
- Southern University Nelson Mandela School of Public Policy and Urban Affairs http://publicpolicy.subr.edu/phd.htm

Summary of Phase 1

Phase I – 1. Background and problem definition

In only 12 years – from 1987 to 1999 – the world's population increased by 20 percent, from 5 to 6 billion (UCS, 1999). This growth, combined with dramatic increases in per capita resource consumption, contributes to increasingly serious social and environmental problems (Meadows et al., 1972; 2004; Daly, 1996; NRC, 1999). These problems will only worsen over the next 50 years as the projected world population nears 9 billion and developing nations become more industrialized. Society, the environment, and economic/industrial development are inherently interconnected. Healthy survival requires a sustainable future, one in which human and industrial systems support an enhanced quality of life by recognizing and seeking to understand this interconnectivity and its harmony. In the coming decades, students with expertise in sustainability issues and planning will be in great demand as the world tries to reverse this looming global crisis (WFEO, 2002; Sutherland et al. 2003; Mihelcic et al., 2003). We believe that society is at the beginning of a new revolution, the sustainability revolution, and students will be one of the forces that drive this revolution.

Phase I – 2. Purpose, objectives, scope

The overall purpose of Phase I of this design project was to investigate the feasibility of substituting natural pozzolans for Portland cement in the construction of engineering infrastructure in the developing world. The evaluation criteria used in this Phase 1 study included: workability, strength, availability, economic, societal concerns, and environmental impact. In particular "high tech" solutions which are not sustainable on a long-term basis in most of the developing world were forgone, and instead students learned to apply "appropriate technology" – defined as *the use of materials and technology that are culturally, economically, and socially suitable to the area in which they are implemented.*

The use of a natural pozzolans for hydraulic cement began in prehistoric times, and was abandoned for western-based Portland cement concrete technology in the early 1900's. In recent years incorporation of natural pozzolans into engineering materials has been largely supplanted by pozzolans derived from industrial byproducts such as fly ash produced from the burning of pulverized coal, silica fume produced from electric arc furnaces, and ground blast furnace slag.

In the industrialized world, natural pozzolans are not considered to be cost effective additions to concrete due to the costs inherent in mining and transporting such materials and the ready abundance of industrial by-product pozzolans (Gray et al., 2003). However, in developing countries, especially those with active or historic volcanism and/or large scale rice production, there are potential large supplies of suitable natural pozzolans. In addition, locally available (and thus cost effective) natural pozzolans may substantially reduce the overall use of Portland cement if simple and reliable field methods can be developed that would judge their suitability for use in concrete.

From 1880 to 1996, the world's annual consumption of Portland cement rose from less then 2 million tons to 1.3 billion tons (Mehta, 1999). Some associated environmental costs are (ICLEI, 2004; Malhortra, 1999):

- after vehicle and utility emissions, cement manufacturing is the largest industrial producer of CO_2 and accounts for over 50% of all industrial CO_2 emissions;
- for every ton of cement produced, 1 to 1.25 tons of CO_2 are produced; and,
- approximately 3,200 lbs of raw materials is required to manufacture 2,000 lbs of cement.

Furthermore, United Nations Millennium Development Goal Number 1 is to "eradicate extreme poverty and hunger." Since more than a billion people still live on less than US$1 a day, there is a need for low cost and a locally available substitutes for Portland cement. Natural pozzolans will most likely be free to local communities, like sand and gravel currently are. Therefore, if a community obtains materials locally, their labor can usually be considered as an in-kind cost to the project's sponsors. Millennium Development Goal Number 7 is to "ensure environmental sustainability" with a target for year 2015 to reduce by half the proportion of people without access to safe drinking water. Water supply projects are one aspect of engineering infrastructure where natural pozzolans might be used.

Three natural pozzolans were evaluated in our Phase I study; volcanic ash, diatomaceous earth, and rice husk ash.

- Laboratory tests were performed on different pozzolan-cement mixes to determine issues related to workability and strength.
- A life cycle assessment (LCA) and economic input-output LCA were performed to further determine the environmental impact of manufacturing 1 ton of Portland cement.
- The global economic savings and potential reduction in anthropogenic CO_2 emissions were estimated, assuming, these natural pozzolans were used in water supply projects to serve the one billion people in the word that do not have access to safe drinking water.
- An economic and social analysis, focused on the Philippines, was performed to support Phase II plans to construct prototype water storage tanks that contain some percent of natural pozzolan substitution.

Phase I – 3. Data, results, findings

Phase I - 3.1. Environmental impacts of cement manufacture

As stated earlier, the use of cement is a major contributor to worldwide CO_2 production. The 1.45 billion Mg of global cement production accounts for 2% of global primary energy use and 5% of anthropogenic CO_2 emissions (Horvath, 2004). A rotary kiln is typically used to manufacture Portland cement. Within the calcination zone, the following reaction takes place

$$CaCO_3 \text{ (limestone)} + \text{heat} \rightarrow CaO + CO_2 \text{ (gas)} \qquad \text{(Equation 1)}$$

Within the sintering or burning zone of the kiln, the following reaction produces several products that are collectively known as clinker[1].

$$CaO + SiO_2 + Al_2O_3 + Fe_2O_3 \rightarrow C_3S + C_2S + C_3A + C_4AF \qquad \text{(Equation 2)}$$

During a typical hydration reaction, clinker reacts with water to provide the cementitious properties that are characteristic of Portland cement. The calcination reaction accounts for approximately 0.51 tons of CO_2 production per ton of clinker manufactured. The CO_2 emissions

[1] C_3S makes up 50-55% of the clinker and provides early strength and set to the concrete. C_2S makes up 19-24% of clinker and imparts long term strength to concrete. C_3A makes up 6-10% of clinker and also imparts early strength and set. C_4AF makes up about 7-11% of clinker and acts as a flux while also imparting the gray color that is characteristic of Portland cement.

associated with the energy used for heating the kiln account for approximately 0.47 tons of CO_2 per ton of clinker manufacturing.

Figure I.1 shows rising global carbon dioxide emissions (measured in metric tons), due to increases in cement production over the last forty years (Hanle, et al., 2004). Figure I.2 shows the rise in CO_2 emissions from cement production in both the U.S and Philippines over the same period. In addition to CO_2 emissions, cement production is a significant emitter of SO_x, NO_x, and particulate matter. Cement production contributes to global warming, over-use of resources, and nonrenewable resource depletion. Regionally, acid rain, water and contamination by sedimentation may occur from cement manufacture. Local cement production may also contribute to noise, vibrations, and scenic ecological degradation.

Figure I.1. Carbon Dioxide Emissions from Hydraulic Cement Production, World (1961-2002)

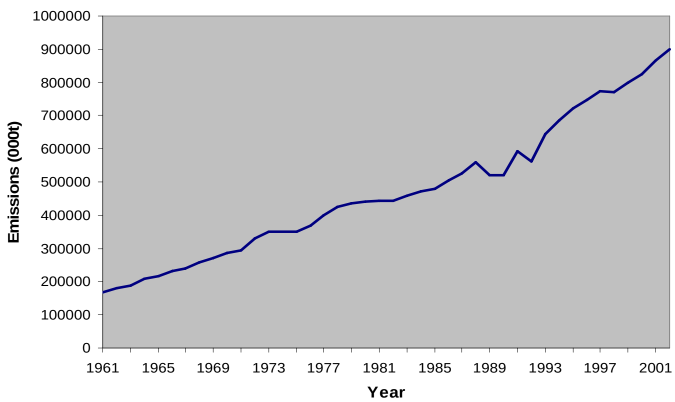
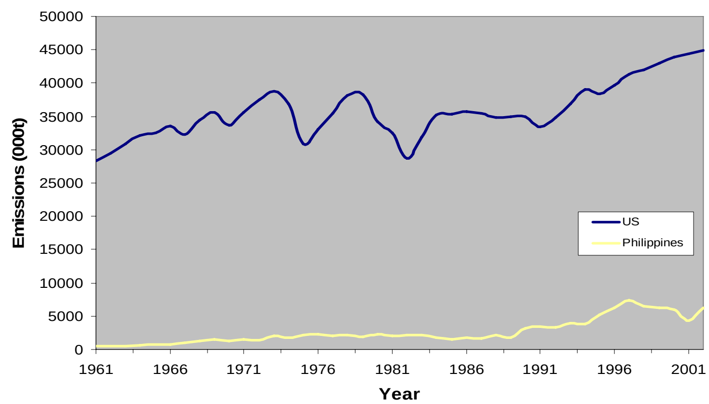


Figure I.2. Carbon Dioxide Emissions from Hydraulic Cement Production in United States and Philippines (1961-2002)



Phase I - 3.2. LCA and economic input-output analysis

Life-Cycle Assessment (LCA) is a method for analyzing and assessing the environmental impacts of a product or process over its entire life cycle. It includes the life stages of extraction of raw materials, processing, manufacture, use, and end of life within its scope. In this study an LCA was performed, based on the quantity of raw materials, energy/electricity, and chemicals required to produce one ton of Portland cement. These quantities were obtained from various established sources, and inputted into the LCA software tool, SimaPro (PRé Consultants, The Netherlands). The LCA in this study was focused only on the environmental impacts from the life states of cement premanufacturing, manufacturing, and transportation. This is because these particular life stages are known to have a greater environmental impact than other life stages.

Eco-Indicator 99 (PRé Consultants, The Netherlands) was used to assess the environmental impacts in SimaPro. Figure I.3 shows the damage assessment obtained from SimaPro. The results show that the manufacturing life stage (i.e., clinkering and calcinations, which is the green section of the barchart in Figure I.3) contributed the greatest amount of environmental stresses (e.g., over 95 of total environmental impact in all categories except one).

To complement the SimaPro LCA, and Economic Input-Output LCA (EIO-LCA) was also performed on the production of 1 ton of Portland cement (the EIO-LCA tool is available at www.eiolca.net). The EIO-LCA is useful because it relates economic activity across the U.S. economy to environmental stresses in specific industrial sectors. Table I.1 provides data on the total release of conventional air pollutants associated with manufacture of one ton of Portland cement and the top three industrial sectors that contribute to this total. The hydraulic cement and electric services industrial sectors are shown to be the greatest contributors to conventional air pollutant emissions from Portland cement manufacturing which suggests these industrial sectors would be a good starting point to focus pollution prevention efforts.

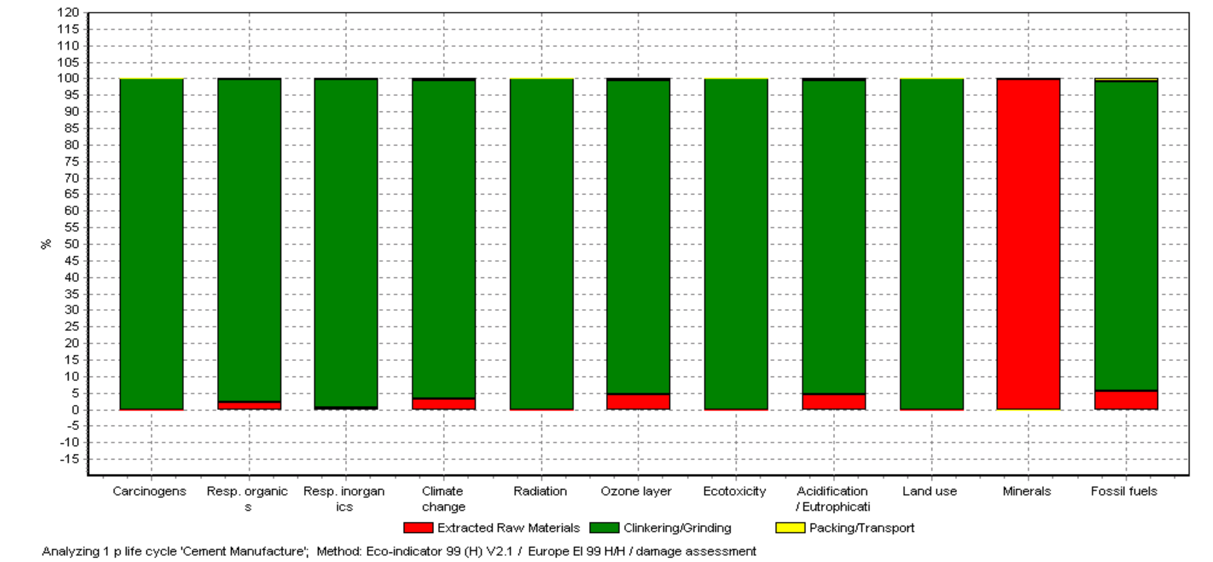


Figure I.3. Damage assessment from extraction, manufacturing and transportation of Portland cement. The results show that the manufacturing life stage, shaded in green (i.e, clinkering/grinding), contributes the greatest overall environmental impact for 10 of 11 impact categories (results obtained from SimaPro).

Table I.1. Estimated releases (in metric tons) of conventional air pollutants from the production of one ton of ready-mixed concrete.

Industrial Sector	SO2	CO	NO_2	VOC	Lead	PM_{10}
Total for all sectors	0.08427	0.055554	0.100836	0.011477	0.000006	0.018903
Cement, hydraulic	0.05543	0.019046	0.057603	0.003654	0.000003	0.011099
Electric services (utilities)	0.02065	0.000662	0.010106	0.000083	0	0.000522
Water transportation	0.00117	0.000349	0.00104	0.000226	0	0.000145

Phase I - 4. Global availability of natural pozzolans

The volcanic ash and diatomaceous earth pozzolans were found to be widely available throughout the world (Figures not shown due to space limitations). Figure I.4 & I.5 suggest that rice husk ash is another potential globally available natural pozzolan because there is an increase in rice husk ash production worldwide (Figure I.4), and in the U.S and Philippines (Figure I.5) over the last 40 years. This increase is directly associated with an increase in consumption of rice as a food staple. The results suggest there is widespread availability of all three natural pozzolans investigated in this study, and they may be available to communities at no cost, such as sand and aggregate (i.e., gravel) are currently available. Part of our Phase II project is to complete a detailed map of the availability of volcanic ash and rice husk ash in the Philippines.

Figure I.4. World Rice Husk Ash Production (1961-2002)

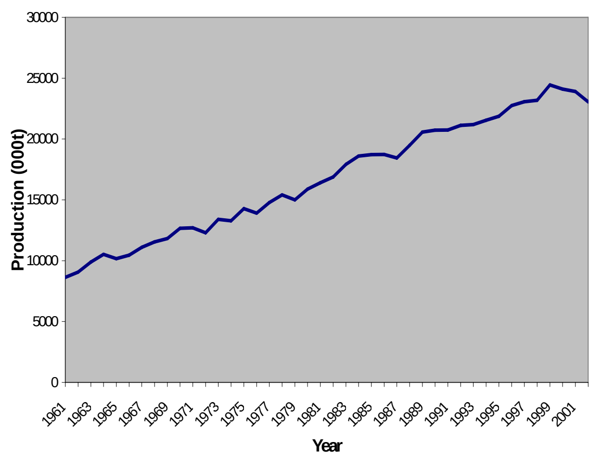
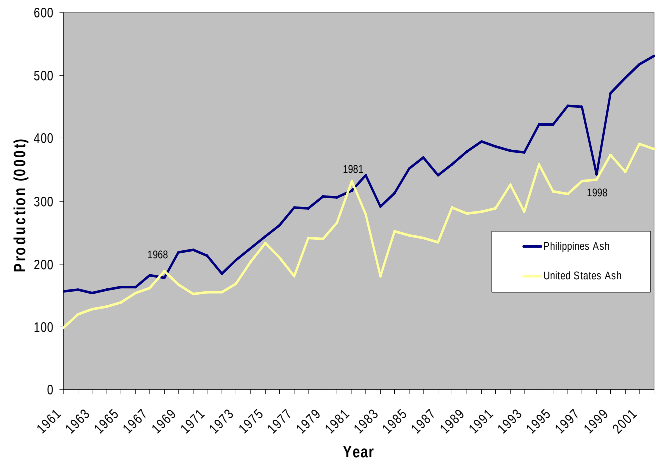


Figure I.5. Rice Husk Ash in the United States and Philippines (1961-2002)



Phase I – 5. Evaluation of strength of natural pozzolan-substituted Portland cement

Three pozzolans were evaluated in this study: volcanic ash, diatomaceous earth, and rice husk ash. The Portland cement used was LaFarge Type I. Initial results of strength and workability tests suggest we can substitute these natural pozzolans for Portland cement at the percentages provided in Table I.2.

Table I.2. Phase I study's recommended percent substitution of natural pozzolans for Portland cement in the manufacture of concrete.

Natural Pozzolan Tested	Highest Percent Substitution Recommended in Phase I (%)
Volcanic Ash	25
Diatomaceous Earth	6.25
Rice Husk Ash	25

All mixing and testing was performed in accordance with appropriate ASTM standards. For example, all unit weight tests were performed in accordance to ASTM Standard C138; slump testing was performed in accordance to ASTM Standard C143, and all concrete cylinders were made in accordance with ASTM standard C192. Compressive strength tests were performed in accordance to ASTM Standard C39. Observations of each pozzolan were made using the Scanning Electron Microscope (JEOL 6400, Peabody MA). Data on the mineral composition of each pozzolan was also collected using X-ray diffraction (Scintag XDS-2000 Cupertino, CA).

Tests results determined that the physical properties of volcanic ash, such as angularity, surface area, and porosity are similar to Portland cement, which would explain why the 0.5 water-to-cement (w/c) ratio could be used for mixing. However, it was necessary to alter the mix design for diatomaceous earth in order to improve the workability. The high surface area and porosity of diatomaceous earth required additional water. Cylinders that were made with a lower w/c ratio produced honeycombing due to poor consolidation, which is an undesirable property in concrete. The diatomaceous earth cylinders also did not break on 45-degree fracture planes. When stressed the cylinders crumbled apart. After the cylinder failed, observations showed the area where the failure occurred seemed to be very powdery. It should also be noted that when the diatomaceous earth cylinders were taken out of their molds, it was observed that the surface seemed soft. This could be due to the large amounts of diatomaceous earth not having enough time to hydrate and form its strength. The rice husk ash mix of 12.5% substitution had a tolerable workability. When the 25% mix was performed at the 0.5 w/c, the concrete was noticeably stiffer and harder to work with, yet still deemed workable for field applications.

The compressive strength of the concrete using volcanic ash is provided in Figure I.6, the strength results for diatomaceous earth are provided in Figure I.7, and the strength results for rice husk ash are provided in Figure I.8. The compressive strengths from the volcanic ash (Figure I.6) were relatively consistent. The 25% mix produced satisfactory results at both the 7-day and 28-day breaks resulting in compressive strength values of over 3,000 psi at 28 days, which is allowable in the construction industry. The 50% mix produced compressive strengths that were significantly below the controls. This mix did not meet predicted strength expectations and therefore is not recommended. The volcanic ash cylinders did have a strength gain between its 7-day and 28-day breaks of about 1,000 psi.

The compressive strength of the concrete using diatomaceous earth (Figure I.7) shows that concrete with a higher diatomaceous earth substitution and a high w/c produced a weaker concrete. Figure I.8 shows that the compressive strength of the concrete using rice husk ash resulted in a concrete with high strength at the 12.5% and 25% substitutions. The compressive strength of the 50% substitution dropped considerably as with the samples substituted with volcanic ash.

Figure I.6. Volcanic ash compressive strength results for pozzolans substitutions of 0%, 12.5%, 25% and 50%. The control strength was higher than all the pozzolans substitutions. Concrete with a compressive strength of greater than 3,000 psi is typically used in the U.S. so the results suggest the samples with 25% substitution of volcanic ash for Portland cement would be appropriate as a building material.

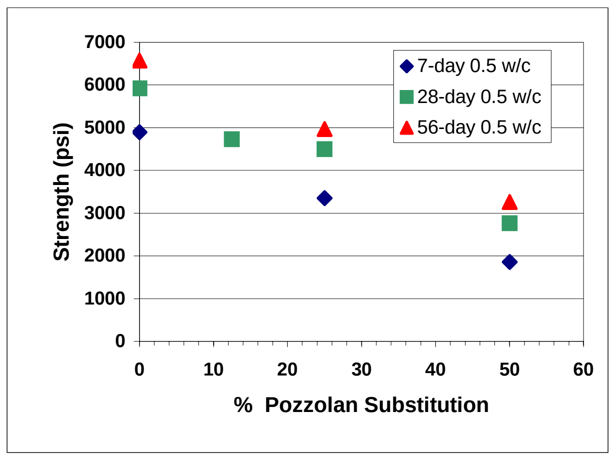


Figure I.7. Diatomaceous earth compressive strength results for pozzolan substitutions of 0%, 6.25%, 12.5%, 25% and 50%. The 6.25 and 12.5% substitutions both had strengths higher than those of the control**.** Concrete with a compressive strength of greater than 3,000 psi is typically used in the U.S. so the results suggest the samples with 6.25% substitution of diatomaceous earth for Portland cement would be appropriate as a building material.

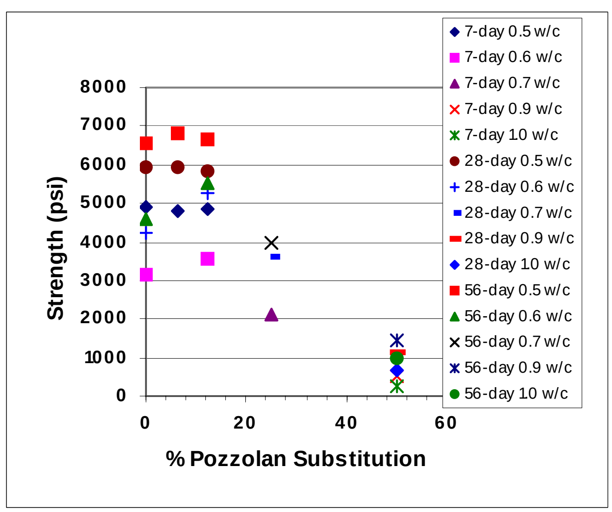
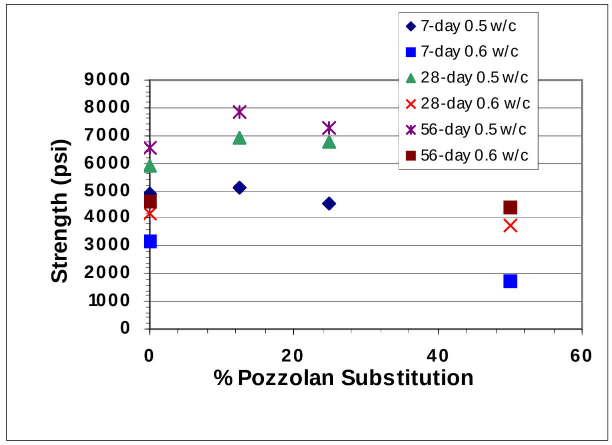


Figure I.8. Rice husk ash compressive strength results for pozzolans substitutions of 0%, 12.5%, 25% and 50%. The 12.5% and 25% substitution had strengths higher than those of the control. Concrete with a compressive strength of greater than 3,000 psi is typically used in the U.S. so the results suggest the samples with 25% substitution as a building material.

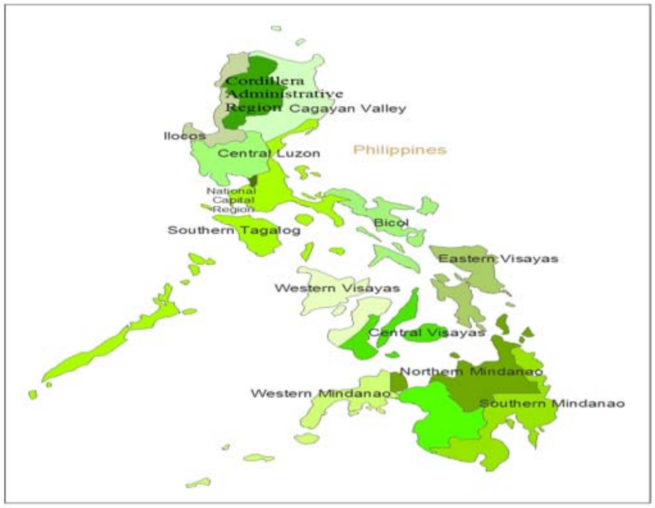


Phase I – 6. Economic and social analysis of the Philippines

The Philippines is one of the many developing countries where an abundance of volcanic ash and rice husk ash can be found. It is also one of many developing countries in need of water sanitation and housing infrastructure investment. Since poor people largely depend on physical labor for income, health and education conditions play an important role in poverty and income distribution (Gerson, 1998). Figure I.9 shows several environmental, social, and economic conditions of the Philippines that suggest this country may benefit from substitution of natural pozzolans for Portland cement in engineering infrastructure for our Phase II efforts.

Poor living conditions may also adversely affect the growth on human capital formation and therefore the potential for Foreign Direct Investment (FDI). In addition, the 20th century has witnessed a large flow of individuals moving from rural to urban and peri-urban areas. For example, Manila, the capital and largest city in the Philippines, serves as an example of an urban region that has attracted large numbers of immigrants from rural areas in pursuit of better jobs and economic opportunity unavailable in rural regions. However, Manila cannot support the full employment demand, even for some educated workers. The result are thousands of people without income and therefore without basic necessities. Some individuals are thus forced into makeshift housing, or housing units made of scrap materials such as metal, glass, cardboard, etc., often in extremely poor condition. Some reports place the number of makeshift housing units at almost one half million in Manila. These houses do not allow for proper sanitation, plumbing for clean water, or electricity for energy demands. The incidences of health problems, education impediments, crime, and instability due to these living conditions create very unattractive investment climates for FDI. Locally available pozzolans would decrease the price of construction materials and can be processed on-site with low-tech training.

A similar threat to human capital formation potential exists in rural areas of the Philippines. Two thirds of people in the rural areas of the Philippines lack access to potable water. This is much higher than the Asian average of one in three people making provision of water supply and sanitation facilities in rural areas a priority of the Philippine Government. Low cost spring-boxes, gravity fed water systems, or rainwater harvesting/storage systems created from natural pozzolans could greatly aid in the governments efforts. This development would be environmentally friendly as well. Providing safe drinking water supply to rural areas via concrete structures would contribute to the health status of the countryside and contribute to human capital development by increasing the number of able workers. As much of the country's agriculture industry is based in rural areas, this would potentially boost production in this sector of the economy.



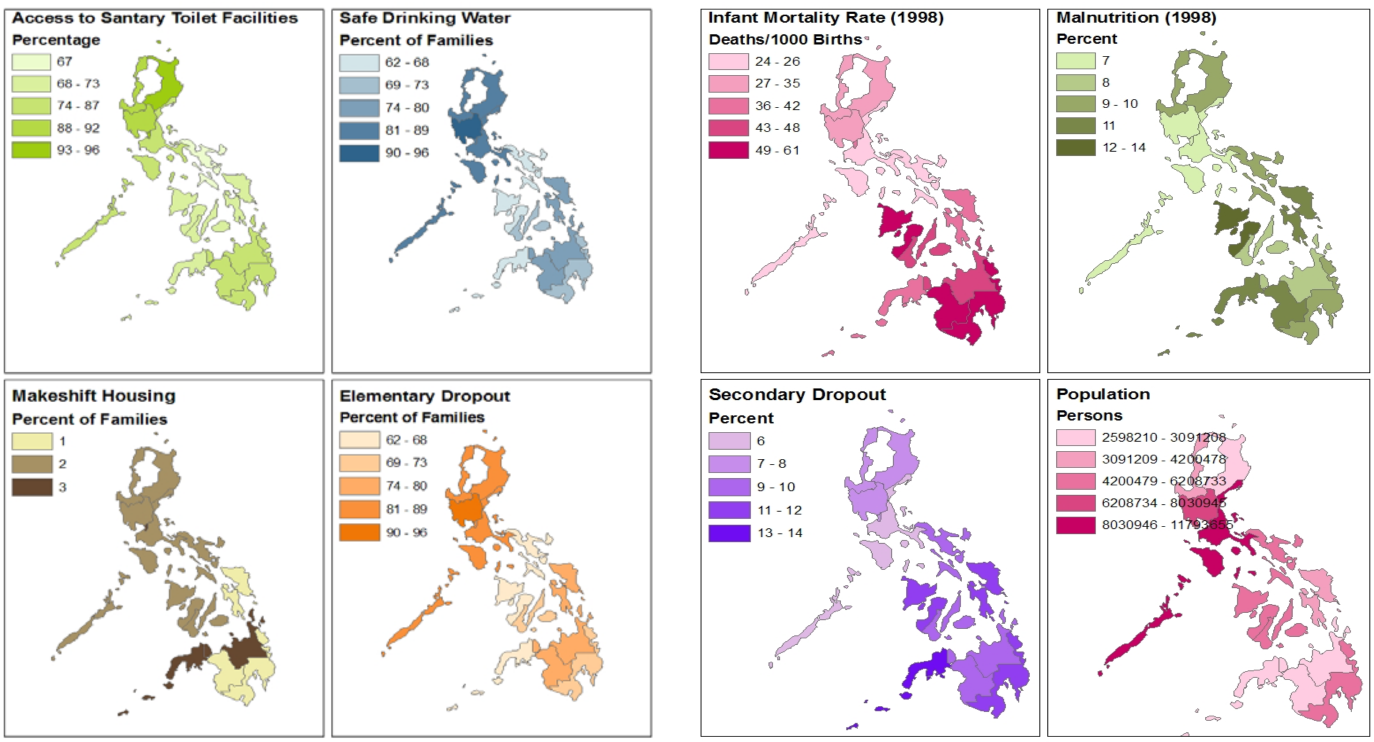


Figure I.9: Current environmental, social, and economic conditions of the Philippines.

Phase I – 6. Discussion, conclusions, recommendations

Two life cycle assessments, using Simpro software and an economic input-output LCA, performed in this study confirmed the regional and global environmental impact of manufacturing Portland cement. Three natural pozzolans were evaluated for the potential substitution for Portland cement in the manufacture of concrete. The three pozzolans were: volcanic ash, rice husk ash, and diatomaceous earth. Compressive strength and workability tests suggested that two of these pozzolans, volcanic ash and rice husk ash, could be substituted for

Portland cement at up to 25% in the manufacture of concrete with no loss in workability or strength.

As an extension of the overall goals of the project, an investigation was performed to quantify the real-world contributions that the implications of the project could entail. Specifically, the potential economic savings (U.S. dollars) and reduction of CO_2 emissions (tons) were estimated with the assumption that these natural pozzolans would be utilized on a global basis, to their fullest extent as determined in this study's strength tests. It was also assumed that the pozzolans would be applied in the construction of either spring-boxes or gravity fed water systems within the developing world.

The estimations were also based on the following assumptions obtained from previous research studies conducted by Michigan Tech graduate students (Niskanen, 2002; Fry, 2004).

- a spring-box sized to serve a community of 574; a spring-box requires 50 sacks of cement (1 sack= 94 lbs.); and each sack of cement used in the production of a spring-box costs 5,000 Cameroon Francs (CFA) and 750 CFA= $1 U.S.
- a gravity fed water system sized to serve a community of 430 people; a gravity fed water system requires 140 sacks of cement; and, each sack of cement used in the production of the system costs 100 Dominican Republic Pesos (DR Peso) and 18 DR Pesos= $1 U.S.

United Nations Millennium Development Goal Number 1 is to "eradicate extreme poverty and hunger." Since more than a billion people still live on less than US$1 a day, there is a need for low cost and a locally available substitutes for Portland cement. Natural pozzolans will most likely be free to local communities, like sand and gravel currently are. A second Millennium Development Goal (No. 7) is to "ensure environmental sustainability" with a target for year 2015 to reduce by half the proportion of people without access to safe drinking water.

The results (summarized in Table I.5) suggest that if the natural pozzolans investigated in this study were used to construct spring boxes or gravity fed water systems for the 1 billion people worldwide that do not have access to safe drinking water, $141 to $451 million could be saved if volcanic ash or rice husk ash were substituted for Portland cement at a 25% level, and $37 to $102 million could be saved if diatomaceous earth was substituted for Portland cement at 6.25%.

As shown in Table I.3, it was estimated that if natural pozzolans were used to construct spring boxes or gravity fed water systems for the 1 billion people worldwide that do not have access to safe drinking water, the total anthropogenic CO_2 emissions could decrease from 0.95 to 3.8 million tons if volcanic ash or rice husk ash were substituted for Portland cement at a 25% level, and from 240,000 to 874,000 tons if diatomaceous earth was substituted for Portland cement at 6.25%.

Table I.3. Estimation of economic savings and reduction in global CO_2 emissions if natural pozzolans were substituted for Portland cement in the construction of spring boxes and gravity fed water systems to serve 1 billion people in the world without access to safe drinking water.

Structure	Pozzolan Usage	Economic Savings	Reduction in CO_2 (tons)
Spring-Box	Volcanic ash or rice husk ash @ 25%	$141,000,000	950,000
	Diatomaceous earth @ 6.25%	$37,000,000	240,000
Gravity Fed Water System	Volcanic ash or rice husk ash @ 25%	$451,000,000	3,800,000
	Diatomaceous earth @ 6.25%	$102,000,000	874,000

The following joint publications, co-authored by engineering students at Michigan Technological University and public policy students at Southern University and A&M College have resulted from this project in the past year. In addition, the student team was recently named a finalist for the UNESCO-Daimler Chrysler Mondialogo Worldwide Engineering Award.

- Harris, R.A. T.D. Eatmon, Jr., C.W.A. Seifert, J.R. Mihelcic, H.E. Muga, "Natural Pozzolans for Sustainable Development: Environmentally Friend Concrete Technology," paper presented at Southwestern Social Science Association Annual Meeting, New Orleans, Louisiana, March 23-26, 2005.

- Mihelcic, JR, H Muga, RA Harris, TJ Eatmon, "Engineering Sustainable Construction Materials for the Developing World: Consideration of Engineering, Societal, and Economic Issues," under review, *International Journal of Engineering Education*, 2005.

Phase II – 7. Formal Partnerships

To date this project has involved 14 engineering students (BS, MS, and PhD) at Michigan Technological University, 4 public policy students (PhD) at Southern University and A&M College, and 29 engineering students at Partido State University (Philippines). As stated previously, this collaboration has already resulted in one publication (Harris et al., 2005) and one publication currently undergoing peer review (Mihelcic et al., 2005).

Michigan Technological University's Sustainable Futures Institute has been collaborating with Southern's University and A&M College's (Baton Rouge, LA) Nelson Mandela School of Public Policy and Urban Affairs on several education and research initiatives. For example, Michigan Tech and Southern were recently awarded National Science Foundation IGERT[2] and REU[3] research grants that focus on graduate and undergraduate research and training of students majoring in engineering, social science, and business with an interest in sustainability. The Michigan Tech-Southern partnership creates a whole that is greater than the sum of its parts, and expands the interdisciplinary reach of both schools. For example, Michigan Tech offers a Ph.D. in several national-ranked engineering disciplines, but does not offer a doctoral degree in Social Science. On the other hand, Southern offers a Public Policy Ph.D. program, but no doctoral degree in engineering. In addition, four Southern University doctoral public policy students involved in this project will be taking coursework at Michigan Tech during fall semester 2005 as part of a recently-initiated graduate student exchange program.

Partido State University (Philippines) is a perfect partner for Phase II of this project (see letter of support). It is located in an area sandwiched between 3 volcanoes, Mt. Isarog, Mt. Asug, and Mt. Mayon, of which Mt. Mayon is still active. The distance is less than 1 hour to each of the 3 volcanoes and all three have different characteristics, which will be important in our technical evaluation of the field evaluation method proposed in Phase II. In 2003, the Philippines ranked 8^{th} in the world in terms of rice production (8.3 million tons) and 8^{th} in terms of rice consumption (9.1 million tons) (Biz Dimension Co., Ltd, 2004). There is also an interest at Partido State in sustainable engineering projects and appropriate technology (e.g., such as use of ferrocement tanks for storage of collected rainwater), and their access to natural pozollans places our team in an excellent position to begin piloting the materials in community-based construction. Michigan Tech also has a Master's International graduate student (Mr. Dan Nover)

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[2] IGERT stands for "Integrative Graduate Education and Research Traineeship"
[3] REU stands for "Research Experience for Undergraduates"

based in Partido State University, in the Sanitary Engineering Department, as part of his service in the U.S. Peace Corps (see attached letter).

We will also initially partner with the Michigan Tech's Sustainable Futures Institute (SFI) and Transportation Institute (MTTI). The mission of SFI is to create and disseminate new methods and processes for generating scientific knowledge and engineering products in support of sustainability decisions and education. As part of its efforts in concrete research, MTTI has four laboratories available for students to utilize in this project. Both SFI and MTTI can also provide links to faculty and staff members that can assist in this project, as well as assist the students in identifying partners for Phase II of the project. In addition, part of this project is extensive data collection and review. For this aspect, students will have access to the 825,000 main and government volumes in the J. Van Pelt Library (Michigan Tech) and the 1-million plus volumes found in Southern University's John B. Cade Library.

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