From Waste to Resource: Fibrous Concrete as an Alternative to Landfilling and Burning Paper in Nogales, Sonora

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Executive Summary

Waste paper creates a significant solid waste problem for Nogales, Sonora, and various individuals and groups living and working in Nogales have sought to identify ways to convert the waste to resource that can be used locally. Fibrous concrete (aka papercrete) is a mixture of waste paper, sand, lime, Portland cement, and water. The Portland cement coats the paper fibers to increase the material's strength and contain the inks and chemicals in the paper. The sand adds thermal mass, reduces flammability and shrinkage, and contributes to a denser, stronger brick. Fibrous concrete also absorbs sound, is flame and fungus retardant, and is insect and rodent resistant. After several years of assessment and testing in Nogales, fibrous concrete emerged as a technology with high potential for converting the city's waste paper into a building material that is affordable, made of available materials, easy to construct using local knowledge and skills, amenable to construction in phases, secure, private, and of low fire risk. However, moving from potential to application requires a complete system from the collection and processing of paper through design and construction.

This project was funded by the U.S. Environmental Protection Agency (EPA) through the Border Environment Cooperation Commission and has aimed at developing and putting in place a system for reducing the paper waste going to the Nogales landfill or being burned, preventing the potential hazards associated with that waste from contaminating the environment, and putting the paper to good use in the local production of fibrous concrete bricks and panels for construction. The project began with the following six objectives:

(1) Efficiently remove paper from Nogales' waste stream;
(2) Utilize the paper in the production of fibrous concrete bricks, wall and roof panels, and mortar;
(3) Construct a demonstration structure of fibrous concrete in Nogales, in a manner consistent with self-help and small-scale housing construction as it is currently carried out in Nogales;
(4) Track all inputs and costs and provide recommendations for a sustainable program that best utilizes materials in the Nogales waste stream;
(5) Collect data on the performance of individual bricks and panels and the overall structure (e.g., monitoring of temperature differentials in an existing house made of fibrous concrete and a standard cinder block house); and
(6) Increase the visibility and acceptability of fibrous concrete materials, both bricks and insulation panels, on the Arizona-Sonora border by sharing information with engineers, architects, and builders, as well as residents.

Summary of Results

The project operated from January 2011 through September 2012 and established a collection and processing center for collecting, safely storing, measuring, and processing waste paper at the Centro de Capacitación para el Trabajo Industrial118 (CECATI), in Nogales, Sonora. After

testing more than a dozen mixtures, project leaders developed a mixture that could meet Mexican standards for brick construction and would cost less than regular bricks being produced and sold in the region. They produced bricks of a standard size, 9x18x40 centimeters (3.5x7x16 inches). The recommended ratio for the final Nogales brick mixture is as follows:
1 kg paper
1 kg Portland cement
0.25 kg lime
8 kg sand

The ratio differs from a mixture commonly used in the United States (1 kg paper, 1.6 kg Portland cement, 1.1 kg sand; http://www.livinginpaper.com/mixes.htm#papercrete), with which project leaders began, in that it reduces the amount of cement to reduce the cost, adds lime to increase the pH of the mixture and prevent the growth of mold, and increases the amount of sand to increase strength and reduce water absorption, shrinkage, and flammability of the bricks. The Nogales mixture produces a brick more consistent with bricks commonly sold in Nogales and therefore more adapted to the Mexican market.

The U.S. mixture proved to be too elastic and unstable to meet Mexican standards for either load or non-load bearing bricks, and bricks produced with the mixture absorbed water at rates much higher than the Mexican standard for even non-load bearing bricks. The structural problems of each individual brick could be addressed by using specialized construction methods and carefully sealing all exterior walls with mortar that is impermeable to water. However, due to the lack of control over how the bricks will be used once they are produced, and the goal of developing a brick for a Mexican market, project leaders refined the approach to develop a brick that retained as many of the thermal properties as possible, but that met Mexican standards for water absorption so that it could be used in any structure according to practices that are common in Mexico.

Critical in the development of a fibrous concrete mixture that could be used to produce bricks was the standardization of a process of pulping the paper, then drying it, and mixing the dried pulp with sand, lime, cement, and water. The initial approach used in this project, advocated by papercrete users in the United States, involved mixing paper, water, sand, and cement at the same time and then draining off large quantities of water (http://www.makepapercrete.com/How-Can-I-Make-Papercrete-.html). While this process results in thousands of air pockets that improved the thermal properties of the final material, it compromises the capacity of the cement, resulting in instability and unpredictability.

Although it is less stable, the U.S. mixture incorporates a greater proportion of paper and therefore has a higher thermal resistance (R-value) than the new Nogales mixture. Many existing homes in Nogales were constructed with cinder blocks and lack sufficient insulation. In addition, the typical home has a galvanized metal roof which requires insulation. To serve the market for insulation for existing cinder block walls and galvanized metal roofs, project leaders began developing and testing fibrous concrete panels and mortars They adapted the U.S. mixture to produce interior insulating panels for walls constructed of wood or cinder/concrete blocks; the cement allows the panels to retain the fire retardant and insect and rodent resistant properties, and their use indoors reduces the concern about water absorption. The recommended ratio for the mixture for producing wall panels is 1 part paper to 1 part cement. This same ratio is recommended for the mortar which is used to join bricks together in the walls. Interior roof panels constructed of this mixture proved to be too heavy for use in without costly additional supports, so the development of an optimal mixture for roof panels is still underway.

Once the formulas and processes for producing bricks, panels, and mortar were finalized, they were used in the construction of a modular demonstration structure, composed of four rooms, totaling 1,034 square feet in area. The cost of the structure was calculated to be slightly less than $250,000 Mexican pesos, a cost comparable to that of a similar structure constructed with standard Mexican bricks. The resulting structure, though, has greater thermal mass and absorbs sound better than a structure built of standard bricks. In addition, the bricks and structure incorporate waste paper and can be produced by hand in a process that does not require specialized equipment or firing, therefore eliminates a significant source of air pollution.

Once the formulas, processes, and construction were completed and project leaders were satisfied that the bricks, panels, and mortar were performing as desired, the final step in the project was to develop a system for increasing the speed and efficiency of production and reducing the costs of the bricks. Through a semi-automated system, the project leaders reduced the cost of individual bricks by almost two pesos apiece and have identified buyers. The CECATI site will continue to be used to produce bricks for sale, and the infrastructure there can be used by individuals who bring their materials and produce their own bricks. To further reduce the cost of producing their own bricks, in the future Mexican residents can access government programs that subsidize the cost of cement up to 50% for self-help construction projects. Details of the development and evaluation of the bricks, panels, and system are provided in the rest of this report.

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Chapter One: Introduction

Need for Project

The management of solid waste, and particularly waste paper, is a significant problem for many communities. According to Nogales, Sonora city officials, between 2005 and 2010, approximately 52,000 pounds of paper were ending up in the municipal landfill each year and an additional 330,000 pounds per year, on average, were being transported out of the region for recycling. On top of that, an unknown amount of paper is burned and contributes to air quality problems in Nogales.[1] As fuel prices rise, shipping waste paper for processing and management will become increasingly less attractive, and the lower quality paper currently being shipped is likely to end up at the landfill as well. In addition to cellulose fibers, clay, and varnish, many types of paper contain dyes and other chemicals that can contaminate soil and are very persistent in the environment.

Since 2003, various individuals and groups living and working in Nogales have expressed interest in and investigated alternative construction technologies, especially to meet the need for low-cost housing. They have also sought ways to convert waste to resource that can be used locally. A 2006 study of alternatives concluded that any successful alternative must be affordable, made of available materials, easy to construct using local knowledge and skills, amenable to construction in phases, secure, private, and of low fire risk.[2]

Fibrous concrete is a mixture of waste paper, sand, lime, Portland cement, and water. The Portland cement coats the paper fibers to increase the material's strength and contain the inks and chemicals in the paper. The sand adds thermal mass, reduces flammability and shrinkage, and contributes to a denser, stronger block. Fibrous concrete also absorbs sound, is flame and fungus retardant, and is bug and rodent resistant. Based on the city's estimates, if all of the waste paper going to the Nogales landfill is used in the production of fibrous concrete there will be sufficient material available for building a home every three weeks. This project was initiated to develop, test, and standardize a process for collecting and processing paper, producing bricks and panels, and making the facility and/or bricks, as well as information about fibrous concrete, available to the people of Nogales. The six project objectives were:

(1) Efficiently remove paper from Nogales' waste stream;
(2) Utilize the paper in the production of fibrous concrete bricks, wall and roof panels, and mortar;
(3) Construct a demonstration structure of fibrous concrete in Nogales, in a manner consistent with self-help and small-scale housing construction as it is currently carried out in Nogales;
(4) Track all inputs and costs and provide recommendations for a sustainable program that best utilizes materials in the Nogales waste stream;

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[1] Austin, Diane, et. al. 2007 *Evaluation of Small Scale Burning of Waste and Wood in Nogales, Sonora.* Report prepared at the BARA, University of Arizona for the Arizona Department of Environmental Quality. November.
[2] Austin, Diane, et. al. 2006.*Thermal Construction and Alternative Heating and Cooking Technologies .Final Report*. Report prepared at the BARA, University of Arizona for the Arizona Department of Environmental Quality.

(5) Collect data on the performance of individual bricks and panels and the overall structure (e.g., monitoring of temperature differentials in an existing house made of fibrous concrete and a standard cinder block house); and
(6) Increase the visibility and acceptability of fibrous concrete materials, both bricks and insulation panels, on the Arizona-Sonora border by sharing information with engineers, architects, and builders, as well as residents.

Project Structure

In 1983, the United States and Mexico signed the Agreement for the Protection and Improvement of the Environment in the Border Area (La Paz Agreement) to provide the foundation for cooperative environmental efforts. The La Paz Agreement has been implemented through several programs, including the Integrated Environmental Plan for the U.S.-Mexican Border (1992-1994) and the Border XXI Program (1996 and 2000). From 2003 through August 8, 2012, the program operated as Border 2012 (after that date it began operating as Border 2020). The Border 2012 program had the stated goal "to protect the environment and the public health in the U.S.-Mexico border region, consistent with the principles of sustainable development" had six explicit goals: (1) Reduce water contamination; (2) Reduce air pollution; (3) Reduce land contamination; (4) Improve environmental health; (5) Reduce exposure to chemicals as the result of accidental release and/or acts of terrorism; and (6) Improve environmental performance through compliance, enforcement, pollution prevention, and promotion of environmental stewardship (http://www.epa.gov/border2012/). The program operated through workgroups, policy forums, and task forces and provided small grants to support projects and serve as seed money to attract additional resources.

The border states of Arizona and Sonora established five task forces to address the Border 2012 program's goals, and those task forces identified specific priorities. This project was designed to address the following 2009 Arizona-Sonora priority areas:

GOAL #3: Reduce Land Contamination

- Reduce waste generation through solid waste management and source reduction practices that lead to measurable environmental results by diverting waste paper and other materials from the municipal landfill to a central site where they will then be processed into bricks

GOAL #6: Improve Environmental Performance through Compliance, Enforcement, Pollution Prevention, and Promotion of Environmental Stewardship

- Promote green purchasing and source reduction practices by demonstrating the efficacy of the fibrous concrete bricks as a replacement for standard cinder blocks.

GOAL #2:Reduce Air Pollution.

- Reduce emissions of air pollutants (especially PM2.5 and PM10) in the border region by reducing burning of paper and other materials and reducing the production of greenhouse gases by increasing the energy efficiency of structures built there

This project was developed through a collaboration of organizations and institutions who had been working together to develop and promote the use of fibrous concrete in northern Sonora and southern Arizona. The initial project partners included leaders and representatives from educational, non-governmental, and business organizations. As the project advanced, the participants and leaders evolved to ensure that the project would meet its goals.

The project was led on the U.S. side of the border by the Bureau of Applied Research in Anthropology (BARA) in the School of Anthropology at the University of Arizona. On the Mexican side, funds were managed by the Fundación del Tecnológico de Nogales, Sonora (Fundación) and the project was led by Grupo Ecológico de Sonora-Arizona (GESA) and Frente Cívico Nogalense, A.C. (Frente Cívico). BARA faculty and students helped manage, support, and evaluate the project. Fundación personnel managed the project funds for the Nogales, Sonora partners. The Centro de Capacitación para el Trabajo Industrial 118 (CECATI) hosted the central project site, providing the facilities and personnel to develop the collection and production facility and demonstration structure. Frente Cívico Nogalense, A.C. (Frente Cívico) took over local project management and provided the engineering and construction expertise to see the project through. Grupo ConFib Flores Magón (Grupo ConFib) helped develop and test fibrous concrete panels, conducted temperature monitoring in a fibrous concrete and cinder block home, and provided outreach to the colonias. Students and faculty from the Centro de Estudios Tecnológicos industrial y de servicios N. 128 (CETis 128) and administrators and students from the Colegio Nacional de Educación Profesional Técnica (CONALEP) helped design and implement the education and outreach program. Students and faculty from the Sustainable Development program of the Instituto Tecnológico de Nogales helped develop the initial collection facility, provide education and outreach, and serve as a liaison to the Fundación.

The project was guided by an advisory board composed of representatives from REFECO (a maquiladora responsible for recycling in Nogales, Sonora), Decorablock (a construction company in Nogales, Sonora), Frente Cívico Nogalense, A.C., CONALEP, CECATI, the Arizona Department of Environmental Quality (ADEQ), the Nogales Department of Public Services, and Colonia Bella Vista.

Chapter Two: Producing Bricks, Panels, and Mortar: From Paper Collection to Distribution

Proper collection, storage, and management of paper is necessary to prevent fires, pest infestations, and dispersal of the paper by the wind. The project was designed to include a central collection and processing facility and satellite sites at several Nogales, Sonora schools. An initial collection and storage facility was obtained in downtown Nogales while the brick production facility was being developed (see Figure 2.1). In addition, two of the schools and the neighborhood production facility operated by Grupo ConFib Flores Magón established their own collection facilities. Once the production facility was completed, collection and storage were moved to the centralized facility. Key priorities for collection and storage of paper include protecting against fire, preventing paper from blowing around or otherwise creating unsightly conditions, and controlling access to documents until they have been repulped. Due to problems with blowing trash, individuals putting materials other than paper in the containers, and the need for the space for other purposes, the school facilities were closed. Due to concerns about the confidentiality of information on paper that was being donated to the project, the neighborhood facility was also closed and all paper collection centralized. As the neighborhood and school facilities needed paper, it was transported from the centralized facility to the satellite sites.

Figure 2.1. Centralized collection facility

A significant goal of this project was to remove paper from the waste stream. However, the amount of paper collected during the project itself was restricted due to the need to standardize production; develop the formulas and processes for making the bricks, panels, and mortar; and complete the demonstration structure. The demonstration structure required 1,700 bricks, produced from 1,050 kg of paper. It also required 202 kg of paper to produce enough fibrous concrete plaster to cover the internal walls of the structure with one inch thick plaster (1 part paper to 1 part cement). An additional 950 kg of paper was used in the early phases of testing bricks and in the educational and outreach activities. The paper was donated by the maquiladora Belden S.A. de CV, Instituto Tecnológico de Nogales (ITN), the federal department of economic development, a private medical clinic, several small businesses, schools, and individuals.

During the project, different approaches were tried and evaluated for processing paper, producing the fibrous concrete mixtures, and making and drying bricks and panels. Throughout the project, the efficiency and safety of the approaches were evaluated. Once the system was in place at the Centro de Capacitación para el Trabajo Industrial118 (CECATI), the centralized collection system was closed and all paper collection and processing moved to the same site. The final production system is the result of the extended testing and modification period.

Standardization of the process of pulping the paper, then drying it, and mixing the dried pulp with sand, lime, cement, and water was critical in the development of the fibrous concrete mixture that could be used to produce bricks. The initial approach used in this project, advocated by papercrete users in the United States, involved mixing paper, water, sand, and cement at the same time and then draining off large quantities of water (http://www.makepapercrete.com/How-Can-I-Make-Papercrete-.html). While this process results in thousands of air pockets that improved the thermal properties of the final material, it compromises the capacity of the cement, resulting in instability and unpredictability.

The photos and text in Figure 2.2 (a through h) illustrate the final system. Key aspects are the (1) initial pulping, centrifuging (with used washing machines), and drying of the paper, (2) recovering the water for reuse; (3) mixing paper pulp, sand, lime, and cement and adding only enough water to make a functional mix; (4) rotating forms so the top and bottom of the bricks are uniform; and (5) drying the bricks in the sun (no firing required).

Figure 2.2.a. Paper collected, weighed, and stored


Figure 2.2.b. Paper pulped


Figure 2.2.c. Pulp centrifuged and water recovered

Figure 2.2.d. Paper pulp dried on racks and stored

Figure 2.2.e. Pulp combined with cement, sand, lime, and water

Figure 2.2.f. Bricks produced

Figure 2.2.g. Bricks dried


Figure 2.2.h. Blocks stored and shipped

Change in Formula

The project began with a mixture commonly used in the United States (1 kg paper, 1.6 kg Portland cement, 1.1 kg sand; http://www.livinginpaper.com/mixes.htm#papercrete) and evaluated the performance of three different types of paper (office paper, newspaper, cardboard) alone and in combination with one another, and also in mixtures of cement only and of cement and lime (see Table 2.1).

Table 2.1. Paper Combinations for Testing

Code	Mixture
CP	Cement + Newspaper (Periódico)
CC	Cement + Cardboard (Cartón)
CB	Cement + Office Paper (Bond)
CCP	Cement + Lime (Cal) + Newspaper (Periódico)
CCC	Cement + Lime (Cal) + Cardboard (Cartón)
CCB	Cement + Lime (Cal) + Office Paper (Bond)
CCBC	Cement + Lime (Cal) + Office Paper (Bond) + Cardboard (Cartón)
CCBP	Cement + Lime (Cal) + Office Paper (Bond) + Newspaper (Periódico)
CCPC	Cement + Lime (Cal) + Newspaper (Periódico) + Cardboard (Cartón)
CCBPC	Cement + Lime (Cal) + Office Paper (Bond) + Newspaper (Periódico) + Cardboard (Cartón)
CB A[1,..,3]	Identification of Sample by Numerical Indices
CCB C[1,..,3]	
CCBC B[1,..,3]	
CCBPC G[1,..,3]	

Figure 2.3. Measuring compression

Each mixture was evaluated for Compression Strength, Volumetric Weight, Specific Weight, Adsorption and Absorption of Humidity, and Fire Resistance. No significant differences were found for the different paper types, or for the inclusion of cement and lime as opposed to cement only. All mixtures produced bricks that were very elastic; none of the bricks met Mexican standards (NMX-C-404-2005) as structural materials (Figure 2.3). Absorption of humidity was measured after 2, 19, and 24 hours (Figure 2.4). As shown in Table 2.2, the bricks became saturated within the first two hours. None of the bricks produced detectable flame; only one produced smoke or gas vapors (the brick with cement and newspaper appeared to have been poorly mixed so the paper ended up on one end) and the bricks only showed minimal carbon deposits on their surfaces after one hour (Figure 2.5). Even after three hours of intense heat, the bricks showed no signs of cracking.

Figure 2.4. Measuring water absorption

Table 2.2. Absorption of Humidity

			Time – Saturation [Hr]			
SAMPLE			2	19	24	
CCBPC I2	W(DRY)=	2.645	3.861	3.926	3.924	W(SATURATED)
			46%	48%	48%	
CCP I2	W(DRY)=	2.706	3.973	4.055	4.05	W(SATURATED)
			47%	50%	50%	

The results of the fire resistance tests on all paper mixtures are shown in Table 2.3 (see also Figure 2.5).

Table 2.3 Application of Fire Source (Blow Torch)

SAMPLE	Time of Application of Fire Source (HRS)	Temperature at the point of application (450<T<530 °C) CHARACTERISTICS PRESENT			
		FLAME	SMOKE	GAS	CRACKS
CCC-C3	0.25	N.D.	N.D.	N.D.	N.D.
	0.5	N.D.	N.D.	N.D.	SLIGHT
	0.75	N.D.	N.D.	N.D.	SLIGHT
	1	N.D.	N.D.	N.D.	LIGHT
	2	N.D.	N.D.	N.D.	LIGHT
	3	N.D.	N.D.	N.D.	LIGHT
CB-A1	0.25	N.D.	N.D.	N.D.	N.D.
	0.5	N.D.	N.D.	N.D.	SLIGHT
	0.75	N.D.	N.D.	N.D.	SLIGHT
	1	N.D.	N.D.	N.D.	SLIGHT
	2	N.D.	N.D.	N.D.	MODERATE
	3	N.D.	N.D.	N.D.	MODERATE
CP-A1	0.25	N.D.	N.D.	N.D.	N.D.
	0.5	N.D.	N.D.	YES	SLIGHT
	0.75	N.D.	YES	YES	SLIGHT
	1	N.D.	YES	YES	MODERATE
	2	N.D.	YES	YES	SEVERE
	3	N.D.	YES	YES	SEVERE
CCBPC-I1	0.25	N.D.	N.D.	N.D.	N.D.
	0.5	N.D.	N.D.	N.D.	N.D.
	0.75	N.D.	N.D.	N.D.	N.D.
	1	N.D.	N.D.	N.D.	SLIGHT
	2	N.D.	N.D.	N.D.	SLIGHT
	3	N.D.	N.D.	N.D.	SLIGHT
CCBC-I4	0.25	N.D.	N.D.	N.D.	N.D.
	0.5	N.D.	N.D.	N.D.	N.D.
	0.75	N.D.	N.D.	N.D.	N.D.
	1	N.D.	N.D.	N.D.	N.D.
	2	N.D.	N.D.	N.D.	SLIGHT
	3	N.D.	N.D.	N.D.	SLIGHT
CCB-D1	0.25	N.D.	N.D.	N.D.	N.D.
	0.5	N.D.	N.D.	N.D.	N.D.
	0.75	N.D.	N.D.	N.D.	N.D.
	1	N.D.	N.D.	N.D.	N.D.
	2	N.D.	N.D.	N.D.	SLIGHT
	3	N.D.	N.D.	N.D.	SLIGHT

(Table 2.3 cont.) SAMPLE	Time of Application of Fire Source (HRS)	CHARACTERISTICS PRESENT FLAME	SMOKE	GAS	CRACKS
CCBP-E2	0.25	N.D.	N.D.	N.D.	N.D.
	0.5	N.D.	N.D.	N.D.	N.D.
	0.75	N.D.	N.D.	N.D.	N.D.
	1	N.D.	N.D.	N.D.	N.D.
	2	N.D.	N.D.	N.D.	SLIGHT
	3	N.D.	N.D.	N.D.	SLIGHT
CC-G3	0.25	N.D.	N.D.	N.D.	N.D.
	0.5	N.D.	N.D.	N.D.	N.D.
	0.75	N.D.	N.D.	N.D.	SLIGHT
	1	N.D.	N.D.	N.D.	SLIGHT
	2	N.D.	N.D.	N.D.	SLIGHT
	3	N.D.	N.D.	N.D.	SLIGHT
CCPC H1	0.25	N.D.	N.D.	N.D.	N.D.
	0.5	N.D.	N.D.	N.D.	N.D.
	0.75	N.D.	N.D.	N.D.	N.D.
	1	N.D.	N.D.	N.D.	N.D.
	2	N.D.	N.D.	N.D.	N.D.
	3	N.D.	N.D.	N.D.	SLIGHT
CCPC H1	0.25	N.D.	N.D.	N.D.	N.D.
	0.5	N.D.	N.D.	N.D.	N.D.
	0.75	N.D.	N.D.	N.D.	N.D.
	1	N.D.	N.D.	N.D.	N.D.
	2	N.D.	N.D.	N.D.	SLIGHT
	3	N.D.	N.D.	N.D.	SLIGHT

*KEY:
N.D. = NOT DETECTED
SLIGHT = FORMATION DE CARBON ON THE SURFACE
LIGHT: FORMATION DE CARBON ON THE SURFACE and FORMATION OF ASHES
MODERATE: PRESENCE OF CARBON AND ASHES
SEVERE: PIECES BREAK OFF FROM THE SAMPLE

As a result of the initial tests, the project leaders determined that all types of paper could be mixed together for brick production (eliminating a potentially time-consuming and costly process of paper separation) and that cement and lime could be used together (increasing the pH of the mix to inhibit mold growth).

Figure 2.5. Test for Fire Resistance

All mixtures absorbed water at rates greater than 100%; the Mexican standard for non-load bearing bricks is 30%. The structural problems of each individual brick could be addressed by using specialized construction methods and carefully sealing all exterior walls with mortar that is impermeable to water. However, due to the lack of control over how the bricks will be used once they are produced, and the goal of developing a brick for a Mexican market, project leaders opted to refine the approach to develop a brick that retained as many of the thermal properties as possible, but that met Mexican standards for water absorption so that it could be used in any structure according to practices that are common in Mexico.

The next step was to develop a procedure for systematically increasing the proportion of sand in the mixture to increase strength/resistance and decrease water absorption. Each mix or batch began with a volume of 19 liters, divided into samples with varying proportions of sand from 0.5 to 8 kg.

Bricks made by hand with all mixtures were evaluated for Specific Weight and Absorption of Humidity (see Table 2.4). Increasing the proportion of sand decreases the thermal resistance of the mixture, so the project leaders sought a mixture that would pass Mexican standards for strength and water absorption while maintaining as high a ratio of paper to sand as possible. The addition of lime did not affect the specific weight or water absorption (see Table 2.3). The recommended ratio for the final Nogales brick mixture is as follows:
1 kg paper
1 kg Portland cement
0.25 kg lime
8 kg sand

This mixture produces bricks of strength and water absorption equivalent to standard Mexican bricks. When produced under higher pressure than can be achieved by hand, the bricks will meet the Mexican standards. In comparison to the initial mixture being evaluated, this mixture uses less cement and thereby reduces the cost, adds lime to increase the pH of the mixture and prevent the growth of mold, and increases the amount of sand to increase strength and reduce water absorption, shrinkage, and flammability of the bricks. The resulting brick is more consistent with bricks commonly sold in Nogales and therefore better adapted to the Mexican market.

Table 2.2. Specific Weight and Absorption of Humidity for Different Mixtures of Fibrous Concrete

		Absorption of Humidity per Immersion[%]									
ID	QUANTITY SAND(KG)	MIXTURES									
		CP	CC	CB	CCP	CCC	CCB	CCPC	CCBP	CCBC	CCBPC
A	0.5	434.751	425.325	471.137	479.295	665.600	N/A	485.092	483.329	427.862	471.393
% Humidity		**146.48%**	**156.18%**	**125.98%**	**117.09%**	**67.62%**	N/A	**122.21%**	**114.92%**	**133.04%**	**126.85%**
B	1	454.194	454.995	507.607	573.190	663.143	575.517	518.233	489.377	514.543	508.186
% Humidity		**134.52%**	**127.47%**	**111.74%**	**97.23%**	**73.45%**	**107.12%**	**101.75%**	**97.20%**	**108.75%**	**111.09%**
C	2	578.570	622.048	581.988	622.163	773.106	661.946	575.460	600.715	577.864	618.188
% Humidity		**91.94%**	**92.49%**	**103.73%**	**85.95%**	**60.60%**	**92.09%**	**96.57%**	**73.37%**	**88.46%**	**80.84%**
D	3	629.511	779.962	N/A	643.759	N/A	705.920	N/A	653.829	648.265	659.145
% Humidity		**78.92%**	**68.97%**	N/A	**81.92%**	N/A	**76.21%**	N/A	**43.91%**	**81.18%**	**75.87%**
E	4	779.905	833.472	783.158	743.266	N/A	N/A	753.740	708.642	726.612	763.022
% Humidity		**57.62%**	**52.35%**	**63.70%**	**60.70%**	N/A	N/A	**67.39%**	**53.67%**	**69.55%**	**57.87%**
F	5	800.693	857.400	834.724	813.406	871.181	781.033	812.099	808.341	810.019	793.300
% Humidity		**60.90%**	**55.77%**	**57.26%**	**63.79%**	**56.90%**	**65.19%**	**65.76%**	**57.17%**	**57.29%**	**60.86%**
G	6	813.333	886.811	897.364	818.418	915.140	799.174	N/A	847.791	826.881	881.104
% Humidity		**58.28%**	**50.84%**	**49.54%**	**57.62%**	**50.51%**	**65.29%**	N/A	**62.78%**	**52.82%**	**52.33%**
H	7	882.594	899.632	935.031	873.995	N/A	N/A	920.465	904.417	875.016	927.460
% Humidity		**49.29%**	**50.89%**	**52.39%**	**49.85%**	N/A	N/A	**55.20%**	N/A	**53.38%**	**45.73%**
I	8	926.084	N/A	996.923	908.851	977.236	N/A	1028.805	925.884	900.154	988.209
% Humidity		**51.81%**	N/A	**40.45%**	**47.04%**	**46.29%**	N/A	**42.80%**	**46.23%**	**49.62%**	**40.73%**

N/A=No data

Variation of Specific Weight of the Mixtures

MIN= 425.325

MAX= 1028.805 241.89%

Table 2.3. Comparison of Specific Weight of Mixtures of Cement and Cement with Lime

Cement Only	Cement and Lime	VARIATION
443.738	502.095	13%
472.265	548.884	16%
594.202	632.778	6%
704.736	662.184	-6%
798.845	739.056	-7%
830.939	812.769	-2%
865.836	848.085	-2%
905.752	900.271	-1%
961.503	954.856	-1%

Although it is less stable, the U.S. mixture incorporates a greater proportion of paper and therefore has a higher thermal resistance (R-value) than the new Nogales mixture. Many existing homes in Nogales were constructed with wood or cinder blocks and lack sufficient insulation. In addition, the typical home has a galvanized metal roof which requires insulation. To serve the market for insulation for existing cinder block walls and galvanized metal roofs, project leaders began developing and testing fibrous concrete panels and mortars (Figures 2.6 and 2.7). They adapted the U.S. mixture to produce interior insulating panels for walls constructed of wood or cinder/concrete blocks; the cement allows the panels to retain the fire retardant and insect and rodent resistant properties, and their use indoors reduces the concern about water absorption.

Figure 2.6. Production of panels at the neighborhood facility of Grupo ConFib

The recommended ratio for the mixture for producing wall panels is 1 part paper to 1 part cement. This same ratio is recommended for the mortar which is used to attach the bricks together in the walls. Interior roof panels constructed of this mixture proved to be too heavy for use in without costly additional supports, so the development of an optimal mixture for roof panels is still underway.

Figure 2.7. Panels made of fibrous concrete in a 1:1 ratio of paper to cement

Samples of the mixtures used for bricks and panels were sent to the laboratory at the Department of Chemical and Metallurgical Engineering at the University of Sonora in Hermosillo for evaluation of their thermal conductivity (see Appendix). The Nogales brick mixture had a value for thermal conductivity of 0.63. The panel mixture had a value of 0.40. This translates to an R-value of 1.6 for the brick and 2.5 for the panel. Standard Mexican bricks and cinder blocks both have an R-value of approximately 1.1. Both the Nogales bricks and the panels have greater thermal resistance than the standard bricks used in Nogales, Sonora.

Block Size

The bricks were initially constructed to be 1 foot wide x 2 feet long. However, bricks of that thickness require that considerable space be devoted to the walls of a small structure, so the first aim was to produce narrower bricks which would take up less space in a building wall but contain the same amount of material (thereby maintaining the thermal mass). To address this, the engineer, project manager, and brick makers reduced the size of the bricks and developed a hand-operated press to be used to compress the bricks under a standard pressure (see Figure 2.8). After experimenting with the press, the project leaders stopped using it because it required too much time in production. The leaders will continue to investigate options for production of compressed bricks. The brick size was changed to 9x18x40 centimeters (3.5x7x16 inches), the size of bricks sold on the Mexican market (Figure 2.9).

Figure 2.8. The hand press

Figure 2.9. The final molds for making bricks

Mixers

Development and testing of mixers that could handle paper created challenges throughout the project. The need to tear and pulp paper to retain long fibers precludes the use of shredders. Some types of paper (such as newsprint) can be readily pulped by simply being soaked in water, but these types are typically of high value and likely to be recycled, so an important project goal has been to ensure that all types of paper can be used. Mechanical pulping of large volumes of paper puts great strain on mixers. Because the different types of paper have different characteristics, there is no standard for estimating the size of motor, shaft for transferring movement from the motor to the blades, or tank that might work best. Consequently, the project leaders designed and experimented with several types of mixers. The need to develop appropriate mixers is not unique to Nogales, though the circumstances in the border region introduced some special challenges, especially to achieve the goal of producing low-cost models that can be constructed locally with locally available materials.

Four mixers were constructed: (1) a stationary mixer that incorporates a diesel motor that can be run on biodiesel; (2) a large, stationary electric mixer that incorporates a differential from a car engine; (3) a smaller, stationary electric mixer that uses a motor from a swamp cooler; and (4) a modified, custom-made mixer with a 120 gallon steel tank, driven by a gasoline motor, mounted horizontally on wheels so it can be moved to different sites where paper needs to be processed (Figure 2.10 a through e). The problems with obtaining the necessary parts for the mixers and retaining skilled welders with the time to work on the mixers led to a search for additional models that could be produced and repaired locally. Once the new process for producing pulp was developed, project leaders were able to use a standard cement mixer to combine the pulp, sand, lime, and cement (Figure 2.10.f).

a. Motor and tank of large capacity stationary diesel mixer that can run on biodiesel (#1)

b. Large, stationary electric mixer with a differential from a car engine (#2)

c. Motor and shaft of small capacity stationary electric mixer (#3)

d. Large capacity horizontally mounted mobile mixer with gasoline motor (#4)

e. Large capacity horizontally mounted mobile mixer after modifications (#4)

f. Regular cement mixer (#5)

Figure 2.10. Mixers developed and adapted for the project

Comparison of Bricks to Others Sold in Nogales

Cinder blocks and earthen bricks are two common materials used in construction of homes in Nogales. Table 2.4 compares the fibrous concrete bricks to the other two materials.

Table 2.4. Comparison of Nogales Fibrous Concrete Bricks to Others Sold in Nogales

Type of Block/Brick	Material	Size (cm.)	Cost	Cost per m^2	R-Value
Cinder Block	Cement and sand	15x20x40	$.71	$8.88	1.1
Earthen Brick	Clay soil (fired)	9x18x40	$.56	$14.00	1.1
Fibrous Concrete Brick	Fibrous concrete	9x18x40	$.50	$12.50	1.6

Chapter Three: Design and Construction of Demonstration Structure

A central goal of this project was to address the need for low-cost, thermally efficient and safe housing for low-income residents of Nogales, Sonora. Therefore, the demonstration structure was designed to be the size and style of a typical house on a small lot in the city. After reviewing several potential sites, the project advisory board selected the campus of the Centro de Capacitación para el Trabajo Industrial118 (CECATI) as the location for the demonstration structure. The technical school is centrally located and accessible from a major roadway in Nogales (Avenido Obregón), serves a wide range of adults from Nogales, Sonora and nearby communities, is next to a major industrial park, and is immediately adjacent to the Colegio Nacional de Educación Profesional Técnica (CONALEP) and a middle school. The structure was located on the northwest edge of the campus, near a driveway and entrance, to facilitate visits by large and small groups. In addition, it is next to the guard station for CONALEP, and CONALEP has agreed to provide security for the structure.

Construction of the Structure

The structure was designed to include a small bedroom, kitchen, bathroom, and (Figure 3.1).

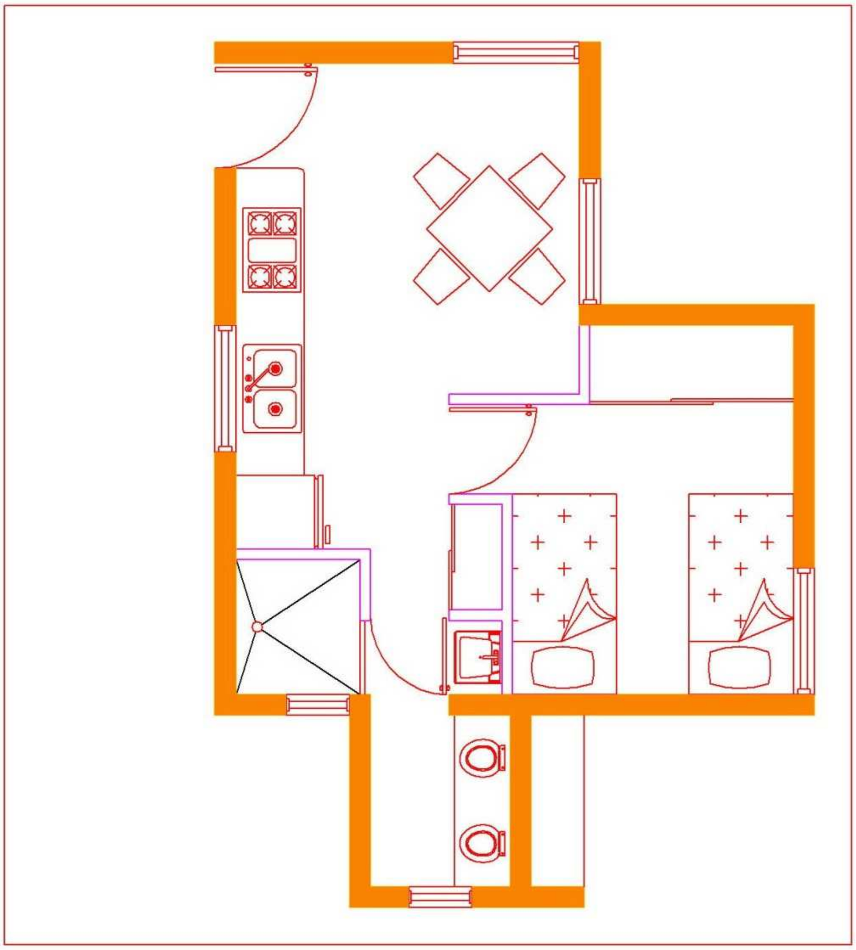

Figure 3.1. Floor plan for the demonstration structure

Construction of the demonstration structure took place from May to September 2012, as documented in Figure 3.2 (a through g).

Figure 3.2.a. Initial site preparation

Figure 3.2.b. Laying the foundation

Figure 3.2.c. Wall construction

Figure 3.2.d. Applying regular cement plaster to exterior walls

Figure 3.2.e. Installing the roof

Figure 3.2.f. Applying fibrous concrete stucco to interior walls

Figure 3.2.g. Adding windows and the door

The fibrous concrete structure provides the foundation for development of an "Eco-Casa" demonstration facility that will inform and educate the public about various alternative building and household technologies, in addition to fibrous concrete. The finished facility will include a composting toilet, passive and active rainwater harvesting systems, a graywater system, small gardens and trees for shade and food, and solar water filtration and heating. Representatives from Frente Cívico Nogalense, A.C., CECATI, and the Bureau of Applied Research in Anthropology (BARA) at the University of Arizona have begun developing a comprehensive educational program for the facility (see also Chapter Four: Outreach and the Future of Fibrous Concrete Production in Nogales).

Monitoring Temperature

The demonstration structure was completed at the end of the project period, so no data were collected on its performance. However, two homes had been built with formulas similar to the initial fibrous concrete mixture (1 kg paper, 1.6 kg Portland cement, 1.1 kg sand) before the project began. Thermometers were placed inside these homes, and a home of a similar size nearby, to compare the change in temperature over time as outside temperatures changed. Data were recorded during the project period; though problems with thermometers limited the information learned from this effort. Figure 3.3 compares the performance of the fibrous concrete home to the standard cinder block home of about the same size for two sample months. As shown, the fibrous concrete brick walls performed as expected, buffering the change in temperature to a greater extent than the cinder block walls. Overall, the fibrous concrete walls appeared to smooth out the peaks and valleys associated with daily and seasonal temperature fluctuations. The bricks made with the new formula will not perform exactly as those bricks produced with the initial formula did, but the data provide an indication of the effect of adding the paper.

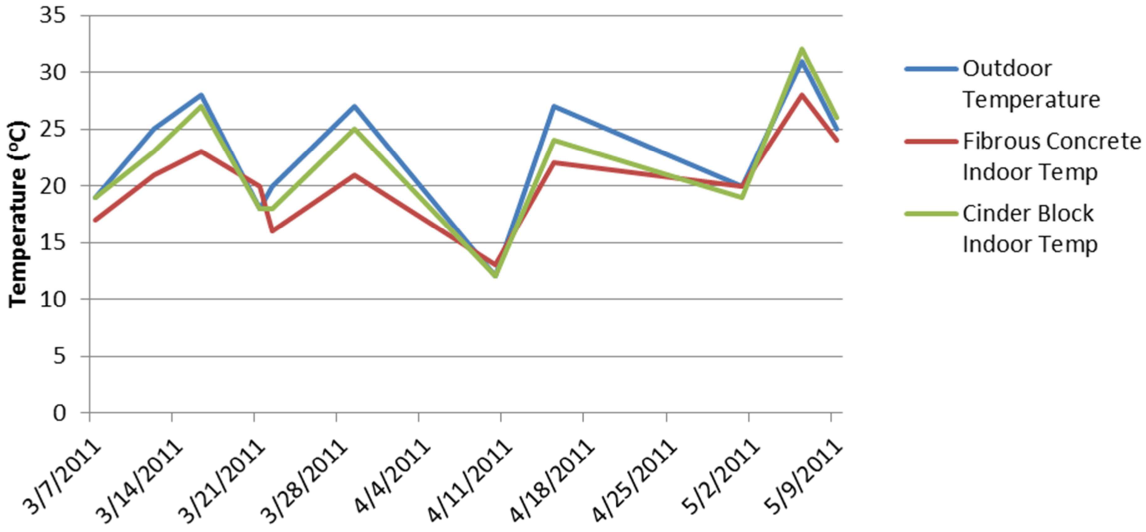

Figure 3.3. Afternoon temperature variation in homes with fibrous concrete and cinder block walls

Chapter Four: Public Outreach and the Future of Fibrous Concrete Production in Nogales

Fibrous concrete will only be successful as an alternative construction material in Nogales, Sonora, and elsewhere in the region, if it is accepted by members of the public as well as specialists such as construction engineers and city officials. Throughout the project, efforts were made to inform and educate residents and leaders of Nogales about fibrous concrete. The advisory board was selected to include a range of individuals with contacts in various social networks in Nogales (see Chapter 1). Workshops and presentations were given at schools and community centers, and information about the project was shared in the newspapers and on local radio and television stations. The production facility was designed to be used by students and community members who want to learn about and produce their own bricks. The demonstration structure was developed to serve as an educational site as well as a model; data on temperature and other aspects of its performance will be collected in the future.

Education and Outreach at the CECATI Facility

Even as it was being developed, the Capacitación para el Trabajo Industrial118 (CECATI) facility was used as an educational facility. Students from the Centro de Estudios Tecnológicos industrial y de servicios N. 128 (CETis 128), the Colegio Nacional de Educación Profesional Técnica (CONALEP), the Instituto Tecnológico de Nogales (ITN), and the University of Arizona (UA) attended workshops at the facility (Figures 4.1 and 4.2). Through an agreement between the CECATI and CONALEP administrators, CONALEP students will continue to work at the facility to fulfill their social service requirements. CETis 128 students worked at the facility during the summer of 2012 to learn the processes and techniques that they could use and adapt for their school's training facility (see also Outreach to High Schools).

Figure 4.1. Brick makers demonstrate process for UA public health students in a service learning course

Figure 4.2. Composting toilet and educational poster at CECATI demonstration facility

Outreach to High Schools

Students and teachers from the CETis 128 and administrators and students from CONALEP participated in workshops and developed programs to continue learning about and producing fibrous concrete after the project period ends. For example, the project construction engineer and students from the Bureau of Applied Research in Anthropology (BARA) led a workshop for CETis 128 students to learn about how different materials can affect the strength, fire resistance, and absorption properties of bricks. They produced a series of bricks to which they added various proportions of waste materials, other than paper (see Figure 4.1). During the summer of 2012, CETis 128 student leaders worked at the CECATI facility to learn the techniques of brick production. The director of CETis 128 agreed to provide labor and a concrete foundation to establish a brick production facility that will be used at the school to continue the development, improvement, and expansion of the brick-making process.

Figure 4.3. Project engineer and CETis 128 students learning about fibrous concrete

Figure 4.4. CETis 128 students designing and carrying out experiments with fibrous concrete

Outreach to Neighborhoods and Community Organizations

Project leaders also organized and led workshops in colonias in Nogales and surrounding communities. These workshops included residents interested in learning about environmental issues in general, as well as about fibrous concrete. Some were targeted at individuals interested in learning about and using fibrous concrete in constructing or insulating their homes and businesses (Figure 3.3).

Figure 4.5. Local entrepreneur learning to apply fibrous concrete insulation to an existing roof

Figure 4.6. Residents of all ages participate in a workshop in Imuris, Sonora

Project leaders also visited papercrete builders in the United States to learn from and share experiences. BARA students worked with a Tucson innovator, Vince Pawlowski, to learn about mixers and designed and constructed two fibrous concrete cubes, one each with 6 inch and 9 inch walls and roof. They installed thermometers inside and outside of the structures to evaluate the difference in temperature between the two and invited project leaders and students from Nogales to visit and learn from their experiences.

Figure 4.7. Vince Pawlowski with his barrel mixer in Tucson, Arizona; This mixer served as the model for one of the project mixer designs (#3)

Figure 4.8. BARA student interns construct and discuss fibrous concrete test structures in Tucson, Arizona with CETis 128 teacher

Project leaders and students also participated in local and regional festivals and fairs, such as the April 13, 2011 Earth Day Expo in Nogales, Sonora (Figure 4.9) and Fiesta Days in Tumacácori, Arizona. They also made numerous presentations to local groups and others in the border community, including attendees at the 2011 Border 2012 National Coordinators Meeting.

Figure 4.9. Project leaders demonstrate fibrous concrete with a hands-on activity at the 2011 Earth Day Expo in Nogales, Sonora

Appendix
Results of Thermal Resistance Tests at the University of Sonora

UNIVERSIDAD DE SONORA
DIVISIÓN DE INGENIERÍA
DEPARTAMENTO DE INGENIERÍA
QUÍMICA Y METALURGIA

Hermosillo, Sonora. 11 de Septiembre del 2012

Resultados de Medición de la Conductividad Térmica
con método de prueba de acuerdo a norma ASTM C177

Tipo de Material: Composito papel-cemento

Solicitante: Ing. Luis Edmundo Pérez

Muestra	k (W/m·K)
Mezcla confib con proporción de 1 kg de papel-1 kg de cemento	0.40
Mezcla confib con proporción de: 1 kg de papel, 1 kg de cemento, 1 kg de cal y 8 kg de arena	0.63

Elaboró:

Hinojosa P.

Dr. Jesús Fernando Hinojosa Palafox
Profesor-Investigador del Departamento
del Ingeniería Química y Metalurgia

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