

## **346: Developing a Low Cost, Sustainable Housing Prototype Using Recycled Waste Materials in Tijuana, Mexico**

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### **Abstract**

This paper describes the development of a low cost, energy efficient prototype house designed for informal settlements of Tijuana constructed from a variety of local manufacturing waste materials. The 35 m<sup>2</sup> prototype demonstrates construction techniques using waste car tires and gabion rock cages as a retaining wall system, wood pallets as a roof truss system, waste newspaper blended with Portland cement as a “papercrete” wall system, waste rice sacks integrated into a vegetated roof system, windows made of sewer pipes and dinner plates, and a simple radiant floor heating system using agricultural irrigation tubing. The prototype was built by a team of students and faculty at the Lyle Center for Regenerative Studies, Cal Poly Pomona and is a follow up to P La Roche’s “A Very Low Cost Sustainable Housing Prototype for Tijuana, Mexico,” that was presented at the PLEA conference in 2006. While the 2006 paper presented computer-simulated performance of the dwelling, addressing the need for low cost, sustainable housing for residents of informal settlements in Tijuana, Mexico, this paper will describe the thermal performance of the structure as an integration of passive and low tech active heating systems for winter application. Results indicate that heating comfort can be achieved passively within a structure constructed of a variety of waste materials available in Tijuana.

This project is extremely relevant given the increasing number of worldwide urban dwellers with inadequate housing, depleting natural resources for building materials, and greenhouse gas contributions associated with energy intensive building materials travelling great distances. We hope the knowledge attained from this project will ultimately be disseminated into other communities with similar needs.

Keywords: thermal performance, informal settlements, recycled materials, papercrete.

### **1. Introduction**

This paper aims to identify effective housing design and construction techniques applicable for communities living in poverty within Tijuana, Mexico. Primary objectives for this project included the development of low cost, energy efficient, and sustainable construction designs that utilize locally available materials for people living within Tijuana. These designs were then constructed and tested in a full-scale prototype at Cal Poly Pomona with the expressed intent that knowledge attained from the exercise would be disseminated to the applicable communities of Tijuana and the world.

## **2. Tijuana, Mexico**

### **2.1 Informal Settlements of Tijuana**

Of the 1.5 million occupants of Tijuana, hundreds of thousands live within informal settlements more commonly referred to as colonias. Many of these colonias are located on the outskirts of Tijuana to the east between Tijuana and Tecate. Observations attained during several field trips indicated that these communities are often lacking in adequate public services such as roads, clean water, and sewer. Structures within these communities are often built with found materials and lack adequate insulation and building envelope seal creating a living environment that can be uncomfortably hot in the summer and cold in the winter.

### **2.2 Tijuana’s Climate**

Tijuana can be considered part of the United States’ climate region #17, which is comprised of the southern California coastal region. This region exists in a semi arid climate that enjoys a near constant cool wind from the ocean, carrying with it humidity. Occasionally wind reverses and blows from the interior of the continent bringing air that is much hotter and dry. As one moves inland sharp contrasts can be noted between the cooler humid air of the ocean and the hotter dry air of the interior, thus many microclimates exist within the region.[1] Temperatures throughout the winter months can range from 5 °C to 23 °C, summer months can vary between 18 °C to 30 °C. Climate data for Tijuana could not be obtained, however data was available from nearby San Diego. Upon analysis of the psychrometric chart from Climate Consultant it becomes obvious that thermal comfort can be achieved in Tijuana through passive means of heating in the winter months and natural ventilation cooling strategies during the summer months. [2]

## **2.0 Tijuana Prototype House**

### **2.1 Prototype Design**

The Tijuana prototype was designed and constructed as a 375 square foot (35 square meter) structure. The “L” shaped design consisted of two connecting spaces, a larger 16’ x 12’ (4.8 x 3.6 meter) main room with an adjoining 8’ x 12’ (2.5 x 3.6 meter) small room.

Above the small room is a low ceiling-sleeping loft. The “L” shape design created an outdoor courtyard area to incite community interaction and function as a work and community space for the inhabitants. The structure was intentionally built with a modular design allowing for ease of future additions onto the dwelling. A south facing passive solar component in addition to a low cost solar radiant floor system were implemented as winter heating strategies. The structure also incorporated high ceilings and operable windows for natural ventilation. A green vegetated roof functioned as an insulator to prevent heat from entering or leaving the space through the roof. A primary objective of the prototype was ease of construction using low cost, locally available materials for inhabitants of informal settlements within Tijuana. Locally available materials included a variety of natural materials such as soil and rock as well as materials acquired from the municipal and manufacturing waste streams such as car tires, wood shipping pallets, paper, sewer pipes, and broken concrete. These materials were utilized in a number of foundation, wall, roofing, and window systems for the prototype.



*Image 1. Tijuana prototype house*

## 2.2 Papercrete Wall System

Papercrete is a fibrous cementitious compound comprised of waste paper and Portland cement. These two components are blended with water to create a paper cement pulp, which can then be poured into a formwork, allowed to dry, and be utilized as a durable building material. It should be noted that papercrete is a relatively new concept with limited applied scope. Since its accidental discovery thirty years ago construction estimates indicate some 50-100 papercrete structures exist in the world, most of these are located in the hot and dry climate of the American Southwest. The current pool of knowledge pertaining to papercrete was obtained predominately through anecdotal field experiments and observations; very little peer-reviewed research exists pertaining to this material.

The use of papercrete not only utilizes an abundant waste resource, but also creates a building material with exceptional insulation qualities. Fully cured papercrete is very much like an aerated paper mache. The material is filled with many tiny air pockets giving it a lightweight characteristic relative to regular

concrete and also provides it with a higher R-value than ordinary concrete. The Center for Alternative Building Studies (CABS) in conjunction with Arizona State University conducted some thermal conductivity tests on a variety of papercrete matrixes. They determined that the R-value of papercrete can vary depending on the components within the matrix however all samples tested ranged within R 2.6 - R 3.2 per inch. [3]



*Image 2. Papercrete block*

The compressive strength of papercrete is not comparable to that of concrete, thus eliminating structural applications such as posts or columns, but it has demonstrated adequate compressive strength qualities for wall systems. Fuller and his team conducted a series of compressive strength tests on a variety of papercrete mixes. Papercrete will not break on compression like concrete, failure was rather determined by deformity as increasing compressive force proved to severely deform the material. The weakest mixtures failed by deformity in the range of 400-500 psi proving that even the weakest compositions could be applicable for load bearing structures at least one story high with a 12 inch thick wall. [4] The strongest mixes exceeded 2000 psi, which would be adequate for load bearing structures of at least two stories with the same wall thickness. [4]

The organic fibrous properties of papercrete allow it to absorb and retain moisture, which can be problematic if not properly accounted for when designing and constructing a papercrete structure. The best defence against problems associated with moisture is limiting exposure to water and providing an avenue for escape in the event moisture gets into the material. Breathability of the material assures unwanted moisture escape from papercrete. Typically a protecting yet breathable coating on the wall such as lime is preferred rather than sealing the wall completely which risks trapping moisture within the material, potentially creating structural instability and an environment for mold, mildew, and fungus growth. Limited exposure to moisture is not detrimental to papercrete, as it will dry to its original state. The issue of moisture and the thermal properties of the material suggest papercrete is best suited for hot and dry climates with potentially detrimental performance in humid climates. There are reports of a papercrete

structure in Colorado that houses a small escargot farming operation. As a result of the farming operation relative humidity levels within the space commonly exceed 80%. The structure has been in such operation for roughly ten years with little sign of structural decay due to the moisture level. This structure might be an indicator of papercrete's resistance to failure due to moisture, but lacks formal research and analysis for the overall health of the building or its occupants.



*Image 3. Papercrete tow mixer and block forms.*

Papercrete was incorporated into the majority of the Tijuana prototype's wall system. The material was manufactured at Cal Poly Pomona by an innovative yet low-tech mixer designed and built for the making of papercrete. The "tow mixer" is a unit that is towed behind a vehicle and utilizes the transfer of energy generated by the turning of the mixers' wheels to power a spinning blade inside the mixer chamber, which serves the purpose of blending a batch of paper, water, and Portland cement into papercrete pulp. The papercrete was shovelled out of the mixer into forms to make blocks sized 5" high by 10" wide by 44" long. A block typically took a minimum of two weeks to fully cure and could take as long as a few months depending upon the block's exposed surface area to the sun and wind as well as the relative humidity of the air where drying. Once papercrete blocks were cured they were set into the wall of the prototype and mortared together with a papercrete mortar. Papercrete mortar was selected as opposed to more conventional cement mortars as it continues to utilize waste paper with expectations that thermal bridging through the wall would be minimized relative to the more thermally conductive nature of cement mortars. Typically a mixture of 5 parts paper pulp to 1 part Portland cement by volume worked well, this is twice the amount of Portland as was used in the blocks. The blocks were cut to fit around the posts of the frame and scoured on top and bottom to create a good bonding surface for the mortar. Cutting was easily accomplished using an electric chainsaw. A gas powered saw is not recommended as the cutting process generates a considerable amount of dust that would quickly clog the air filter on the saw. Walls were built in this fashion around the entire structure to roughly five feet above the slab. In an attempt to expedite the process the upper half of the walls were set by pouring the papercrete into a set of forms directly on the wall.

The pour in place method proved to be more efficient for numerous reasons. The wall was being built much faster as pouring papercrete onto the wall eliminated the steps of pouring and setting blocks. This also created a wall that functioned as one monolithic system with no gaps between pours for air infiltration. Building the wall with blocks tended to create gaps between the blocks as the mortar shrank while it dried. These had to be filled later with more papercrete or expandable foam to prevent air infiltration into the structure, consuming more time. The wall was poured to the roofline without framing for windows. Windows were to be cut in place at a future time using the chainsaw.

The exterior wall was finished with a papercrete plaster comprised of the same higher Portland to paper ratio as that of the papercrete mortar. This demonstrated a continued use of waste newspaper while also creating a breathable envelope allowing any moisture to escape that may infiltrate the wall.

### **2.3 Vegetated Green Roof System**

A low cost green roof was implemented on the larger west-facing roof of the prototype. The plants and soil were intended to provide shade protection from the hot afternoon sun and serve as a thermal mass on the roof in an attempt to draw heat from within the building during the summer. Through the winter months the green roof would function as an insulating barrier for the structure holding heat within. The roof would also absorb the force of heavy rains, mitigating the harmful effects of rainfall runoff and erosion, a serious problem in the colonias of Tijuana.

The green roof was designed to be constructed in a manner that utilized minimal technology, low cost materials, and require little to no maintenance. An impermeable layer of plastic was placed on top of the roof decking as a moisture barrier. Long tubular "rice sack" like bags cut into four foot sections were filled with a growth medium containing 50% native soil and 50% perlite, effectively reducing the load being placed on the rooftop and has moisture retention properties that would benefit the plants. The bags were then placed on the roof in rows, with the length of the bag oriented perpendicular to the low end of the roof.

The bag method proved to be inexpensive, lightweight, and an easy method for transporting the soil to the roof. The bags allow water to pass through them while providing a structure around the soil as the roots establish themselves. When positioned on the roof, a number of slits were cut into the topside of the bag where a variety of sedums and succulents were planted. These plants would functionally shade the roof preventing summer overheating with little need for water, maintenance, or soil depth as they were selected for their shallow root systems. The bags are photodegradable to sunlight, thus over time the surface of the bags diminished creating a layer of soil over the roof.



Image 4. Sedums in rice sack green roof system

#### 2.4 Solar Radiant Floor Heating System

During a January field trip to Tijuana students observed interior floor slabs of Corazon homes below 15°C, living spaces were extremely cold. The Tijuana prototype incorporated a passive solar component but also experimented with a low cost, easy to assembly solar radiant floor heating system. The objective of this system is to heat the prototype space by means of transferring solar energy into the floor slab by circulating water through an inexpensive, low-tech heat transfer system.

The structure was built with a slab on grade concrete foundation. While pouring the slab a very low cost black plastic irrigation tube was snaked throughout the concrete. The tubing was placed five inches apart in rows.

The radiant floor system received its heat from a solar collector constructed from inexpensive parts and mounted on the southwest exterior wall surface of the structure. The solar collector was a constructed box made of 2" X 6" lumber, OSB, and a one-inch layer of insulating Styrofoam board. The interior of the box was painted matte black for optimal heat absorption and emittance. The same black plastic irrigation tubing was wound in spiral within the collector. The box was then covered with a piece of transparent plastic Plexiglas allowing solar radiation to pass through but still retain as much heat within the box as possible. A small water circulation pump on a timer moved water through the thermal collector and the floor to transfer the heat absorbed by the sun's energy in the collector to the slab, which would then radiate into the space.

The tubing within the collector and the floor was chosen for its low cost and ease of assembly. Commercial grade solar thermal collectors are constructed using copper piping as the medium for transferring heat to water. The conductivity of copper makes it an ideal material for this task however the cost of copper and the skills and tools required to assemble such a device would be prohibitive for residents living within informal settlements of Tijuana.

#### 2.5 Automotive Tire Foundation

A foundation and soil retention system made of automotive tires was incorporated into the prototype. Waste automotive tires were set in rows offset at the seams. Earth was packed into each individual tire using a sledgehammer and tamper. Soil was built up against the tire wall to

level out the grade for the floor slab of the prototype

#### 2.6 Wood Pallet Roof Truss System

Wood shipping pallets are already widely used in Tijuana as a building material for walls. Their potential use for a roofing system was explored by developing a very low cost and strong wood pallet truss system supporting the west facing green roof. This idea was inspired by pallet truss systems developed by Builders Without Borders [5]. Scrap wood shipping pallets were obtained at no cost and disassembled into individual wood pieces. A jig was built on the ground so that 5 trusses could easily be assembled uniformly. The ends of 2" x 4" wood members obtained from the pallets were butted against each other and sandwiched between the flatter wood members obtained from the top of the pallet, thus one can create a 2" x 4" member of any length. The flatter wood pieces were also used as cross members. The sandwiched points as well as the cross members were bound with Liquid Nails and 8d nails. The truss system on the prototype house is currently supporting the green roof with a calculated water saturated weight of 20 lbs per sq/ft. These trusses were constructed at a very low cost of \$5-10 each.



Image 5. Wood pallet roof truss system

#### 2.7 Windows

None of the windows for the structure were framed prior to the pouring of the papercrete walls. Holes were cut into the existing walls with the use of an electric chainsaw and simple windows were built from 2" x 4" lumber and single pane glass. Four of these windows were mounted on the south side of the structure for passive solar heating; one more was placed on the west side for air ventilation and afternoon light.

The north side of the structure was fitted with six circular windows nine inches in diameter. Circular holes were cut in the wall where sections of a nine inch recycled PVC sewer pipe were set. The pipe was then fitted with a \$0.99 IKEA clear glass dinner plate creating an extremely inexpensive yet architectural interesting portal window. The windows functioned well to emit ambient northern light into the space with minimum surface area for heat loss to the atmosphere at night.



Image 6. Window made of a sewer pipe and a dinner plate set in papercrete wall.

### 3. Tijuana Prototype Thermal Performance Analysis.

#### 3.1 Experiment Design

The Tijuana Prototype House was subject to a series of tests pertaining to thermal performance as an attempt to understand how the structure was performing as a compilation of integrated systems. Tests were conducted during the winter and focused on the structures heating performance by means of various passive and low tech active heating systems integrated into the design and construction of the structure. These designs for heating as well as the structures ability to retain heat through quality insulating techniques and tight envelope seal provided a basis for analysis of the thermal performance of the structure.

Four series of tests were performed through the month of February. Air temperature readings were collected within the structure using Onset HOBO data collectors as well as one outdoor air temperature sensor. The first series tested the ability of the south facing passive solar design to heat the space as well as the papercrete wall's ability to retain heat gain through the night. The second series tested the heat gain within the structure by means of the passive solar design as well as the solar radiant floor. Thus the south facing windows were exposed allowing solar energy into the space and the solar radiant floor was operating during the hours of 9am-4pm. Throughout the five-day period of the third series the south facing windows were covered with a one-inch sheet of Styrofoam board, preventing solar radiation from entering the space by means of the windows. However the solar radiant floor was operating in an attempt to understand how well the radiant floor performed on its own to heat the space. During the fourth series the windows remained covered and the radiant floor was turned off, thus the structure was receiving no form of active or passive heating.

#### 3.2 Analysis Procedure

The performance of the four series were analysed using the Temperature Difference Ratio (TDR) methodology proposed by Givoni. TDR is a concept that standardizes the ability of a building to reduce or increase indoor temperature as a function of the outdoor temperature swing. Givoni developed a calculation that compares the

difference in maximum outdoor temperature with the maximum indoor temperature for any given test day and its relation to the swing of outdoor temperature for that same day, which is the difference of maximum outdoor temperature and minimum outdoor temperature. [6]

$$TDR = (T_{maxout} - T_{maxin}) / (T_{maxout} - T_{minout})$$

This equation was developed to provide a ratio of indoor performance relative to outdoor swing for the summer time cooling of spaces. This is indicative by the first half of the equation were maximum outdoor temperature is ideally higher then the maximum indoor temperature. The series of tests run on the Tijuana Prototype was concerned with wintertime heating. Thus the equation was modified for the assumption that ideal winter performance would have a higher indoor maximum temperature then outdoor maximum temperature. The equation used for the temperature difference ratio of the wintertime performance of the prototype was:

$$TDR = (T_{maxin} - T_{maxout}) / (T_{maxout} - T_{minout})$$

The TDR's for each day of a given series were then averaged over the period of the series to provide an average temperature difference ratio of the entire series. A higher TDR value represents a larger temperature difference between the outdoor swing and the indoor performance. An ideal temperature difference ratio for a passively heated structure on a given day or averaged series is one. A negative TDR indicates that outdoor conditions were better then indoor.

#### 3.3 TDR Experiment Results

Temperature Difference Ratio (TDR)		
Series	Main Room 1.5 Meters Above Slab	
Series 1: South facing windows exposed and solar radiant floor off	0.1	Best Performing Series
Series 2: South facing windows exposed and solar radiant floor on	0.49	
Series 3: South facing windows covered and solar radiant floor on	0.25	
Series 4: South facing windows covered and solar radiant floor off	-0.06	

Chart 1. TDR of the four series

The data indicates the temperature difference ratio of series two as the best performer of all the series. Both series one and two utilized passive solar heating via the south facing windows. During series two the solar radiant floor was operating in conjunction with the windows, which could lead one to the conclusion that the radiant floor, was a significant contributing heat source based on the TDR performance of series two. Another possible explanation for the poor TDR performance of series one can be attributed to

anomalies within the data collected during the first series.

Testing during series one lasted seven days, five of which were chosen for the analysis of TDR. During the first four days of series one extraordinarily high outdoor air temperatures were recorded relative to the outdoor air temperatures recorded during the preceding series. Chart 2 exhibits calculations of the average TDR with these additional two days at the end of series one when outdoor temperatures were cooler and more closely represented that of the last day in series one as well as the other three series. The seven day TDR analysis of series one indicates a higher TDR of 0.3, an average of just the last three days of series one provides a TDR of 0.75, 50% higher than the TDR of series two.

TDR: A Closer Look at Series 1

Series Name and Number	Main Room 1.5 Meters Above Slab	Main Room 1.5 Meters Above Slab w/ 2/14 & 2/15 (2 additional days)	Main Room 1.5 Meters Above Slab w/ 2/13-2/15 (last 3 days only)
Series 1: South facing windows exposed and solar radiant floor off	0.1	0.3	0.75
Series 2: South facing windows exposed and solar radiant floor on	0.49		
Series 3: South facing windows covered and solar radiant floor on	0.25		
Series 4: South facing windows covered and solar radiant floor off	-0.06		

Chart 2. TDR re-examined in series 1.

A similar anomaly is identified in series three where once again evidence supports the solar radiant floor performing well when compared to the fourth series when the radiant floor was off and the outdoor air temperatures were actually performing better than the indoor air temperatures. Day two of series three was overcast resulting in a lower maximum outdoor air temperature and higher minimum outdoor air temperature than the other days within the series. The resulting TDR for this day was considerably higher than the other days of the series driving the average up despite the fact that the radiant floor was not transferring heat to the slab, as there was minimal direct solar radiation during this day. By removing this day and only averaging the remaining four days within the series the TDR for series three lowers to 0.07.

TDR: A Closer Look At Series 3

Series	Main Room 1.5 Meters Above Slab	Main Room 1.5 Meters Above Slab without Day 2
Series 1: South facing windows exposed and solar radiant floor off	0.1	
Series 2: South facing windows exposed and solar radiant floor on	0.49	
Series 3: South facing windows covered and solar radiant floor on	0.25	0.07
Series 4: South facing windows covered and solar radiant floor off	-0.06	

Chart 3. TDR re-examined in series 3.

This leads to the conclusion that the solar radiant floor was not a significant source of heat for the space indicative of the insignificant TDR difference when compared to series four where the radiant floor was not activated.

The passive solar component performed better than the radiant floor demonstrating once again that simplicity in design and construction can be more desirable than complicated systems. Although further analysis of the radiant floor suggested that it was in fact working to increase the temperature of the slab surface, it was not providing a significant amount of heat for the comfort of the occupants.

#### 4. Cost Analysis

An estimate of the cost associated with constructing the Tijuana prototype was calculated. Cost is broken down by prototype system and represents an estimate of total cost. Costs associated with research for systems are not included here; this estimate represents material costs for the as built structure. Labor, administrative, and transportation costs are also not included. This project worked in conjunction with an organization that builds homes for a people within informal settlements of Tijuana for a nominal cost of \$6,000. This was the target budget for the development of this prototype, which the team managed to undershoot with a total material cost of \$3,700.

Tire Retaining	\$0
Gabion Wall System	\$850
Framing System	\$760
Pallet Wood Truss System	\$40
Green Roof System	\$185
Papercrete Wall System	\$385
Papercrete Mixer (Assembly, Maintenance,	\$475
Floor Slab	\$300
Solar Radiant Floor System	\$285
Windows and Door	\$325
Tools (students and LCRS had most tools already)	\$100
<b>TOTAL ESTIMATED COST</b>	<b>\$3,705</b>

Chart 4. Material cost estimate of prototype

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## 5. Conclusion

This project has demonstrated that alternative construction and design techniques can be implemented in low cost housing for informal settlements of Tijuana, Mexico. A fusion of proven sustainable design and innovative new technologies utilizing locally available waste materials can provide comfort, security, and an ecologically sensitive home for people within these communities. It is the expressed intent that the knowledge attained throughout this project be disseminated to the appropriate organizations and communities within Mexico and the world.

## 6. Acknowledgements

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