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DESIGN, LABORATORY TESTING, AND YIELD LINE ANALYSIS OF A FERROCEMENT PIT LATRINE SLAB

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DESIGN, LABORATORY TESTING, AND YIELD LINE ANALYSIS OF A
FERROCEMENT PIT LATRINE SLAB

By

Larry Alan Schirmer Jr

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Civil Engineering

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This report has been approved in partial fulfillment of the requirements for the Degree of
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Preface

As a Peace Corps Volunteer in Panama between 2013 and 2016, I completed a full term of service in the Water, Sanitation, and Health sector working in the indigenous community of Llano Junco in the Comarca Ngäbe-Buglé. During that time I worked closely with community leaders to form the first Sanitation Committee with the purpose of self-funding a latrine project. As part of that work, I experienced the factors that arise in development work that hinder otherwise motivated communities from realizing the improved sanitation access they seek.

When I arrived in my community, the culture of open defecation was already beginning to shift. Where as defecating in the open was common practice in the past, community members that had moved away from the practice expressed many reasons for building a latrine. It is dangerous to use streams after a storm or go into dense overgrowth at night because poisonous snakes are more likely to be around. Also, community members who interact more with people who live in nearby towns expressed shame when there was no latrine for those who were used to using a toilet. The public health benefits of having latrines were not a primary concern.

Self-funding the latrine project that I led proved more difficult than expected. For subsistence farmers, as most families provided for themselves in Llano Junco, money is not the basis of daily life. Most of the money that families had on a regular basis came from welfare programs which are intended for early child development and school expenses. Another factor that made saving money for this project challenging was money management

skills. The majority of my community had never opened a bank account (the closest bank was three hours away), and the day-to-day priorities made saving and trusting people to handle the money arduous.

Another challenge in realizing our project was the amount of physical labor involved in building a pit latrine. Five people would spend all day picking at the ground to dig a single twelve-foot deep pit all the while pulling the dirt out of the hole with a rope tied to a 5-gallon bucket. The slab required carrying a 94-pound bag of cement and ten 5-gallon buckets of river sand up more than 500 feet of elevation change in the heat of the day, work I was never well suited for. Additionally, there was also 45 feet of 3/8th-inch rebar and the tools for mixing the concrete that had to be acquired. All of this preparation work took months to complete because it had to be scheduled around the regular work they needed to do to maintain their fields.

During the last part of my Peace Corps service, and throughout my extended year of service as Peace Corps' Sanitation Coordinator for the country, I developed this Master's report in an effort to propose an alternative that involves less work for communities to build the latrines they want. The work began by building six overly reinforced slabs in communities where volunteers were placed using a material that volunteers and communities were comfortable with, ferrocement. The new design showed promise in its early stages and was further developed in the labs on Michigan Technological University's campus after my service ended. This report describes the development process and the results gained from the work.

Abstract

Access to sanitation for rural and indigenous Panamanians is the vision of global efforts to improve their quality of life. As part of on-site work from the Peace Corps to change public perceptions about open defecation, the author designed and tested a new type of ferrocement latrine slab to reduce the amount of materials involved in building latrines and by extension the manual labor involved. In the course of this investigation, a sanitation based case study establishes the precedent for working with ferrocement in these areas, and the author explores the history and structural properties of ferrocement. In laboratory experiments, six 3 to 4-inch slabs proved to be reliable under extraordinary stress while reducing the amount of materials by 75% compared to a conventional reinforced concrete slab. Overall, this study validates the new design that makes a dramatic improvement in material efficiency. The test results are limited to the specimens constructed and evaluated during this experiment, but results show potential for what can be done in the field.

1. Introduction

Addressing a community's public health needs regarding sanitation is fundamentally a people-centric concern where technical solutions play only a small role. It is necessary to take a step back and look at the larger social structure that a new design fits into, i.e., to validate working with ferrocement in rural Panama. Social models can be explored to contextualize the social structure of a given community and how that structure impacts behavior.

People as individuals differ on many levels. Each has current and future needs, attitudes, experiences, and world views that make one varied and unique. It should also not be surprising that each of these characteristics is in a constant state of change throughout life. These qualities create differences on so many dimensions that it becomes surprising to find any two in common, but it is the commonalities that cause people to self-organize, which leads people to find an identity or a sense of solidarity in the virtues they have in common. To maintain membership in social communities, people adopt roles that reflect the status they have in their respective community. As individuals, people are infinitely different and unstructured, but community forms a clear and robust self-maintaining structure (Sobel 1981).

The social structure formed by people has profound impacts on the behavior of individuals. Each group develops implicit or explicit rules that help guide expected behavior. Examples of this are individuals waving on a walking trail while passing by but not on a city sidewalk; consider also the process of self-organizing in lines. These norms create a culture

where individuals can feel rewarded for their actions, or in the opposite case shamed for behaviors that go against the communities rules (Heberlein 2012).

Although in-depth analysis of social models is beyond the scope of this report, London's history in the 1850's creates an interesting case study for exploring these models. The public health revolution that occurred during this time illustrates the interplay between a community's cultural and social structure and how technological solutions are adopted to solve the problems at hand. More than a century later, rural communities in Panama may be undergoing a health revolution, potentially with new technological solutions.

1.1. London Case Study

Between 1830-55, known as the Golden Age of Mapping, the practice and art of mapping grew into a large piece of culture for Londoners. After London's accelerated growth in the late 1700's, Londoners became increasingly fascinated by their city. There was a lot of confusion about where social classes in the city situated themselves, and the detailed descriptions and themed maps provided a simple line to differentiate. These low-fidelity maps fed into pre-existing stereotypes by associating the filth with the lower class. Poor sanitary conditions over time became linked to economic depression and crime, contributing to the belief that to have a healthy city, all corruption ought to be removed (Cohen 2005).

With all of this focus on public health, the city made a point to work on a plan to improve the local sewage conditions. In 1855, all of the local sanitary authorities around the city combined into the Metropolitan Board of Works (MBW). At the time, all of the city's sewage flowed through a frail system of awkward channels towards the River Thames, but

there were constant concerns over the safety of the method because of the smell. In the mid-nineteenth century, the prevailing belief was that illness transmission occurred by something that could be seen or smelled (Miasmatic Theory) was still a firmly held belief. Plans were in the works to efficiently and safely handle the city's waste, but the MBW was short on money and caught in bureaucratic gridlock (Cohen 2005).

In 1858, there was a drought, an otherwise ordinary environmental occurrence, but that year the river reached its effluent carrying capacity. With low flow in the river, the North Sea's tide was taking the city's human waste out to sea and then flushing it all back into the city. History recorded that the smell associated with the drought was strong, distracting, and caused people to feel genuinely ill. Feeling sick because of a stench was right in line with Miasmatic Theory, and the smell gripped everyone's attention. For weeks everyone in the city did everything they could to suffer through what became known as the 'Great Stink.' Desperate for relief, the House of Commons realized that the sewage plan that the MBW had engineered was their best option (Cohen 2005).

With the approval from city officials, London Engineer Joseph Bazalgette set his plan into motion. Expanding the city's sewage system at this scale meant laying the foundation for modern sanitation systems and ending any 'Great Stinks' from happening again in the future. The system was described as being of 'unparalleled magnitude,' and included treatment, underground sewage lines, pumping stations, and holding tanks. Under this new system, sewage could be disposed of in the River Thames in a managed way (at high tide) (Reid 1999).

In the mid-19th century, the social structure of London stereotyped the upper and lower class as either productive or filthy. For Londoners, there was a community-imposed norm that viewed poor sanitary conditions as shameful. Despite having the motivation and vision to design a system to handle their public health needs effectively, there was not enough incentive to follow through. When the 'Great Stink' set in, though, filth infiltrated into the lives of the upper class, and they could not ignore the assault on their articulated norm that it needed to be removed.

This case study demonstrates that the problem in London and the solution they chose was only a small part of a larger mechanism. Individuals had a plan for the future but were not able to bring it to life until civic duty and community shame empowered them to maintain the constructed divisions between social classes in the community. It is argued that these insights have an impact on the way development work in Panama is addressed. The inequalities between the urban and rural social classes of Panama create a similar power dynamic as in 19th century London.

1.2. A Modern Application

Panama (Fig. 1) has a population of 3.71 million, where 12.3% are indigenous and live in the mountains or the jungle (CIA 2017). The Peace Corps focuses its efforts on reaching these remote communities. In these isolated regions, the majority of the people are subsistence farmers who seldom need to leave the area, although some do to find work or continue schooling elsewhere.

FIGURE 1 - A MAP OF PANAMA SHOWING THE LOCATION OF THE AUTHOR'S COMMUNITY

For subsistence farmers, the food they eat comes from the fields they manage, and the materials that form their housing are mainly derived from materials grown locally. People change and adapt their homes and diets around the seasons. Members of the family often come and go throughout the year to take work during seasonal harvests. Money is perceived to be tight for most because daily work involves providing for one's family through family-owned fields. Selling produce is challenging because of the difficulty of reaching these areas with commercial markets by truck, especially in the rainy season. Getting around, and transporting materials and crops from the field, is mostly done on foot or occasionally by horse, and often requires travel times on the order of several hours (Fig. 2). The difficulty of getting large or heavy materials or tools into a worksite is another constraint.

FIGURE 2 - STEEP HILLS AND FOOT TRAILS IN THE COMARCA NGÄBE-BUGLÉ

As a Water and Sanitation Volunteer, the Millennium Development Goals (MDGs) shaped the initiatives and projects for the author. The primary work was influenced by target C of goal seven, "By 2015, halve the proportion of people without sustainable access to safe drinking water and basic sanitation" (WHO 2013). In the framework of the MDG's, the writers explicitly stated, "We consider certain fundamental values to be essential to international relations in the twenty-first century. These include Freedom, Equality, Solidarity, Tolerance, Respect for Nature, and Shared Responsibility" (Kates 2017 p. 16). These socially charged values set the tone for the type of sustainability the MDG's were meant to address and for the global social structure intended to improve the lives of those at all corners of the world.

These inspiring values impact rural Panamanians when interested communities reach out to Peace Corps for help. The areas in which volunteers are placed have already identified

the community's needs and requested a volunteer to assist them in their efforts. For areas where pit latrines are appropriate, such as in mountain regions, the conventional solution in the field is to construct a semi-permanent reinforced concrete slab over the pit. This slab requires carrying ten 5-gallon buckets of river sand from a local river source by hand or horseback, and it weighs as much as one thousand pounds when finished. This constraint imposes a constructibility barrier to building a household latrine.

The pit-latrine slab that the author designed during his service uses only three 5-gallon buckets of sand while providing sufficient service strength for its intended purpose. The slab weighs 75% less than its reinforced concrete counterparts. This makes the slabs portable and removable, lending to local conventions of adapting to future needs. By using ferrocement, the design also borrows from the visual and material language consistent with the water tanks previously constructed by volunteers in the region. A premise of this work is that cheaper and lighter latrine slabs will form the basis for a more appropriate sanitation solution for people who live in remote, hard-to-reach areas and have little expendable income.

According to a study performed by another Returned Peace Corps Volunteer in 2013, only one in three people in the area in which the author served have access to improved sanitation. While open defecation was down from 12% to 5% between 1990 and 2005, rural and indigenous communities still have opportunities to make improvements in this area (Midkiff 2013). One of the methods employed by volunteers to address this problem is to change the perception of these behaviors and the norms around open defecation. The theory

behind this intervention holds that peer pressure and obligation to maintain status in the community compel individuals to follow the established norms (Lickel 2014). In this case, individuals are compelled to seek latrines as an alternative to open defecation. The premise of this study is that, when solutions to these social problems are within reach and in line with the community's vision for the future, ferrocement can provide a viable technological solution within the complex cultural structure in rural Panama.

2. Ferrocement Design

This report explores a new pit latrine slab design using ferrocement. The design uses a quarter the amount of aggregate and is twenty-five percent cheaper than the reinforced concrete slab that it replaces. For the last decade, ferrocement has been gaining popularity among Peace Corps Volunteers in Panama as a low-cost alternative for household water tank construction. The benefits of using ferrocement over reinforced concrete are that each slab makes more efficient use of materials, and moving fewer materials to a job site keeps the result lighter and reduces the extensive manual labor ordinarily involved in concrete construction. Through a comprehensive exploration, the development of a new ferrocement pit latrine slab is broken into three distinct stages: defining the problem it addresses, specifying the solution through background research, and verifying the design in the lab using field construction techniques.

The problem this design addresses is part of a larger mechanism that involves defining the cultural framework of the respective society, understanding a community's own plan for the future, outlining the issue, and picking the solution that is most in line with the community's vision of the future. The solution to the problem is explored by first understanding the material's history and structural properties and by defining the design constraints. This process allows the finished product to be appropriate and leverage the current practices in the field. A proof load test on six complete slabs was then performed to validate the design. The purpose was to demonstrate that the design calculations produce reasonable results and to provide a means of verifying construction quality.

2.1. Background and History of Ferrocement

The design of the ferrocement slab is influenced by three different factors: design standards, serviceability, and material availability. Ferrocement is part of the reinforced concrete family, and the limitations established in the design equations apply to both. The design models prove useful in describing what is acceptable regarding loading and serviceability, or deflection. Serviceability, including user perception, is also important in establishing these slabs as a trusted alternative to the reinforced concrete slabs. Factors such as stiffness, cracking and appearance are relevant to making the slab socially acceptable. Materials play arguably the largest role in shaping the ferrocement slab design. The water tanks made of the same material use hexagonal wire mesh, so this particular type of mesh is an obvious choice over the many other types available. This wire mesh, sold in three-foot, four-foot, or five-foot widths is available from local stores. Sand is also available at local hardware stores, but purchase price and transportation costs often prohibit this option. Communities often source their sand from a local river to save on these expenses.

American Concrete Institute Committee report 549 defines ferrocement similarly to how the original patent described it in 1855 (Naaman 2000). In 1852, a Frenchman named Joseph-Louis Lambot submitted a patent for “Fer-Ciment,” which he based on the technique perfected while building two row boats in 1848 and 1849:

My invention shows a new product which helps to replace timber where it is endangered by wetness, as in wood flooring, water containers, plant pots etc... . The new substance consists of a metal net of wires or stacks which are connected or formed like a flexible woven mat. I give this net a form which looks in the best possible way, similar to the articles I want to

create. Then I put in hydraulic cement or similar bitumen tar or mix, to fill up the joints (Naaman 2000 p.1).

The earliest known uses of cement span back to 3000 B.C., during the times of the Romans. Lime, gypsum, and natural cement-based mortars joined stone blocks together or plastered to coat the structures. These early materials could only be used productively in compression, and for thousands of years designers accepted this constraint. It would not be until the time of Lambot when feasible reinforced designs began to take shape. Working independently, three men documented using cement in a new way. Lambot invented ferrocement, the French gardener Joseph Monier invented the idea of embedding thin iron bars into large planting pots, and the Englishmen Wilkinson pioneered the idea of building long concrete beams by incorporating old mining ropes in the underside of the beam's tension layer (Balaguru 2009).

In the decades that followed this discovery, engineers started describing the structural properties of reinforced concrete based on Thaddeus Hyatt's work in the United States (Balaguru 2009). At the time, steel mills were only equipped to produce larger diameter iron bar. The technology of the time made manufacturing the small diameter bars necessary for ferrocement too expensive. This constraint hindered the business model, scale, and research justification of ferrocement. With the growth of ferrocement stunted, reinforced concrete became the material of choice for the world's construction needs (Naaman 2000).

Until the early 1940's ferrocement went largely forgotten. During the two World Wars, a shortage of steel plates forced Italian boat engineers to develop new construction

techniques for the war effort. These engineers chose to work with a familiar type of reinforced mortar. Their success went on to inspire the greatest master of ferrocement to take on the material (Balaguru 2009).

A few years into the Second World War, the famous Italian engineer/architect Pier Luigi Nervi began experimenting with ferrocement, leading to the successful 165-ton motor sailer *Irene*. The vessel featured a 1.4-inch thick hull, weighed less than a wood counterpart of similar size, and took full advantage of the elastic, flexible, and crack resistant qualities of the material. Nervi is credited with coining the term ‘ferrocement’ and is the material’s earliest scientific contributor (Balaguru 2009).

Thanks to the incredible work done by Nervi, ferrocement was resurrected as an attractive boat building material. Between the early 1940’s and 70’s, the material gained acceptance first among the Italian Navy and then later across the world, including the United Kingdom, New Zealand, Canada, and Australia (Naaman 2000 p4). Ferrocement does not require expensive equipment or extensive training, making its barrier to entry reasonable and low-cost. It also has a high strength-to-weight ratio; however, the material's applications were limited to mainly boats, simplistic housing, food storage silos, and irrigation troughs. Ferrocement lacks integration into accepted building codes, which prohibits its use in modern construction. At this point, engineers had not fully described the structural properties of ferrocement. Towards the end of this period of ferrocement renaissance, however, interest in the regions of Australia, the UK, and New Zealand sparked interest in the US National Academy of Sciences (NAS) in 1972 (Balaguru 2009).

A report put together by a NAS Panel caused the American Concrete Institute engineers to start to pay serious attention to ferrocement for the first time. In 1974, ACI formed Committee 549 with the "mission to study and report on the engineering properties, construction practices and practical applications of ferrocement and similar materials and to develop standards and safeguards for ferrocement construction" (Sabnis 1978). The work that this committee collected, and the subsequent research and symposiums, form most of the body of technical literature on the material. Although the engineering definition has not been amended in several decades and boat makers have come to use other materials, people in developing regions continue to use ferrocement to meet their daily needs (Balaguru 2009).

By 2009, ferrocement was being used in Panama by volunteers in the Peace Corps. In one application, volunteers used ferrocement to make composting latrines more culturally relevant for those who preferred to water wash. The thin cementitious material was made to store water and form toilet seat inserts to convert regular seats into bidets. In 2012, the sanitation sector incorporated ferrocement water tank construction into the training manual for all incoming volunteers. In 2013, when the author was introduced to the technology, volunteers were designing a technique to apply ferrocement to a flat slab that could be used to cover a one-meter square latrine pit. Their efforts were unfortunately unsuccessful, which formed the basis for this research and report (Gram 2016).

2.2. Design Considerations

As a thin cementitious material, ferrocement is advantageous for these creative solutions because of its high strength-to-weight ratio. Nervi spent a significant amount of time working with the material and found that the specific surface of reinforcement is the single quality that distinguishes it as a distinct material from conventional reinforced concrete. This property defines the amount of surface area that the steel shares with the surrounding mortar. Because the section is thin and the reinforcement distributed throughout, the specific surface is up to ten times that of reinforced concrete (Sabnis 1978). Samples with larger specific surface values are more ductile, resistant to shrinkage, and have a higher strength-to-weight ratio (Baston 2009).

The design process for ferrocement has been specified in a way to allow for the use of the design equations familiar to those who have worked with the reinforced concrete code ACI 318. General design terms like the Nominal Moment Strength (M_n), yield strength of steel (f_y), and the depth of the compression layer (a), are common to ferrocement and reinforced concrete design. The primary difference in design is calculating the area of steel (A_s). For ferrocement, the embedded wire mesh deforms under high tensile loads and its resistance is reduced based on wire type and direction. The terms that encompass this behavior are the efficiency factor and volume fraction (Baston 2009).

Ferrocement is part of a rather large family of composite materials, which include reinforced concrete, prestressed concrete, and fiber reinforced concrete. They all share the same ingredients (cement, aggregate, and reinforcement), just in different configurations,

proportions, and mix processes. Ferrocement is a unique type of thin-walled reinforced concrete made of Portland cement mortar and one or more layers of wire mesh. Sections of ferrocement can be arranged to follow any planar or convex/concave shape. Even though ferrocement has more in common with laminates in terms of its appearance and application, it is still considered a type of reinforced concrete. The material is composed of skeletal steel surrounded by a cemented aggregate mixture, where the reinforcement is arranged in layers to help shape the structure rather than just placed to accommodate tensile stresses (Balaguru 2009).

Ferrocement can be made relatively thin, as thin as 0.75," because it lacks coarse aggregate such as rock. The material consists of a combination of sand, cement, and wire mesh. Smaller, more angular sand will improve performance, but the technical definition specifies sand passing a #8 sieve. The water-to-cement ratio can range between 0.35-0.55, by weight, and the cement-to-sand ratio can vary between 1-2.5. The wire in ferrocement is special because of its continuousness. There are three types of continuous wire meshes available: square, expanded metal, and hexagonal. Of these types, there can be different varieties such as woven and galvanized. The shape also plays an influential role in the reinforcing strength the mesh can contribute in each direction (Naaman 2000).

According to Beam Theory, for concrete beam sections, the extreme outer edges carry the majority of the bending stress (Wight 2012). The tension is carried mostly by the embedded reinforcing steel, and the compression is carried often only in the top half inch of concrete. The area in and around the neutral axis does not contribute significantly to the

strength of the section but does add to its self-weight. By removing the concrete in the center (Fig. 3), the slab continues to be strong enough for service loads while reducing weight and material.

FIGURE 3 - HOLLOW SLAB (LEFT) VS FILLED SLAB DESIGN (RIGHT)

Addressing the barriers of owning a latrine involves designing a slab that uses materials that are easier to transport to the job site, is constructible, and offers the option to reuse the slab in the future. Currently, reinforced concrete slabs (Fig. 4) are a reliable solution, but the solid concrete construction requires moving a large volume of aggregate to the work area. Additionally, the added weight from this concrete makes moving the slab in the future impractical, if not impossible. Each one of the slabs, according to the design currently in use, calls for ten 5-gallon buckets of well-graded sand/gravel and a full bag (94lbs) of cement (Fig. 5). Each one of these slabs weighs more than one thousand pounds.

FIGURE 4 - CONVENTIONAL REINFORCED CONCRETE SLAB WORK SITE

FIGURE 5 - CONVENTIONAL REINFORCED CONCRETE SLAB DESIGN

By adapting the design of 55-gallon ferrocement water tanks as a replacement for the reinforced concrete latrine slab, a system of connected plates concentrates structural material in the outer edges, thereby removing the need for material where it is less effective. This change reduces the overall weight of the slab and reduces the pre-construction barrier by decreasing the amount of materials needed at the job site. The design has a width and length similar to the reinforced concrete slab (48in x48in), along with a comparable thickness (3in) (Fig. 6).

FIGURE 6 - FERROCEMENT SLAB DESIGN

2.3. Designing with Ferrocement

For a simple reinforced concrete beam calculation, the nominal moment capacity can be found by the following equation:

$$\phi M_n = \phi A_s f_y \left(d - \frac{a}{2} \right) \quad (\text{Eq. 2.3.1})$$

where,

M_n = nominal moment capacity ($lb - in / ft$)

ϕ = reduction factor for tension controlled sections

A_s = area of steel (in^2)

f_y = yield strength of steel (lb/in^2)

d = distance from the top of the section to the center of steel (in)

a = depth of the compression block (in)

If the reinforcement in this example were to be replaced by wire mesh, the only term necessary to reevaluate is the area of steel (A_s). This term is expanded to take into consideration the direction of the reinforcement, the volume that the steel takes up relative to the total composite, and the total cross-sectional area of the composite. The following equation is given for effective area of reinforcement, which is analogous to the area of steel (A_s),

$$A_{ri} = \eta_o V_{ri} A_c \quad (\text{Eq. 2.3.2})$$

where,

A_{ri} = effective cross-sectional area of reinforcement of each layer (i) (in^2)

η_o = efficiency factor of mesh reinforcement in the loading direction considered

V_{ri} = volume fraction of mesh reinforcement in each layer (i)

A_c = gross cross-sectional area of reinforcement in the direction considered (in^2)

The efficiency factor represents a given mesh layer's ability to resist tensile loads. There is a broad range of reduction factors, as demonstrated in Table 1, which describe the efficiency of each layer. For example, hexagonal mesh in the longitudinal direction is 50% stronger than in the transverse direction. The factor makes the material's anisotropic qualities easy to understand and calculate. Sabnis (1978, p. 10) describes this relationship as, "The global efficiency factor η (eta), when multiplied by the volume fraction of reinforcement, gives the equivalent volume fraction (or equivalent reinforcement ratio) in the loading direction considered. In effect, it leads to an equivalent (effective) area of reinforcement per layer of mesh in that direction."

TABLE 1 - GLOBAL EFFICIENCY FACTORS

Mesh Type	Woven Square	Welded Square	Hexagonal	Expanded Metal	Longitudinal Bars
Longitudinal η	0.50	0.50	0.45	0.65	1
Transverse η	0.50	0.50	0.30	0.20	0
At 45°, diagonal	0.35	0.35	0.30	0.30	0.75

The volume fraction is given by:

$$V_r = \frac{V_{reinforcement}}{V_{composite}} = \frac{N W_r}{h \gamma} \quad (\text{Eq. 2.3.3})$$

where,

N = number of Layers

W_r = Unit Weight of Reinforcing Mesh (weight per unit area lb/yd^2)

γ = density of reinforcement material (lb/ft^3)

h = thickness of ferrocement element (ft)

The volume fraction is the critical value for describing the amount of wire mesh in a section of ferrocement. In the effective area of reinforcement calculation, the volume fraction that each layer contributes to the overall strength of the composite is needed (Naaman 2000).

The yield-line analysis method was chosen to model the two-way behavior of the ferrocement latrine slab. The technique is well established and flexible enough to accommodate special design scenarios. This analysis equates the work done by applied loads as they travel through a displacement to the internal energy created by the resisting moments along the yield lines as they travel through a rotation. The nominal moment capacity alone is appropriate for beam sections and one-way slabs because the one yield-line that controls yielding conditions can be directly described in terms of the nominal moment capacity. For square slabs, there are multiple diagonal yield lines that resist the applied loads, making the moment capacity a component of the full analysis (Fig. 7) (Wight 2012).

FIGURE 7 - YIELD LINES FOR SQUARE SLABS

For a square slab with no hole, the total internal work from the four yield lines is given by:

$$IW = 4 \cdot m_b \cdot 2 \cdot \delta \quad (\text{Eq. 2.3.4})$$

where,

IW = internal work done by the yield moments along yield line ($lb \cdot ft$)

m_b = moment capacity diagonally along the yield line per unit length ($lb - ft/ft$)

δ = total deflection at the center of the slab caused by the applied load (Fig. 8) (ft)

FIGURE 8 - DEFLECTION FOR SQUARE SLABS

For a square slab with no hole and a uniformly distributed loading over the entire surface, the total external work is the sum of the work contributed by each of the four triangular slab segments formed by the yield lines. The external work for each segment is equal to the total loading on each segment times the vertical deflection of the centroid of that loading. The area of each segment is:

$$(L)\left(\frac{L}{2}\right)\left(\frac{1}{2}\right) \text{ or } \left(\frac{L^2}{4}\right)$$

where,

L = width of slab (ft)

The vertical deflection of the centroid of this area is:

$$\left(\frac{\delta}{3}\right)$$

So the external work contributed by each segment is:

$$q_f \left(\frac{L^2}{4} \right) \left(\frac{\delta}{3} \right)$$

where,

q_f = uniformly distributed load placed over the entire slab surface (lb/ft^2)

L = width of slab (ft)

δ = total deflection at the center of the slab caused by the applied load (ft)

The external work for all four segments is:

$$EW = 4 \left[q_f \left(\frac{L^2}{4} \right) \left(\frac{\delta}{3} \right) \right] = q_f (L^2) \left(\frac{\delta}{3} \right) \quad (\text{Eq. 2.3.5})$$

where,

EW = external work done by the applied loading ($lb \cdot ft$)

For slabs with a hole in the center, the equation for internal work (Eq. 2.3.4) is adapted to account for the reduction in this area. This equation contains a term that describes the length of each bending yield line. In this case, the line is interrupted by the hole, and its reduced contribution to internal work is reflected in the equation.

$$IW = 4 \cdot (m_x + m_y) \left(1 - \frac{r}{L_d} \right) \cdot \delta \quad (\text{Eq. 2.3.6})$$

where,

m_x = moment capacity in the x-direction per foot ($lb - ft/ft$)

m_y = moment capacity in the y-direction per foot ($lb - ft/ft$)

r = radius of the center hole (in)

L_d = the diagonal length of the slab from a corner to the slab center (in)

For this equation, m_x and m_y replace the bending moment term m_b by:

$$m_b = \frac{1}{2}m_x + \frac{1}{2}m_y$$

The external work expression is modified to reflect a concentrated load applied around the rim of the center hole. If P is the total concentrated load, then it is assumed that a fourth of this load is applied at the rim of each of the four triangular slab segments. The external work for each of the four triangular segments is equal to:

$$\left(\frac{P}{4} \right)$$

times the vertical deflection of the center of pressure of the rim area, δ_{cp} . Using Figure 8 and similar triangles:

$$\frac{L/2}{\delta} = \frac{L/2 - r_{cp}}{\delta_{cp}} \quad \text{or} \quad \delta_{cp} = \left(\frac{L/2 - r_{cp}}{L/2} \right) \delta = \left[1 - \frac{r_{cp}}{L/2} \right] \delta$$

So the total external work from the four slab segments is:

$$EW = \left[\left(\frac{P}{4} \right) \left(1 - \frac{r_{cp}}{L/2} \right) \delta \right] 4 = P \left(1 - \frac{r_{cp}}{L/2} \right) \delta \quad (\text{Eq. 2.3.7})$$

where,

P = the concentrated applied rim load (lb)

r_{cp} = radius of the center of pressure (in) (Fig. 9)

FIGURE 9 - ILLUSTRATED TERMS FOR EXTERNAL WORK

3. Testing

3.1. Laboratory Testing

Testing for this project served two central objectives. The first is to validate the calculations proposed in the previous section in a way that respects the low-tech methods with which these slabs would be constructed in the field. The second is to provide a means of verifying the construction quality of each slab. Having a way to validate the design calculations will establish confidence in the process and allow designers to build on this research in the future. By utilizing a non-destructive test in the lab, the method can serve as a way to validate the construction quality of slabs of this type.

A Proof Load Test is a performance check. The experiment runs under the premise that loads applied to the structure that exceed the service needs provide evidence of a minimum acceptable reliability (Ellingwood 1996). Under perfect conditions, one would expect the slabs to perform comparably to the load specified in the design equations. It is the purpose of this test to evaluate whether a slab is capable of sustaining loads that are between the ideal ultimate strength and the minimum acceptable strength.

To demonstrate minimum acceptable reliability, the author chose a service load of 550 pounds, representing a person or persons totaling 320 pounds with a live-load safety factor of 1.7. Slabs may be stressed to a variety of levels during service, but the amount of weight was chosen as a worst case scenario for people, persons, or objects (in the case where the latrine might be used for storage) centrally located on the slab at any given time.

To demonstrate serviceability under load, the flexure and cracking of the slabs will be evaluated. The reinforced concrete design code ACI 318 defines acceptable amounts of service deflection under live load and cracking. The slab, in this context, does not interact with other components of the structure which necessitates strict flexural restrictions. As such, the slab falls under the limit of “ $L/180$,” which allows for a vertical deflection in the center of the slab to be its full horizontal length divided by 180. With this limit, people who use the slab should have no reservations or discomfort concerning its flexure.

Based on load specified by the theoretical calculations as the slab’s ultimate capacity, the slabs are not expected to fail in laboratory tests under these conditions. The method used to model each slab proposes that a slab will strain along its yield lines, so there is some expectation that the slab, during the test, will show signs of this cracking behavior during the test. Additionally, the slabs are expected to demonstrate evidence of stress beyond the limits defined in the ACI code at the height of the stress test.

3.2. Construction of Specimens

Two types of ferrocement slabs were constructed for this experiment—slabs with and without internal walls. Before this experiment, the ferrocement slabs were constructed in the field using interior walls to help transfer load from the top plate to the bottom. Over the course of doing a thorough structural analysis, it was found that the thickness of the slab could be reduced and that the interior walls may not be necessary. Tables 2 and 3 outline a bill-of-materials, and Figures 10 - 19 provide a brief outline of how each type of slab was constructed.

TABLE 2 - CONSTRUCTION MATERIALS

Type of Material	Description	Type One Amt	Type Two Amt	Cost
5-gallon Bucket	The standard multi-purpose bucket used for storing sand and forming the center hole	1	1	\$3.00
6 mil Plastic Sheeting	A water-proof layer of plastic for forming a mold liner (at least 70" by 70")	1	1	\$19.00 for 10'x25'
2" by 8" Board	Rough cut construction board used to form the mold (96")	1	1	\$6.30

TABLE 3 - SLAB MATERIALS

Type of Material	Description	Type One Amt	Type Two Amt	Cost
Chicken Wire	4 foot tall roll for wall and floor reinforcement	69"	63"	\$37.00 for 50'
Portland Cement	94lb bag	3 / 4 bag	3 / 4 bag	\$11.00 / Bag
Mortar Sand	Sand that is #8 sieve passing and clean	15 gallon	15 gallon	\$2.75 at \$0.82/ft ³
Rebar Wire	Used as additional reinforcement and to fix chicken wire together	875"	1262"	\$5.00 for 400' roll

3.2.1. Slab with Internal Walls

The mold was prepared by cutting the outside boards to 46" and connecting together end-to-end. A sheet of plastic was then cut to 70" square and laid inside the mold. The first piece of chicken wire to be placed in the mold was for the base. A hole was cut into the center of the 48" by 48" piece of wire using the bottom of a 5-gal bucket as a template. An inch on each side of the wire sheet was folded up to allow the piece to lie flat. Pieces of wire 48" by 3"

were then added to the outside walls and made to overlap with the folds in the base and the other sides. At the center of the base, a 5-gal bucket was set with a loop of 3" tall wire wrapped around it. The wire for the interior walls extended from the center of the outer wall to the wire around the bucket. At the base and top of the bucket wire, a loop of rebar wire was added and looped around itself. Additionally, rebar wire was passed behind these loops and run along the bottom of the interior walls (Fig. 10).

FIGURE 10 - MOLD PREPARED WITH CHICKEN WIRE WALLS AND FLOOR LAID OUT

To the side, small batches of a sand-cement mix were made and mix was applied to the bottom and side-wall wire mesh (Fig. 11). The mix was measured to a 1:2.5 cement-to-sand ratio with a 0.6 water-to-cement ratio. The very top of the wall, approximately half an inch, was left exposed for a later step. After all of the area has mix applied with a trowel, the entire mold was covered with leftover plastic and let to cure overnight. The following day, the mold was filled with sawdust and tamped by foot to ensure maximum compression (Fig. 12).

FIGURE 11 - APPLY FERROCEMENT TO THE BASE AND OUTER WALLS

FIGURE 12 - THE CENTER IS FILLED WITH SAWDUST

To prepare for the top layer or mortar, plastic was then laid over sawdust and tucked into the sides. A half-inch of sawdust was pulled away by hand on either side of the internal wire to make room for the walls. Seven pieces of 16.5 gauge rebar wire were then laid in each direction along the top. Each piece was hooked into the exposed chicken wire in the outside wall and tightened. The wires on either side of the bucket passed through the top of the

interior wall chicken wire. Three wires pass on either side of the bucket, and wire in the center was cut short to loop into the top loop around the bucket and attach to the outside wall (Fig. 13). The remaining mortar was batched to cover the top and fill interior walls. The slab was then covered and left overnight (Fig. 14).

FIGURE 13 - THE TOP PLASTIC IS ADDED

FIGURE 14 - THE TOP PLATE IS PLACED

3.2.2. Slab without Internal Walls

For these slabs, special care was taken in laying the plastic liner in the 46" by 46" mold. Prior to this slab, plastic was placed under the assumption that the mortar would fill into the corners and flatten the bottom. The plastic was smoothed on the bottom and side, and the corners properly folded to ensure these areas did not develop thin spots. The top of the plastic was taped to the mold, holding it in place (Fig. 15).

FIGURE 15 - MOLD IS PREPARED WITH PLASTIC LINING

All of the reinforcing wire was assembled to the side before any mix was batched. Three pieces of rebar wire were braided together and weaved into the bottom chicken wire on either side of the center hole. Hooks were formed on the ends to secure the outside walls. This wire served to aid the base wire in laying completely flat and added to the overall strength of the wire mesh. The outside walls were cut to 3" and added to the 48" square base wire. Each end of the base wire that was folded up helped connect the outside walls to the base (Fig. 16).

FIGURE 16 - THE REINFORCING WIRE IS PREPARED

A thin layer of mortar was then applied to the bottom and sides of the mold. The entire piece of reinforcing wire was added to the mold all at once, and the wire was gently pressed into the mortar. Next, mortar was placed around the center bucket, and a three-inch tall piece of chicken wire was wrapped around the bucket. The slab was then covered and left overnight (Fig. 17).

The mold was filled with sawdust and carefully tamped by foot to ensure maximum compression (Fig. 18). Plastic was laid on top of the sawdust in two overlapping pieces. Seven pieces of rebar wire were laid in each direction along the top, with each piece hooked into the exposed wire in the outside wall and tightened. The wires on either side of the bucket passed through the interior walls. The remaining mortar was batched to cover the top, and the slab was again covered overnight to cure (Fig. 19). The slabs were stored in the lab in ambient air for more than 28 days before testing.

FIGURE 17 - THE BASE AND SIDEWALLS ARE CAST

FIGURE 18 - THE CENTER IS FILLED WITH SAWDUST

FIGURE 19 - THE TOP IS CAST

3.3. Testing

For testing, a stand was constructed to recreate the way the slab would be supported in the field. Before each testing session, the slab was loaded into the testing stand, and the front of the stand was screwed into place. Setup also included moving a ladder into place (for ease of loading), sliding a debris catch under the slab, and weighing and centering a loading drum and drum seat (Fig. 20). Once everything was situated, an audio recording was started and a camera was trained on a measuring stick attached to the drum (Fig. 21).

Concrete cylinders provided the majority of the load for each test. Six to seven cylinders were placed in a bucket and weighed collectively. Buckets were passed up the ladder and gently unloaded into the drum. Cylinders were arranged in tightly packed levels with rows stacking one upon the next until the cylinders reached the top. Water was then weighed in the buckets and gently poured into the bucket to fill in the empty space. A four-point load stabilizer was in place to prevent lateral displacement of the drum (Fig. 22). None of the six slabs tested needed this safety measure.

Each of the slabs was left loaded overnight (i.e. approximately 20 hours). After each test, the initial and final deflection was recorded, as well as the total amount of load added to the slab. The initial deflection was recorded before any weight was added and the final deflection recording happened while all of the load was in place. After this point, the drum was unloaded similarly to how it was loaded, a cylinder at a time loaded into buckets to be passed down the ladder. The slab was then lifted out of the stand with a jack and set aside on a pallet. The slabs were all weighed, and their stress cracks marked and illustrated.

The test setup was designed to allow as much visibility as possible above and below the slab. From the bottom, the legs of the stand extended down from each corner by six inches to leave enough room to inspect the condition of the bottom during testing. Additionally, the legs extend up to keep the slab centered and secure. The slab was simply supported in the stand so as to model a field environment. The seat was placed between the drum and top of the slab to concentrate all of the weight on the center rim. The seat's height was designed to make visual inspection around the top possible as well (Fig. 20).

FIGURE 20 - THE FULL SET SETUP ILLUSTRATED

As a separate mechanism, a load stabilizer was set around the stand. For each test, the stabilizer was kept close to the drum. The stabilizer was positioned to the left and right of the stand and did not touch the stand nor the drum. The separation allowed the drum to freely pass all of the load directly onto the slab without interruption. A ladder was used to aid in placing pre-weighed debris in the drum (Fig. 21).

FIGURE 21 - THE FOUR-POINT LOAD STABILIZER AND LOADING LADDER

There were two metrics measured in this experiment—the deflection at the center of the slab, and the total weight added on the slab. The deflection was measured by means of a camera trained on the shadow cast on the yard stick. The shadow was cast from a florescent light fixture attached above. This marking eliminated any issues with camera parallax. The weight was measured on an industrial scale prior to being placed in the drum. The drum and drum seat were also included in these measures (Fig. 22).

FIGURE 22 - DEFLECTION MEASUREMENT

3.4. Results

Care was taken throughout every step of the construction process, but consistency proved challenging using hand tools and field techniques. As illustrated in Table 4, there was significant variability in nearly every respect, including depth of the section overall, thickness of each plate, and the load amount. In each case, the amount of load and the final deflection was monitored.

The data collected on each slab include the self weight, average thickness, applied load, deflection, and resulting crack pattern. Each slab's thickness was measured at the corners, sides, and center. This data was then averaged to find the overall thickness of the slab. The smallest amount of deflection that could be measured for this study was 1/16 inch, recorded in eighths of an inch. Table 4 summarizes data collected on each slab. The crack patterns by slab type are illustrated in Figures 23 and 24.

TABLE 4 - DATA COLLECTED DURING TESTING

	Self Weight (lb)	Thickness (inches)	Live Load (lb)	Deflection (inches)
Slab 1 - Type I	258	3.4 +/- 0.4	646	1 / 8
Slab 2 - Type I	240	3.4 +/- 0.4	584	***
Slab 3 - Type I	261	3.7 +/- 0.4	640	3 / 16
Slab 4 - Type II	327	4.1 +/- 0.4	650	1 / 16
Slab 5 - Type II	264	3.0 +/- 0.4	656	5 / 16
Slab 6 - Type II	266	3.2 +/- 0.4	653	1 / 8

***** THE DEFLECTION DATA FOR THE SECOND SLAB WAS LOST DUE TO A SUDDEN SMALL DROP FROM WEIGHT SHIFTING IN THE BOTTOM OF THE BUCKET.**

Illustrated Crack Patterns

Slab One

Self Weight: 258 lbs
 Thickness: 3.4" +/- 0.4
 Live Load: 646 lbs
 Deflection: 1/8"

(A)

Slab Two

Self Weight: 240 lbs
 Thickness: 3.4" +/- 0.4
 Live Load: 584 lbs
 Deflection: ***

(B)

Slab Three

Self Weight: 261 lbs
 Thickness: 3.7" +/- 0.4
 Live Load: 640 lbs
 Deflection: 3/16"

(C)

FIGURE 23 - CRACK PATTERN IN SLABS WITH INTERNAL WALLS

Illustrated Crack Patterns

Slab Four

Self Weight: 327 lbs
Thickness: 4.1" +/- 0.4
Live Load: 650 lbs
Deflection: 1/16"

(A)

Slab Five

Self Weight: 264 lbs
Thickness: 3.0" +/- 0.4
Live Load: 656 lbs
Deflection: 5/16"

(B)

Slab Six

Self Weight: 266 lbs
Thickness: 3.0" +/- 0.4
Live Load: 653 lbs
Deflection: 1/8"

(C)

FIGURE 24 - CRACK PATTERN IN SLABS WITHOUT INTERNAL WALLS

3.5. Discussion

Despite the variability, each slab performed very well in resisting the applied load. Both types of slabs were stressed beyond what is defined as minimally acceptable and did not show signs of strain beyond surface cracks. The limits of reliability as determined by this experiment are constrained to slabs with thicknesses ranging between three and four inches, and to loads ranging between 580 lbs and 656 lbs over a single 24-hour loading cycle. In the field, sustained loads for this amount of time are uncommon (unless the latrine is used improperly for storage). Only one load cycle was possible for this test, and pit latrine slabs expect to see at least a quarter of this load over thousands of quarter hour cycles.

Given that each slab is 46in wide, the limit of deflection should be 0.25in. It could be argued that this is an overly restrictive limit considering that the slab will not interact with any other construction components. During testing, all six slabs gave no indication visually that they were overly stressed. In keeping with the defined deflection limit, only slab five showed sign of concern, with the exception of the inconclusive result from slab two. Slab five is also the thinnest slab of the six. If serviceability could be assumed as being free from reservation about the performance of the slabs under stress, then the author holds the opinion that all six slabs met this requirement.

As expected, each slab demonstrated signs of stress in the form of hairline cracks on the bottom of the slab. As shown in Figures 23 and 24, the crack patterns for each test are distinct to the slab. It was common for cracks to propagate towards and throughout thin spots in the base plate, specifically where the mold plastic was folded or rippled. In the case of slab

4 (Fig. 24 A), the mortar around the base plate reinforcing wire shrunk as a result of the curing process and the resulting thin area attracting cracks. The cracks that were a direct result of loading stress did not follow the expected yield line pattern (as would be formed during yielding conditions), which suggests that the slabs were either still in an elastic stage, or the load pattern caused stress to be distributed in unexpected ways. One reason for this could be the non-homogenous construction. Further, yield line calculations often assume the plate is a single mechanical body, and the loading in this experiment may have caused a punching shear around the center hole not considered in the analysis. Classifying the exact type of cracking pattern is outside the scope of this study (Wight 2012).

4. Conclusions

While living and working alongside indigenous Panamanians during his Peace Corps service, the author noticed how much manual labor dictates daily life. Conventional methods of improving access to improved sanitation require extensive manual labor, including gathering sand and carrying it more than a mile from the local river. This motivated investigation of a ferrocement latrine slab to reduce the materials involved in a sanitation project and therefore minimize the amount of manual labor involved.

Between 2015-2016 six slabs were prototyped in Panama and many of the constructibility challenges were addressed. These slabs were six inches thick and had internal walls. The prototypes were well received by community members and performed well, despite the lack of previous successful designs or a way to define the structural properties of ferrocement. This led to a review of the available literature on ferrocement's structural properties and how to design a latrine slab using the yield line method. Recognizing there would be too much variability and too little resources to conduct a thorough ultimate strength analysis, the decision was made to evaluate the design methods against an acceptable proof load.

With the tools, materials, and practices developed in the field, six 3-to 4-inch thick ferrocement slabs proved to be reliable under extraordinary stress in the lab, while reducing the amount of materials by 75% compared to conventional reinforced concrete slabs. The research validates that the new design is adequate and makes a dramatic improvement in material efficiency. Among the two types of slabs, there was no noticeable difference in

performance, which suggests that the design is still conservative. The test is limited to the specimens constructed and evaluated during this experiment, but results show potential for what can be possible in the field.

The constraints and limitations of working in the field influenced the methods explored in this report, and it was intended that the conclusions be as relevant as possible in guiding researchers or sanitation workers in the future. As a practical note, building ferrocement slabs in the field without internal walls saves an extra step in the construction process. These slabs are also easier to build overall because the wire configuration can be assembled separately.

4.1. Impacts

Building all six slabs by hand in the lab made construction more difficult and the end result more variable, but manual construction makes the final design relevant for remote areas. In the Comarca Ngäbe-Buglé, where the design was first tested, everything is done by hand. The people who live in this area build their own houses, cut their own roads, and grow all their food by hand. Chain saws are typically the only power tools anyone has access to. A design that respects these local practices is critical.

Community leaders reach out to Peace Corps to invite volunteers to help them solve the technical challenges that they face. For the communities the author was most involved in, sanitation was their primary development concern. They were already highly motivated to take steps to improve their state of access and practice of sanitation. They saw real value in building latrines but seemed to get tripped up by saving money and collecting all the

materials at the job site. A constant battle with tropical weather makes paths uneven and hard to traverse by any means other than on foot or by horse. These specific physical barriers to entry in building latrines are relieved with the improvements demonstrated in ferrocement slabs. A minor reduction in price makes saving money easier, and a dramatic reduction in materials means less heavy materials need to be transported by foot.

Additionally, the slab is transportable which makes it reusable and opens the opportunity to justify shallower pits (families often choose to dig deep pits to increase the life of their latrine). There is also an opportunity for local business. A team of trained individuals in the area could make and proof test slabs in a covered area and people could come and carry them to the latrine pit. This could streamline the slab construction process and remove a large part of managing a project at the household level.

4.2. Future Work

The results of this report are preliminary and offer many opportunities to explore this technology further. Knowing the ultimate load capacity of various sizes of ferrocement slabs could offer insight into the optimal size based on strength and materials. Also, the crack patterns could not conclusively show signs of yielding or yield line behavior. Testing more samples could indicate whether the yield line method is an appropriate way to describe non-homogeneous (hollow) slabs structurally.

The second version of the ferrocement slab, which the author recommends be adopted in the field (see Appendix II for a detailed design manual), uses 3/4 of a bag of cement and three buckets of sand. During the development of this report, the author made attempts to

reduce the amount of cement to half a bag so that a whole bag could be split between two slabs. For environments like the tropics, prolonged exposure to the humidity reduces the effectiveness of the cement and for that reason was seen as a priority. For future work, the author recommends less cement-rich mortar be explored to meet this constraint.

The second version of the slab also has a thin layer of embedded saw dust and complex side wall construction. There is an opportunity to combine the top and bottom ferrocement plates, and remove the saw dust and side walls to aid in the slab's constructibility. The author has reservations about the ductility of ferrocement slabs thinner than three inches with the amount of reinforcement currently prescribed. This concern is demonstrated in the testing data outlined in Table 4, where the thinnest slab showed a significant increase in deflection. If made thinner, work will need to be done to increase the strength of the slab with additional chicken wire layers in order to maintain the strength found in the second version slab.

5. References

- Balaguru, P.N. Report on Ferrocement. ACI, Detroit. 2009.
- Baston, Gordon B., Zollo, Ronald F., Balaguru, Perumalsamy N., Naaman, Antoine E., Iorns, Martin E. Guide for Design, Construction, and Repair of Ferrocement. ACI, 2009.
- CIA, "The World FactBook Panama", 26 Feb. 2017 https://www.cia.gov/library/publications/the-world-factbook/geos/print_pm.html
- Cohen, William A., Ryan Johnson. Filth, Dirt, Disgust, and Modern Life. Minnesota, Minneapolis. 2005. pp. 51-132.
- Ellingwood, Bruce R. Reliability-based condition assessment and LRFD for existing structures. Elsevier, Baltimore. 1996.
- Gram, Louis. "Any help with ferrocement history." Message to Larry Schirmer 13 May 2016. E-mail.
- Heberlein, Thomas A. Navigating Environmental Attitudes, Oxford, New York. 2012.
- Kates, Robert W., Thomas M. Parris, Anthony A. Leiserowitz. What Is Sustainable Development? https://www.hks.harvard.edu/sustsci/ists/docs/whatisSD_env_kates_0504.pdf Accessed 10 Feb. 2017.
- Lickel, B., Kushlev, K., Savalei, V., Matta, S., & Schmader, T. "Shame and the Motivation to Change the Self." *Emotion*, vol. 14, no. 6, 2014, pp. 1049-1061, PsycARTICLES, <https://services.lib.mtu.edu:5003/docview/1626165160?accountid=28041>, doi:<http://services.lib.mtu.edu:2080/10.1037/a0038235>.

- Midkiff, Jacob B. Post-Project Assessment of Pit Latrines in Rural Panama. Michigan Technological University, Houghton, MI. 2013. <http://digitalcommons.mtu.edu/etds/692/>
- Naaman, Antoine E. Ferrocement and Laminated Cementitious Composites. Techno Press, Ann Arbor. 2000.
- Reid, Timothy E. H. "Engineering feat that rid London of cholera and the 'Great Stink'." *Times* [London, England], 4 Aug. 1999, p. 18. *Academic OneFile*, services.lib.mtu.edu:2142/ps/i.do?p=AONE&sw=w&u=lom_mtu&v=2.1&it=r&id=GALE%7CA58566029&asid=e6641c80f8f16b18ff69bb30ef304281. Accessed 9 July 2017.
- Sabnis, Gajanan M. "Ferrocement — Past and Present." Ferrocement - Materials and Applications. ACI, Detroit. 1978. pp.1-8.
- Sobel, Michael E. "Lifestyle and Social Structure - Concepts, Definitions." Academic, New York. 1981, pp. 49-54.
- "WHO | MDG 7" World Health Organization, Sept. 2013. http://www.who.int/topics/millennium_development_goals/mdg7/en/
- Wight, James K. Reinforced Concrete Mechanics and Design. 6th ed. Pearson, Boston. 2012, pp. 785-811.

All photos and illustrations created by author.

6. Appendix I - Design Calculations

Terms and Definitions

A_s = the total effective cross-sectional area of reinforcement per direction (in^2)

A_c = the cross-sectional area of the ferrocement composite (in^2)

d = distance between the top surface and the center of reinforcement (in)

f'_c = compression strength of the cement-sand mix (psi) **

f_y = yield strength of chicken wire (psi)

L = full width of slab (46in)

L_d = full yield-line length (in)

$L_y = L_d - r_o$ = Reduced yield-line length (in)

m_b = moment capacity in the direction of the plastic hinge per foot ($lb - ft/ft$)

m_x = moment capacity in the x-direction per foot ($lb - ft/ft$)

m_y = moment capacity in the y-direction per foot ($lb - ft/ft$)

P = concentrated rim load (lb)

q_f = load per square ft (lb/ft^2)

r = hole radius (5.165 in)

r_{cp} = center of pressure radius (in)

r_o = hole outer radius of pressure area (in)

V_{ri} = volume fraction of mesh reinforcement in each layer (i)

W_r = unit weight of chicken wire reinforcement (0.1 lb/ft^2)

α = angle between outer edge and the center of the slab ($degree$)

γ_r = density of chicken wire (490 lb/ft^3)

δ = the total differential deflection caused by the applied load at the center of the slab

η_o = directional efficiency factor

Internal Work - General Equations for a Square Slab

This development of the internal work expression is based on the approach presented by Wight (2012) for a general rectangular slab.

The bending moment capacity along a diagonal yield line is equal to the moment capacity per unit length, m_b , times the length of the yield line, L_d . Reinforcement in the x and y directions contribute to m_b based on the angle α .

where,

$$L_1 = L_d \cdot \cos \alpha$$

$$L_2 = L_d \cdot \sin \alpha$$

The amount that $m_y \cdot L_1$ contributes to $m_b \cdot L_d$ direction:

$$(m_y \cdot L_1) \cos \alpha$$

The amount that $m_x \cdot L_2$ contributes to $m_b \cdot L_d$ direction:

$$(m_x \cdot L_2) \sin \alpha$$

$$m_b \cdot L_d = m_x(L_d \cdot \sin \alpha) \sin \alpha + m_y(L_d \cdot \cos \alpha) \cos \alpha$$

this yields a general expression for the bending capacity along a diagonal yield line:

$$m_b = m_x \sin^2 \alpha + m_y \cos^2 \alpha$$

The ferrocement slab has a total length (L) on both sides making the angle $\alpha = 45^\circ$

The internal work of each yield line is equal to the moment strength along the yield line, m_b , times the length of the yield line and the total rotation of each side of the slab's yield line. The total internal work is equal to the sum of the 4 yield lines.

$$IW = \sum m_b L_d \theta_t$$

Looking at section 1-1 which is taken perpendicular to a yield line, the angle $\theta_1 = \theta_2$ can be expressed in terms of the vertical deflection, δ , of the center of the slab. For a slab with a hole in the center, the length of each yield line is L_y and the internal work expression becomes:

$$IW = m_b \cdot L_y (\theta_1 + \theta_2) \quad (\text{eq. 1})$$

for small angles, $\sin \theta_1 = \theta_1 = \frac{\delta}{L_d}$

$$IW = m_b \cdot L_y \left(\frac{\delta}{L_d} + \frac{\delta}{L_d} \right)$$

$$IW = m_b \cdot L_y \left(\frac{2\delta}{L_d} \right)$$

$$\text{for } m_b = \frac{1}{2}m_x + \frac{1}{2}m_y$$

$$IW = \frac{1}{2}(m_x + m_y) 2 \left(\frac{L_y}{L_d} \right) \delta$$

$$IW = (m_x + m_y) \left(\frac{L_d - r}{L_d} \right) \delta$$

$$IW = (m_x + m_y) \left(1 - \frac{r}{L_d} \right) \delta \quad (\text{eq. 2})$$

Internal Work Calculations

Length of the Yield-Line

$$L_y = L_d - r$$

$$L_d = \sqrt{\left(\frac{L}{2}\right)^2 + \left(\frac{L}{2}\right)^2}$$

where,

$$L = 46in$$

$$r = 5.165in$$

$$L_d = \sqrt{\left(\frac{46}{2}\right)^2 + \left(\frac{46}{2}\right)^2} = 32.5in$$

$$L_y = 32.5(in) - 5.165(in) = 27.34in = 2.28ft \quad (eq. 3)$$

Moment Capacity of chicken wire per quadrant for 1ft:

x-direction

$$A_s = \eta_o \cdot V_r \cdot A_c = \eta \cdot \frac{N W_r}{h \gamma_r} \cdot A_c$$

where,

A_s = the total effective cross-sectional area of reinforcement per direction (in^2)

$\eta_o = 0.3 \rightarrow$ directional efficiency factor

V_r = volume fraction of mesh reinforcement in each layer (i)

A_c = the cross-sectional area of the ferrocement composite (in^2)

$N = 1 \rightarrow$ one layer of wire

$W_r = 0.1 \text{ lb/ft}^2$

$h = 20mm \rightarrow 0.0656 \text{ ft} \rightarrow$ thickness of composite

$\gamma_r = 490 \text{ lb/ft}^3$

$$A_s = 0.3 \cdot \frac{1 \cdot 0.1(lb/ft^2)}{0.0656ft \cdot 490(lb/ft^3)} \cdot (0.0656ft \cdot 1ft) = 6.1 \times 10^{-5} ft^2$$

$$A_s = 0.0088 in^2$$

$$a = \frac{A_s \cdot f_y}{0.85 \cdot f'_c \cdot b} = \frac{0.0088(in^2) \cdot 36,000(psi)}{0.85 \cdot 5600(psi) \cdot 12(in)} = 0.00554 in$$

where,

a = depth of the stress block (in)

b = the width of the slab (or the width of the strip being inspected) (in)

f_y = yield strength of chicken wire (psi)

f'_c = compression strength of the cement-sand mix (psi) **

** Special care was taken in the lab to follow a pre-tested mix specification (Naaman 2000 p. 18) (2.5 sand-to-cement ratio and a water-to-cement ratio of 0.6). It is reasonable that this compression strength can be achieved on the field if the mix specification is followed.

$$\phi M_n = \phi \cdot A_s \cdot f_y \left(d - \frac{a}{2} \right) = 0.9 \cdot 0.0088(in^2) \cdot 36,000(psi) \left(3(in) - \frac{0.00554(in)}{2} \right)$$

where,

ϕM_n = nominal moment capacity per 1 ft slab section ($lb - ft / ft$)

d = distance between the top surface and the center of reinforcement (in)

$$\phi M_n = 854.6 lb - in$$

$$\phi M_n = 71.2 lb - ft \text{ per ft} \quad (\text{eq. 4})$$

y-direction

$$A_s = \eta_o \cdot V_r \cdot A_c = \eta \cdot \frac{N W_r}{h \gamma_r} \cdot A_c$$

where,

$\eta_o = 0.45 \rightarrow$ directional efficiency factor

$N = 1 \rightarrow$ one layer of wire

$W_r = 0.1 \text{ lb/ft}^2$

$h = 20\text{mm} \rightarrow 0.0656 \text{ ft} \rightarrow$ thickness of composite

$\gamma_r = 490 \text{ lb/ft}^3$

$$A_s = 0.45 \cdot \frac{1 \cdot 0.1(\text{lb/ft}^2)}{0.0656\text{ft} \cdot 490(\text{lb/ft}^3)} \cdot (0.0656\text{ft} \cdot 1\text{ft}) = 9.2 \times 10^{-5} \text{ft}^2$$

$$A_s = 0.013 \text{in}^2$$

$$a = \frac{A_s \cdot f_y}{0.85 \cdot f'_c \cdot b} = \frac{0.013(\text{in}^2) \cdot 36,000(\text{psi})}{0.85 \cdot 5600(\text{psi}) \cdot 12(\text{in})} = 0.00819 \text{in}$$

$$\phi M_n = \phi \cdot A_s \cdot f_y \left(d - \frac{a}{2} \right) = 0.9 \cdot 0.013(\text{in}^2) \cdot 36,000(\text{psi}) \left(3(\text{in}) - \frac{0.00819(\text{in})}{2} \right)$$

$$\phi M_n = 1261.9 \text{lb} - \text{in}$$

$$\phi M_n = 105.2 \text{lb} - \text{ft per ft} \quad (\text{eq. 5})$$

Moment Capacity of wire braids in the second version slab

braid = 3 weaved 16.5 gauge rebar wire

$$\begin{aligned} 16.5(gauge) &= 0.048(in) \text{ diameter} \\ &= 0.024(in) \text{ radius} \end{aligned}$$

rebar wire area:

$$\text{area per wire} = \pi(0.024(in))^2 = 0.0018(in^2)$$

$$\text{area per braid} = 0.0054(in^2)$$

x-direction and y-direction capacity for wire braids

$$a = \frac{A_s \cdot f_y}{0.85 \cdot f'_c \cdot b} = \frac{0.0054(in^2) \cdot 45,000(psi)}{0.85 \cdot 5600(psi) \cdot 23(in)} = 0.0022in$$

$$\phi M_n = \phi \cdot A_s \cdot f_y \left(d - \frac{a}{2} \right) = 0.9 \cdot 0.0054(in^2) \cdot 45,000(psi) \left(3(in) - \frac{0.0022(in)}{2} \right)$$

$$\phi M_n = 655.9lb - in$$

$$\phi M_n = 54.7lb - ft \text{ per direction per quadrant}$$

$$\text{width of each quadrant} = 23in \rightarrow 1.917ft$$

$$\phi M_n = 28.53lb - ft/ft \quad (\text{eq. 6})$$

Total Moment Capacity per Quadrant in each Direction for Slab One:

m_x slab one

$$(IW \text{ eq. 4}) \rightarrow 71.2 \text{ lb-ft/ft}$$

m_y slab one

$$(IW \text{ eq. 5}) \rightarrow 105.2 \text{ lb-ft/ft}$$

Total Moment Capacity for Slab One:

$$IW = (m_x + m_y) \left(1 - \frac{r}{L_d} \right) \delta \quad (\text{eq. 2})$$

where,

$$m_x = 71.2 \text{ lb-ft/ft}$$

$$m_y = 105.2 \text{ lb-ft/ft}$$

$$r = 5.165 \text{ in}$$

$$L_d = 32.5 \text{ in}$$

$$\begin{aligned} IW &= (71.2 \text{ lb-ft/ft} + 105.2 \text{ lb-ft/ft}) \left(1 - \frac{5.165 \text{ (in)}}{32.5 \text{ (in)}} \right) \delta \\ &= 148.35 \text{ (lb-ft/ft)} \delta \text{ per quadrant} \\ &= 148.35 \text{ (lb-ft/ft)} \delta (4 \text{ quadrants}) = 593.4 \text{ (lb-ft/ft)} \delta \end{aligned} \quad (\text{eq. 7})$$

Total Moment Capacity per Quadrant in each Direction for Slab Two:

m_x slab two

$$(IW \text{ eq. 4}) \rightarrow 71.2 \text{ lb-ft/ft}$$

$$(IW \text{ eq. 6}) \rightarrow 28.53 \text{ lb-ft/ft}$$

$$m_x = 71.2(\text{lb} - \text{ft/ft}) + 28.53(\text{lb} - \text{ft/ft}) = 99.73 \text{ lb} - \text{ft/ft}$$

m_y slab two

$$(IW \text{ eq. 5}) \rightarrow 105.2 \text{ lb-ft/ft}$$

$$(IW \text{ eq. 6}) \rightarrow 28.53 \text{ lb-ft/ft}$$

$$m_y = 105.2(\text{lb} - \text{ft/ft}) + 28.53(\text{lb} - \text{ft/ft}) = 133.73 \text{ lb} - \text{ft/ft}$$

Total Moment Capacity for Slab Two:

$$IW = (m_x + m_y) \left(1 - \frac{r}{L_d} \right) \delta \quad (\text{eq. 2})$$

where,

$$m_x = 99.73 \text{ lb} - \text{ft/ft}$$

$$m_y = 133.73 \text{ lb} - \text{ft/ft}$$

$$r = 5.165 \text{ in}$$

$$L_d = 32.5 \text{ in}$$

$$\begin{aligned}
IW &= (99.73(lb - ft/ft) + 133.73(lb - ft/ft)) \left(1 - \frac{5.165(in)}{32.5(in)} \right) \delta \\
&= 196.36(lb - ft/ft) \delta \text{ per quadrant} \\
&= 196.36(lb - ft/ft) \delta (4) = 785.43(lb - ft/ft) \delta \quad (\text{eq. 8})
\end{aligned}$$

External Work Calculations

$$h_w = 10.33 \text{ in}$$

$$r_i = 5.165 \text{ in}$$

$$r_o = r_i + 1.5(in) = 6.665 \text{ in}$$

Find Radial Distance to Center of Pressure

$$A_1 = \frac{\pi r_o^2}{4} = \frac{\pi (6.665(in))^2}{4} = 34.9 in^2$$

$$\bar{x}_1 = \frac{4r_o}{3\pi} = \frac{4 \cdot 6.6659(in)}{3\pi} = 2.8 in$$

$$A_2 = \frac{\pi r_i^2}{4} = \frac{\pi (5.165(in))^2}{4} = 20.9 in^2$$

$$\bar{x}_2 = \frac{4r_i}{3\pi} = \frac{4 \cdot 5.165(in)}{3\pi} = 2.19 in$$

$$\begin{aligned} \bar{x} &= \frac{\bar{x}_1 A_1 + \bar{x}_2 (-A_2)}{A_1 - A_2} \\ &= \frac{2.8(in) \cdot 34.9(in^2) + 2.2(in) \cdot (-20.9(in^2))}{34.9(in^2) - 20.9(in^2)} = 3.7 in \end{aligned}$$

Find Symmetrical Distance to Center of Pressure

$$r_{cp} = \sqrt{3.7^2 + 3.7^2} = 5.2 in$$

Calculate External Work

$$EW = P \cdot \left(\frac{\frac{L}{2} - r_{cp}}{\frac{L}{2}} \right) \delta \cdot 4 = P \cdot \left(1 - \frac{2 r_{cp}}{L} \right) \delta \cdot 4$$

where,

EW = work done by load applied to the structure ($lb - ft$)

P = applied load (lb)

L = full width of slab (46in)

r_{cp} = center of pressure radius (in)

δ = the total differential deflection caused by the applied load

** the equation for external work is multiplied by four, one for each concentrated load point

$$EW = P \cdot \left(1 - \frac{2 \cdot 5.2(in)}{46(in)} \right) \delta \cdot 4$$

$$EW = 3.1 P \delta$$

Calculate Max Rim Load

Slab One

$$IW = 593.4lb - ft/ft \delta \text{ and } EW = 3.1 P \delta$$

$$P = \frac{593.4lb - ft/ft \delta}{3.1\delta} = 191.67lb \text{ per quarter}$$

$$P_{total} = 766.7lb$$

Slab Two

$$IW = 785.43lb - ft/ft \delta \text{ and } EW = 3.1 P \delta$$

$$P = \frac{785.43lb - ft/ft \delta}{3.1\delta} = 253.7lb \text{ per quarter}$$

$$P_{total} = 1014.8lb$$

7. Appendix II - Ferrocement Slab V2 Design Manual

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