Porous Concrete Waste Filtration

MQP Report

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Executive Summary

In Ethiopia, diarrhea is one of the leading causes of death after neonatal disorders[1], which are complications in fetal development. Diarrhea is responsible for more than one out of every ten deaths among children[2]. By installing equipment for the basic human need of restroom hygiene, the number of annual child deaths has the potential to decrease drastically. As of August of 2019, with the help of the Global Sustainability Assistance Program (GSAP), Ethiopia has begun to introduce microflush toilets to its communities. The conceptual purpose of the microflush toilets is to help resolve both malnutrition and sanitation problems simultaneously, through vermiculture. Human waste, when treated via vermiculture, can be utilized as fertilizer, which helps crops stay healthy. The successful implementation of microflush toilets could be a step in the right direction towards resolving the issues of poor sanitation and malnutrition in Ethiopia.

The waste that is generated in microflush toilets is separated by a filter-digester system, collecting solid waste while letting liquid waste filter through. The liquid waste, or filtrate, is processed naturally in a soak hole, which is a miniature version of a leaching field. The solid waste is turned into fertilizer via earthworms. The earthworms begin the process of vermiculture in the digester bed, which is the part of the microflush toilet that sits below the toilet and collects all the human waste. The separation of solid and liquid waste is done because the concentration of sodium in urine has the potential to kill the earthworms that fuel the system that creates fertilizer from human waste. These microflush toilets eliminate the need to transport the solid waste to a waste processing plant to acquire fertilizer by allowing earthworms to carry out the

[1] "CDC in Ethiopia." *Centers for Disease Control and Prevention*, Centers for Disease Control and Prevention, 11 Feb. 2021, https://www.cdc.gov/globalhealth/countries/ethiopia/default.htm.

[2] Tesfaye TS, Magarsa AU, Zeleke TM. Moderate to Severe Diarrhea and Associated Factors Among Under-Five Children in Wonago District, South Ethiopia: A Cross-Sectional Study. Pediatric Health Med Ther. 2020 Oct 19;11:437-443. doi: 10.2147/PHMT.S266828. PMID: 33117059; PMCID: PMC7584513.

aerobic process of naturally composting the human waste.

A typical GSAP toilet uses five layers of fine wire mesh and a layer of sand and gravel to separate liquid human waste from solid human waste. This wire mesh is not produced in Ethiopia and, therefore, would need to be imported for it to be used in Ethiopian GSAP microflush toilets. Due to the cost, the common materials, such as the wire mesh, used in microflush toilet filtration technology are unavailable to the population that needs low-cost toilets the most. Therefore, a need arose for a suitable, cost-effective replacement for such materials. Currently, Ethiopian microflush toilet builders are using slabs of porous concrete as a replacement option for the unavailable mesh material that other countries are implementing for filtration purposes, since the porous concrete slab is much more cost efficient to produce. Porous concrete, also known as pervious concrete, is concrete that is formed without the addition of the fine aggregate. The omission of the fine aggregate in the mix creates empty pockets, or voids, that allow liquids, gaseous matter, and fine particulates to pass through the finished concrete, acting as a type of filter.

The use of porous concrete slabs as a filtration device is simple in concept, yet there are some unexplored elements in the implementation of it for filtering human waste. Ideally, when all the waste is flushed along with the greywater, which is the water and soap the occupant has used to wash their hands, the liquids would permeate through the porous concrete slab, and only the solid waste would remain above the slab. However, solid waste that is loosely compacted or closer to liquid in consistency may fill the voids within the concrete slab, effectively clogging the slab and no longer allowing it to serve its purpose as a filter. Clogging is common in other porous concrete applications; to mitigate this, the concrete must be pressure washed on a yearly basis. This type of maintenance equipment may not be readily available for the average Ethiopian microflush toilet owner or user, so clogging needs to be mitigated or avoided, whenever possible.

The goal of this project is to find an optimal concrete mix ratio of cement, water, and coarse aggregate that can be standardized to maximize the efficiency of the voids for liquid filtration, providing uniformity in the slab creation process. With a standardized mix ratio, Ethiopian toilet-makers and users can expect identical results in the filtration performance for each concrete slab, facilitating the scheduling of maintenance and fertilizer harvesting. By running a permeability test, the rate at which water moves through the porous concrete can be quantified. This test is important for the purpose of calculating the most effective void ratio, which would allow liquids to flow through the porous concrete without becoming clogged by solid waste.

Based on a multitude of articles on the creation and ratios of porous and pervious concrete[3], the ideal mix ratio for porous concrete has a water-cement ratio of between 0.25 to 0.45, depending on the materials used. Generally, the larger the aggregate used for the concrete, the more porous the concrete will be. A mix of three parts aggregate to one part cement was used as the control mix. If ⅜" pea gravel is used as the aggregate, the water ratio is one quart of water per three gallons of gravel (and one gallon of cement). By producing multiple test samples of porous concrete with different water-cement ratios, an ideal ratio of water, portland cement, and pea gravel for filtration, strength, and maintenance of the voids in the concrete can be determined.

Three porous concrete samples of five different water-cement ratios between 0.25 and 0.45 were made. Once the differing mix ratios were cured, the next step was to replicate the conditions that the permeable concrete could be exposed to in Ethiopia. In order to determine the efficiency of the permeable concrete, it must first be determined how effective it is at filtering liquid from solid matter, which should remain on the surface. For the test of permeability, the

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[3] *How to make pervious concrete*. Pervious Products. (2018, April 6). Retrieved February 20, 2023, from https://perviousproducts.com/make-pervious-concrete/

concrete must be put under stresses and uses similar to the concrete that is already in use in Ethiopia. First, the control experiment tested the rate at which 100 mL water was filtered through the concrete without being obstructed by the solid matter. During the second round of experiments, testing was performed to observe how long the water would take to filter through the concrete when there is solid and liquid material on the concrete, which replicated human feces and urine. Since, for sanitary reasons, actual human excreta cannot be used during experimentation, it was determined that 6 g ground bananas would be used as an adequate substitute for fecal matter, and 100 mL coffee would serve as a replacement for urine. Bananas were selected due to the similar consistency, texture, and potential pH level of mashed bananas and loose human fecal matter. Coffee is selected for a similar reason, as both coffee and urine have a low pH of 5. Their slightly acidic chemical nature will impact the concrete in a similar manner, so the results should be accurate enough to those found in Ethiopia.

Based on the results of the aforementioned tests, a written instructional manual was produced, detailing what was found during experimentation and how to produce a consistent mix. Due to the low filtration rates recorded during the experiment, a decision was made to test an alternative filtration tool, window screen mesh. In this experiment, a mesh layer was suspended using a PVC cylinder, under the same conditions as the porous concrete. Using 300 mL of coffee and 6 g of banana, enough to cover the surface of the mesh, the coffee was poured on the concrete. In three separate tests, 100 mL of coffee was poured each time on the mesh and very quickly flowed through into the container below. In each part of the experiment the coffee flowed through the mesh almost instantly. In between each experiment the banana was adjusted so that it covered the entire mesh, but in any area where there was a smaller layer of banana the coffee was able to flow through. The data collected from the mesh experiment proved that the mesh is a more viable option than the concrete for waste filtration. During all the permeability tests performed by using mesh, the samples did not experience clogging from solid waste and were able to allow the free flow of the coffee.

Regardless of the mix design, the porous concrete alone could not effectively separate solid waste from liquid waste. Although most mix designs allowed liquid to quickly flow through the voids of the concrete, once solid waste was introduced, the voids rapidly filled with the solid material, nearly completely preventing the liquid flow. Without reliable access to pressurized water or advanced cleaning technology, the concrete is likely to remain partially clogged, even after unclogging maintenance. For the safety and health of the potential user of the GSAP microflush toilet, it is not recommended to solely use porous concrete as a filter for the toilet's digester bed. The recommended alternative option is to use fine mesh, such as window screening material, in conjunction with the porous concrete in the Ethiopian GSAP microflush toilet's design.

Design Statement

The purpose of this project was to determine whether porous concrete was a viable material to be used as a filtration device for microflush toilets in Ethiopia. In order to determine if this was possible, concrete samples were designed by the team in the lab to emulate some of the potential concrete mixes that would be utilized for these slabs in Ethiopia. Multiple samples of differing mix ratios were created to determine if different ratios performed better as a filtration device.

Once the samples were set, a basic filtration experiment with water was designed and implemented, with the goal of determining whether liquid could filter through the material on its own. This was designed to identify some mixes as not porous, so that further testing would not be conducted on non-porous samples.

An additional porosity test that was designed to be in correspondence with the previous test, utilizing bananas and coffee in order to simulate human waste. These materials were selected as simulants for this experiment due to the similar consistency bananas have to human waste, as well as the similar pH rating coffee has when compared to urine. The test was then conducted by placing mashed bananas onto the sample and filtering coffee through it. This was done to simulate solid waste laying on top of the filtrating concrete slab. The test itself was designed to determine if the concrete slab could reliably filter human waste without clogging up due to the amount of solid waste.

Professional Licensure Statement

Professional licensure is essential for the credibility and reliability of the profession of engineering. An engineer with a professional license may create, sign, or stamp drawings and other professional documents within their registered state. An engineer's stamp or seal of approval means that the signed documents are acceptable by the professional Standard of Care and standards of engineering practice. These standards are in place to ensure engineers practice safely, ethically, and with the care of others in mind.

In order to become a licensed professional engineer, one must first obtain a bachelor's degree from an ABET-accredited program in an engineering field. Then, they must pass the Fundamentals of Engineering exam, the first of two computer-based exams that cover material relevant to the test taker's selected field of engineering. Following that, they must gain four years of engineering experience in their selected engineering field, practicing under the supervision of a licensed professional engineer. The final step in one's journey to obtain professional licensure is to pass the Principles and Practice of Engineering Exam, the second exam provided by the National Council of Examiners for Engineering and Surveying (NCEES).

Once professional licensure is obtained, some states require that the practicing engineer completes continuing education requirements, often in the form of Professional Development Hours (PDH). While some states do not require a licensed engineer to study further, the responsibilities of the engineers licensed in those states are held in similar regard because of the arduous licensure requirements. These requirements are stringent because the engineers who complete them hold the highest of responsibilities, public safety. Professional Engineers will be accountable for the quality of their work and the work of others that they review. Also, they may provide testimony for legal matters relevant to their areas of expertise. Above all, they are bound by a strict Code of Ethics, created by the National Society of Professional Engineers (NSPE), that ensures they are beholden to the safety of the public.

Abstract

Through this porous concrete MQP, our team analyzed a revolutionary toilet design which is able to separate solid and liquid human waste to be later used as fertilizer for crops in Ethiopia. The effectiveness of using porous concrete as the filter for human waste was studied and tested. The group placed concrete samples of varying mix designs under the conditions that they would experience in Ethiopia. After analyzing the results, it was determined that porous concrete was not a suitable filtration device.

Authorship Page

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Design Statement	Justin Aguilar	All Members
Licensure Statement	Michael Peck	All Members
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Introduction

Millions of Ethiopian citizens live without knowing where their next meal will come from. Inflation, which has worsened due to the COVID pandemic, has increased the number of citizens living in poverty to as many as 35 million people [4]. The vast majority of the 105 million residents of Ethiopia are almost entirely reliant on agricultural harvest to put food on the table. Unfortunately, the weather in Ethiopia is extremely unpredictable and leaves crop harvests vulnerable. The country is no stranger to droughts, and the lack of rainfall can be devastating to the soil and farm animals. Considering that roughly 67% of Ethiopians are involved in the farming field, primarily involved in intensive subsistence farming, it is essential that these people have access to healthy soil that yields crops and plenty of water.

When the soil and the weather do not accommodate healthy growing conditions, the people of Ethiopia are susceptible to malnourishment. Malnourishment can lead to a large array of health concerns and is a leading cause of death in children. Being able to protect crops from drought and contamination is vital to the health and wellness of the millions who rely on these crops.

Human waste, when treated via vermiculture, can be utilized as fertilizer. Doing so would help with malnourishment, by helping crops stay healthy. Additionally, this could help with sanitation, which is another major issue in Ethiopia that greatly affects the health of the Ethiopian population. According to the WaterAid's 2017 report, "Ethiopia ranks the worst worldwide with the highest percentage of its population [93%] living without toilets." [5] Without

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[4] *Poverty in Ethiopia: Causes & effects – rainbow FTF*. Rainbow for the Future | Just another WordPress site. (2016, July 22). Retrieved October 6, 2022, from https://rainbowftf.ngo/destitute-people/poverty-ethiopia/#:~:text=One%20of%20the%20poorest%20countries,severely%20affected%20by%20food%20insecurity

[5] on 15 November 2017 In Ethiopia, Prabasi, S., & Ethiopia. (n.d.). *Out of order: The State of the world's toilets*. WaterAid US. Retrieved October 6, 2022, from https://www.wateraid.org/us/media/out-of-order-state-of-the-worlds-toilets#:~:text=India%20remains%20the%20nation%20with,of%20anywhere%20in%20the%20world. https://archpublichealth.biomedcentral.com/articles/10.1186/s13690-021-00566-8#citeas

toilets, people relieve themselves outdoors. Disease is not only spread by the accumulation of human waste in the environment, but also by the multitude of people that are unable to wash their hands adequately – due to the residents' limited access to proper sanitation equipment. Because they suffer from malnutrition during their developmental stages, many children in Ethiopia are more susceptible to water-borne illnesses and diarrhea. Diarrhea can be lethal, especially in a place with a short supply of clean drinking water, as it can cause dehydration and a loss of nutrients. In Ethiopia, diarrhea is one of the leading causes of death after neonatal disorders[6], and is responsible for more than one out of every ten deaths among children[7]. By installing equipment for the basic human need of restroom hygiene, the number of annual child deaths has the potential to decrease drastically.

As of August of 2019, Ethiopia has begun to introduce microflush toilets to its communities. The conceptual purpose of the microflush toilets is to help resolve both malnutrition and sanitation problems simultaneously, through vermiculture. The successful implementation of microflush toilets could be a step in the right direction towards resolving the issues of poor sanitation and malnutrition in Ethiopia.

[6] "CDC in Ethiopia." *Centers for Disease Control and Prevention*, Centers for Disease Control and Prevention, 11 Feb. 2021, https://www.cdc.gov/globalhealth/countries/ethiopia/default.htm.

[7] Tesfaye TS, Magarsa AU, Zeleke TM. Moderate to Severe Diarrhea and Associated Factors Among Under-Five Children in Wonago District, South Ethiopia: A Cross-Sectional Study. Pediatric Health Med Ther. 2020 Oct 19;11:437-443. doi: 10.2147/PHMT.S266828. PMID: 33117059; PMCID: PMC7584513.

Background

One major contributing factor to the spread of diseases in Ethiopia is the lack of hygienic facilities for people to relieve themselves in. The need for sanitary restrooms in impoverished African communities caught the attention of the Global Sustainable Aid Project (GSAP), a non-profit organization that seeks to empower communities in need. GSAP began to focus on becoming heavily involved in sustainable projects in 2009, starting with the development of a new type of toilet that initially debuted in Ghana, but is now spreading to other countries around the world. Pioneered by Dr. Stephen Mecca, Professor of Physics at Rhode Island's Providence College, the GSAP toilet is described as an "off-grid, sustainable, environmentally friendly, low cost, odor- and fly-free toilet that reuses the small amount (1 cup) of greywater from a previous user's hand wash to isolate waste and flush the toilet"[8]. These toilets are typically constructed and owned in small-scale residential areas, meant for 2-3 families to share, with a typical family size being 5-6 people[9].

The waste that is generated in microflush toilets is separated by a filter-digester system, collecting solid waste while letting liquid waste filter through. The liquid waste, or filtrate, is processed naturally in a soak hole, which is a miniature version of a leaching field. The solid waste is turned into fertilizer via earthworms. The earthworms begin the process of vermiculture in the digester bed, which is the part of the microflush toilet that sits below the toilet and collects all the human waste. The separation of solid and liquid waste is done because the concentration of sodium in urine has the potential to kill the earthworms, which fuel the system that creates fertilizer from human waste. These microflush toilets eliminate the need to transport the solid

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[8] Global Sustainable Aid Project. "GSAP Microflush Toilets." *Global Sustainable Aid Project*, 2022, https://globalsustainableaid.org/gsap/gsap-microflush-toilets/.

[9] Global Data Lab. "Area Database (v4.1), Average Household Size." *Global Data Lab*, 2022, https://globaldatalab.org/areadata/hhsize/ETH/.

waste to a waste processing plant to acquire fertilizer by allowing earthworms to carry out the aerobic process of naturally composting the human waste. The procedure of retrieving the fertilizer is completed every two years, by removing the cover from the digester bed and extracting the rich compost for agricultural use. As Ethiopia has problems with malnutrition and sanitation, microflush toilets can help mitigate both issues, by both providing fertilizer for farming as well as reducing the amount of disease spread due to low access to toilets.

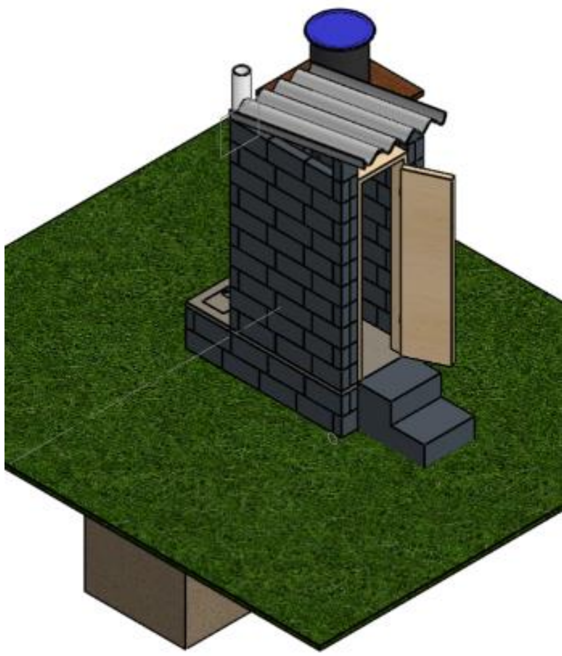

Figure 1: CAD model GSAP toilet[10]

Figure 2: Image of GSAP toilet[11]

A typical GSAP toilet uses five layers of fine wire mesh and sediments, such as gravel, in order to separate liquid human waste from solid human waste. The household size digester bed for the toilets is approximately 3' x 6', and the size for a school would be approximately 4' x 7'; this larger size is used in order to retain a similar duration of time between required

[10] Global Sustainable Aid Project. (2013). Specifications of GSAP Toilet_1, pg. 1. Pawtucket; Global Sustainable Aid Project.
[11] Global Sustainable Aid Project and Ghana Sustainable Aid Project. (2013). GSAP Microflush Toilet Locally sourced and fabricated Rural Pour Flush Model Instructions, pg. 6. Pawtucket; Global Sustainable Aid Project.

maintenance periods while accommodating for the increase in rate of use caused by the larger number restroom occupants. This wire mesh is not produced in Ethiopia and, therefore, would need to be imported from a country that does produce or manufacture it for it to be used in Ethiopian GSAP microflush toilets. A standard sheet of fine wire mesh with dimensions of about 4’ x 50’ costs an average of $87. A standard 3’ x 50’ sheet of wire mesh costs an average of $46. With Ethiopia’s per capita gross national income of $960[12], the common materials, such as the wire mesh, used in microflush toilet filtration technology are unavailable to the population that needs low-cost toilets the most. Therefore, a need arose for a suitable, cost-effective replacement for such materials. Currently, Ethiopian microflush toilet builders are using slabs of porous concrete as a replacement option for the unavailable mesh material that other countries are implementing for filtration purposes, since the porous concrete slab costs roughly $30 to procure all of the necessary components.

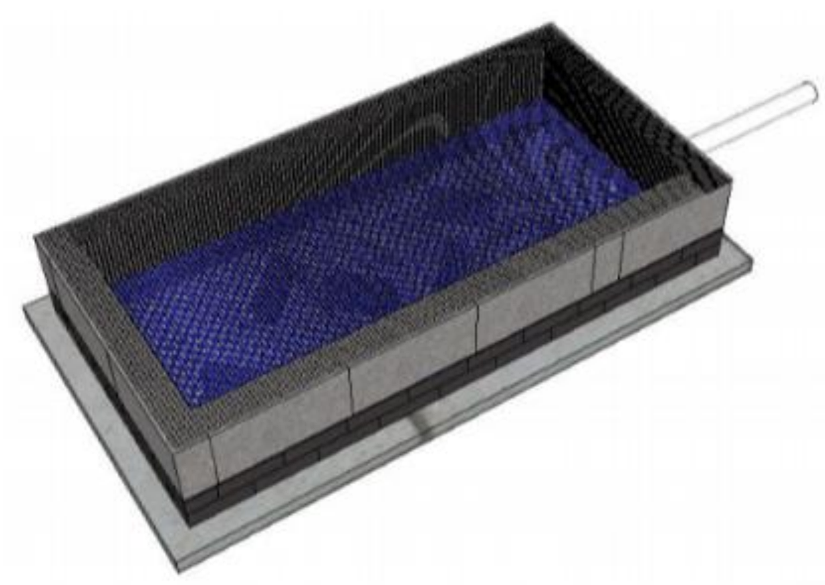

Figure 3: GSAP with mesh in digester bed[13]

[12] World Bank. “GNI per Capita, Atlas Method (Current US$) - Ethiopia.” *Worldbank.org*, https://data.worldbank.org/indicator/NY.GNP.PCAP.CD?locations=ET.

[13] Global Sustainable Aid Project and Ghana Sustainable Aid Project. (2013). GSAP Microflush Toilet Locally sourced and fabricated Rural Pour Flush Model Instructions, pg. 24. Pawtucket; Global Sustainable Aid Project.

Typically, concrete is a mixture of cement, water, coarse aggregate, and fine aggregate. After concrete is mixed and poured, it needs to be cured. The curing process is performed by maintaining thermal and moisture conditions for a duration of time that varies based on the intended function of the concrete to ensure the concrete remains hydrated while it hardens, which is vital to the overall strength of the concrete. Should the concrete not maintain a sufficient level of moisture content while it is drying, the lack of hydration can cause the volume of the concrete to reduce, often forming cracks in the concrete; this is known as shrinkage. The aggregate has mechanical properties that allow it to increase the strength of the concrete and reduce shrinkage. The use of aggregate also reduces the cost of the concrete, as cement is the most expensive component and can be partially replaced by aggregate. The fine aggregate provides the concrete with a more compact and uniform consistency, by filling in areas around the coarse aggregate.

Porous concrete, also known as pervious concrete, is concrete that is formed without the addition of the fine aggregate. The omission of the fine aggregate in the mix creates empty pockets, or voids, that allow liquids, gaseous matter, and fine particulates to pass through the finished concrete, acting as a type of filter.

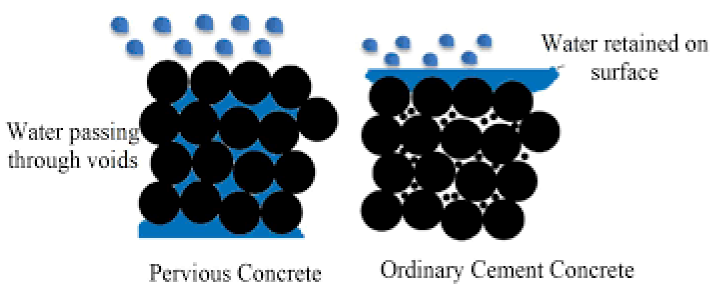

Figure 4: The comparison between compositions of pervious concrete and ordinary concrete[14]

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[14] Vijayalakshmi, Ramalingam. "Recent Studies on the Properties of Pervious Concrete; a Sustainable Solution for Pavements and Water Treatment." *Civil and Environmental Engineering Reports*, 1 Sept. 2021, https://www.sciendo.com/article/10.2478/ceer-2021-0034.

The voids lower the compressive strength of the concrete, reducing its ability to handle heavy loads. Due to this, porous concrete is not ideal for structural applications. However, porous concrete is useful in a wide variety of cases where a relatively stable, durable surface is required and where excess moisture would be problematic, like parking lots or sidewalks. This type of concrete is widely used, by large-scale construction companies and by smaller-scale local producers, for stormwater management. According to Reports and Data, a market research company, "The global pervious pavement market size was USD 17.03 Billion in 2020 and is expected to reach a value of USD 25.52 Billion by 2028[15]." The inexpensive cost of porous concrete production, compared to the cost of wire mesh, and its ability to allow liquids to pass through the voids, acting as a filter, made porous concrete seem like a sustainable, cost-effective replacement for typical microflush toilet filtration materials to Ethiopian GSAP microflush toilet builders.

The use of porous concrete slabs as a filtration device is simple in concept, yet there are some unexplored elements in the implementation of it for filtering human waste. Ideally, when all the waste is flushed along with the greywater, which is the water and soap the occupant has used to wash their hands, the liquids would permeate through the porous concrete slab, and only the solid waste would remain above the slab. However, solid waste that is loosely compacted or closer to liquid in consistency may fill the voids within the concrete slab, effectively clogging the slab and no longer allowing it to serve its purpose as a filter. Clogging is common in other porous concrete applications; to mitigate this, the concrete must be pressure washed on a yearly basis. Pressure washing is important as it removes small particles, such as dirt, allowing rainwater to flow through the concrete and into the ground, so as to avoid a large accumulation of water on the surface of the concrete.

[15] Reports and Data. "Construction and Manufacturing - Pervious Pavement Market." *Reports and Data*, Mar. 2021, https://www.reportsanddata.com/report-detail/pervious-pavement-market.

One goal for the project is to find an optimal concrete mix ratio of cement, water, and coarse aggregate that can be standardized to maximize the efficiency of the voids for liquid filtration, providing uniformity in the slab creation process. With a standardized mix ratio, Ethiopian toilet-makers and users can expect identical results in the filtration performance for each concrete slab, facilitating the scheduling of maintenance and fertilizer harvesting. By running a permeability test, the rate at which water moves through the porous concrete can be quantified. This test is important for the purpose of calculating the most effective void ratio, which would allow liquids to flow through the porous concrete without becoming clogged by solid waste.

Another goal for the project is to assess the potential types of failure that porous concrete can experience while being used for human waste filtration. There are five main types of failure when it comes to concrete, which are chemical, mechanical, fire, stray currents, and corrosion. For the focus of this project, the porous concrete only undergoes mechanical and chemical stresses that can cause the concrete to fail. Corrosion failure happens when the steel rebar, often used in standard concrete for structural reinforcement, is exposed to outside elements and corrodes. Due to porous concrete's unique nature and ability to allow liquids to flow through the concrete, the use of steel rebar would be pointless. Also, the concrete will not be exposed to stray currents, as it will be a component of an outdoor microflush toilet, which is an off-grid technology. There is a possibility of fire; however, the failure of the concrete would not cause structural safety issues like that of a multiple story concrete building. Mechanical failure happens when the concrete undergoes stresses such as overloading of weight that causes cracks. A compressive strength test can be completed to find the amount of force the porous concrete can handle without cracking or rupturing[16]. Cracking can reduce the

[16] “The 5 Main Types of Concrete Failure.” *Bluey Technologies*, https://www.bluey.com.au/featured/5-concrete-failure.

effectiveness of the separation of solid and liquid waste through the porous concrete by allowing larger particles to enter the voids, potentially clogging them more easily. Chemical failure is a process where chemical reactions weaken the strength of the concrete. Concrete begins to deteriorate when in contact with acids below 6.5 pH[17]. Urine can be highly acidic with a range of 4.6 to 8.0 pH values[18]. During this project, the efficiency of porous concrete as a filter for human waste will be investigated.

[17] "How Humidity & Ph Affect Concrete Degradation." *How Humidity & PH Affect Concrete Degradation - Polygon Group*, https://www.polygongroup.com/en-US/blog/how-humidity-and-ph-affect-concrete-degradation/.

[18] "Urine Ph." *Ucsfhealth.org*, 6 Oct. 2020, https://www.ucsfhealth.org/medical-tests/urine-ph-test#:~:text=Normal%20Results,from%20pH%204.6%20to%208.0.

Methodology

Through interviews and meetings with the staff members who have worked with microflush toilets directly, the materials that are typically used to mix porous concrete were determined, recorded, and procured. Though it would be ideal to replicate the conditions that the toilets are subject to in Ethiopia as accurately as possible, the simulation of a climate similar to Ethiopia's was not possible during the experimentation phase. Experimentation needed to be conducted in a laboratory at Worcester Polytechnic Institute to ensure materials were accessible for all students involved in the experiment. Due to this, the cement made during experimentation was cured under much more moderate temperatures than those found in Ethiopia. Using Portland cement and ⅜" pea gravel in a variety of water-cement ratios, various tests were performed in order to examine the ability of the concrete for human waste filtration. The necessary frequency of maintenance of the concrete was also examined.

To become more informed about porous concrete, interview requests were sent to companies who have experience working with such material. An interview was conducted with Michael Sheehan and Mick Albro from Sterling Concrete. This interview was conducted in person at WPI, where a set list of questions was constructed to ask the interviewees. During this interview, there was a discussion about what mix ratios they would recommend, as well as some ideas for potential maintenance and cleaning of a concrete slab.

Based on a multitude of articles on the creation and ratios of porous and pervious concrete[19], the ideal mix ratio for porous concrete has a water-cement ratio of between 0.25 to 0.45, depending on the materials used. Generally, the larger the aggregate used for the concrete, the more porous the concrete will be. A mix of three parts aggregate to one part cement was used as the control mix. If ⅜" pea gravel is used as the aggregate, the water ratio is

[19] *How to make pervious concrete*. Pervious Products. (2018, April 6). Retrieved February 20, 2023, from https://perviousproducts.com/make-pervious-concrete/

one quart of water per three gallons of gravel (and one gallon of cement). By producing multiple test samples of porous concrete with different water-cement ratios, an ideal ratio of water, portland cement, and pea gravel for filtration, strength, and maintenance of the voids in the concrete can be determined.

Since Ethiopia does not have the same municipal capabilities for water treatment, minor errors will be assumed, as it is not easily determinable if there is something in their water that has the ability to hinder the construction of the concrete, such as an excessive amount of phosphorus. For our tests, we tested with the assumption that the water would not negatively affect the production of concrete in Ethiopia, as there has been no reporting or evidence of concrete failure in Ethiopia solely due to water quality.

The first step in creating samples of porous concrete was to arrange for the procurement of materials and to develop a plan to determine how to proceed with testing. Since the bottom of a cylindrical mold could be removed to turn the mold into a pipe for permeability testing, cylindrical molds that were in the Kaven Hall laboratory were used to cure the concrete. In order to establish a standard that would ensure the testing results would be comparable, the weight between each sample was measured such that all samples were relatively similar sizes.

All of the materials that were utilized for this project were found at a local Home Depot. In order to become more familiar with the Ethiopian mixing process, a meeting was held with Achirri Ismael, a Program Manager for Social Science at WPI and the project representative who witnessed the microflush toilet construction process in Ethiopia. From this interview, it was found that the Ethiopian construction workers were using portland cement. Therefore, the portland cement found at Home Depot was assumed to cause little to no difference in the final product. Portland cement, ⅜ in gravel concrete, shovel, bucket, and PVC for pouring samples were acquired from Home Depot, and the remainder of the materials, such as a screwdriver and scale, were provided by the school.

Each weight for the cement, gravel, and water was selected based on recommended values of previous recordings of porous concrete ratios. Starting with the volume of one cylindrical mold, which was 42.4 cubic inches, the volume of mixed concrete required to produce three samples, each being one-third the total cylindrical volume (14.13 in3), and an excess, in case it should be needed, was calculated. The total volume produced of each concrete sample was approximately 80 cubic inches. This volume was then converted into cubic meters, since the selected reference value from an article (reference 16) was given as density in the International System of Units (SI units), 500 kilograms per cubic meter (kg/m3). From this point, the volume was multiplied by the given density value to calculate the adjusted mass (in grams) required to attain the desired mix design ratios. Throughout the first day of concrete pouring, the mass of the cement and the gravel were kept nearly identical between samples, which was about 655 grams for cement and 1,965 grams for the ⅜ inch gravel, as illustrated in figures 5 and 6 below. In tables 1 and 2 below, the exact numbers for the mass for each component were recorded, as well as the total mass of each sample.

Figure 5: Image of coarse aggregate being weighed

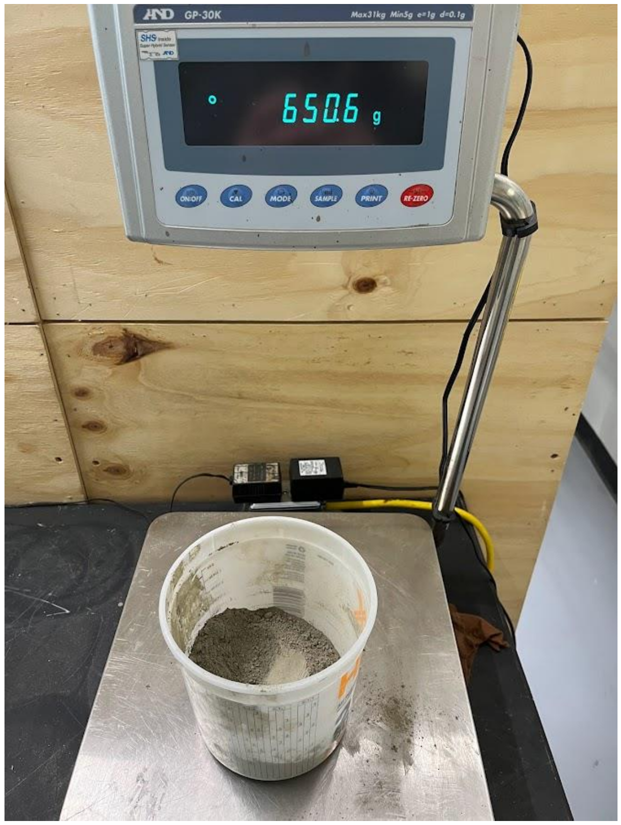

Figure 6: Image of Cement being weighed

Mix Design	**Water-Cement Ratio**	**Mass of Cement (g)**	**Mass of Water (g)**	**Mass of Gravel (g)**
1	0.250	655.7	164.4	1965.2
2	0.350	655.0	229.3	1965.4
3	0.450	655.5	294.8	1965.0
4	0.200	655.0	132.3	1965.5
5	0.275	655.0	182.1	1965.1

Table 1: *Mix Design Ratios for Mix Designs 1-5.*

	Mass of Sample (g)				
Sample #	***Mix Design 1***	***Mix Design 2***	***Mix Design 3***	***Mix Design 4***	***Mix Design 5***
1	*360.4*	*513.7*	*558.0*	*417.8*	*423.5*
2	*359.5*	*523.5*	*553.2*	*420.6*	*450.3*
3	*360.1*	*535.0*	*560.0*	*421.1*	*450.0*

Table 2: Mass of Samples for Mix Designs 1-5.

After the cement, gravel and water were weighed out, the next step in the sample production process was to combine the materials and form the concrete. A large bucket, which was cleaned in order to prevent outside contaminants from impacting the results, was used for mixing. First, 1,965 grams of gravel were added to the empty bucket.

Next, half of the water was added to the gravel. After the water was added, the components in the bucket were mixed using a power drill with a paddle attachment, ensuring that all of the gravel was dampened, as depicted in figure 7.

Figure 7: Image of gravel and half of water mix (before added cement)

Then, while the gravel was being stirred continuously, the cement was slowly added to prevent clumping. Once all of the concrete was added, the remainder of the water was added to the mix. The concrete mixture was then continuously mixed in a bucket using a power drill with a paddle attachment, ensuring that there were no clumps of cement stuck together and that the materials were mixed evenly.

Once the differing mix ratios were mixed, the next step was to replicate the conditions that the permeable concrete could be exposed to in Ethiopia. Since permeable concrete is not a major structural component of microflush toilets, it was determined that the implementation of a compressive strength test was not required. In order to determine the efficiency of the permeable concrete, it must first be determined how effective it is at filtering liquid from solid matter, which should remain on the surface.

Unfortunately, porous concrete's ability to allow liquid and other small materials to flow through it can become less effective over time. In addition, pervious concrete will collect fine minerals in the small voids in the concrete as the concrete is used. Gradually, these deposits in the concrete will slowly impact the flow of liquids through the concrete. If the concrete is to be used for filtration purposes, a determination must be made regarding the porous concrete's ability to filter the solid from the liquid waste. Unfortunately, many of the areas in Ethiopia where porous concrete is being used in this manner do not have adequate access to the technology that is commonly used to clear porous concrete such as vacuums, leaf blowers, and power washers. Therefore, determinations on how long it will take before the concrete needs to be cleaned, and whether there are materials available to the Ethiopian citizens which can be used to clean the concrete must be made.

For the test of permeability, the concrete must be put under stresses and uses similar to the concrete that is already in use in Ethiopia. First, the control experiment tested the rate at which 100 mL water was filtered through the concrete without being obstructed by the solid matter. The second round of experiments tested how long the water would take to filter through the concrete when there is solid and liquid material on the concrete, which replicated human feces and urine. Since, for sanitary reasons, actual human excreta cannot be used during experimentation, it was determined that ground bananas would be used as an adequate substitute for fecal matter, and coffee would serve as a replacement for urine. Bananas were selected due to the similar consistency, texture, and potential pH level of mashed bananas and loose human fecal matter. Coffee is selected for a similar reason, as both coffee and urine have a low pH of 5. Their slightly acidic chemical nature will impact the concrete in a similar manner, so the results should be accurate enough to those found in Ethiopia.

In the lab, a volume of 100 mL of coffee and 6 g of banana was used in order to test the porosity and clogging rate of the porous concrete. The first step in the process of testing the filtration of the concrete was suspending the concrete sample above a catch basin for the testing material. The bananas were mashed and placed on top of the concrete slab. Next, coffee was deposited onto the concrete slab in order to stimulate urination. The duration of time that passed as the coffee flowed through the concrete was recorded. This was repeated multiple times per sample, showcasing whether the time for liquid to flow through the sample increased (indicating clogging). The volume of the liquid that accumulated below the sample was measured to account for any liquid that may be trapped within the voids of the sample. Next, the solid waste on top of the concrete was collected, weighed, and compared to the original quantity to determine how much solid waste remained in the porous concrete. The efficiency of the concrete was then rated based on the rate at which liquid flowed through each sample, prior to and after the addition of solid material. The experiment setup is shown below, in figure 8.

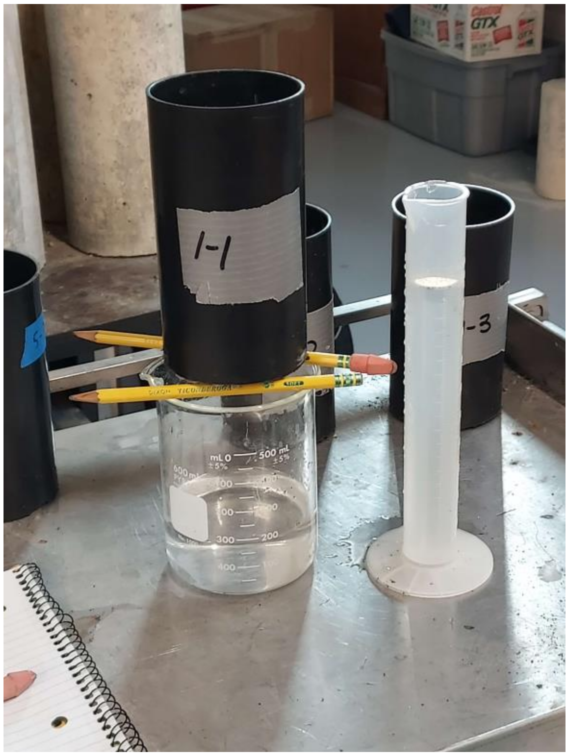

Figure 8: Basic setup for porosity & clogging tests

Based on the results of the aforementioned tests, a written instructional manual was produced, detailing what was found during experimentation. The manual is a document with a tabulated format, with written instructions on the right and associated images of each instructional step on the left. If porous concrete is found to be a suitable replacement for wire mesh as a filter, the manual details how to produce a consistent mix, in order to create the mix that was found to be most effective for filtration, strength, and longevity. If porous concrete is not found to be a suitable replacement, the manual will detail what was found to be the most effective, and state why this mix is still not adequate enough to be utilized for filtration. If an alternative solution is discovered for filtration, the manual will also discuss this alternative.

Based on the experiment results, a decision was made to test an alternative filtration tool, window screen mesh. In this experiment, a mesh layer was suspended using a PVC cylinder, under the same conditions as the porous concrete. Using 300 mL of coffee and 6g of banana, enough to cover the surface of the mesh, the coffee was poured on the concrete. In three separate tests, 100 mL of coffee was poured each time on the mesh and very quickly flowed through into the container below. In each part of the experiment the coffee flowed through the mesh almost instantly. In between each experiment the banana was adjusted so that it covered the entire mesh, but in any area where there was a smaller layer of banana the coffee was able to flow through.

Results

To gather more information on porous concrete, emails requesting an interview were sent to professional concrete producers and construction companies in Massachusetts. While there are porous concrete mix ratios online, companies with 10+ years of experience in mixing and producing concrete were expected to give further input on specific situations and complications not mentioned on the internet. A total of 12 emails were sent out before receiving a response from Sterling Concrete, who “offers comprehensive commercial and residential ready-mixed cement for poured foundations, walls, driveways, and sidewalks – along with flowable fill, concrete blocks and more.”[20] Mick Albro and Micheal Sheehan from Sterling Concrete graciously came to WPI and met for an hour to discuss the project and offered multiple solutions. Ultimately, after considering multiple methods to reduce clogging of solid waste in the porous concrete, the agreed upon solution was to focus on cleaning the voids in the concrete as it won't matter how the concrete is made or what ratios are used, clogging will always be an issue. Some other recommendations they had were to use viscosity modifying admixtures (VMA) which are used to increase the strength in porous concrete and increase the bond between cement and aggregate.[21] While this is a good suggestion, it is to be assumed that VMAs are not readily available for the intended users in Ethiopia, due to the cost increase they cause to concrete production. Void size was also discussed as smaller voids would lead to less waste entering and clogging the pores, however, larger voids would be easier to clean. They also reassured that well water was okay to use as they use it on jobs when it's available. Lastly, they came up with a solution to collect the liquid waste, flip the concrete slab over and use it to flush out the solid waste caught in the voids to save water. While this method does not have the

[20] “Experience: Sterling Concrete: Massachusetts.” *Sterling Concrete*, 27 Feb. 2021, https://sterlingconcrete.net/about/experience/.

[21] “Viscosity Modifying Admixtures (Vmas) in Concrete.” *The Constructor*, 3 Dec. 2018, https://theconstructor.org/concrete/viscosity-modifying-admixture-vma-concrete/5903/.

same force as a pressure washer might have, the typical method of cleaning, flipping over the concrete slab allows for the liquid to push the solid through the voids that it already fit through, instead of forcing it through the rough edges the waste is getting caught on, thus requiring less force. Given the design of the toilet and slab, this option does not appear to be easily implementable, as the current design does not allow for easy access to the concrete slab to be turned regularly. In a future iteration or design of the microflush toilet, this idea could potentially be revisited, but the redesign of the entire microflush toilet was beyond the scope of this project.

When creating concrete samples to be tested, not all of the chosen mix ratios were set. Once both Samples 2 and 3 set, it was observed that the mix ratio had too high of a concentration of water, and no voids for liquid to pass through, causing the concrete to be non-permeable. Inversely, Sample 4 did not set at all, which is believed to be due to that mix design not having a high enough water content (0.20 water-cement ratio). Using these samples as the upper and lower limit for the water concentration, it was possible to mix four more samples between these limitations which all concluded in porous concrete. For the basic permeability test utilizing only water and no solids, sample 1 (0.25 water-cement ratio) took 7.41 seconds on average to have 100 mL of liquid flow through it. Sample 5 (0.275 water-cement ratio) had an average of 4.40 seconds to have 100 mL flow through. Since samples 1 and 5 did pass the basic permeability test, they were utilized for future porosity and clogging testing. These test results can be seen below, in table 3.

	Water porosity test (100 mL of water) Rate of Filtration (seconds)				
Sample #	***Mix Design 1***	***Mix Design 2***	***Mix Design 3***	***Mix Design 4***	***Mix Design 5***
1	10.38	not porous	not porous	did not set	5.03
2	5.94	not porous	not porous	did not set	3.61
3	5.91	not porous	not porous	did not set	4.57

Table 3: Basic porosity test results.

For tests involving substitutes for urine and fecal matter, multiple trials were conducted with liquid to simulate constant use of the microflush toilet onto already existing waste. In order to replicate the conditions of actual usage, the banana was crushed and pressed against the concrete in order to cover the entire concrete sample. For the first sample, liquid flow stopped relatively quickly, clogging up before the first 100 mL of liquid passed through. After adding 300 mL of water to the sample, 175 mL of the 300 mL managed to flow through the sample before flow slowed significantly, almost to a complete stop. For sample 5, the sample performed significantly better, having 285 mL of the 300 mL flow through before significantly slowing down to essentially no flow. These results can be seen below, in table 4. While this shows promising results, it does still show some clogging, showing that this mix-design would likely still clog up after long-term use in an actual microflush toilet.

Sample #	Test #1 (sec)	Notes on Test #1	Test #2 (sec)	Notes on Test #2	Test #3 (sec)	Notes on Test #3	Final Volume/100 (mL)
1.1	47.5	After the 47.5 seconds the concrete clogged, leaving a small volume of liquid above the concrete	16.39	Flow stopped after 16.39 seconds leving roughly half of the liquid above the concrete	1.04	Small amount of liquid flowed through before the concrete completely clogged leaving the amjority of liquid above the concrete	176/300
5.1	6.57	All liquid flowed through concrete	8.05	Concrete clogged after 8.05 seconds, leaving small volume of liquid above concrete	13.31	Clogged after 13.31 seconds leaving more liquid above concrete than Test #3 of smaple 5.1	285/300

Table 4: Simulated excreta porosity test (only for porous samples) results.

Using the data from experimentation, a manual on the methods used to make porous concrete was created. The manual functions as a step-by-step instructional guide, detailing the techniques used to make a porous concrete slab with a water-cement ratio 0.275. Since the permeability test results reflect that porous concrete is ineffective for use as a filtration device for human waste, the manual serves as a guide for those who wish to repeat or change the experiment and those who wish to use porous concrete for purposes other than GSAP toilet waste filtration.

The data collected from the mesh experiment proved that the mesh is a more viable option than the concrete for waste filtration. During all the permeability tests performed by using mesh, the samples did not experience clogging from solid waste and were able to allow the free flow of the coffee.

Conclusion

Based on the results of the permeability tests that were conducted using food items as human waste substitutes, it was determined that porous concrete clogs far too quickly to be used as a filtration device in GSAP microflush toilets without the use of additional materials to assist in filtration, such as fine wire mesh. Regardless of the mix design, the porous concrete could not effectively separate solid waste from liquid waste. Although most mix designs allowed liquid to quickly flow through the voids of the concrete, once solid waste was introduced, the voids rapidly filled with the solid material, nearly completely preventing the liquid flow.

Without reliable access to highly pressurized water or advanced cleaning technology, the concrete is likely to remain partially clogged, even after unclogging maintenance. In Ethiopia, the most probable method of unclogging the porous concrete would be to lift out the concrete slab, rotate it upside down, and either allow gravity to force the solids out over time, or use some form of concussive force in order to eject remaining solid waste from the voids. This method would not prove to be sustainable, as the required frequency of maintenance would likely be multiple times per month and would require multiple people or some sort of lifting apparatus to elevate the slab from the digester bed. For the safety and health of the potential user of the GSAP microflush toilet, it is not recommended to solely use porous concrete as a filter for the toilet's digester bed.

The recommended alternative option is to implement fine mesh, such as window screening material, in the Ethiopian GSAP microflush toilet's design. The mesh is much more effective in restricting the flow of large solid particles, allowing liquid to flow and avoiding clogging. The mesh can be easily cleaned with less water and cleaning agents than the concrete would require if it were used on its own. Furthermore, the mesh does not require training to construct and can be used from recycled mosquito nets or window screens. Due to the abundance of mesh netting, its performance in permeability tests, and its cost efficiency to use and replace, it is recommended for use in conjunction with porous concrete as a filtration device for human waste in GSAP microflush Toilets.