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Feasibility of Using Pervious Concrete in Tropical Climate

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Abstract* – *Floods are one of the costliest natural disasters in the world and represent a common hazard to the Caribbean, specifically to Puerto Rico. Floods can be local, impacting neighborhoods and communities, or large-scale, impacting regions or the entire Island. Some floods develop slowly, sometimes over a day or more. However, flash floods can develop quickly, sometimes in just a few minutes and without visible rain signs. Urban development still needs to integrate water systems safely and sustainably into urban space. This article explains an alternative concrete design could reduce flood areas and address this to manage urban flood risks better. Pervious concrete constitutes an efficient best management practice stormwater management solution not just for flood mitigation, but also for water reuse.

Index Terms -concrete, pervious, floods, reuse, Puerto Rico.

I. INTRODUCTION

Pervious Concrete is an eco-friendly type of Concrete with filtration qualities, developed to decrease adverse environmental effects mainly in cities with highly developed, such as urban heat island effect, water shortage in watersheds, and the most impactful mass floods caused by runoff water from heavy precipitation events.

This type of Concrete has been implemented in some private projects in Puerto Rico. Nevertheless, it is a product that can be implemented in all of Puerto Rico, making a significant impact on the environment, unlike the Portland Concrete mainly used.

The increased urbanization in Puerto Rico has caused the land used to change from natural pervious ground into impervious layers. The impervious layers have reduced the groundwater recharge and increased the frequency of flash floods and urban heat island (UHI) effects in the San Juan Metropolitan area. One engineered way to reduce the effect of impervious layers without affecting the development can be to utilize pervious concrete pavements suitably. Pervious concrete pavements provide multiple benefits, such as increased groundwater recharge, reduced UHI effects, and a skid-resistant riding surface. However, the utilization and implementation of pervious concrete pavements in Puerto.

II. LOCAL CLIMATE

The geographic location of Puerto Rico makes it suitable for Tropical weather; the past years have unleashed a series of precipitations that cause huge floods, destroying hundreds of homes, sweeping away cars, and leaving thousands without power. On July 2013, San Juan, Puerto Rico (PR) received 36 cm of precipitation.

Unfortunately, the worst flood disasters in Puerto Rico have not been due to major events. Contrarily, many of these events do not reach a recurrence period of 5 years. As was the case of precipitation that occurred on September 19, 2011, in a parking lot located in Puerto Rico's western area. A Precipitation of 110 minutes caused great damage to many vehicles and floods in a significant number of storehouses in Mayaguez City [1].

An island such as Puerto Rico whose area is 13800 km^2, where 1488 km^2 is prone to flooding with a recurrence period of 100 years. About 11% of the Puerto Rico total area will enable major flooding.[1]

Almost 90% of all-natural disasters in the United States lead to flooding and 20% of all flooding claims happen in low to moderate flood-risk areas. [1]

Some of the flooding events in the city of Mayaguez, Puerto Rico, and the damage being made by flooding are shown in Figure 1. In this case, flood water levels rose faster, leaving less time for the people to evacuate this parking lot; on top of there not being any system for early flood warnings.

Figure 1. Flash flood in Mayagüez, Puerto Rico (Sep 19, 2011).

The Puerto Rico government has spent a large sum of money on repairing damages caused by flooding.

The most frequent types of flooding in Puerto Rico are river flooding, flash flooding, and coastal flooding. River flooding occurs when the discharge of water exceeds the river's banks and flows onto floodplains. Communities lying close to rivers and streams are most affected by river floods. Flash floods have rapid water velocity, sudden rises in water levels, and substantial amounts of debris.

Flash floods typically occur after long, intense amounts of rainfall in flat areas such as parking lots, avenues, roads, and residential development on flooding areas. In a typical flash flood, the water velocity is about nine feet per second, which is strong enough to move objects weighing around 100 pounds and is equivalent to the damage caused by 270 mph winds. Flash floods can destroy houses and roads, killing people who may be in their paths, and causing great destruction in the area established.

The last one is coastal flooding, causing severe damage along coasts resulting from wave actions. Puerto Rico has three types of rocky coastal cliffs and headlands, mangrove coast, and sand or gravel beaches; the last one is the most affected by wave actions in some cases occurring erosion and loss of coast. The loss of the coast is an optimal zone for flood-by-wave action.

Another factor in implementing pervious concrete is the soil's lack of permeability. Soil permeability is an essential property of soil classification and depends on the soil type; this affects the quantity and velocity of water infiltration, how much an area can flood, and the recovery time of an area after a flood event.

The permeability varies according to soil texture, the finer the soil texture, the slower the infiltration and low permeability. Puerto Rico has a wide range of textures ranging from fine textures, such as clayey soils, to coarse textures, such as sandy soils. A representative soil of Puerto Rico is the Bayamon Soil.

The Bayamon series consists of very deep, very slowly permeable soils on coastal plains with a fine texture and a high percentage of clay. A portion of Puerto Rico was analyzed using a soil map provided by the United States Department of Agriculture – Natural Resources Conservation Service (USDA-NRCS).

Figure 2 presents the percentages of texture in the representative area in Puerto Rico, in which the clay encompasses most of the basin area with 62.4% of the total area. This proves that the Puerto Rico soils are mainly composed of clay, meaning they have low permeability, therefore, contributing to flooding by having poor drainage.

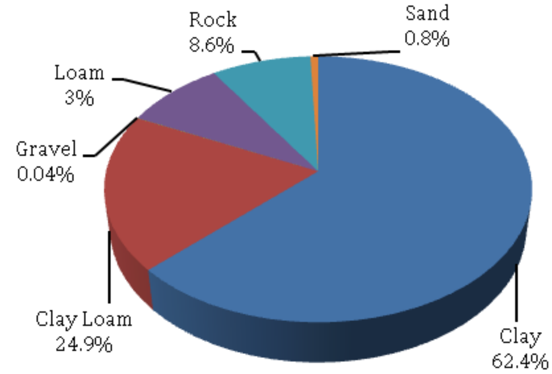

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Figure 2. Soil percent in the representative area

III. FLOOD HAZARD ZONE DESIGNATION

In recent years in Puerto Rico, the impervious construction, such as roads, avenues, and parking lots, has increased. They will also result in reduced infiltration and more rainfall turned into runoff water, producing flooding.

Most land classified by the Federal Emergency Management Agency (FEMA) as having a high risk of flooding (presumable based on elevation, slope, and proximity to the water), tends to have soils with poor internal drainage. The FEMA data determined the 100-year flood zone in Puerto Rico, as seen in Figure 3.

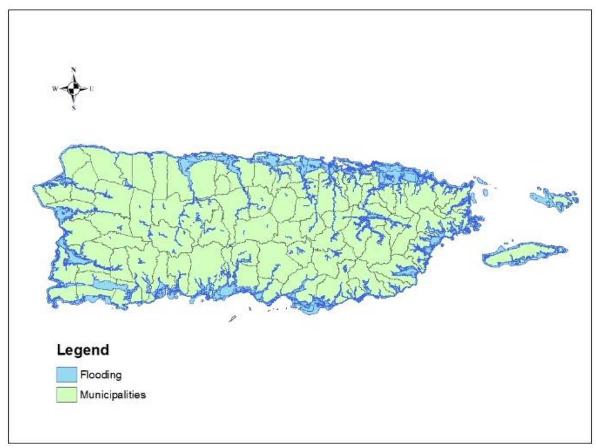

Figure.3 Puerto Rico 100-year flood zone

Recently, the Commonwealth of Puerto Rico estimates the chances of flooding in a determined area by using Flood Insurance Rate Maps (FIRMs). The maps utilize Geographic Information System (GIS) to know historical flood data and hydrological data to map floodplains according to specific risk designations. There are several different risk designations associated with FIRMs.

The major differentiation for flood zones is generated using the frequency of flooding. 100-year flood zones are likely to have a 1% annual chance of flooding or a 26% chance of flooding during a thirty-year mortgage. The Planning Board of Puerto Rico is the local agency designated to be responsible for flood management around the island. In January 2010, this agency put into effect the “Special Flood Hazard Areas Regulation” to provide more stringent measures on building within designated flood zones. No new structures may be built on floodways, there is much infrastructure located in floodplains that can still suffer damage from flooding.

In recent years, floods have become more frequent, and the use of pervious concrete is one of the solutions for these flash floods.

In January 2022 there was a flood that affected cities such as Guaynabo, Naranjito, Bayamon, Loiza, and San Juan. There were approximately 4 inches of rain left from this phenomenon, with additional causes like traffic congestion, floated cars, and damage to private property. (Figure 4)

Figure.4 Flash flood January 2022 (wapa.com) [2]

IV. PERVIOUS CONCRETE

Pervious concrete is a particular type of concrete with high porosity, used for applications on concrete surfaces that allows water from precipitation and other sources to pass through by infiltration, reducing surface runoff from a site, in the process, recharging soils – groundwater levels. This type of concrete permits water infiltration and reduction of flooding levels, also filling the aquifers with high-quality water, due to the natural soil below the pervious concrete that acts as a filter.

A Pervious Concrete is an eco-friendly type of concrete, with filtration qualities, developed to decrease negative environmental effects mainly in cities, such as, urban heat island effect, shortage of water in watersheds, and the most impactful, mass floods caused by runoff water from precipitation. This type of concrete has been implemented in some private projects in Puerto Rico, nevertheless, it is a product that can be implemented in all of Puerto Rico making a great impact on the environment, unlike the Portland Concrete mainly used.

Looking at it from a mixture perspective, Pervious Concrete isn’t that different from Portland Concrete, yet from an environmental perspective the differences are exceedingly clear. Our day-to-day concrete is mainly composed of cement, water, sand, and coarse aggregates. The cement and water are used to create the cement paste that’ll serve as a glue for the aggregates that are the ones that contribute to the strength of the concrete. Meanwhile, the sand is used to infiltrate and fill the voids created in between the coarse aggregates, consequently, adding to its strength and avoiding bubbles in the concrete which could cause internal cracks and debilitation.

Now, Pervious Concrete differs from Portland cement concrete because of its permeability; to create this permeability, it needs voids. It needs to be careful not to create an abundant number of voids since this can decrease the concrete’s strength by causing internal cracks. The materials needed to create a Pervious Concrete mixture are the same as Portland cement concrete but eliminate the sand. By eliminating the sand, the mix will be cement paste and coarse aggregates, and this gives room for the voids needed for the concrete to be permeable yet still have strength for its purpose. This concrete design requires more precision in the aggregate size and added Admixtures. If it has too many voids can cause a debilitation in the concrete.[3]

Unlike other concretes, Pervious Concrete does not solely rely on itself for strength since it goes together with a system. The Concrete’s system is the base used underneath the Concrete; this system not only helps stabilize and strengthen the Concrete’s resistance but also serves as a natural filter for the water going through it. Pervious Concrete’s system consists of three layers, the subgrade, the aggregate base, and the pervious concrete pavement.

The first layer at the bottom is the subgrade, and this layer is typically made with the same natural soil as the area of the project. In some rare cases, this layer could be changed to another type of soil if the natural soil is extremely low on permeability. The thickness of this layer is usually the largest of the three since it is the natural soil of the area. This layer must be compacted for it to be able to provide support and strength to the rest of the layers.

The second layer, which goes on top of the subgrade layer, is the aggregate base or gravel base. This layer is essential since it is a temporary storage for the water filtering through the pervious concrete.

It is composed of angular rocks; the size range of the rocks depends on the project and the subgrade layer. The angular rocks let the water filter through easily to get to the subgrade layer where they might not filter as fast. This layer must be thick enough depending on the site's average precipitation since it will temporarily retain the water that will slowly filter through the subgrade to the sub-watershed of the area.

On another case, if the site area's average precipitation is abundant compared to the filtration rate of the natural soil, an option to counter this would be to create an under-drain in the gravel layer to take some of the water to a drainage system. This under-drain is usually done with trenches and perforated pipes for when the levels of water retained in the gravel layer get too high, and they can drain without going back up to the surface and flooding the area.

Last layer and the star of the show is the pervious concrete layer. This layer is usually around six to eight inches thick, depending on the future use of this.

Its thickness makes it the thinnest of all three layers of the system. Pervious Concrete pavement is applied very differently from Portland Concrete, in fact, it is a lot more tedious. This layer must be applied by sections which will depend on the size of the project. When being applied, the worker must act fast; one should use a roller to flatten and set the surface of the layer, and another must continuously apply oil to the roller, so the working tool does not retain part of the mixture, wasting material and damaging the finished look.

After completing the application, the most important part is curing the pavement. By curing the pavement, the pavement gains more strength, and it is usually done by adding humidity to the pavement which can be done with a spray or mist equipment as well as with a hose. While adding humidity to the pavement, it must rapidly be covered with plastic for it to start the curing process. The plastic mainly used is a 6-mm thick type, preferably white or clear, never dark since because of the albedo could heat up and evaporate the humidity. The curing process is left for around a day or two since it cannot be left the preferable 28 days because of the project's deadline. After removing the plastic, the pavement and the entire system of the pervious concrete are complete and ready for use.

Pavement complete, it is easily viewed that there is an esthetical difference between the pervious concrete and the Portland regular concrete. The previous concrete appears more rustic and rougher, meanwhile, the regular concrete appears smoother and more modern. This aesthetic difference between them occurs because of the previously mentioned; the pervious concrete has a much higher porosity than the regular concrete since it needs to be permeable. Some people will prefer the regular concrete because of its clean finish and the fact that, if not designed properly or not given the proper finish, the pervious concrete can damage shoes; specifically thin heels like stilettos. The heels would get damaged because of the voids, if the voids are too big then the heels could get stuck, causing an accident. Yet, when designing pervious concrete, the use of the pavement is always taken into consideration.

Now when the Pervious Concrete is completed there is still work to be done and that is maintenance. The pervious pavement's maintenance is crucial for its durable function, unlike Portland Concrete, which is rarely maintained, and it still serves its purpose. If the Pervious Concrete is not maintained the voids in the pavement, which give the permeable properties, will clog reducing the filtration until there is none. This care must be done regularly for it to be effective, especially if the pavement is near vegetation which in Puerto Rico is very common. Maintenance for this type of pavement is frequently done by power washing and/or vacuuming to unclog the pavement's voids without damaging the pavement's finish, which a pressure hose could do.

V. DESIGN

The materials used to design a Pervious Concrete Pavement, as mentioned before, are:

<u>Cement Paste</u> – Contains water and cement.
<u>Coarse Aggregates</u> – The aggregates must be angular to create the voids needed for water infiltration.
<u>Additives</u> – Not mandatory but helpful in certain situations.

With an average proportion in water content, void content, and aggregate size of:

<u>W/C Ratio</u> – 0.3 to 0.4
<u>Void Ratio</u> – 25% to 32%
<u>Coarse Aggregate Sizes</u> – 6mm to 20mm

The proportions of the materials in the Pervious Concrete may vary depending on the project's requirements in compressive strength, filtration needed, and of course the amount of pavement depending on the project's size.

Pervious Concrete Pavement is usually implemented in parking lots and sidewalks and after some extensive research was found three different designs that could help to effectively drain the precipitation from heavy storms. Of course, this will be dependent on the developer that can plasm the design correctly.

First design analyzed, was the design specifically for sidewalks, which had these specifications:

<u>W/C Ratio</u> – 0.33
<u>Void Ratio</u> – 10%
<u>Compressive Resistance</u> – 17.47 MPa
<u>Coarse Aggregate</u> Sizes – 2.8mm

The second design analyzed was designed specifically for the City of Chiclayo in Peru, which contained [4]:

W/C Ratio – 0.3
Void Ratio – 27.5%
Coarse Aggregate Sizes – ¾ inches (19.05mm)
Additive – 500 mL of SikaCem (Plasticizer)

Third and last design utilized in our research was a Pervious Concrete Pavement with recycled aggregate to help the environment, containing:

Water Permeability – 8.5 mm/s
Porosity – 20%
Coarse Aggregate Replacement for Waste Materials – 15%
Coarse Aggregate Sizes – 5mm to 13mm

Now our design in Puerto Rico was taking into consideration the climate and precipitation capacity of the island. Considering these while working with Segarra Engineering and Consulting Group, PSC [5]; specializes in pervious concrete. The design batch was the next:

W/C Ratio – 0.31
Void Ratio – 18%
Coarse Aggregate Size –3/8 inches (9.5mm)
Additive – MasterMatrix VMA
Additive – GLENIUM 3030

In the Figure 5 it is possible view the design made in this research in which the estimated filtration rate is 2 cm/sec. this rate is considered optimal for the elaborated design. The samples in this test were made in slab and cylinder shape since it is convenient for testing.

Figure.5. Pervious concrete Slab and cylinder

After the sample curing, the next step was testing the slab, Figure 6. In the first trial obtained, the result shows a percentage of voids higher than expected; the infiltration would be faster.

The higher void percentage could be a cause of the compact method being used. In this case, with pervious concrete, it is challenging to maintain trough out the many samples, so it is preferred to avoid compaction and apply the mixture into molds similarly.

After obtaining the samples, they must test them and define infiltration rate and aggregate gradation.

The first experiment of filtration rate used the Pervious Concrete slab seen in Figure 6. This sample was first saturated to simulate the beginning of precipitation before its regular rate of infiltration

Figure.6. Pervious Concrete Slab

After saturation, another test was decided to experiment with 100ml of water, Figure 7. Was used this amount of water and poured onto the slab. The experiment was done several times, obtaining a similar result in all.

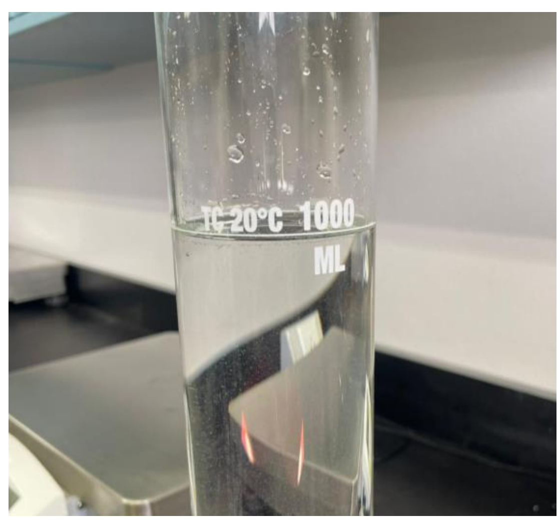

Figure 7. 100ml of Water Used in the First Experiment

After saturation, the result for the first experiment of filtration rate concluded in filtration of steady rate water after 5 seconds of pouring continuous water onto the slab. This filtration rate, although fast, is excellent for the island considering the climate and the average precipitation levels. If this design is used, depending on the subgrade layer of the system, the gravel layer might need a few extra inches since the filtration will likely be faster than the infiltration in the subgrade layer.

In the second experiment, a sieve gradation was done of the coarse aggregate used in the mixture for the Pervious Concrete samples. The indications stated that the aggregate was a 9.5mm average size, so in deciding the range of sieves to use, the result showed six, which were ¾ inches, 3/8 inches, No.4, No.10, No.20, and No.200, see Figure 8.

Figure 8. Tower of Sieves Used in the Aggregate Gradation

The sieve analysis was made by weighting all the sieves and pan individually, then adding the remains of the same aggregate used in the mixture in the test and putting the tower of sieves in a sieve shaker for better results. The shaking process took around 5 minutes and then was took the tower out and weight the sieves and pan individually again to obtain the weight of the retained aggregate in each sieve. From the start of the second round of weighting it was clear which sizes were the large majority in the aggregates, No.4 and No.10. see Figure 9 and Figure 10.

Figure 9. Sieve No.4 with the Aggregate Retained from Sieve Test

Figure 10. Sieve No.10 with Aggregate Retained from Sieve Test

In the second experiment, we took the weight data of the first weighted sieves and subtracted them from the second weighted sieves with aggregate to obtain solely the aggregate's weight retained per sieve size. With this information, was calculated the accumulative weight of the aggregates being retained, the passing-through weight, and the passing-through percentage (%) which was used for the chart below for analysis, Figure 11.

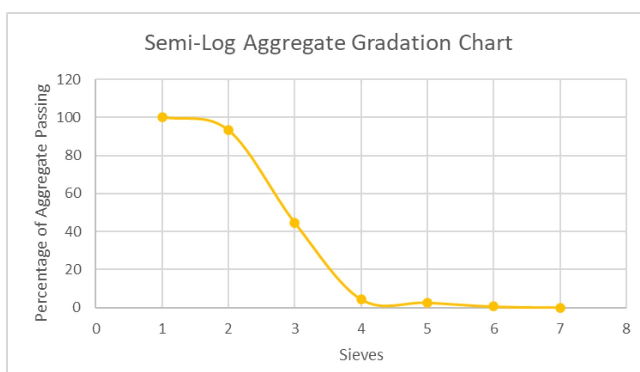

Figure 11. Semi – Logarithmic Chart of the Gradation of the Aggregate Used in the Mixture

Pervious Concrete sample had an average size of 2mm to 4.75mm. As it is possible to see in Figure 11, most of the passing percentages were at sieves 3/4in and 3/8in to drastically go down 44% passing in No.4 and then a 4% passing in No.10, to then barely being anything else in the rest. This reinstates our findings that about 90% of the aggregate used in the mixture was 2mm to 4.75mm.

An optimization of aggregate sizes is advisable to demonstrate the correct size in the material selection [7].

VI. CONCLUSION AND RECOMMENDATIONS

Pervious concrete pavements have substantial benefits, such as maintaining a more natural hydrological balance and reducing the volume of runoff by trapping and slowly releasing precipitation into the ground and not allowing it to flow into drains or receiving waters. Also, it reduces the concentration of pollutants both physically, chemically, and biologically, such as bacteria, microbes, plants that grow between the paving stones, etc. Pervious concrete can cool the urban runoff temperature, reducing stress and impacting the surrounding stream or lake. Also, it is a more economical solution and helps to use less salt for parking lots to defrost in winter. It also has a useful life of 20 to 30 years.

It cannot be used on surfaces exposed to sewage, as it can contaminate groundwater. It also cannot be used on high-traffic or high-traffic streets. It is not recommended to use when the ground has a slope greater than 20%. And another disadvantage is that its permeability is lost over a long time since the empty spaces are saturated with fine materials, this requires constant maintenance.

Its permeability and porosity depend on the mechanical properties, the mixing ratio, and the compaction methods. If compaction is exceeded, it reduces its permeability by sealing the pores. the weight of the permeate is around 70% of regular concrete and is determined according to the specifications of ASTM C1688.

The use of pervious concrete is highly recommended, knowing the results, thrown in the different designs, the best behavior was obtained for a rate of 2 cm/sec, which is considered high and efficient.

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