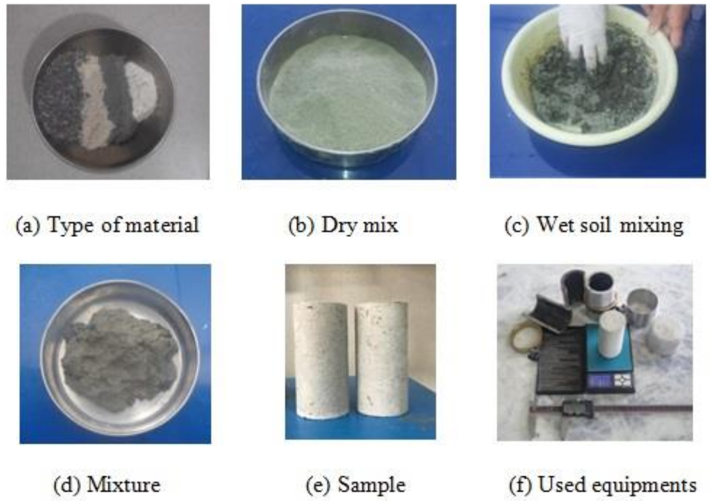

Figure 2. Sample preparation procedures

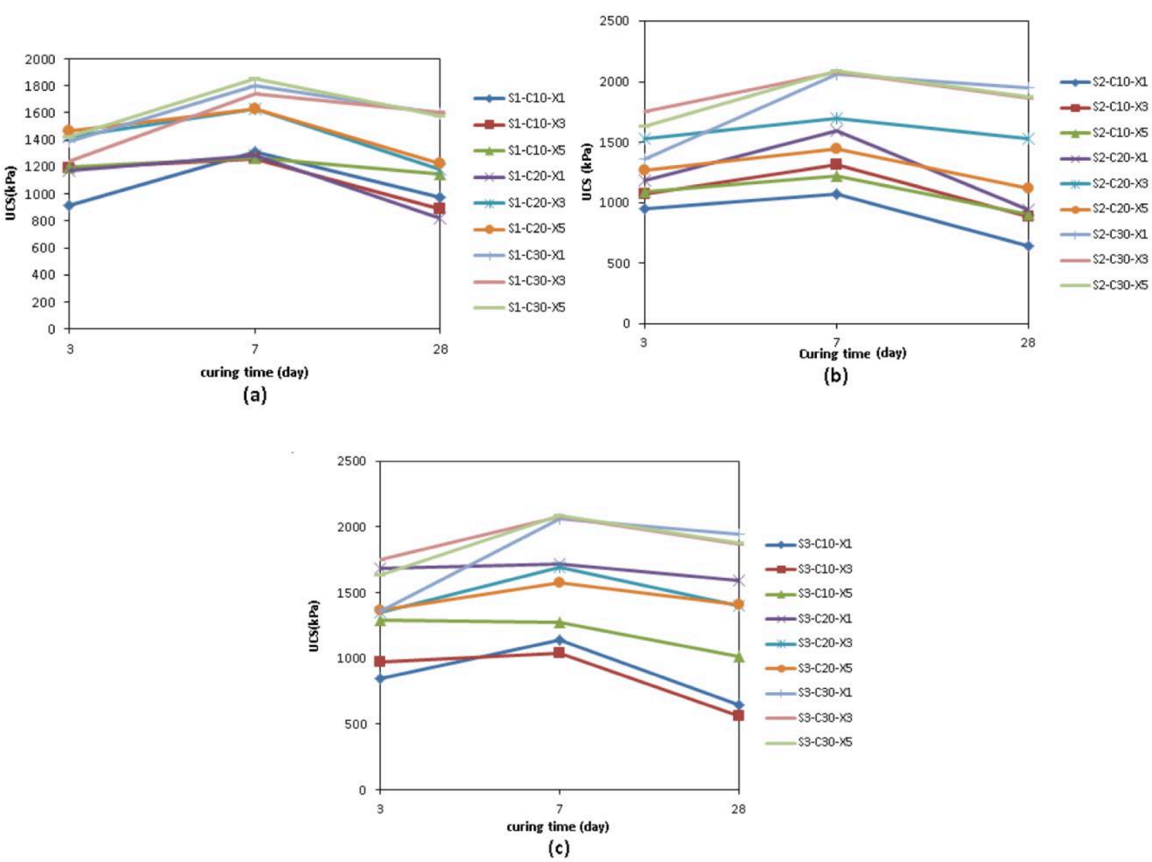

Figure 3. Effect of curing time on unconfined compressive strength of samples a)S1 b) S2 c) S3

To prepare the samples, sand and bentonite were weighted dry and poured into the container with proposed proportions. The amount of sand and bentonite in all of the studied samples were considered constant. Then additives like cement and xanthan gum were weighted and added to the soil with predetermined percentages relative to the dry weight of the soil according to Table

3. In this regard, the dry unit weight of used soils after mixing and packing was determined 11.86 kN/m^3. All materials were mixed dry carefully to achieve a homogeneous mixture. Then the mortar was sealed by adding water to the mixture with a water-to-soil ratio of 35% and mixing it for 2-3 minutes. UCS test specimens were compacted in 5 layers in molds with diameter and height of 50 and 100 mm, respectively. After 24 hours, they were removed from the mold and processed and in the open air at a temperature of 20°C (Figure 2). The permeability and the UCS tests were performed on the prepared specimen under different curing times. The specimens were cured for 3, 7 and 28 days.

Unconfined compressive strength (UCS) test

The experiments performed on the specimen in this study were performed by a controlled strain method according to ASTMD2166-66.

Permeability test

Since the permeability characteristics of the sample is one of the most important components in the selection of the mortar mixing program, the falling head permeability test was carried out on the samples using a fully automated device according to ASTM.D5084-03.The molds used in the test had a diameter and height of 68 and 50 mm, respectively. Samples were processed at 20°C and subjected to permeability tests in the prescribed conditions.

RESULTS AND DISCUSSION

Unconfined compressive strength test

The effect of curing time on the strength characteristics

The results of soil 1 (S1) with various values of cement and xanthan gum for the curing times of 3, 7 and 28 days are shown in Figure 3. It can be found that with an increase in curing time up to 7 days, the UCS of the samples increased, and from 7 to 28 days, the strength of specimens decreased. This can be attributed to hydration of cement up to 7 days. After drying of samples from 7 to 28 curing days, the rigidity of bonds between the additive materials and soil reduced ductility and behavior of the samples changed from ductile to brittle state.

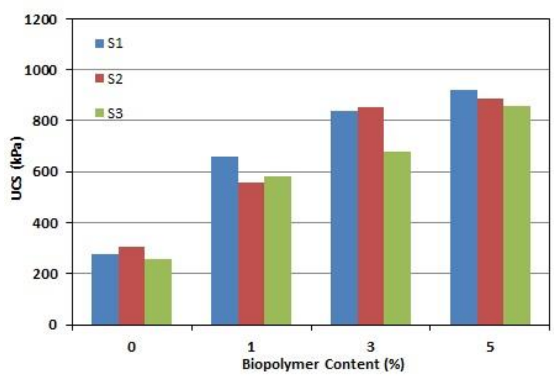

Figure 4. Effect of biopolymer addition on UCS of samples after 7 days curing time

The effect of the biopolymer addition on the strength characteristics

The variations of compressive strength of all three types of soil for different values of biopolymers after 7 day curing time is shown in Figure 4. It is observed that with increasing the amount of biopolymer, similar to Cabalar et al. (2018) the UCS of soils increases, such that by adding 3% of the xanthan gum, the unconfined compressive strength is at least 2.65 times the plain soil. This increase is higher for the composition of soil 1 (S1) compared to the other two soils because the particles of bentonite in this soil can cause better hydrogen and electrical bonding between the monomers of xanthan gum and bentonite (Land 2010).

The effect of cement addition on the strength characteristics

The variations of the UCS for all three types of soil for different values of cement after 7days curing time are indicated in Figure 5. It is observed that with the increase in the amount of cement, the UCS increase in all types of soils. As it is seen, by adding, 30% of cement to soil 3 (S3), the UCS is at least 6.5 times. Also, most changes are related to S3 and it can be attributed to the higher amount of sand in its combination.

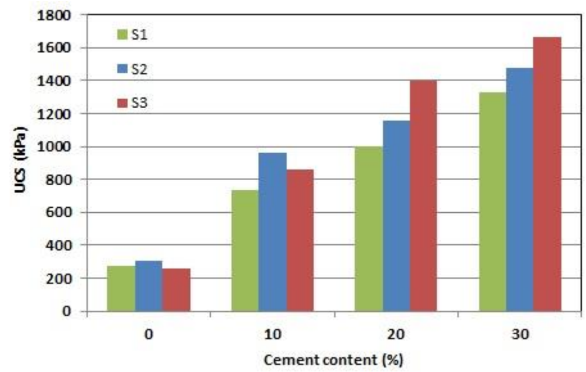

Figure 5. Effect of cement on unconfined compressive strength of untreated soils after 7 days curing

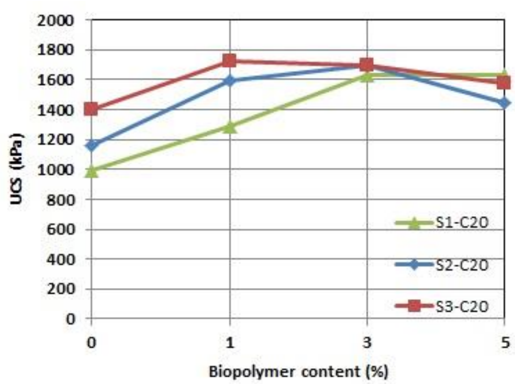

Figure 6. The effect of biopolymer content on UCS in soil-cement mixture after 7 days curing time

The effect of biopolymer addition on the UCS of soil - cement mixture

The variations of the unconfined compressive strength for all soil and % 20 cement mixtures is shown in Figure 6at curing time of 7 days. According to the this figure, the addition of xanthan gum increases unconfined compressive strength in all of the specimens due to the filling of voids and increase interlocking between the sand particles in sand adhesion by the xanthan gum gel as well as the hydrogen and electric bonds of biopolymer monomers with bentonite.

The effect of cement addition on the UCS of soil -biopolymer mixture

The results regarding the effect of cement on the UCS of soil-xanthan biopolymer mixtures showed that with increasing cement, the unconfined compressive strength of the samples increases significantly. It is found that by adding 10% cement to the mixture of S1 containing 1% xanthan gum, the UCS increased from 660.88 kPa to 1312.86 kPa.

Permeability test

The results obtained from UCS tests on untreated and treated soils after 7 days of curing time revealed that this curing time has a more considerable effective on the strength behavior of samples. So, in this study, the effect of adding cement and biopolymer on the permeability of samples was determined after 7 days curing time.

The effect of cement addition on permeability coefficient

The results of cement addition on the hydraulic behavior for untreated different soils under7 days curing time are investigated. It is noted according to Table 4 that with increasing cement content, permeability coefficient increases due to shrinkage characteristics.

Table 4.Permeability coefficient values of soil- cement mixtures after 7 days curing time

Samples	**Permeability coefficient[m/s]**		
	Curing time (7 day)		
	S1	**S2**	**S3**
Untreated Soil (S)	3.44E-9	3.45E-9	3.78E-9
S-C10	4.98E-9	5.17E-9	5.13E-9
S-C20	5.36E-9	6.27E-9	5.81E-9
S-C30	7.2E-9	7.35E-9	7.61E-9

Effect of biopolymer addition on permeability coefficient

Figure 7 shows the results of permeability experiments on different soil samples containing 10, 20 and 30% of cement, which were mixed with 1, 3 and 5% biopolymer, after 7 days of curing time. According to the mentioned figure, the addition of biopolymer decreases the permeability so that this downward trend continues up to 3% bentonite content and the permeability increases with the increase of the biopolymer. It can be seen, in Soil 1 (S1), addition of 30% xanthan gum biopolymer decreases permeability by 135%, while the addition of 5% xanthan gum reduces the permeability value by 53%. Since cement hydration causes the shrinkage and increased penetration of the soil, the addition of 3% of the biopolymer reduced the shrinkage and, as a result, the permeability decreased, that can be attributed to the water retention capacity of the used biopolymer, but with the increase of the biopolymer, joints and cracks increase due to its lack of complete reaction of soil and water due to non-reacted biopolymer in the soil matrix that caused to porous rises in the sample and increases the permeability value of the specimens (Figure8).

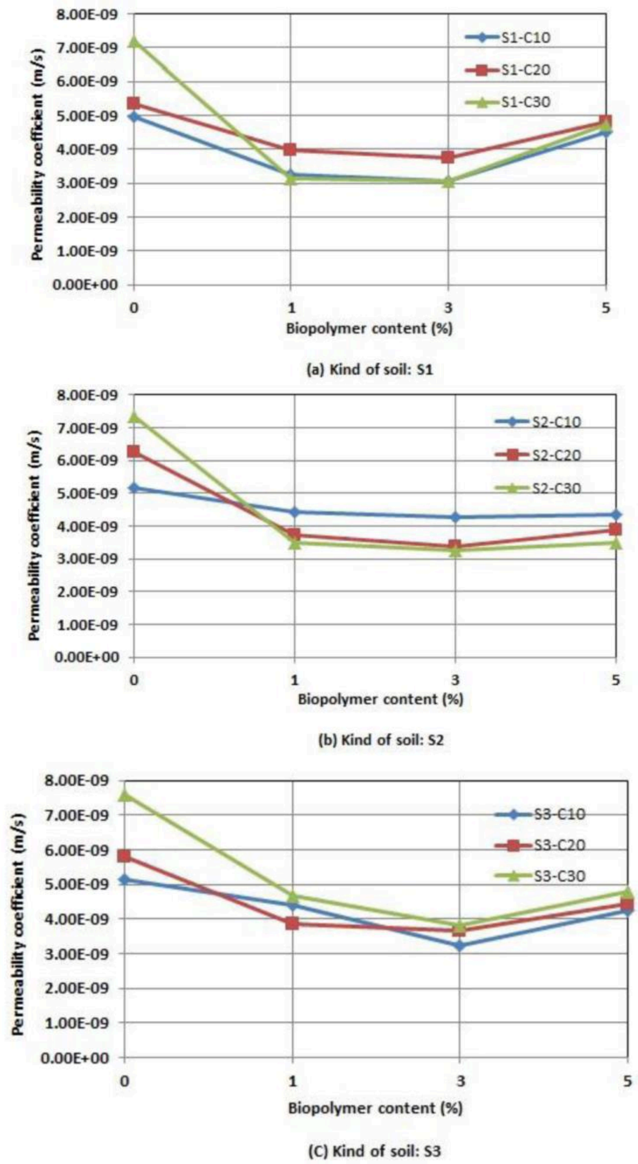

Figure 7. Influence of biopolymer addition on permeability coefficient of samples

SELECTION OF THE MOST SUITABLE MIXTURE

Among different soil compositions with cement and biopolymer admixtures, according to the derived results, the composition was chosen that had the least shrinkage, low permeability and acceptable unconfined compressive strength. With the economic considerations, among these mixtures, S3-C10-X1 was selected as the most appropriate mixture for the waterproofing mortar in channel joints due to its appropriate permeability, shrinkage rate, compressive strength and economical considerations.

Figure 8. Non-reacted biopolymer in the tested samples

CONCLUSIONS

Due to the durability problems and environmental issues of conventional materials used in the sealing characteristics of mortars in irrigation channel, this study focused to find a mixture without the common problems by using the environmentally compatible materials (biopolymer). Unconfined compressive strength and permeability tests were conducted. The following results were obtained:

1. Xanthan gum showed the greatest effect on the unconfined compressive strength of soil Type 1 (75% sand and 25% bentonite).
2. The addition of cement to the soil increased the permeability value due to shrinkage caused by the hydration of the cement. The 10 % cement additions to sand-bentonite mixture increase the permeability coefficient to 2 times under 7 day curing approximately.
3. By increasing the percentage of cement under constant biopolymer ratio, the unconfined compressive strength increases in all mixtures. The findings also reveal that each 10% additional cement resulted in 23% to 75% increase in unconfined compressive strength of samples that curing time was 28 days.
4. It was observed that unconfined compressive strength of all specimens increased in the first 7 days curing time between 2-51 %, and then decreased between 5-43 % under different cement and biopolymer contents.
5. Addition of xanthan gum reduced the permeability coefficient of the untreated soil and soil-cement mixture. The biopolymer addition to 10 % cement -soil mixtures resulted in reduction in permeability coefficient between 18 to 38 % under 7 day curing.
6. The unconfined compressive strength increased in mixtures of soil, cement and biopolymer by increasing the amount of biopolymer in the studied samples.
7. In the present study, the mixture containing 85% sand, 15% bentonite, 10% cement and 1% xanthan gum biopolymer with lowest coefficient of permeability, the lowest shrinkage value and suitable unconfined compressive strength is recommended as the most suitable mixture for practical applications.

REFERENCES

Akbulut, N., and Cabalar, A.F. (2014). "Effects of Biopolymer on Some Geotechnical Properties of Sand."*New Frontiers in Geotechnical Engineering.,* 28-37.
Ayeldeen, M., and Negm, A. (2014)."Using Biopolymer Materials to Enhance Sandy Soil

Behavior."*14th International Multidisciplinary Scientific GeoConference SGEM*.
Ayeldeen, M.K., Negm, A.M., El Sawwaf, M.A., andKitazume, M. (2017)."Enhancing the behavior of collapsible soil using biopolymers."*Journal of Rock Mechanics and Geotechnical Engineering.,* 9,329-339.
Bouazza, A., Gates, W. P., andRanjith, P. G. (2009)."Hydraulic conductivity of biopolymer-treated silty sand."*Geotechnique.,*59,71–72.
Cabalar, A.F., Awraheem, M.H., and Khalaf, M.M. (2018). "Geotechnical properties of a low – plasticity clay with biopolymer." *American society of civil engineers.*
Chang, I., Im, J., Prasidhi, A.K.,and Cho, G.C. (2015)."Effects of Xanthan gum biopolymer on soil strengthening."*Construction and Building Materials*., 74, 65–72.
Kazemi, A., R., Salahshor, J., Delgosha, H.A. (2006)."Sealing materials of concrete channals(Lining) – Asphalt." *National conference on irrigation and drainage network management.*
Khachatoorian, R., Petrisor, I.G., Kwan, C., and Yen, T.F.(2003)."Biopolymer plugging effect laboratory-pressurized pumping flow studies."*Journal of Petroleum Science and Engineering.,* 38,13– 21.
Land, L. (2010)."Physical and microbial responses of dredgedsediment to two-soil-stabilizing amendments,xanthan gum and guar gum, for use in coastalwetland restoration." *Master of Science Thesis*, The Department of Oceanography and Coastal Sciences, Louisiana State University.
Latifi, N., Horpibulsuk, S., Meehan, C.L., Majid, M.Z.A., Tahir, M.M., and Mohamad E.T. (2016)."Improvement of problematic soils with biopolymer—an environmentally friendly soil stabilizer."*Journal of Materials in Civil Engineering.,* 29,1-11.
Qureshi, M.U., Chang, I., and Al-Sadarani.K. (2017)."Strength and durability characteristics of biopolymer-treated desert sand."*Geomechanics and Engineering.,* 12, 785-801.
Tabarsa, A.R., Latifi, N., Cristofer L, M., and Kalehiwot, N.M. (2018). "Laboratory investigation and field evaluation of loess improvement using nanoclay – A sustainable material for construction." *Construction and Building Materials*., 158, 454 – 463.
Taytak, B., Pulat, H.F., and Yukselen-Aksoy, Y. (2012)."Improvement of engineering properties of soils by biopolymer additives."*3rd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering*., 851-856.
Wiszniewski, M. and Cabalar, A.F. (2014). "Hydraulic conductivity of a biopolymer treated sand." *New Frontiers in Geotechnical Engineering.,* 19-27.

Post-Fire Mudflow Prevention by Biopolymer Treatment of Water Repellent Slopes

Mahta Movasat[1] and Ingrid Tomac[2]

[1]Ph.D. Student, Structural Engineering Dept., Univ. of California San Diego, La Jolla, CA. E-mail: mmovasat@eng.ucsd.edu
[2]Assistant Professor, Structural Engineering Dept., Univ. of California San Diego, La Jolla, CA. E-mail: itomac@ucsd.edu

ABSTRACT

This paper investigates geomechanics of post-fire mudflows and proposes slope erosion prevention by treating the hydrophobic soil with a biopolymer. Exposure of organic matter in shallow soil layers to high temperatures produces gasses that make soil grain surface hydrophobic. Change in hydrological process, loss of vegetation, increase in the erosion rate, flooding, and recently seen catastrophic mudslides are consequences of post-fire water repellency in soils. This study uses experimental laboratory approaches to better understand the onset of soil erosion and fluid-particle interaction in a water repellent slope. Environmentally friendly xanthan gum is proposed to treat the hydrophobic sand with a hypothesis that the highly hydrophilic biopolymer powder will balance water repellency in hydrophobic soil. Rain simulation tests are conducted on natural, hydrophobic, and treated poorly graded fine sand. It is observed that the xanthan gum decreases the rate of erosion and consequently has a potential for reducing the risk of mudslides.

INTRODUCTION

Hydrophobicity occurs due to the burning of an accumulated organic matter in soil when the by-product gasses build a water-repellent layer on soil grain surfaces during fire intervals. The amount of organic matter, soil texture, fire severity, and vegetation type affect the severity of water repellency in soil (Doerr et al. 2000; DeBano 2000). Water repellency or hydrophobicity in soil inhibits water infiltration, which results in water pooling on the soil surface and elongation of the wetting process (Doerr et al. 2000). Furthermore, soil hydrophobicity is responsible for the increase of soil erosion and forms preferential flow paths changing the hydrological characteristics of watersheds (DeBano 1981; DeBano and Krammes 1966). The rate of soil erosion can increase more than one order of magnitude in forests which have experienced wildfires, and the surface runoff and loss of protective litter can lead to significant surface erosion and catchment-scale sediment yields (Scott and Van Wyk 1990). Mudflows, triggered by rainfall, can occur suddenly and travel at high velocity. Post-fire debris flows in different locations such as Australia, United States, and Canada have caught researcher's attention to do more investigation about it. South-eastern Australia experienced a lot of landslides, mudflows and flash floods following the wildfires in the period of 2003-2009 (Nyman et al. 2011). The study indicates that short-duration intense rainfalls triggered a debris flow in the regions that were burnt with high severity. Numerous debris flow and erosion events following the fire in western-United States have been reported as well. A torrential rainfall at hillslopes of Storm King Mountain in Colorado caused debris-flow in this region, which was burned earlier by a wildfire (Cannon et al. 2001). Moody and Martin (2001) suggested initial estimates of the upper limits of runoff to predict floods after wildfires in mountainous terrain. Galena fire in Black Hills, South Dakota, Buffalo Creek fire in the Front Range, Denver, Colorado and Cerro Grande fire across Jemez Mountains, Los Alamos, New Mexico were studied for post-fire rainfall-runoff relations (Whitesides 1989; Interagency Burned Area Emergency Rehabilitation 2000; Moody and Martin 2001). Debris flows in Southern British Columbia is another example of post-fire debris flow and floods (Jordan and Covert 2009). Three different triggering mechanisms for debris flows were observed: 1) runoff-triggered debris flows, channel bed and bank erosion due to high discharge, 2) progressive sediment bulking of runoff with eroded material from water head and 3) landslide-triggered debris flows. However, in burned areas runoff-triggered debris flow due to erosion of channel by high discharge was the most common observed mechanism and it was stated that debris flow initiation mechanism in burned areas is different from the unburned areas. A rainfall simulator can be beneficial to investigate rainfall-induced erosion, debris flows and the hydrological process during rain. Several studies have used rain simulators to study different aspects of rainfall and its consequences (Asadi et al. 2011; Lora et al. 2016; Mhaske et al. 2019; Zhang et al. 2016). The similarity of the drop in terms of size, velocity, impact angle or performance similarities such as spatial uniformity, rainfall duration and intensity are considered as main categories for design considerations in proper rain simulation (Iserloh et al. 2013).

The objective of this study is to perform a laboratory investigation to better understand the triggering process of a mudflow in water repellent slopes during rainfall and to investigate the potential of using Xanthan gum biopolymer as a treatment to remediate soil erosion. Xanthan gum is a polysaccharide mainly used as a food additive and rheology modifier. Recent studies indicated that Xanthan gum strengthens granular soils by increasing the inter-particle attraction forces. Moreover, Xanthan gum increases the ability of soil to hold water (Chang et al. 2015). Laboratory triaxial tests performed by Lee et al. (2019) indicate the higher overall shear strength in xanthan gum-treated soil.

METHODOLOGY

1. Experimental Setup

A laboratory-scale rain simulator is designed and built to study the soil erosion and mudflow in hydrophobic slopes. The experimental setup shown in Figure 1 is built in the Geomechanics laboratory of the University of California San Diego. The rain simulator setup is built of three parts: an acrylic sand box, pumping system and a nozzle, and a supporting PVC frame. Rain intensity, flow rate, and spatial uniformity are considered as the most important factors for controlling rain simulations and investigating surface erosion mechanisms.

An acrylic box with dimensions of 30 x 120 cm is built with a depth of 20 cm. 15 cm out of this 20 cm from the bottom is used to prepare the sand layer and 5 cm remaining part is allocated for runoff observation. The box is divided into two flumes. Holes are drilled with a diameter of 0.5 cm and a spacing of 10 cm at the bottom plate to allow the water to drain. At the end of each flume, an acrylic runoff funnel is attached to collect the water and sand particles. To produce the slope, two support angle steel frames are built and fixed to hold the box inclined. The slope of the box can change by changing the height of the steel frames. In this investigation, the angle of slope is fixed to be 20°.

A 0.635 cm diameter tube connects the nozzle to the pumping system. The pump is a 1/12 horsepower electric pump which has a maximum flow rate of 1.36 m^3/hour. Three different nozzles are tested to choose the best nozzle that gives the target rain intensity and the best spatial uniformity. The rain intensity is selected based on the 13 mm in five minutes rain intensity reported for the recent rain in Santa Barbara County which caused a mudflow in this area. (Schleuss et al. 2018). The nozzle used for this experiment is *BETE-WL1* full cone nozzle with a 90° spraying angle. The single nozzle is attached to the center of the PVC support frame, above the center of the acrylic box at a height of 1.5 m as shown in Figure 1. The target rain intensity is 16 cm/hour and the flow rate needed for this intensity is 0.1 m^3/hour with a pressure of 68.9 kPa.

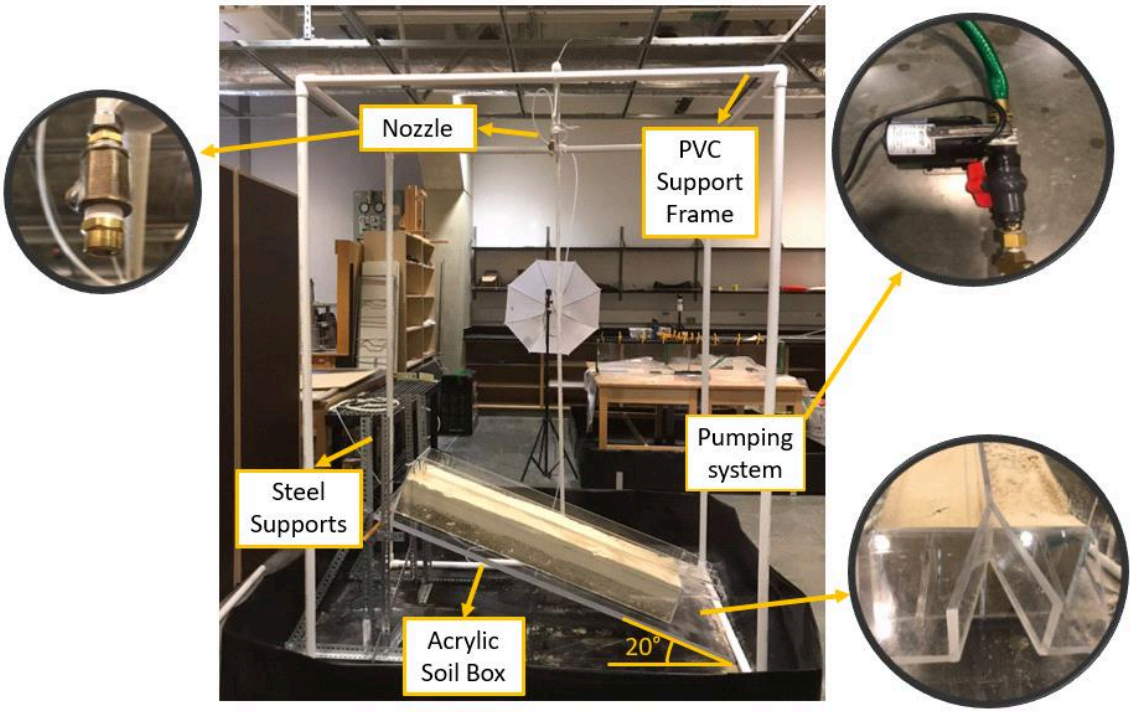

Figure 1. Experimental setup of the rain simulation experiment.

A PVC frame is built with 5 cm diameter PVC pipes. The whole system is placed inside the frame. The frame performs as a support for the spraying system. The tube is attached to the frame and the nozzle is attached to the center of the frame. The nozzle height can change by changing the height of the frame's center section.

2. Sample Preparation

Ottawa F-65 silica poorly graded (SP) sand with rounded grains is used in this study. The coefficient of uniformity is C_u =1.61 and the coefficient of curvature is C_c = 0.96. According to the existing literature (Karim et al. 2018; Lee et al. 2015), to prepare the hydrophobic sand, first, the sand is oven-dried for 48 hours. After 48 hours, the oven-dried sand is submerged in a solution of 10% n-octyltriethoxysilane and 90% isopropyl-alcohol for 48 hours. The submerged sand is washed later to remove any reactive compound and oven-dried again for 24 hours. Oven-dried samples show higher water repellency compared to air-dried samples according to Lee et al. (2015). Water drop penetration test is conducted to measure the severity of hydrophobicity and the results indicate that hydrophobic sand is classified as a severely water repellent soil. Two rain simulation experiments are conducted. Each of these tests is described in detail in the following part. In both tests, four volumetric water content sensors are installed along the central line of each flume as shown in Figure 2c. The sensors are embedded in a depth of 3 cm from the