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Erosion Control of Slopes Using Paddy Straw Geomesh

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Abstract:
Erosion of newly constructed embankments due to rainfall is a regular phenomenon in which the raindrop impact leads to the disintegration of the embankment soil particles, slowly leading to slope failure. One of the erosion control measures includes market-established erosion control products made up of jute and coir. These products are useful but cost-prohibitive. Therefore, to provide a low-cost alternative for erosion control of newly constructed slopes, a handmade Paddy Straw Geomesh '6PSG-12' (6 referring to its thickness in mm and 12, referring to its 12 mm x12 mm aperture size) is indigenously developed. The field tests for estimating erosion control capabilities are cost-prohibitive and time-consuming; the various erosion control products are tested on a bench-scale level before field tests [1]. Hence, the quantification of Erosion is done using the Bench scale (laboratory) test, and validation is done by field test [2] [3]. The proposed 6PSG-12 genomes used in the present work for erosion control satisfy all required properties, viz. tensile strength, durability, etc.

'Bench-scale testing' of 6PSG-12 specimens is carried out under a 'Simulated rainfall' of known intensity using in-house developed 'drip' type 'Rainfall Simulator' (RS). The simulated rainfall is made to fall on a 'bare slope' and a 'slope covered with PSG.' The test results show that the 6PSG-12 specimens effectively control the Erosion of slope made up of 'Well-graded gravel with sand' to the extent of 91.29 %, under the simulated rainfall of intensity 130 mm/hour for 30 minutes. The erosion control products made with other natural materials like Jute, Coir, and Paddy straw are difficult to compare with each other; since these perform under different environmental conditions. Still, the erosion control efficiency of Paddy Straw 6PSG-12 Geomesh is found to be 91.29%, which is comparable with 'Jute mesh' and 'Coir net,' reported as 92% and 90%, respectively [4]. The 'Effective cover factor' of Paddy Straw Geomesh (i.e., the ratio of 'soil loss on the protected slope' to the 'soil loss on the unprotected slope') works out 0.089, which is also encouraging.

Keywords: *Paddy Straw Geomesh (PSG), Newly constructed embankment, Rainfall simulator, Laboratory scale plot, Simulated rainfall, Drop size distribution, Erosion*

I. Introduction

The Erosion of a newly constructed embankment, especially due to rainfall, is a common phenomenon in which the raindrop impacts dislocate the embankment soil particles. The accumulated runoff causes gully and reel erosion. It finally results in the transportation of soil sediments, seriously endangering the stability of the embankment. Such Erosion is controlled using Rolled Erosion Control Product (RECP), made from natural fibers like jute, coir in different forms, like woven and non-woven meshes and blankets. Such protection is necessary for the first rainy season only, as vegetation grows on the embankment in a few months, protecting the slope from Erosion in due course of time.

Although established, jute and coir erosion products possess certain disadvantages like being cost-prohibitive and possessing excessive durability. This is overcome through this work by developing a handmade 'Geomesh' using abundantly and almost freely available material 'Paddy straw.' It is also pertinent to note that the manufacturing cost of paddy straw geo mesh 6PSG-12 is as low as Rs.68/-per sq. m, as compared to Rs.120/-sq. m., for jute, and Rs.100/sq. m., for coir mesh type similar erosion control products. Hence, 6PSG-12 shall prove to be the alternative low-cost erosion control product possessing adequate required durability in just half of the cost.

Suresh Kumar et al. (2019)[5] have observed that around 23 million tonnes of paddy straw are burnt annually in the state of Punjab, Haryana, Uttarakhand, and Western Uttar Pradesh), adding huge quantities of pollutants to the atmosphere. Therefore, the Paddy Straw Geomesh would be useful not only for controlling the rain-induced Erosion of slopes of the newly constructed embankment; but also for preventing air pollution due to its burning as a conventional mode of paddy straw disposal.

Various Index properties of Paddy Straw Geomesh (6PSG-12) viz. Tensile strength, 'Drapability' and 'Durability' for its usage as erosion control material are found out after testing in accordance with respective & appropriate code/s (Halkude, S. A. and Katdare, 2014[6]; 2015a[7a], 2015b[7b]). The properties of 6PSG-12 Geomesh are found satisfactory and conform to the required standards and are shown in Table 1.

Table 1: Index Properties of Paddy Straw Geomesh

Sr. No.	Index Property	Value	Test method
1	Thickness (mm)	6.00	[8]
2	Mass per unit Area in gm/ m^2 (GSM)	1525.00	[9]
3	Aperture Size (mm x mm)	12 x 12	[10]
4	Bulk Density (kg/m^3)	170	11]
5	Specific Gravity (No Unit)	0.17	[11]
6	Tensile Strength (kN/m length)	7.70	[12]
7	Elongation (%)	15.80	[12]
8	Drapability (%) (in Dry state)	85	[13]
9	Stiffness in Dry state (Mg-cm.)	80000	[14]
10	Maximum Swell (%)	20	[10]
11	Maximum Water Absorption (% Weight Gained)	230	[10]

According to the Manual of Erosion Control Technological Council, ECTC (2006)[2], the capacity of the erosion control product, like 6PSG-12, is decided by the Bench scale (Laboratory scale) test and validated by field test. The field test being cost-prohibitive and time-consuming, is preceded by the laboratory-scale test to ascertain the erosion control usability.

The essential components of Bench-scale testing of RECPs are Rainfall Simulator (RS) and a laboratory-scale test plot. Researchers in the past have used more than 100 small portable rainfall simulators (Either 'Drip type' or 'Nozzle type') with plot dimensions, less than 5 m^2 (most of them are less than 1 m^2), to obtain erosion data with and without RECP, under controlled conditions of simulated rainfall throughout duration up to 30 minutes [15][16][17][18]. Other researchers [19] have worked with even smaller durations of 5, 10, and 20 minutes for simulated rainfall in laboratory-scale erosion experiments. Studies have also pointed out that there is no standardization of rainfall simulation in the category of small-scale portable rainfall simulators [20][21]. Thus, the simulators differ in design, rainfall intensities, and rain spectra, making it difficult to draw a meaningful comparison between the results.

It is opined after reviewing many 'nozzle' and 'drop forming' type of rainfall simulators. The drop forming Rainfall Simulators can produce rainfall intensities up to 200 mm/hr and provide raindrop size up to 5.0 mm [22]. In another similar research, the drop-forming type of RS is generally easy to handle, portable, and can produce raindrops of size between 2 mm and 5 mm [23]. In one erosion control study, the researchers have used 1.2 mm size drippers with raindrops falling from a height of 3.0 m to produce raindrops of a maximum 3.5 mm size over a plot area of 1.3 m^2 (0.50 m x 0.26 m)[24]. These studies have further mentioned that the drop forming smaller rainfall simulators should be placed at sufficient height, preferably 3.0 m and above, to achieve the required 'terminal velocity' of the raindrop[25][26].

Hence, the bench-scale performance test on 6PSG-12 is carried out using an indigenously developed 'Drip type' rainfall simulator over the plot size of 1.02 m^2. The other parameters chosen are rainfall intensity of 130 mm/hr, rainfall duration of 30 minutes, and median raindrop diameter of 3.10 mm, falling from a height of 3.53 m, satisfying the requirements of ECTC's Manual (2006)[2]and ASTM D-7101-08[3].

II. EXPERIMENTAL WORK

Index properties viz. Tensile strength, 'Drapability' and 'Durability' of Paddy Straw Geomesh (6PSG-12) from the erosion control point of view are found out by the authors after testing as per respective appropriate codes [6][7a][7b]. The properties of 6PSG-12, conforming to the required standards, are as summarized in Table 1.

A. Soil for Laboratory Plot area

The soil used in the 'Bench scale test' is the same as that used to construct canal embankment. The engineering properties of the said soil are determined in the laboratory and are as summarized in Table 2 below.

Table 2: Properties of soil used for 'Bench scale test.'

Sr. No.	Soil Property		Value	Test method
1	Particle size distribution	Sand	30%	[27]
		Gravel	70%	
		Uniformity coefficient	6.7	
		Coefficient of curvature	1.06	
2	Optimum Moisture content (OMC)		15.76%	[27]
3	Maximum Dry Density (MDD).		1.8 kg/m^3	[27]

Considering the particle size distribution of soil (Table 2), as per the UCSC system described by researchers, the soil is classified as 'Well-graded gravel with sand'[28][29]. Disturbed soil possessing properties as shown in Table 2 is brought from the site and is compacted at 'Optimum moisture content' to attain 'Maximum dry density' as shown in Table 2 to prepare the test-bed for the Bench Scale Erosion Test.

***B. Rainfall Simulator*:** The 'drip type' of Rainfall simulator (RS), in the form of a PVC pipe grid, is designed and fabricated using 15 mm diameter PVC pipes with a grid size of 0.9 m x 0.6 m, with 2 intermediate supports. A total of 24 orifices of 1.0 mm diameter are drilled with 0.15 m c/c longitudinal spacing and 0.20 m lateral spacing. In the form of a PVC pipe grid, the details of RS are shown in Figure 1.

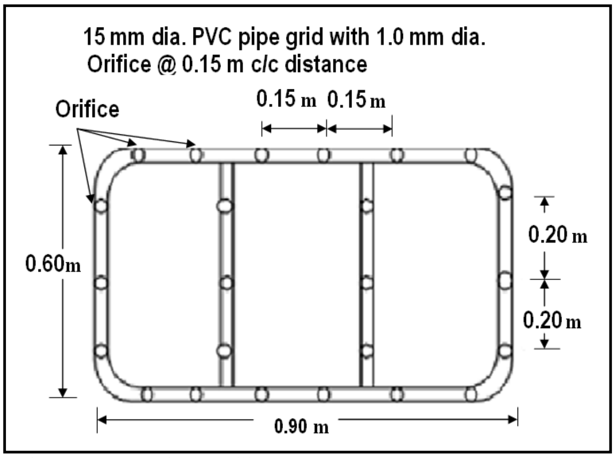

Figure 1: 'Rainfall Simulator' made up of PVC pipe grid (Plan view)

***C. Bench-scale Erosion Test Setup*:** The bench-scale erosion test set up ensuring a 'constant head water supply' and other control arrangements to produce artificial rainfall through 'Rainfall Simulator' mounted on a laboratory plot area is shown in Figure 2. The 'Rainfall Simulator' is connected to a 200-liter capacity (Tank B). The Tank 'B' receives continuous water supply from overhead water (Tank A), placed just above Tank B. Therefore, Tank 'B' has a constant depth of water in the tank at all times, thus ensuring the constant head of water over the Rainfall Simulator. The 'Rotameter' (discharge measuring instrument) is fitted between 'discharge control valve' and the flexible pipe connected to RS (PVC pipe grid) to monitor the discharge of water passing through PVC pipe grid, thereby adjusting the intensity of rainfall in mm/hr.

The laboratory-scale plot is prepared using Galvanized Iron trough of size 1.52 m (length) x 0.67 m (width) x 0.2 m (depth), having a surface area of 1.02 m^2. The trough is placed at 3H: 1V slope in a brick masonry tank, as shown in Figure 3. A rectangular steel frame structure of 3.6 m height is constructed, projecting beyond the brick masonry tank periphery for placing 'Rainfall Simulator' at different levels. Arrangements are done in such a way that the 'Rainfall Simulator' can be placed at any of the three vertical distances 1.53 m, 2.53 m, and 3.53 m between the center of the inclined laboratory-scale plot and 'Rainfall Simulator,' placed in a horizontal position. The total assembly is covered from the surrounding three sides with windscreens to minimize wind disturbance. The photograph of the laboratory-scale plot area without and with PSG is shown in Figures 3 and 4.

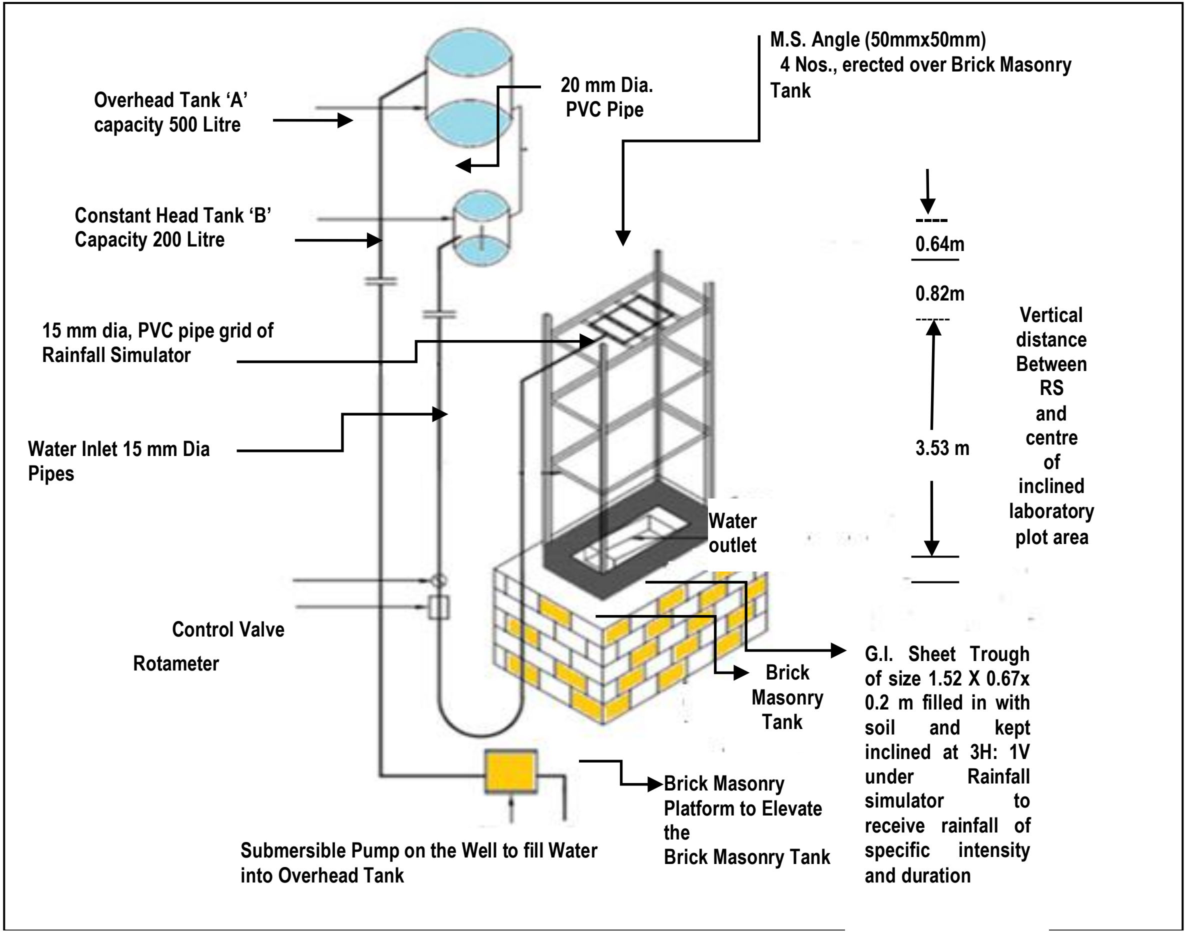

Figure 2: Bench-scale Erosion Test Set up

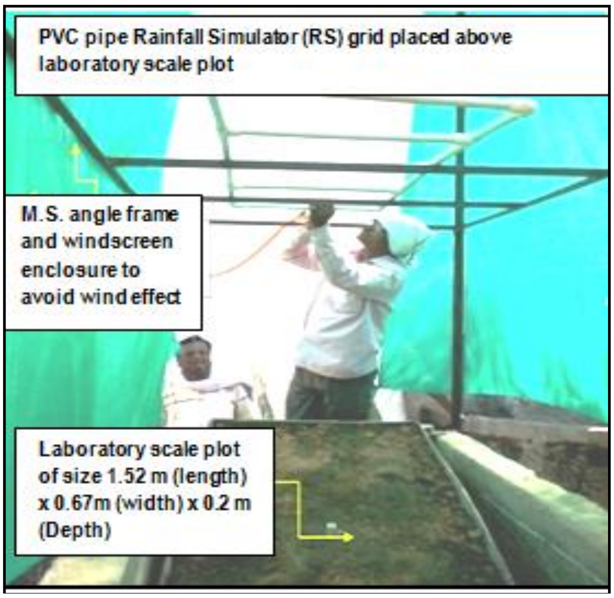

Figure 3: Rainfall simulator placed over MS angle frame over laboratory plot

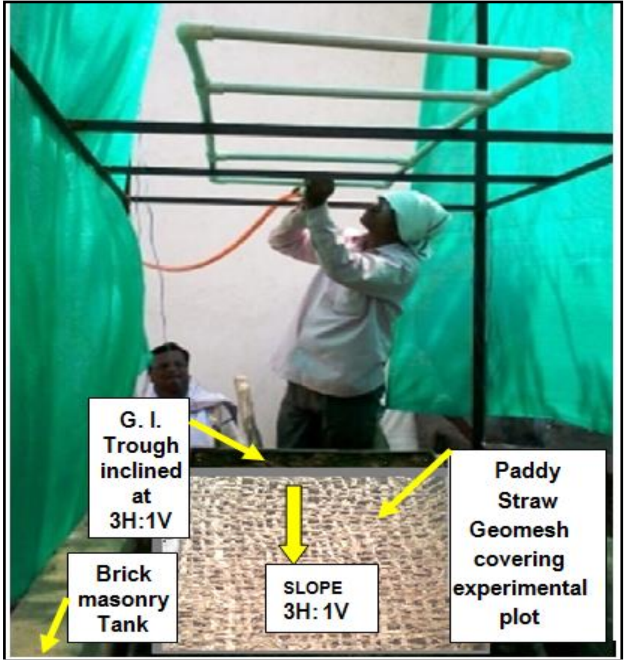

Figure 4: Paddy straw Geomesh '6PSG-12' laid over the 'Test plot.'

III. METHODOLOGY

A. Calibration of Rainfall Simulator

The 'Rainfall Simulator' is calibrated by repetitive discharge measurements, released for generating 'simulated rainfall.' The discharge is collected in a separate tank of 300 litre capacity, collecting water for 15 minutes. Three different control valve positions are set to generate three different 'Simulated Rainfall' intensities, viz. 90, 110 and 130 mm/hr. For each of these three positions of the control valve, the discharge is also verified by observing the 'Rotameter' reading fitted in the system.

B. Estimation of Rain Drop Size

The 'Flour pellets method' is used to measure the drop size distribution of the simulated rainfall[24][34]. This method consists of exposing pans with 2 cm wheat flour depth to simulated rainfall events for 5-10 seconds and then air-drying the flour pellets for 48 hours. The hardened flour pellets produced due to water contact are then sieved and weighed. The equivalent drop size (D_d) in mm with respect to the mass of a Pellet (M_p) gm is then calculated by using Equation 1.

$$D_d = 13.18\, Mp^{0.34} \qquad (1)$$

The drop size distribution curve is plotted as 'Cumulative % finer' verses 'Drop size.' The drop size corresponding to 'Cumulative 50 % finer' is obtained from the graph, known as a 'Median drop size.'

Typical calculations for estimating equivalent drop diameter for 130 mm/hr rainfall intensity and 3.53 falling height are shown in Table 3. The plot of 'Cumulative percentage finer' verses 'drop size' of simulated rainfalls of 90, 110, and 130 mm/hr falling from height 3.53 m is plotted and is shown in Figure 5.

The study of the graph in Figure 5 shows that 'Simulated rainfall' of the intensity of 130 mm/hr only is capable of producing the required median raindrop size in a range of 3.0 mm to 3.5 mm (3.10 mm in this case) and satisfies the requirements. Other combinations with the rainfall intensities 90 mm/hr and 110 mm/hr with a fall distance of 2.52 m are rejected since they cannot produce the required 'median drop diameter.' Thus, the calibrated RS in the present case satisfies the requirement of ECTC's Manual (2006)[2] and ASTM D-7101-08[3] for Bench-scale testing.

Table 3: Drop size distribution of 'Simulated rainfall' of 130 mm/hr and falling height 3.53 m

Sieve size mm	Number of pellets retained on the sieve	The total mass of retained pellets in (mg)	Average mass of the pellet (M_p) (mg)	Equivalent drop diameter (D_d) using Equation 1 (mm)
4.75	4	180.0	45.000	4.592
3.35	9	162.0	18.000	3.363
2.36	66	869.0	13.167	3.024
1.68	11	70.0	6.364	2.361
	Total= 90			

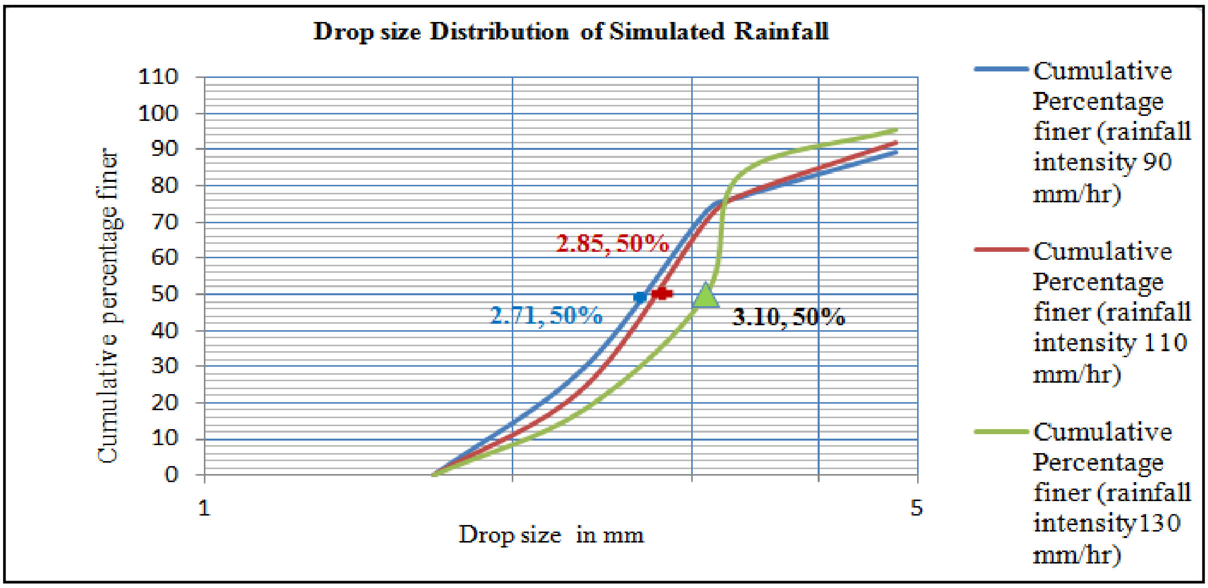

Figure 5: Drop size distribution for three rainfall intensities with a fall distance of 3.53 m

C. Spatial Distribution of Simulated Rainfall

The raindrops falling from the rainfall simulator are allowed to fall in 24 nos. of evenly spaced beakers of 100 ml capacity each. The beakers are uniformly placed at the centers of 24 marked rectangles of size 0.25 m x 0.15 m on the laboratory plot area of size 1.50 m x 0.60 m. The simulated rainfall is continued for 300 seconds, and the depth of water collected in each of the 24 beakers due to simulated rainfall is recorded.

The uniformity in the spatial distribution of the 'Simulated rainfall depth' is measured in terms of 'Christiansen coefficient (Cu),' using the standard deviation in the depth of water collected in beakers (σ) and the mean depth of water collected in beakers (μ), given by equation-2 [31].

$$Cu = 100(\,1.0 - \frac{\sigma}{\mu}) \qquad \textbf{(2)}$$

The value of (C_u) using Equation (2) is found to be 85.28%, which is more than the desired value of 84%, as mentioned in experimental work [32]. Thus, the intensity and uniformity in the distribution of the simulated rainfall are found to be satisfactory and acceptable.

D. Bench scale Erosion Test

A bench-scale erosion test is carried out for assessing the performance of Paddy Straw Geomesh 6PSG-12 for erosion control. During the bench-scale test, RS kept at the height of 3.53 m generates a 'Simulated rainfall' of 130 mm/ hr, on the laboratory plot size of 1.52 x 0.67 m, filled with soil as described earlier and set at an angle of 18.43^{0}, i.e., with a slope 3H: 1V. Initially, the test was carried out for three simulated rainfalls of 10, 20, and 30 minutes duration on the bare plot. The runoff, along with eroded soil of the plot area, was collected at the lower end of the slope and dried out to record the mass of eroded soil. The test plot was restored to its standard normal position and covered with 'Paddy Straw Geomesh.' The entire experiment was repeated to record the mass of eroded soil in the presence of PSG covering the test plot. The 'Effective cover factor (Vm),'

The ratio of soil loss from a protected slope to the soil loss from an unprotected is given by equation 3.

$$Vm = \frac{Soil\ loss\ from\ protected\ soil\ surgace}{soil\ loss\ from\ unprotected\ soil\ surface} \qquad (3)$$

E. Validation of Experimental Setup

The experimental values of various parameters like discharge passing through RS, discharge, and velocity passing through a single orifice, drop diameter of raindrops for 130 mm/hr rainfall intensity of simulated rainfall, generated by RS are shown in Table 4.

Table 4: Hydraulic Parameters for validation of the Bench Scale Erosion Test

Sr. No.	Hydraulic parameter and requirement	Requirement as Per ASTM D-7101-08	Hydraulic Parameters of Experimental setup	Method/ Equation used
1	Intensity of Rainfall	130 mm ± 5 mm/ hr	130 mm/ hr	Calibration and actual measurement
2	Drop distance of rainfall	Minimum 2.0 m	3.53 m	Actual measurement
3	Rainfall duration	30 minutes	10, 20 & 30 minutes	
4	Raindrop size	Median diameter 3.0 mm to 3.5 mm	3.10 mm	Flour Pellet Method and Equation 2

Table 4 shows that all four hydraulic parameters viz. intensity of rainfall, drop distance, rainfall duration, and raindrop size are achieved as per ECTC's criteria in the bench-scale test setup using Rainfall Simulator. This also satisfies the natural rainfall characteristic described by researchers [25], which states that the median drop size increases with increasing rainfall intensity.

Table 5: Calculations for the 'Kinetic Energy of the storm.'

Sr. No.	Hydraulic parameter	Equation used	Value
1	Striking velocity	$(\mathrm{v}^2 = u^2 + 2\, g * s)$	8.54 m/sec
2	Terminal velocity of a falling drop of 3 mm size	$Vt = \sqrt{\left[\frac{4gD}{3C_d}\left\{\frac{\rho_w}{\rho_a} - 1\right\}\right]}$	7.96 m/sec
3	The volume of simulated raindrop	$\text{Volume} = \frac{4}{3}\pi r^3$	1.414 $\mathrm{x}10^{-8}$ m^3
4	Kinetic energy (KE) of median size simulated raindrop	$(KE)\text{of median drop} = \frac{1}{2}mv^2$	0.0004476 Joule
5	KE of Storm	$(KE)\ \text{storm} = \text{kinetic energy}(KE)\mathrm{D}$ $\text{x No. of raindrops}$	2443.81 Joule

F. Kinetic Energy of a storm

The kinetic energy of rainfall measured in Joule is a measure of its potential ability to detach soil from the slope. It is estimated by first calculating the kinetic energy of each raindrop that strikes the ground surface and then multiplying it by the number of drops in the storm. The calculations of Kinetic Energy of the storm are presented in tabular form in Table 5.

In the present case, the Kinetic Energy of the simulated rainstorm, for 5209288 number of raindrops, falling for 30 minutes with rainfall intensity of 130 mm/hr, works out 2443.81 Joule. When expressed as volume-dependent (Joule m-2 mm-1), the same Kinetic Energy works out to 18.43 Joule m^{-2} mm^{-1}.

This value of Kinetic Energy is sufficient to cause splash erosion, and it is comparable with the average kinetic energies of 21 to 24 Joule m^{-2} mm^{-1}as found out by researchers [33].

G. Erosion Test on 'Laboratory Test Plot' covered by Paddy Straw Geomesh (6PSG-12)

Bench-scale erosion tests were performed on a laboratory test plot, using simulated rainfall 'without covering the test plot and 'with a cover of Paddy Straw Geomesh (6PSG-12)'. The mass of eroded soil in kg was recorded in both the cases (uncovered & covered with PSG) for three rainfall events of 10, 20 and 30-minute durations, respectively, with the intensity of simulated rainfall 130 mm/hr. The recorded mass of eroded soil in each case is tabulated in Table 6.

The performance of PSG is studied for its effectiveness as an erosion control product on the slope. Accordingly, the 'Effective cover factor' of PSG is found using Equation 3, and the values being 0.061, 0.078, and 0.087 kg/sq. M for three simulated rainfall durations of 10, 20, and 30 minutes respectively. These values being negligibly small, i.e., less than 0.1 kg/sq. m. of area, it establishes the effectiveness of 6PSG12 for erosion control. The study of Table 6 further reveals the average values of soil eroded for three rainfall durations of 10, 20, and 30 minutes covered ~~by~~ Paddy Straw Geomesh being 0.056, 0.125 & 0.175 kg/sq. m. respectively on a test plot, indicating that soil erosion increases with the increase in rainfall duration. This is due to the fact that initially, before the rainfall, the soil is in a dense state consisting of moisture @ optimum moisture content (OMC) or less. Therefore, in the initial stages of simulated rainfall, water infiltrates into the soil mass due to its 'under-saturated' condition, leading to less surface runoff, leading to lesser Erosion.

Table 6: Erosion Test Performed on the Test Plot without and with Paddy Straw Geomesh Cover

TEST NO	Mass Of Eroded Soil In 10 Minute Duration (Kg)		Mass Of Eroded Soil In 20 Minute Duration (Kg)		Mass Of Eroded Soil In 30 Minute Duration (Kg)	
	Without 6PSG-12	**With 6PSG-12**	**Without 6PSG-12**	**With 6PSG**	**Without 6PSG-12**	**With 6PSG-12**
1	0.922	0.058	1.672	0.129	2.054	0.183
2	1.041	0.062	1.736	0.134	2.173	0.192
3	0.869	0.052	1.516	0.121	1.935	0.162
Average Soil Erosion (kg) from the total test plot area	0.944	0.057	1.641	0.128	2.054	0.179
Unit Soil Erosion (kg/sq.m.)	0.925	0.056	1.609	0.125	2.014	0.175
"Effective cover factor"	0.061		0.078		0.087	
Average of soil saved from Erosion (%) due to the provision of PSG.	93.93		92.20		91.31	

However, during the long duration of rainfall, the soil mass attains complete saturation in the initial few minutes and starts losing its shear strength, causing more Erosion. Also, for rainfall of longer durations, raindrop impact disintegrates and dislocates the soil particles making them flow outward & downward along with runoff water, thus leading to more Erosion than early stages. The study also reveals that such Erosion is substantially reduced by providing 'Paddy Straw Geomesh' cover, which reduces the soil loss due to Erosion to the extent of 90% due to the reduction of infiltration of rainwater into the slope soil.

H. Experimental Results and Discussions

In general, it is observed that the Paddy Straw Geomesh (6PSG-12) enables average saving in soil loss due to Erosion to the extent of 93.93 %, 92.20 %, and 91.31 % for the rainfall event of 10, 20, and 30 minutes respectively. The Paddy Straw Geomesh 6PSG-12, due to its sacrificial quality, can be promoted as a 'Green product' as it provides a substitute to the burning of abundantly available paddy straw. It also offers an environment-friendly and sustainable solution to abundant Paddy Straw's disposal problem coming out as agricultural waste. The use of Paddy Straw Geomesh 6PSG-12 not only reduces the 'splash erosion' but also prevents further rill and gully erosion. The 'Effective cover factor' calculated for 6PSG-12 for 130 mm/hr intensity of rainfall for 30 minutes duration works out to be 0.089, which indicates the Paddy Straw Geomesh for erosion control of slopes. All above makes Geomesh 6PSG-12 a perfect alternative to use as an erosion control product.

I. Advantage in terms of Carbon Credits

The major pollutants emitted by the burning of the crop residues are CO_2, CO, CH_4, N_2O, NO_x, and SO2, black Carbon, non-methyl hydrocarbons, volatile organic compounds, and particulate matter. All these contribute enormously to global warming. One tonne of paddy straw on burning releases 3 kg of particulate matter, 60 kg of CO, 1,460 kg of CO_2, 199 kg of ash, and 2 kg of SO_2 (Gupta et al. 2004). The black carbon emitted during the process of burning residue warms the lower atmosphere. It is also the second-highest contributor to global warming after CO_2. Proposed use of Paddy Straw for manufacturing 'Paddy Straw Geomesh' for erosion control of manmade slopes will certainly help reduce substantial emission of black carbon delivering radiative energy balance of the climate system [34]. It will also reduce greenhouse gas emissions in the atmosphere, fetching a good amount of 'Carbon Credits' [35] due to this alternate usage, in place of burning of paddy straw as its conventional disposal mode.

IV. CONCLUSION

The present research work aims at promoting 'Paddy Straw Geomesh' as a low-cost erosion control product. It is concluded that the effectiveness of PSG to control Erosion of slopes is significant to the extent of @ 91%. Hence, it is established that the 'Paddy Straw Geomesh product is an alternate low-cost erosion control product, which can be used for newly constructed embankments of canals, roads, etc., in comparison with similar cost prohibitive products made of jute and coir. Therefore, by virtue of such alternate usage, it is possible to discourage incessant seasonal burning of Paddy Straw in the field, thereby leading to severe air pollution. The promotion of manufacturing and using ‘Paddy Straw Geomesh’ as a green product will also reduce its disposal problem and generate rural employment while contributing to the reduction of the ‘Carbon footprints.’

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