Sediment Trapping Efficiency of Straw and Hay Bale Barriers and Gabions

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Laboratory and field investigations were undertaken to determine the sediment-trapping efficiency of straw and hay bale filter barriers and gabions. A flume was designed and built for the laboratory portion of the study and 21 bales were tested. Trapping efficiencies varied from 46 to 88 percent; the overall average was 68 percent. No significant differences were noted in the efficiencies of straw and hay, and the bulk density and porosity of the bales correlated poorly with the trapping efficiencies. Field observations of contractor-placed bale barriers showed a high percentage of failures. Most failures were due to undercutting, end flow, and washouts. Experimental field barriers with numbers and positions based on the universal soil loss equation were installed in place of the unmodified barriers. To minimize barrier failures, loose straw was wedged under and between the bales making up the barrier, the barrier length was extended so that the bottoms of the end bales were higher than the top of the lowest middle bale, and loose straw was scattered behind each barrier. Trapping efficiencies approximating laboratory efficiencies were obtained with the experimental barriers. Gabions filled with crushed stone yielded significantly lower trapping efficiencies than straw and hay bales yielded. However, a layer of straw in the bottom of the gabion increased the efficiency to levels comparable to those of straw bales.

Because of the possible degradation of water quality in streams from sediment and the resulting adverse effects on downstream ecology, the Virginia Department of Highways and Transportation has placed a high priority on improving erosion and sedimentation controls on highway construction sites. The purpose of these controls is to provide an effective temporary means of controlling construction-generated sediment before the establishment of a permanent vegetative cover.

In Virginia, the ultimate aim of the control program is good vegetative cover, and the program includes provisions for early, staged, and temporary seeding aimed at establishing a strong stand of vegetation as early as possible in the construction cycle. Even with this maximum effort at vegetation establishment, experience has shown that significant numbers of temporary erosion and sediment control measures are required particularly during early construction activity (1). Temporary measures include various types of barriers and retention structures designed to filter and impede the flow of runoff waters. Although a number of measures have been found to be valuable, the single most commonly used measure is the straw or hay bale filter barrier (usually referred to indiscriminately as straw barrier). One can judge from visits to other agencies, field observations, and personal communications that these barriers appear to be widely used.

Despite the widespread use of straw barriers little appears to be known about their sediment-trapping efficiency. Field observations of trapped sediment and impeded storm water flow in Virginia and other states have indicated that these barriers can be effective. The level of effectiveness, however, seems to be unknown. A search of the literature turned up neither data on straw barrier trapping efficiency nor a rational method for determining the number of barriers or distribution. The purpose of this paper is to report on laboratory and field tests of the trapping efficiencies of straw and hay bale barriers. Included are discussions of common problems resulting from improper field placement and maintenance. A secondary purpose was to test stone and stone-and-straw-filled gabions in a similar manner.

The first priority in the study was to determine the level of efficiency that could be expected of bale barriers under ideal conditions. Also of interest were the relative efficiencies of straw and hay. Answers to these basic questions were pursued under controlled conditions in the laboratory.

METHOD

A test flume was designed so that sediment-laden water could be filtered through either one or two bales. The flume was constructed of 1.9-cm-thick (¾-in-thick) plywood and coated with a waterproof paint (Figure 1). For most of the comparative tests, only a single bale was used. The test followed a set procedure.

1. The bale was mounted securely in the flume and flushed several times with clear water.
2. A total of 250 liters (65 gal) of 10 000-ppm and 400 liters (104 gal) of 20 000-ppm water-soil mixtures

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Publication of this paper sponsored by Committee on Hydrology, Hydraulics, and Water Quality.

were prepared and kept in suspension by mechanical agitation.

3. A 50-liter (13-gal) volume of 10 000-ppm water-soil mixture was poured rapidly into the flume, allowed to flow through the bale, and caught in a 114-liter (30-gal) container.

4. The effluent was mechanically agitated and a depth-integrated sample was withdrawn by using a DH48 hand sampler.

5. Steps 3 and 4 were repeated 5 times with the 10 000-ppm mixture.

6. Eight runs were then made with the 20 000-ppm mixture according to steps 3 and 4.

7. The 13 effluent samples were oven dried in pre-weighed evaporating dishes and weighed to the nearest 0.01 g.

8. The average parts per million of suspended sediment for each of the 13 samples was then computed and a grand average was calculated.

With these data, the trapping efficiency of each bale was computed from the formula

$$\text{Percent efficiency} = \frac{SS_{in} - SS_{out}}{SS_{in}} \times 100 \qquad (1)$$

where SS = average suspended solids concentration.

Twenty-one bales were tested for trapping efficiency. At the same time, the porosity of each bale was determined by using measurements of bulk density (grams per centimeter^3 of the whole bale) and fiber density (grams per centimeter^3 determined by pycnometer). Porosity E of each bale was found from

$$E = 1 - \frac{\text{bulk density}}{\text{fiber density}} \qquad (2)$$

Table 1 gives the bulk density, fiber density, porosity, and percentage of sediment trapping efficiency for all bales tested. As shown by the data given in Table 1, the single bale filtering efficiency ranged from 46 to 88 percent with an overall average value of 68 percent. Double thicknesses (2 bales) were found to be approximately two-thirds more efficient in filtering than single bales. A t-test showed that no significant difference in the relative filtering efficiency of straw and hay could be ascertained from the data. Porosity appears to have a low correlation with filtering efficiency. Thus any scheme to pretest the efficiency of bales by using porosity or bulk density would likely meet with little success.

Other potentially useful observations were made during the bale tests. First, a linear decrease in the portion of the bale wetted by the water and sediment mixture was noted as the mixture went through the bale. It appears that, as the lower portion of the bale becomes clogged with mud, flow corridors are found in the higher, cleaner portions of the bale. The suspended solids retention was found to be nearly constant with each succeeding test.

Second, bales prewet and allowed to stand for several days were observed to show marked improvement in trapping efficiencies. A prewet bale was first tested in the normal way. After several weeks, it was tested again and its efficiency had increased from 74 to 98 percent. Prewetting apparently swells the individual fibers and promotes growth of fungi within the bale (if the temperature is not too low), which significantly increases trapping efficiency.

Finally, suspended sediment was noted to be removed in two ways: (a) by the filtering action of the bale and (b) by the settling out of the coarsest particles in the pond area behind the bale. This dual mechanism of sediment removal is similar to that observed many times in the field.

FIELD OBSERVATIONS

The widespread use of straw bale filter barriers in Virginia allowed observations to be made on a large number of barriers placed under a variety of field conditions. Although some barriers were observed to be quite effective, a high percentage showed a significant degree of failure due to improper initial placement or improper maintenance.

Barrier failures were noted to be mainly of three types.

1. Undercutting, shown in Figure 2, is a placement problem. It is caused by improper bale-to-soil contact, which allows storm water to run under the bale. The resulting concentrated flow tends to cut a channel under the bale. The process of channelization mobilizes sediment in addition to that generated upstream from the bale. Elimination of undercutting can be accomplished by entrenching and backfilling the bales to a depth of 5 to 8 cm (2 to 3 in) before staking or by wedging loose straw from a broken bale under the bale after staking.

2. End flow, also shown in Figure 2, occurs when storm waters flow around the end of the barrier. As in the case of undercutting, end flow can result in a higher concentration of suspended sediment downstream from a barrier than that reaching the barrier from upstream. Elimination of end flow can best be ensured by extending the barrier where possible so that the bottoms of the end bales are higher than the top of the lowest center bale. This placement forces water to pond and flow over rather than around the lower bale or bales.

3. Washouts, a third common type of failure, occur when bales are moved by high-velocity storm waters. Movement may vary from a few centimeters to distances far downstream. In either case the integrity of the barrier is destroyed and its effectiveness impaired or eliminated. Washouts can be eliminated by careful staking and limiting the use of straw barriers to low-energy flow situations.

The data given in the following tabulation provide percentage figures for the efficiency of one series of contractor-placed straw barriers:

Flow Barrier	Efficiency	Flow Barrier	Efficiency
A	+56	E	+1
B	-35	F	+25
C	-83	Average	-7
D	-1		

Flow was from barrier F to barrier A in the ditch line. Barriers were 61 m (200 ft) apart and were constructed of wheat straw. Rainfall occurred on August 4, 1974. The trapping efficiency was determined by sampling storm water downstream and upstream from a barrier by using a large plastic syringe to obtain a depth-integrated sample and by computing the percentage of efficiency as in the laboratory tests. The presence of negative numbers indicates that in some cases suspended sediment was actually higher downstream from the bales than it was in storm water reaching the barrier from upstream. In every case, high downstream concentrations were correlated with one or more of the barrier failures previously listed. Field observations indicated the presence of a few barriers partially or wholly buried by sediment. Improper maintenance is clearly indicated in these cases.

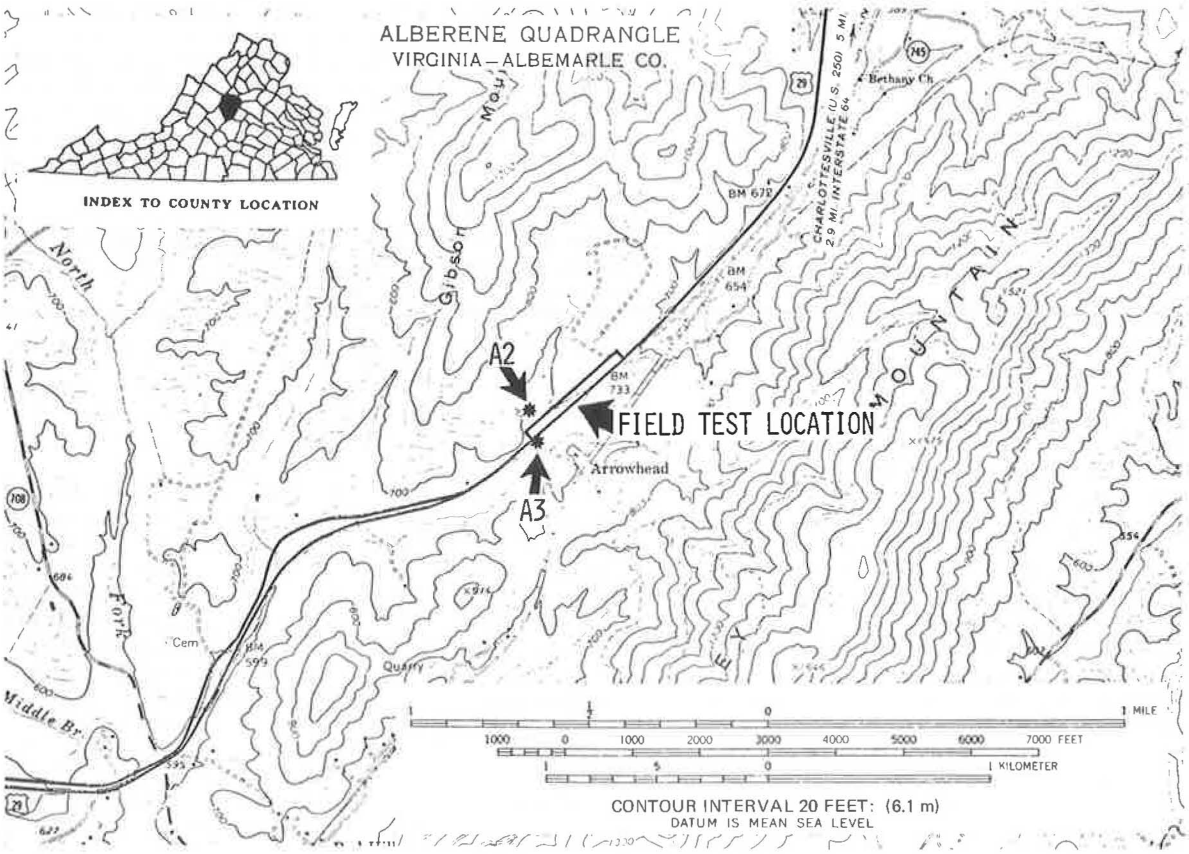
Figure 1. Apparatus for testing the trapping efficiency of a bale.

Figure 2. Improperly constructed and maintained filter barrier.

Table 1. Summary of laboratory bale tests.

Type of Bale	Bulk Density (g/cm^3)	Fiber Density (g/cm^3)	Porosity	Efficiency (%)
Hay, orchard grass	0.087	1.43	0.838	78
	0.086	1.43	0.838	78
	0.127	1.30	0.902	56
	0.124	1.19	0.894	—
	0.153	1.35	0.887	66
	0.120	1.43	0.916	64
	0.183	1.16	0.842	64
Straw, barley	0.104	1.45	0.928	46
Straw, wheat	0.094	1.20	0.921	65
	0.104	1.31	0.921	65
	0.071	1.37	0.948	62
	0.087	1.47	0.941	62
Hay, fescue	0.111	1.45	0.923	56
	0.101	1.59	0.936	71
	0.103	1.35	0.942	74
Hay, timothy, orchard mixed	0.130	1.24	0.895	88
	0.137	1.33	0.897	—
	0.125	1.15	0.891	83
Straw, oats	0.078	1.07	0.927	76
	0.089	1.16	0.924	72
	0.079	1.12	0.929	—

Figure 3. Location of field tests.



FIELD EXPERIMENTS

After observations were made of the relatively high efficiencies of straw bales in the flume experiments in the laboratory and the low efficiencies measured for straw barriers in the field, the question immediately arose, Could barriers be placed in the field that would match or nearly match the sediment-trapping efficiencies observed in the laboratory? To attempt to answer this question, we selected a test site on a project in central Virginia (Figure 3). Here, US-29 was undergoing conversion from a 2-lane to a 4-lane facility. The project proved to be ideal because it traversed moderately erosive Piedmont soils and was located close enough to the Virginia Highway and Transportation Research Council laboratories so that frequent and detailed observations of the field experiments were possible.

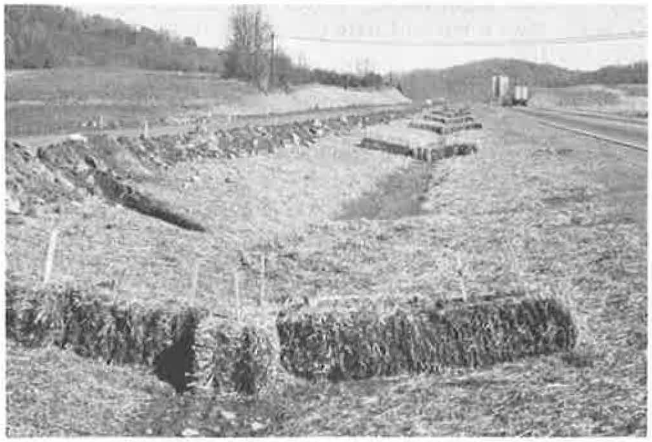
The efficiency measurements given in the tabulation on contractor-placed straw barriers were taken on a series of unmodified barriers placed on the project by the contractor. Figure 2 shows a barrier located on this project. Before the experimental barriers were placed, all of the old barriers were removed.

The number of experimental barriers to be placed per 30.5 m (100 ft) of roadway was determined by using a computer program developed by Poché and based on the soil loss equation (2). Each barrier was placed by using the criteria discussed in the section on field observations. That is, (a) straw was wedged under each bale after staking (subsequent field investigations in Virginia have indicated that a small amount of loose soil placed by shovel and lightly compacted along the upstream edge of a bale barrier eliminates undercutting and significantly aids barrier efficiency), and (b) the bottoms of the end bales were higher than the top of the lowest center bale. In addition, loose straw was scattered on the upstream side of each barrier to provide an increased filter travel length. Field observations indicate that subsequent movement of the loose straw tends to seal any undetected openings in the barrier. A typical experimental barrier is shown in Figure 4. The following tabulation gives percentage figures for trapping efficiency of barriers for storm events subsequent to placement of the experimental barriers:

	Efficiency	
Flow Barrier	Rainfall on Nov. 6, 1974	Rainfall on Dec. 1, 1974
A	67	-11
B	76	30
C	79	-5
D	98	46
E	35	37
F	64	50
G	34	19
H	28	-38
I	32	–
Average	57	16

Flow was from barrier I to barrier A in the ditch line. Barriers were 30.5 m (100 ft) apart and were constructed of wheat straw. The data from the storm of November 6 clearly indicate that the sediment-trapping efficiency of field barriers can approximate that obtained under laboratory conditions. Unfortunately, the average trapping efficiency for the storm of December 1 dropped significantly because of the failures of barriers A, C, and H. These failures vividly point out the need for constant surveillance and close attention to maintenance.

Figure 4. Experimental barriers in place.



GABIONS

Four laboratory tests were performed by using bale-sized gabions filled with crushed stone and crushed stone and straw mixtures. Two sizes of crushed stone were used: a fine mix of stone approximately 0.9 to 1.9 cm ($^{3}/_{8}$ to $^{3}/_{4}$ in) in diameter, and a coarse mix of stone 3.8 to 6.3 cm ($1^{1}/_{2}$ to $2^{1}/_{2}$ in) in diameter. The results are given in the following tabulation:

Stone Size	Without Straw	With Straw
Fine mix	32	62
Coarse mix	29	58

The straw added to the stone was placed as a 2.5-cm (1-in) layer of compressed straw in the bottom of the gabion, and crushed stone was placed on top.

Based on these experiments, stone alone apparently will yield low trapping efficiencies even at relatively small sizes. However, the efficiency approximately doubled with the introduction of a bottom layer of straw and approached the efficiency of straw and hay bales. It should be noted that relatively low flows of simulated storm water were generated in the laboratory so that much of the filtering action involved the thin straw layer. Field flows would be expected to be greater during high-intensity storm events.

Field observations of stone-filled gabions indicate a high permeability and probably a low filter efficiency. However, use in or along live streams, where straw bales are discouraged, appears to be a beneficial one for stone-filled gabions. Placement downstream from in-stream construction retards stream velocity and bank erosion and traps streambed load that may be injurious to downstream benthic communities.

CONCLUSIONS

Laboratory and field investigations were undertaken to determine the sediment-trapping efficiency of straw and hay bale filter barriers and gabions. Based on a combination of laboratory and field experimental results and field observations, seven conclusions appear to be justified.

1. Laboratory tests of a series of straw and hay bales performed in a specially designed flume yielded sediment-trapping efficiencies ranging from 46 to 88 percent and averaged 68 percent.
2. Use of the t-test showed no significant differences in trapping efficiencies between straw and hay bales.

3. A bale prewetted and allowed to stand for several days yielded significantly better sediment-trapping efficiency than a normal bale prewetted immediately before testing.

4. Normal field placement of straw filter barriers often results in failure because of undercutting, end flow, and washouts.

5. The efficiency of field barriers can approximate that measured in the laboratory if barriers are placed in accordance with the criteria used to place the experimental barriers on US-29. These criteria are (a) entrenching or wedging loose straw under staked bales, (b) extending barrier so that the bottoms of the end bales are higher than the top of one of the center bales, and (c) breaking up a bale and scattering loose straw behind each barrier.

6. Laboratory tests of stone-filled gabions showed relatively low (29 and 32 percent) filter efficiencies that were approximately doubled with the addition of a 2.5-cm (1-in) layer of compressed straw at the bottom.

7. Based on field observations, gabions appear to be well suited to in-stream use to slow stream velocity and trap bed load.

ACKNOWLEDGMENT

The opinions, findings, and conclusions expressed in this report are ours and not necessarily those of the sponsoring agencies.

REFERENCES

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