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of coarser material can be computed within very close limits.

(iv) The optimum dry density for such a mixture is then computed.

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IX b 7

SOIL STABILIZATION WITH SOFT AGGREGATES

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OBJECT.

The object of this paper is to bring to the notice of Soil Engineers of different countries, an original method of mechanical soil stabilization, fit for use in areas where gravel is not available within economic distance.

INTRODUCTION.

India is a vast country. There is immediate need to provide many thousands of miles of all-weather road in order to connect the thousands of agricultural villages with agricultural markets. Neither can the country afford to provide such large mileages of the expensive higher type of pavement, nor does the small intensity of traffic on these rural roads, warrant such heavy expenditure per mile of road. In search of a solution of this stupendous problem of a cheap all-weather road, the writer travelled through Great Britain, France, Belgium, Italy, Switzerland, Germany, Czechoslovakia, Holland, Denmark, Norway and Sweden in 1936 and 1937 and studied with the local Soil Scientists and Soil Engineers all that was being done in the field of Soil Stabilization. Even chemical stabilization of soil was ruled out on the score of cost. It was decided that Gravel Stabilization was all that India could afford.

The snag however was that gravel is not sufficiently universally available in India to allow of its use in more than a few restricted areas. The only substitute that is cheap as well as universally available is aggregate broken from burnt brick.

THE RESEARCH PROBLEM.

Experiments were carried out by the conventional gravel stabilization methods, after substituting graded brick aggregate for gravel. As was only to be expected, the brick aggregate, being comparatively soft, got its sharp corners rounded off by rubbing against its neighbours, during the vibration set up in the body of the road crust, by fast moving traffic. The effect was accentuated by the slow moving bullock cart with its high local intensity. The result was the rapid breaking up of the interlock of the coarse aggregate and consequent disintegration of the road crust. It was noticed however that the brick aggregate was reasonably strong against surface abrasion under the bullock cart and motor traffic. The research problem to be solved was therefore to provide a safeguard against the crushing of the adjoining sharp corners of the brick aggregate, through rubbing against one another due to the vibration set up in the road crust by traffic.

LABORATORY RESEARCH.

Laboratory research was started in the writer's private laboratory in the Punjab on return to India in 1938. All attempts at sufficiently improving the hardness of the brick aggregate through chemical and other treatments having failed, attention was diverted towards providing physical protection to the individual particles of the aggregate itself within the body of the crust. The quantity of graded soil in the soil-aggregate mixture, was so adjusted, that in addition to filling the voids in the aggregate, the soil also provided a thin coating round each particle. This thin coating of soil round each particle, not only acted as mortar for holding together the particles of the coarse aggregate but also prevented the adjoining bits of aggregate from rubbing against each other under traffic vibration. It had the additional advantage of acting as a shock absorber, against traffic shocks, thus doubly protecting the coarse aggregate.

It was found that the requirements of this type of soil-aggregate mixture are reasonably satisfied, if the proportion of soil and coarse aggregate is 4 parts of aggregate to 8 parts of soil, making 10 parts of mixture.

In a mixtue of this kind, there being no interlocking of the coarse aggregate, the soil mortar naturally plays the most important part and consequently careful attention has to be paid to the design of soil mixtures, keeping in view the climatic conditions and traffic requirements of the locality. In the design of soil mixtures, the writer follows the American System.

SMALL SCALE FIELD EXPERIMENTS.

A few small lengths of road totalling about five miles were constructed by this method in 1939-40 and opened to unrestricted traffic. They were inspected in April 1940 and then again in May, 1944 by the Soil Research Sub Committee, of the Indian Roads Congress. The Committee found the behaviour of these lengths under traffic, over a period of four years, so encouraging, that they recommended to Govt. of India that a full scale experiment of about 25 miles of road constructed by this method and backed by an official Soil Laboratory should be financed.

FULL SCALE OFFICIAL EXPERIMENT.

The whole of Batala-Srigobindpur Road about 17 miles long and a length of about 7 miles on the Batala-Dera Baba Nanak road in the Punjab were selected for a full scale official experiment, because there was a fair amount of mixed traffic and the soils ranged from fat clay, through fine silt to pure sand. The rainfall represented average Punjab conditions.

Work was carried out mostly by manual labour, because of its cheapness in India. The use of machinery was restricted to heavy rolling.

The various stages of design and constraction are briefly described below. These will be of special interest to countries where manual labour is still cheaply available.

a) Preliminary Soil Survey.

A visual classification of soils along the entire length of the existing earth road was done, keeping in view the behaviour of different lengths under traffic in different weather conditions. Topographical data and figures of rainfall etc. were also collected. The object of the survey was to fix the specifications.

b) Soil Sampling.

As a certain amount of banking was necessary to keep the road immune from flooding, the soil for stabilization purposes had to be borrowed from areas outside the formation width of the road.

In the alluvial plains of India, the characteristics of the soil deposits change at short intervals, and therefore soil samples are taken from fixed points which can be located when soil is to be actually borrowed.

Soil samples were taken at points a quarter of a furlong apart and 70 feet from the centre line of the road. One foot depth of soil was sampled, after removing the top loose soil, one foot being the specified depth of borrow-pits.

c) Testing of soils.

The following routine tests were carried out on each sample:

(i) Sieve analysis through Nos. 10, 40 and 200 American Standard Sieves.
(ii) Liquid limit.
(iii) Plastic limit and plasticity Index.

Table 1 shows analysis of some typical soils on the experimental roads.

d) Design of soil mixtures.

Soil mixtures were designed to the following specifications for a rainfall of about 40 inches per year:

Base Course.

Thickness - 4.5 inches of soil mixture (uncompacted)
Sand Content - not less than 50%
Plasticity Index. 4.0 to 7.5 (the lower P.I. to be used where natural soil of the P.I., with the given sand content is available. The higher P.I. to be used when a high plasticity clay is to be used in the mixture).

Wearing Course.

Thickness - 4.5. inches of (uncompacted) soil and brick aggregate mixture consisting of 8 parts soil and 4 parts aggregate.

TABLE I

Batala Srigobindpur Road-Analysis of Soil Samples

SAMPLE No.	Locality	Sieve analysis. Percentage retained on sieve				Physical Constants.		
		No.10	No.40	No.200	Passing through No.200.	Liquid limit.	Plastic limit.	Plasticity Index.
70.	M.15/1 1st Qr.	-	1.1	47.7	51.1	19.6	12.95	6.65
71.	M.15/1 2nd Qr.	-	0.9	47.6	51.4	19.78	12.9	6.88
72.	M.15/1 3rd Qr.	-	0.7	45.3	53.9	I9.03	12.8	6.23
73.	M.15/1 4th Qr.	-	9.9	48.6	50.4	18.9	12.0	6.9
74.	M.15/2 1st Qr.	-	0.4	42.8	56.7	19.4	12.4	7.0
75.	M.15/2 2nd Qr.	-	0.7	38.9	60.4	20.65	3.51	7.14
76.	M.15/2 3rd Qr.	-	0.9	42.9	56.1	20.45	13.8	6.6
77.	M.15/4 4th Qr.	-	0.9	35.6	63.4	20.1	I3.3	6.8
78.	M.15/3 1st Qr.	-	2.3	37.5	60.4	21.07	14.66	7.01
79.	M.15/3 2nd Qr.	-	0.6	37.9	61.4	20.5	13.4	7.1
		ANALYSES OF SOIL ADMIXTURES.						
Mile 16.	Admixture deposit.							
(a) M.15/1	village Kala	-	-	-	100.0	41.8	16.4	25.4
(b) M.15/1	Canal Sand	-	3.4	88.3	88.3	Non plastic sand.		
(c) M.15/7	Pond Clay	-	1.0	11.9	88.9	40.2	20.5	I9.7
Mile 17.								
M.16/5	Canal Sand	-	2.1	95.3	2.5	Non plastic sand.		
Mile 18.								
M.17/4	1½ft.below the layer near gap.	-	-	15.0	85.0	36.4	18.8	I7.6
Mile 19.								
M.18/6	1 ft.below the layer near the pond	-	-	11.8	88.1	35.0	18.1	16.9

TABLE II

Batala Srigobindpur Road

Tentative Design of Mixtures

BASE COURSE Mix.No. Locality		Designed. Plasticity Index.	Sand %
37. M.7/2 1st and 2nd half.			
Local soil(1st & 3rd Qr.) Sand M.6/6,1st half.	50% 50%	7.3	52
38. M.7/3 1st half.			
Soil M.7/3,1st qr. Sand M.6/7,1st half.	60% 40%	7.0	51
39.M.7/3. 2nd half.			
Soil M.7/3,3rd qr. Sand M.6/7,1st half.	55% 45%	7.3	55
40. M.7/4 1st half.			
Soil M.7/4,1st qr. Sand M.6/7,1st half.	50% 50%	6.9	51
41. M.7/4.2nd half.			
Local soil-7/4, 3rd qr. Sand M.6/7, 1st half.	60% .40%	7.3	50
42. M.7/5.1st half.			
Soil M.7/5,1st qr. Sand M.6/7,1st half.	50% 50%	7.2	50
43. M.7/5 2nd half.			
Soil M.7/5 3rd Qr. Sand M.6/7,1st half.	40%(screened) 60%	7.0	50
44. M.7/6 1st & 2nd half.			
Soil M.7/6 2nd or 3rd Qr. Sand M.6/7 1st half.	40%(screened) 60%	7.0	51
45. M.7/7 1st & 2nd half.			
Soil M.7/7 1st or 3rd Qr.	45%(screened) 55%	7.2	50
46. M.7/8 1st half.			
Soil M.7/8 1st Qr Sand M.6/7 1st half.	75% 25%	7.3	53

WEARING COURSE

41. M.6/8 1st Qr.			
Local soil.	100%	10.2	39
42. M. 6/8 2nd Qr.			
Local soil Sand M.6/7 1st half.	85% 15%	11.9	37
43. M.6/8 3rd. Qr.			
Local soil Pond clay M.7/1 Sand M.6/7 1st half	50% 25%(screened) 25%	11.5	34
44. M.6/8. 4th Qr.			
Local soil. Pond clay 7/1 Sand M.6/7 1st half.	60% 20%(screened) 20%	11.7	33
45. M.7/1 1st half & 2nd half.			
Local soil(1st & 3rd Qr.) Sand M. 6/7 1st half.	85% 15%	12.0	44
46. M.7/2 1st and 2nd half.			
Local soil (1st & 2nd Qr.) Pond clay 7/1 left Sand M.6/7, 1st half.	70% 5% 25%	11.5	33
47. M.7/3 1st half.			
Soil M. 7/3 1st Qr.	100%	1.6	34
48. M. 7/3. 2nd half.			
Soil M.7/3 3rd Qr. Sand M.6/7 1st half	90% 10%	12.0	42
49. M.7/4 1st Qr.			
Soil M.7/4 1st Qr. Sand M.6/7 1st half.	85% 15%	11.7	31
50. M.7/4 2nd half.			
Soil M.7/4, 3rd Qr.	100%	12.2	32

Sand Content of Soil - Not less than 33%.
P.I. of soil - 9.5 to 12.5

Table 2 shows some typical designs of soil mixtures.

e) Collections of soils.

Soils, as specified in the designed mixtures, were dug out and collected in stacks in required quantities every half a furlong; the continuous process is not practicable in India as soils change considerably at short intervals.

f) Pulverising of soils.

The soils were them pulverised separately with the backs of spades to such a state of fine-ness that about 80% of the soil is under 5/16 inch size.

In the case of fat hard clays (P.I. over 20) the pulverised stuff was actually screened through a 5/16 inch screen.

g) Dry mixing and stacking.

The different soils in the case of base course and soils with aggregate in the case of wearing course were then mixed in the dry state by turning them over with spades and shovels. After this, stacks about 15 inches in height were prepared and levelled carefully on top.

h) Checking up of mixed stacks.

A representative sample was taken from the mixed stack, and checked up in the mobile field laboratory, for correctness of P.I. and sand content. Any serious departure was set right by adding the requisite admixture soil.

i) Addition of moisture.

Optimum moisture was determined in the field laboratory and poured carefully over the stacks, small earth sides having been provided to retain the water. The water was added towards evening to stacks earmarked for laying next morning and allowed to soak down overnight.

Necessary allowance was made for evaporation losses and absorption by brick aggregate as determined by actual expermentis from time to time.

j) Laying and rolling.

After remaining in contact with moisture for several hours, the wet base course mixture was sliced off from the stacks in small lots, mixed as required and laid on the prepared subgrade with the help of templates, to a cross slope of 1 in 24.

The base course was rolled by means of light sheeps foot rollers driven by a pair of bullocks each. The intensity of pressure on the feet of the rollers was about 100 lbs. per square inch. The rolling was finished off by means of a 6 ton power roller.

The wearing course was rolled with a 6 ton power roller. Rolling was continued till the wheels of the roller made no appreciable impression on the surface. A heavy sprinkling of water was then given to the road and left overnight. In the morning the surface was again rolled to finish.

k) Curing.

The road was kept closed to traffic for 4-5 days and was heavily sprinkled with water during this period. After this, water sprinkling of a lighter nature was continued for another 10-14 days and controlled traffic was allowed to run over the road, beginning with motor traffic only and gradually extending to all kinds of traffic.

l) Treatments of Gaps.

To pass drainage water during heavy rain the road was depressed in suitable lengths, the depressions being called gaps. To protect the gaps, from damage by flowing water, they were given a black top surfacing. This was done by first giving a tack coat of cold penetration bitumen at the rate of 21 lbs. per 100 square feet and then the usual 2 coat surface treatment with 28 lbs. of tar or 35 lbs. of bitumen and 5 cubic ft. of grit per 100 square foot.

Photographs 1 - 5 show some of the above stages of construction and the road actually under traffic.

Pouring water for optimum moisture over a wearing course stack.

FIG. 1

Base course stack ready for laying after moisture has soaked through.

FIG.2

COST OF WORK.

Only a 10 ft. width of road was stabilized, the rest of the formation being ordinary earth.

The actual average cost per mile of the base course and wearing course only, including laboratory charges was Rs. 7081/- or about 530 pounds Sterling per mile. At prewar labour rates, this would work out to Rs.2600/ - or about 195 pounds sterling.

Sheeps foot roller drawn by a pair of bullocks at work.

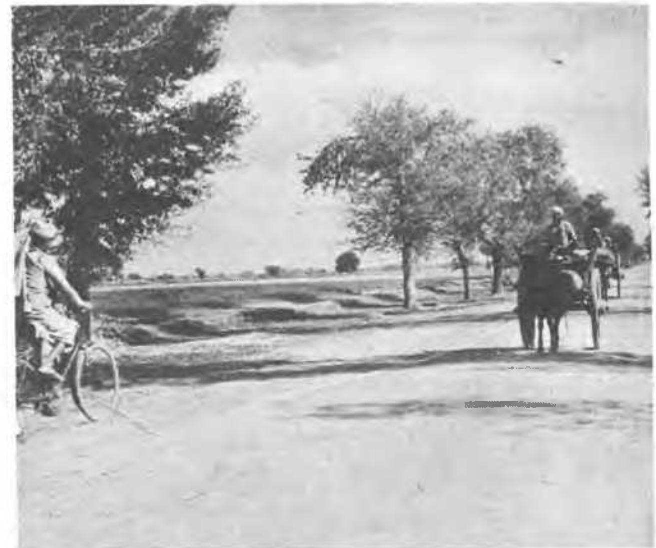
FIG. 3

Patch repairs.

FIG. 4

At prewar rates the cost of different types of standard road pavement in the Central Punjab compares as follows, with the type of road under description:

Cost per 100 square feet.	Rupees	Pounds Sterling.
a) Cement concrete slab 4" thickness	40.0	3.0
b) Water bound Macadam $4\frac{1}{2}$" stone metal over $4\frac{1}{2}$" brick soling, surfaced with 2 coats of bituminous material and 5 Cft. grit.	24.0	1.79
c) Water bound Macadam $4\frac{1}{2}$" stone metal over $4\frac{1}{2}$" brick soling.	19.0	1.42
d) Stabilized soil $4\frac{1}{2}$" mixture of graded soil and brick aggregate over a base course of $4\frac{1}{2}$" graded soil surfaced with a tack coat of cold penetration bituminous material and 2 coats of bituminous surfacing with 5 Cft. grit.	11.2	0.84
e) Stabilized soil, $4\frac{1}{2}$" mixture of graded soil and brick aggregate wearing coarse of $4\frac{1}{2}$" graded soil	5.2	0.39



A photograph of Batala Srigobindpur road, taken in August 1947, about three years after construction.

FIG. 5

MAINTENANCE.

The maintenance of this type of stabilized road is different from that of the conventional gravel road in that it does not need periodical grading with mechanical graders. All that is required is to remove the wearing course where-ever a patch occurs, mix a little water and molasses (in the ratio of 3 : 1) to bring it up to near about optimum moisture and ram it back with a hand rammer. Molasses is used to give a little extra strength to the soil to make up for the facts that it is not practicable either to determine exact optimum moisture, for each patch or to cure the small patches before opening them to traffic. It has also been noticed that the slight rutting that takes place during the dry weather gets more or less smoothed out automatically under the traffic, during the wet weather. The road thus remains almost free of ruts and pot holes and the whole section wears evenly.

It has been found that the cost of maintenance of this type of road converted into prewar rates is under Rs.150/- (L. 11.24 Sterling) per mile per annum (exclusive of bridges and culverts and roadside structures) This compares very favourably with the cost of maintenance of other types of pavement.

BEHAVIOUR UNDER TRAFFIC.

Except for small stretches totalling a little under 5% of the experimental length, the entire road has behaved very well indeed for about three years now. The Batala-Srigobindpur road has generally behaved better than the Batala Dera Babananak road. The traffic using the road is about 200 tons a day consisting of motor trucks,buses and cars as well as bullock carts and horse drawn vehicles.

The road was inspected by the Soil Research Sub-Committee of the Indian Roads Congress in December, 1945 when a large portion of the road-

has been under traffic for a year. The Sub-Committee commented as follows:
"The Sub-Committee are of the opinion that it is certain, that the unsurfaced soil stabilized road is a most promising form of cheap road construction for the light traffic prevalent on the roads which have so far been constructed and are under construction".

The road was last inspected by the writer in August, 1947 when it had been under traffic for about 3 years. After the partition of the country in August, 1947 civil disturbances started and all the labour fled leaving the road absolutely unattended for about 4 months. During the same period, very heavy refugee traffic passed over some portions of the road and according to reports received, has damaged those portions rather badly.

LIFE OF THE ROAD.

At every mile levels are being taken periodically with respect to fixed bench markes, with a view to watch the rate of wear of the road under traffic. Levels are taken at the crown of the road and also in the ruts or wheel tracks. Average of readings at six sections 20 feet apart at each mile-stone is being taken. Indications so far are that the rate of wear under a traffic of about 200 tons per day is about half an inch per year. It has also been indicated that the whole section is wearing more or less uniformly.

The thickness of the compacted wearing course is a little over three inches and it may thus be assumed that the life of this course will be 5-6 years. This type of road is however recommended for light village road traffic only. The experiment was put on a district major road in order to get accelerated results. The life of such a road crust on a village road would be much more than 5-6 years.

SUMMARY.

A method has been evolved for the mechanical stabilization of soils in areas where gravel is not available, but only softer aggregates like brick ballast are to be had. The standard grading curves for gravel stabilization are inapplicable in such a case because the particles of brick aggregate being comparatively soft will have their sharp corners rounded off by rubbing against one another in the body of the crust under traffic vibration and thus cause a rapid disintegration of the road crust from with-in by breaking of the interlock.

The method consists in so adjusting the proportions of coarse aggregate and graded soil that each particle of the coarse aggregate will have a thin protective layer of graded stable soil round it. This will prevent the aggregate particles from rubbing against their neighbours under traffic vibration and getting crushed round the corners. The suitable proportion has been found to be about 8 parts of graded soil.

The method provides a base course of graded soil and a wearing course of equal thickness consisting of graded soil and graded brick aggregate. The base course is compacted with a sheeps foot roller and the wearing course with a 6 ton power roller, the total thickness of the crust being 6 to 7 inches.

The grading of the soil is of paramount importance in this method and specifications of soil mixture for the two courses are carefully fixed with regard to local climatic and traffic conditions. The recommendations of A.A.S.H.O. are generally kept in view in fixing the specifications of the soil mortar.

Experiments over a period of eight years have shown that this type of road is an all weather road and is fit to carry all prevalent traffic on minor roads in rural areas. The cost in central Punjab per 100 square ft. at prewar rates is Rs.5-2 (£ 0.39) for unsurfaced and Rs. 11.2 (£ 0.84) for black top surfaced stabilized road, as against Rs. 19/.- (£ 1.42) for unsurfaced water bound macadam and Rs. 24/- (£ 1.79) for black top surfaced water bound macadam of similar thickness.

The road wears almost uniformly over its cross section and remains free from serious cuts and potholes. The life of the 3 inches thick wearing course, on the three year old full scale official experiment 25 miles long, is expected to be 5-6 years. The official experiment is on a district major road, whereas this type of construction is recommended for district minor and village roads carrying much less traffic and therefore expected to give a much longer life of wearing course than 5-6 years.

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IX b 8

ADAPTION OF LOCALLY AVAILABLE MATERIALS FOR USE IN CONSTRUCTION OF EARTH DAMS

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A comprehensive review of the literature on the compaction of embankment materials and the design of embankments reveals that the two subjects are not usually blended to take most advantage of the properties of soils producing the most economical design. Proctor (245) x), Woods (356), Porter (a) and many others have investigated the properties of soils so that today there is reasonably complete knowledge of how soils can be expected to react under a controlled process of compaction. Taylor (292),

x) Numbers refer to listings given in the "Selected Bibliography on Soil Mechanics" ASCE Manual of Engineering Practice No. 18. Letters refer to appended bibliography.