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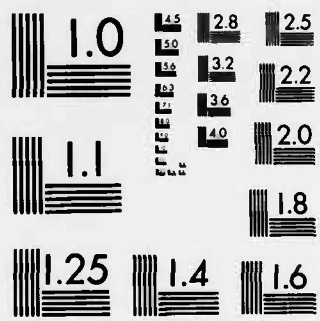

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Program Engineering &
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Washington, D.C. 20591

State of the Art Survey on Confined Base Courses for Utility Airport Pavements

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April 1983

Final Report

U.S. Department of Transportation
Federal Aviation Administration

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16. Abstract

The report reviews the state-of-the-art in the use of confining methods for loose on-site materials as a stabilizing medium for utility airport pavements. Much field experimentation on expedient types of pavements is in progress by some Federal and State agencies, but a theoretical base has not yet been developed for predicting performance. It is shown that well developed specifications exist for membrane encapsulated soil layer systems, but none exists for sand-filled cellular systems. Present experimentation points to certain problems that must be corrected before sand-filled systems can be used for civil aircraft pavements. Recommendations are offered that could provide a predicitive methodology.

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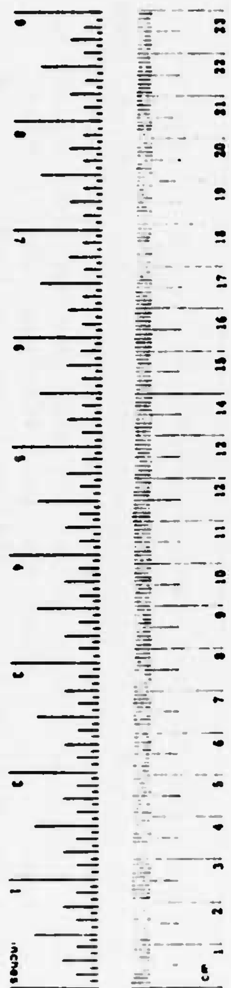
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

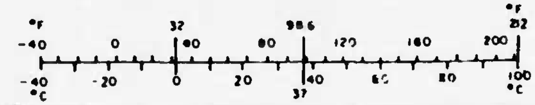
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



60 mph = 52.1 knots (nautical miles per hour)
60 mph = 88'/sec   1g = 32.2'sec^2

1 mph = .87 knots
1 knot - 1.15 mph

PREFACE

This study was undertaken as an in-house effort by the Program Engineering and Maintenance Service of the Federal Aviation Administration (FAA) to investigate the applicability of confined base course and subgrades material for civil aviation utility pavements. The effort was requested by the Office of Airport Standards, FAA as part of a program to provide optimum standards and guidelines for design and construction of alternative and expedient airport pavements.

During the preparation of this report, Mr. Ray Fowler was Program Manager of the Airports Technology Program and Mr. Thomas O'Brien was Acting Division Manager. The Service Director was Mr. Martin Pozesky.

ACKNOWLEDGEMENTS

The cooperation of personnel at the U.S. Army Corps of Engineers in Vicksburg, Mississippi and Hanover, New Hampshire was vital to the successful completion of this project. Important information was also collected from consulting engineers and state officials in Alaska. The Office of Airport Standards in the Federal Avaiation Administration also offered invaluable assistance.

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I. INTRODUCTION

Airport pavements are currently sited in areas where subgrade quality meets certain standards specified by local, state, or federal agencies or where the quality can easily be improved by replacement with imported material or by stabilization procedures. In general, water logged locations can be drained, clayey subgrades may be treated with lime, and stabilization can be effectuated by adding portland cement, flyash, or other materials to increase subgrade strength. Where these methods are not feasible, mechanical stabilization methods may be successful. These methods involve protecting the base and subbase courses from the ingress of water. Effective confinement may be accomplished by encapsulating membranes, placing vertically side-by-side short sections of pipes, or by mats with vertically oriented cells.

A need for expedient pavements with confined base and subbase courses exists in areas where standard quality aggregates for conventional designs are not locally available and where the cost of importation of these materials would be prohibitive. Such an area is in certain remote parts of Alaska where the most convenient form of transportation is by light aircraft using small utility type airports. The Alaska Department of Transporation has demonstrated an exploratory interest in this type of expedient pavement and is sponsoring research at the University of Alaska to develop a theoretical model. As yet there are no theoretically based standards relating expected performance with material quality and construction methods for this type of airport pavement. It appears that the expedient design investigated in this report is feasible from a technical standpoint, but that some work is required to establish criteria through analytical studies and field experimentation to make it applicable to civil aviation aircraft. Criteria for the use of encapsulating membranes for civil airport pavements have been empirically developed, but the methodology for the use of a sand filled grid system has not been developed for airport application. Most of the criteria that exist on confined base course systems were the results of efforts by the U.S. Army Corps of Engineers and the information contained in this report was gathered from publications provided by that agency and from interviews with its engineers.

II.

REVIEW AND DISCUSSION OF FIELD EXPERIMENTATION

From publications reviewed to date, it appears that the Corps of Engineers is the only agency that has performed systematic tests on confined soil systems to increase the bearing capacity of soft ground. The controlling factors were military expediency and time. Some less important factors were labor costs, transportation costs, and long term performance. In addition, while construction equipment such as graders and compactors facilitated construction, they were, nonetheless, unnecessary in emergency situations. For civilian applications, the relative importance of some of these factors vary. But, circumstances may dictate that an airport pavement be sited in areas where the ground is soft and where there is no alternative but to adopt expedient measures. The need for confinement of loose soil is shown in Figure 1 provided by the Corps of Engineers in a field demonstration project.

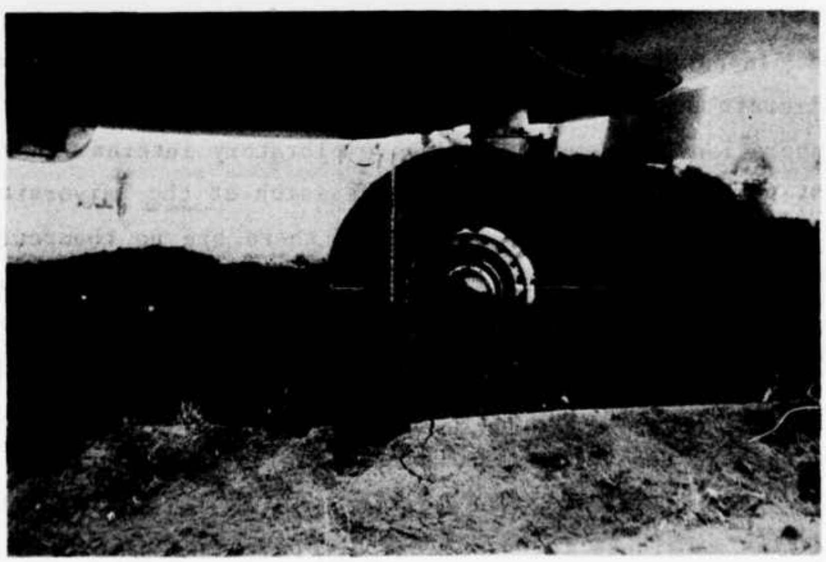

Figure I. Unstablized Pavement Under Aircraft Wheel
Courtesy Waterways Experimental Station, USCE

Field experimentation performed in 1976 and 1977 by the Corps[1] concentrated on relating the number of coverages which a 10-wheel military truck could make on different types of confinement systems before an 11-inch (27.9 cm) rut depth developed. Subgrade strength in these tests varied for 12 different confinement systems from 0.9 to 3.3 CBR (California Bearing Ratio). Confinement techniques included steel and aluminum mats or grids, wire mesh, gabions filled with rocks or sand, fabric linings, and plastic tubing filled with sand. Results of these tests showed that when compared with a control section of 14 inches (35.6 cm) of crushed stone over soft ground, the most effective technique was derived from wire gabions filled with 3-inch to 7-inch(7.6 cm to 17.8 cm) rocks. Somewhat similar effectiveness was derived from closely spaced metallic planks laid across the wheel paths. Fabric lined gabions, or 6-inch (15.2 cm) tubes, filled with sand also out-performed the control section. Crushed stone placed directly over fabric especially when the fabric rested on wire reinforcement performed better than the control section. Reductions in design thickness requirements using some of these techniques amounted to 50 percent or more.

The tests to investigate the performance of grid type systems were designed by the Corps of Engineers to approximate service under military conditions. A military truck was used to traverse the test pavement and rut depths were allowed to reach 11.0 inches (27.9 cm). It would be necessary to use a different type of load cart to simulate a design aircraft gear, and permit a maximum rut depth of perhaps 2.0 inches (5.1 cm) only for civil aircraft pavement research purposes.

Field tests have now been initiated by the Corps of Engineers in Vicksburg to develop performance standards for confined beach sand. This aspect has promise for direct application to civil aviation since utility airports could easily be sited on beach front property with intermodal transport accessibility. The parameters which are being considered as important would have to be reviewed and perhaps modified in order to make the proposed standards applicable to non-military aircraft.

For instance, it is believed by many aircraft operators that maximum permissible roughness of a pavement is an important consideration for civilian aircraft. In a research project sponsored by the FAA in cooperation with the Air Force[2], it was shown that runway roughness was a primary cause of acceleration in the cockpit. The level of acceleration experienced was a function of roughness and structural properties of the aircraft. The tests to determine performance of different types of grids to resist rutting at various traffic levels should terminate at a maximum roughness of about 1.0 inch per foot (8.3 cm per meter) run of pavement. Displacement of cargo and fracture of landing gears that may be caused by severe pavement roughness are other considerations that are even more important in civilian aircraft operation.

The Corps of Engineers[3] evaluated the effects on unpaved runway surfaces of heavy cargo aircraft with high flotation characteristics (285 sq. inches, or 1 838 cm sq., total contract area). Tests were conducted on sandy clay and clayey sand with CBR values ranging from nine to 15 at sites in Florida, South Carolina, and Texas. Readings were taken for water content density, CBR and Airfield Index (AI) (an expedient means of measuring soil strength by a right circular cone type of penetrometer). On the basis of the tests performed in 1980, and failure criteria defined as ruts more than three inches(7.6 cm) deep, elastic deflection more that 1.5 inches (3.8 cm), or subsidence more than four inches (10.2 cm) as measured by a 10 ft (3.0 m) straight edge, relationships were validated to relate allowable coverages with tire pressure, wheel load, CBR of subgrade material and top soil thickness requirements. These relationships are shown in Figure 2 for fine grained cohesive soils.

The required thickness of soil to be placed above the subgrade was computed from the following Ladd and Barber equation:

$$\text{Log } t = -1.02165 + 0.63624 (\log p) + 0.21484 (\log P) + 0.23937 (\log C) - 0.40281 (\log CBR_s) - 0.31404 (\log CBR_c)$$

where

t = thickness of soil placed above subgrade, in.

p = average tire contact pressure, psi

P = ESWL, Equivalent Single Wheel Load, lb.

C = number of coverages

CBR_s = strength of subgrade soil

CBR_c = strength of soil layer placed over the subjgrade

In using this equation, the ESWL must be determined at the depth equal to the thickness calculated. (1 in. = 2.54 cm, 1 psi=6.89kPa, 1lb (force) = 4.45N, 1 kip = 1,000 lb.)

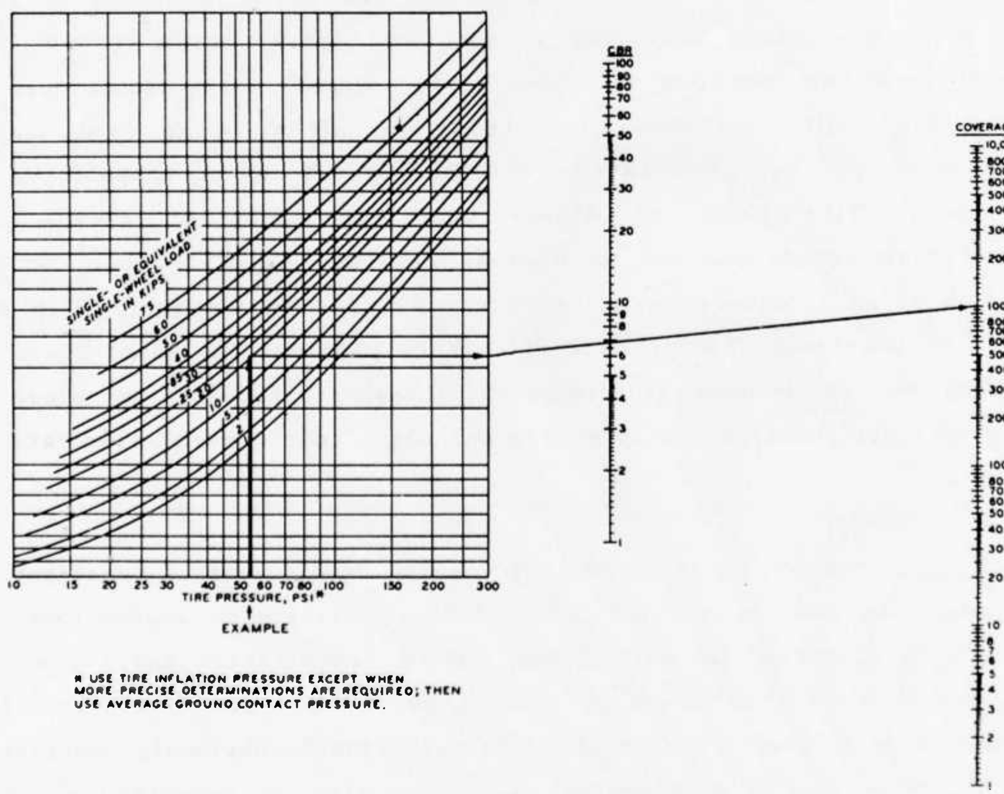

Figure 2. Unsurfaced Pavement Design Criteria Nomograph
Courtesy U.S. Army Corps of Engineers[3]

In these tests it was demonstrated that the greatest dislodgement of surface material occurred during turning maneuvers, but the study could not include effects of touchdown or braking on unpaved surfaces. The effects on sandy soil could not be predicted by the nomograph because of severe displacement. It, therefore, appears that mechanical confinement could find useful application in noncohesive soils. Such a device to confine pavement layers in cells for utility airports has indeed been considered in areas of undrained subgrades or loose sand. The system has also been introduced by the Federal Highway Administration (FHWA) and the Department of Interior for rural roads.

Initial cost could be a disincentive unless the cost of importing good materials for the base course is prohibitive. Factors which must be considered in a cost comparison analysis would also include the cost of the grid which for the plastic type is $1 per square foot ($10.75 per m^2), and for aluminum $2.30 per square foot ($24.73 per m^2). At this time at least two companies are known to be engaged in the manufacture of collapsible grid systems. Despite the initial cost and labor intensiveness of the installation, the grid system may be competitive in some areas like parts of Alaska where the cost of gravel for conventionalpayments may run as high as $190 per ton ($210 per tonne). Rigid metallic landing mats costs nearly $21 per square foot ($226 per m^2), are cumbersome, heavy and difficult to handle. The manufacture of a lighter mat is, however, in prospect. These mats have the advantage of being reusable and transportable from one place to the next as operations warrant.

Ease of construction could be improved by the development of construction procedures to reduce required labor force. Difficulty encountered in maintaining elevation on soft ground during installation could also be overcome by common construction procedures. The type of construction equipment applicable to this type of installation is obviously restricted to those with low tire pressures, and compaction of material into the cells should be by vibration and not by the application of a direct force. But installation experience of the Corps suggests that initial filling of selected cells for anchoring grid sections has to be performed manually.

Membranes and Fabrics Systems:

Waterproof confinement systems tested by the Corps provide some mechanical support as well as keeping the base course dry. The migration of fines from the subgrade up into the base and subbase has been the source of subgrade deterioration in many instances. When this occurs, grade line elevation loss occurs because of cavity development. The presence of a membrane separating these layers generally stops the upward movement of particles thereby preserving subgrade elevation. Field experiments conducted at Fort Hood in the 70's by the Corps showed that excavated material enclosed in sheets of plastic, when used as a base performs effectively as an alternate pavement system.

Intermittent saturation of the subgrade by water from rain or melting snow causes fines, because of their lesser specific gravity, to be dislodged. (The water causing this condition may have entered through cracks or joints in the pavement, or from the shoulders.) Fine grained material that is held in suspension is forced up through openings in the pavement because of overburden or traffic forces. The loss of this material, therefore, results in pockets between the subgrade and the upper layers of pavement which when again filled with water can create pumping problems or even more rapid deterioration in a freeze condition.

Work on Membrane Encapsulated Soil Layers (MESL) sponsored by the Federal Aviation Administration[4] and performed by the Corps has led to implementable recommendations for design, construction procedures, and material specifications for airport pavements. MESL airport pavement systems consist of compacted soil between upper and lower waterproof membranes. One of the important requirements in all pavements is that base, subbase and subgrade are able to spread applied surface loads without overstress. When fine grained soils are compacted at or near optimum moisture content, good bearing capacities are possible. Dramatic loss of this capacity is, however, experienced when these soils absorb water. Full scale tests performed at Vicksburg, Ms and Fort Hood, Texas, have been conducted in which these soils were encapsulated in a waterproof membrane. A typical section is shown in Figure 3. The subgrade is primed with an asphalt application and a polypropylene sheet of six mil (15.24x10-3 cm) thickness is laid. Backfill is placed and compacted after which a tack coat and covering sheet are placed. The section is then ready for a surface coat.

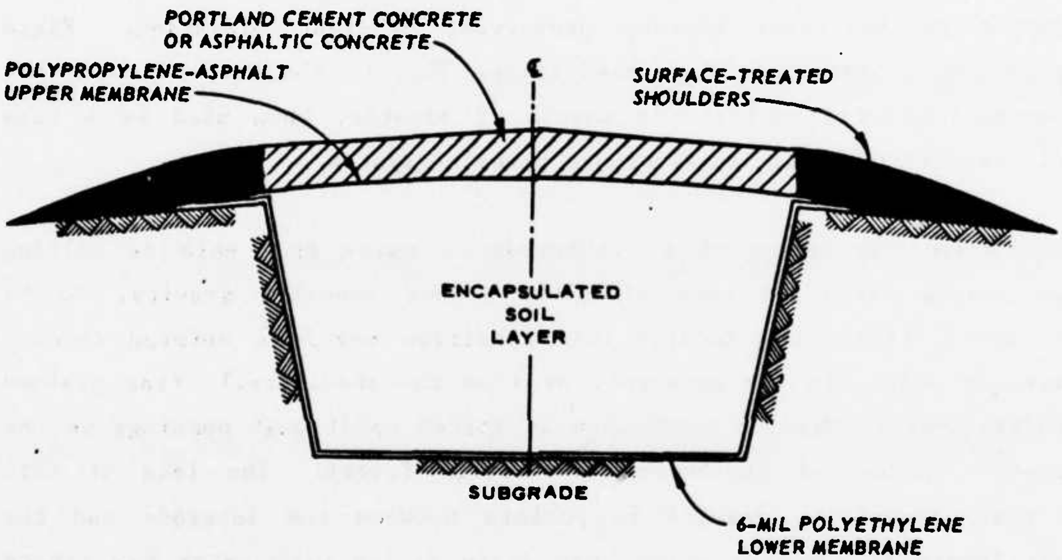

Figure 3. Typical Cross Section of a MESL Airport Pavement
Courtesy of U.S. Army Corps of Engineers[8]

Results of experimentation by the Corps have led to the conclusion that MESL may provide up to 50 percent savings in construction costs while delivering equal performance with conventional designs. During these tests it was also shown that under critical combinations of very heavy wheeloads (360,000 lb or 1 601 kN gross) and poor foundation soils (4.0 CBR) pavement performance improved with an MESL system of lesser thickness than a conventional system would require. The work was limited to fine grained material since the membranes were generally punctured by granular, angular soils. A summary of some traffic test results from this work is shown in Figure 4.

Summary of Traffic Test Results from August 1968-July 1969 (After Reference 5)

Test Item	Location: Test Facility	Location: Station From	Location: Station To	Date Installed	Expedient Surfacing Material and Configuration	Type of Subgrade or Base Course	Pretraffic Surface CBR*	Total No. of Passes	Comments
27A	Road	19+90	20+60	9 Nov 67	Polypropylene-asphalt single surface	Lean clay, cement and lime treated	30 (Lime) 5C (Cement)	5480	Negligible damage
27B	Road	21+70	22+03	9 Nov 67	Polypropylene-asphalt single surface	Lean clay, cement treated	50**	5480	Negligible damage
29A	Road	18+68	19+05	29 May 68	Polypropylene-asphalt single surface	Clayey gravel	15	3840	Negligible damage
29B	Road	19+05	19+25	29 May 68	Polypropylene-asphalt double surface	Clayey gravel	15	3840	Negligible damage
29C	Road	19+55	19+90	31 May 68	Polypropylene-asphalt single surface	Lean clay, lime treated	20†	3840††	Failed in wheel paths after 3210 passes, successfully repaired
29D	Road	20+60	21+20	14 June 68	Polypropylene-asphalt single surface	Lean clay, cement treated	20†	3840††	Failed in wheel paths after 3210 passes, successfully repaired
30A	Road	19+25	19+42	31 May 68	DuPont polypropylene-asphalt, single surface	Clayey gravel	25**	3840	Negligible damage
30B	Road	19+42	19+55	31 May 68	DuPont polypropylene-asphalt, double surface	Lean clay, lime treated	20†	3840	Negligible damage
30C	Road	21+20	21+70	14 June 68	Polypropylene-asphalt single surface with 3-ft-wide run of DuPont polypropylene along ℄	Lean clay, cement treated	20†	3840	Negligible damage
31	Loop	25+00	31+00	17 Oct 68	Polypropylene-asphalt single surface	Lean clay	15	1760	Completely failed at 475 passes
32	Loop	31+00	31+50	5 Aug 68	Polypropylene-asphalt double surface and T15 membrane bottom	Lean clay	14	1760	Minor damage
33	Loop	31+50	32+50	26 July 68	Polypropylene-asphalt double surface and T15 membrane bottom	Lean clay	18	1760	No damage
34	Loop	32+50	33+88	19 July 68	Polypropylene-asphalt single surface and T15 membrane bottom	Lean clay	16	1760	No damage
35	Loop	33+88	34+25	16 Oct 68	Polypropylene-asphalt single surface double bottom	Lean clay	11	1760	No damage
36	Loop	34+25	34+75	16 Oct 68	Polypropylene-asphalt single surface single bottom	Lean clay	11	1760	Moderate damage

Figure 4. Field Performance Data

Many other construction procedures using fabrics have been designed for subgrade protection. In one method a pervious membrane that allows the passage of water, but not of fines, is laid across the pavement subgrade surface and turned down at the shoulders. This method has been used where complete encapsulation was not practical. Both methods require large quantities of fabric material and entail additional labor costs, but may be quite essential for the long term performance of the pavement.

The effectiveness of the MESL derives from the ability to keep the encapsulated material in a dry state. (Recommended moisture content of the soil is two percent below ASTM D1557-70 optimum moisture content.) Experience has shown that looseness of soil particles, losses in compaction, and reduction in bearing strength of soils, occur with increases in water content. Punctures in the membrane or unsealed joints cause water to enter and reduce efficiency; subsequent drainage of the soil material is rendered difficult by the very presence of the membrane. As mentioned earlier, coarse angular aggregates should not be encapsulated since they cut the membrane. Experimental results were based on the encapsulation of lean to heavy clay material. Also, encapsulated loose, sandy material tended to shove under the weight of the roller when the surface course was being compacted.

Some tests to establish design criteria for unsurfaced runways serving heavy aircraft were reported in 1971 by the Corps[6]. From the data in these tests, empirical relationships were formulated to predict the number of passes that could be made by a vehicle before a three-inch (7.6cm) rut depth in the surfacing developed. Two of the principal factors were not applicable in very weak or loose material. It has been suggested that a designer should first provide a confinement system, determine the CBR, and then apply the Ladd & Barber formula.

Flexible Cells:

Soil confining devices are sometimes fabricated in the form of cells made of synthetic material which is expanded to 40 times their volume for installation (Figure 5). These cells are, in general, rigid enough for easy handling and are not designed to withstand vertical forces. The effectiveness derived from this system is due to the ability to resist some lateral displacement of the soil in the plane of the grid thereby increasing the compressive strength of the cohesionless material inside the grid cells.

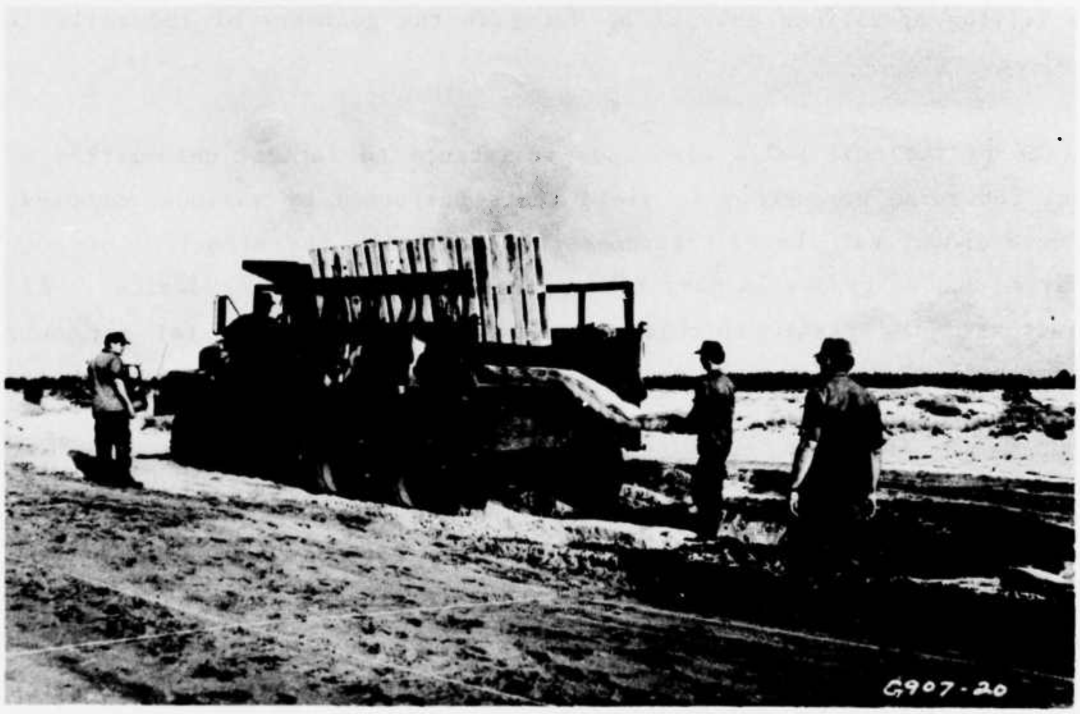

Figure 5. Transportability of Grids. Courtesy Waterways Experimental Station, USCE

One problem that may be obviated by proper construction procedure is that it is difficult to maintain the location of the grid once it is laid. An effective solution may be to drive vertical pegs through the grid to a sufficient depth to effectuate anchorage. These pins are also effective in preventing the grid elements from curling. Another practice is to fill the corner cells of a panel with soil and to install a working platform there (Figure 6).

Another problem that should be addressed regarding synthetic materials is that some inelastic extensions may occur before resistance to deformation develops. Since a principal objective of the method is to assist in resisting shear forces that would spread the soil particles away from under the load, the ability of the cell walls to resist small deformation is an important requirement. Also, because of the flexibility of this cell structure, special care has to taken to fill the cells with pavement construction material without crimping the grid elements. Construction machinery should be used to perform filling operations only if by doing so the geometry of the cells is not impaired.

Corrugation of the cell walls also adds resistance to lateral deformation by providing increased strength. In field tests performed by various agencies, it has been shown that the effectiveness in increasing the stability of poor base courses and subgrades is many times greater than any other devices. All other factors being equal, corrugated grids require more material per unit area for fabrication than plain grids and are, therefore, more expensive and heavier to transport.

The problem of deterioration of the material is an important one. It should be expected that steel and aluminum grids will corrode over time but no documentation of loss of effectiveness due to this process is known to exist. Because this type of installation is generally due to expediency, a life of 5 to 10 years may be all that is necessary. Some experts believe that grids fabricated from black high-density polyethylene can have a life of up to 40 years.

Rigid Cells:

Open cell mats are sometimes fabricated from metal rather than synthetic material. These have the advantages of inextensibility of cell walls and some capacity to resist vertical loads from traffic. The problem of inelastic deformation of the walls due to excessive vertical loads can be overcome by a sufficiency of cover for the system. The lower the grid below the wearing course, the less likely it is to buckle from traffic loads.

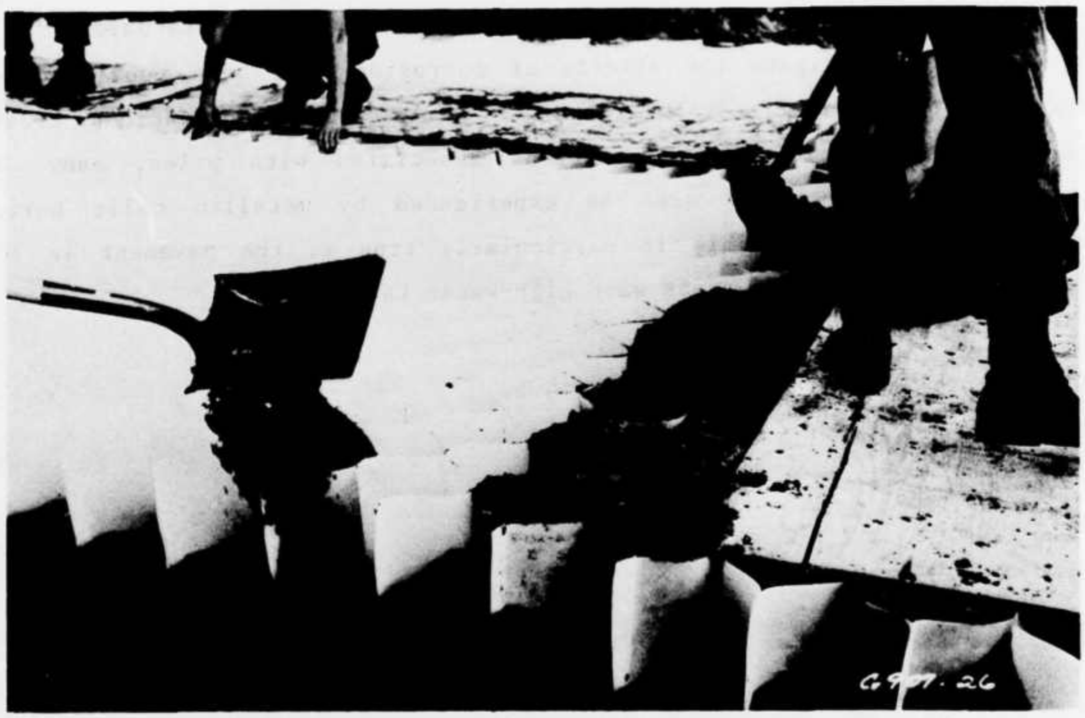

Figure 6. Initial Filling of Cells. Courtesy Waterways Experimental Station, USCE.

Other methods employed to stabilize soft ground for paticular traffic involve "griddle type" blocks of portland cement concrete or thermoplastic material placed after some surface preparation. The National Concrete Masonry Association [10] has published an information series with construction specifications and design curves for these units. Applications include cellular block paving for city streets and parking areas; paving block thicknesses are specified based on axle load, load repetitions and strength of the supporting soil, etc. The widest usage of these blocks (sometimes weighing as much as 90 lbs or 40.9 kg.) is in the area of revetment for river training, beach control and embankment slope portection. For utility low cost airport pavement application these cells could be of value since an overlay above the grids might not be necessary. However, current manufacturers specifications require a first course of gravel or stone which may not be locally available in some remote areas.

Much research has been performed to determine the rate of deterioration of steel elements in harsh environments. Some of this work has lead to the publication of monographs by the National Bureau of Standards,[11,12] and procedures to mitigate the effects of corrosion have been published by the American Iron and Steel Institute.[13] While these publications treat the more adverse environmental conditions associated with piles, many of the problems outlined could also be experienced by metallic cells buried in expedient pavements. This is particularly true if the pavement is located near shore lines, or in areas with high water tables.

III ANALYTICAL CONSIDERATIONS

A rigorous analysis of stresses, strains, and permanent deformation of the confined soil system under aircraft loading is essential for a rational and economical design. In this area of unconventional pavement systems, it became evident that a very limited attempt has been made to formulate along mathematical lines the amount of contribution that the membrane or grid system makes in improving bearing strength. Any three dimensional finite element analysis capability which exists could probably be modified to account for the presence of a restraining system.

The results of research work by the Corps were analyzed by consulting pavement engineers[7] in 1979 at Champaign, Illinois. It was reported that for fabrics placed between soft subgrades and base or subbase courses, an axisymmetric finite element analysis (assuming stress dependent, elastic materials) shows that the soil at the interface moves horizantally up to 15 percent of the maximum vertical movement. The report addresses the basic stress redistribution effects of the fabric, the tension in the material that produces an upward force on the soil above, the changes in the material properties of the granular material that occur under stress, and the bending moment capability of the combined system. Some important considerations essential in development of a mathematical model were suggested.

A rational formulation of the cellular confinement system in terms of stresses, strains, and permanent deformations would perhaps be simpler with metallic elements rather than plastic elements. A mechanistic study of failure modes associated with sand filled grid systems was performed by the University of California at Berkeley[15], and reported in 1979. The study was sponsored by the Corps of Engineers, Geotechnical Laboratory. The failures considered were those due to cell penetration into the subgrade, cell bursting, wall buckling, rutting and loss of bearing capacity, wall bending along with material deterioration. The analysis was based on basic soils mechanics principles and results were compared with laboratory tests at the University and prior experimental results collected by the Corps. Some agreement between theory and practice was obtained for only some failure modes possibly because some of the assumptions and hypotheses were speculative. A re-evaluation, refinement and consideration of dynamic effects of loads on the grid using the reported approach may provide valuable criteria. The most apparent problem, that of buckling of the metallic grid elements, had not been sufficiently addressed. The material characteristics of the plastic elements have also not been considered as a factor in determining the redistribution of forces in the confined soil system (Figure 7).

A complex problem that would arise in a mathematical approach is to account for slippage. In a certain field test project[8], it was explained that compaction of the wearing course over the upper layer of membrane in a MESL system was rendered impossible by slippage of the wearing course. Various degrees of slippage would affect the efficiency of transmission of shearing forces to the underlayers. An analysis would necessarily require many simplifying assumptions.

(The use of grid elements for pavement surfaces in conceptually similar to embankment earth reinforcement. This is a method employed to restrain embankments against slippage. Embankments whose slopes exceed angles of internal friction and those in which soil shear strength is impaired by saturation have been successfully stabilized by this method. The technique involves separating layers of earth that form the embankment with horizontally placed metallic strips. The Corps of Engineers[14] has developed a theoretically based design methodology to stabilize earth masses using the results of extensive full-scale testing.)

Figure 7. Typical Buckling of Unsupported Grid Elements.

Courtesy of Waterways Experiment Station

IV WEARING COURSE

It was observed during site visits at Vicksburg in 1981 that even after several passes of traffic, the test section performed effectively in those areas where the slope was gradual and where there were no horizontal curves. Where the slopes were steep and around curves, the test vehicle wheels caused considerable damage to the top two or three inches (5.1 or 7.6cm) of the pavement, and this resulted in escape of the sand and in some places extraction of the grid frame itself. The explanation was offered that this system is generally weak in resisting shearing forces and that in order to protect the grid and enclosed sand, an effective surface course at least 1 inch (2.54 cm) thick should always be installed. Also, the top inch (2.54 cm) of confined material should be stabilized with emulsified asphalt to inhibit shifting of the material. It has been suggested that dislodgment of the grids around curves can be prevented by incorporating the wearing course into the top portion of the cell wall.

A proposed modification was that the sand would be wet down and then sprayed with emulsified asphalt to get about one inch of penetration. The use of cutback asphalt for the surface treatment was also considered. In these experiments it was found that a square grid dimension of 8-in x 8-in (20.3cm x 20.3cm) was best in terms of performance for trucks. The performance depended to a somewhat lesser extent on the class of sand used to fill the grids (Figure 8).

It appears that if a bituminous wearing course is placed over mechanical grids, it should be designed with a high Marshall stability so that the amount of shear force from traffic to be resisted by the cell walls can be minimized. In many instances, tender mixes with low stability laid at airport turning areas have shown signs of shoving. Using such mixes with a grid system would produce bending of the cell wall in the direction of the displaced mat and even perhaps extraction of the grid. It might be advisable to consider the use of mix designs with Marshall stability in excess of 3,000 lbs. (13.3kN) for toppings over grid systems in airport applications.

Figure 8. Application of Tack Coat. Courtesy Waterways Experimental Station, USCE.

Airport pavement designs conforming with the requirements of FAA standards, P-401, Bituminous Surface Course, have generally yielded mixes with Marshall stabilities between 2,500 and 4,000 lbs (11.1 and 17.8 kN). One reason is the requirement for fractured faces of crushed stone. At airports where the use of confined systems is considered expedient it is not likely that crushed stone would be readily available. However, because of the desirability of a shear resistant cover, enough crushed stone should be included in the job mix to attain high Marshall stabilities through aggregrate interlock.

The factors that dictate the use of confined base course systems are generally those where the availability of crushed stone aggregate is limited. Therefore, it may be impossible to obtain even a small quantity of this material in order to achieve high stability. An alternative approach may be to use low penetration asphalt in the job mix. Although problems of brittleness arise with aging of these asphalts and cracking in colder climates may be a problem, the high stability attainable could make this a reasonable approach.

Sand-asphalt mix may be the only economical top course material available in certain localities where grid confinement systems are feasible in strenghening loose material. The standard P-401 surface course specification would likely be too expensive or unnecessary for this application. Field experimentation has demonstrated, as already noted, the need for a protective top course over the tops of grids. The use of sand-asphalt would only necessitate the mixing of locally obtainable sand and small quantities of asphalt. Specifications are not yet available to set optimal proportions of sand and asphalt in a job mix formula and studies in this area would be worthwhile.

It is reported that there is no "good" gravel available in the western part of Alaska[9]. Such aggregate would have to be transported over great distance and at considerable cost to the job sites. Many pavements are, therefore, surfaced with sand asphalt mixtures only and in some instances wearing courses with this material are as thick as six inches (15.2 cm). In combination with sand-filled grid systems, thickness of this type of wearing course vary from two to three inches (5.1 to 7.6 cm). In other situations, a simple soil-cement-asphalt mixture for a top course should be considered especially where the local conditions consist of silt or clay and no nearby sand source exists. The use of sand-asphalt over the grid may have to be limited to pavements serving light aircraft only because Marshall stability values would not satisfy FAA requirements.

V. CONCLUSION

Based on the literature review presented in this report, it is evident that a great deal of site experimentation has been performed by the Corps of Engineers on mechancial methods of maintaining or improving the load carrying capacity of on site materials. The work that was performed on the encapsulation of soil layers in waterproof membranes provided implementable criteria for small airports. This confinement method could also have application in areas of frost succeptibility by eliminating the need for replacement of the native material by imported nonsucceptible fill.

Work on sand filled grid systems at various sites has produced insight on the behavior of grids in soil confinement. The experiments have also highlighted problem areas such as; the failure of this system to resist lateral forces imposed by turning vehicles and when the grids are unassisted by a wearing course. Results have also shown that these lightweight grid material must be protected from direct vertical forces since the elements will otherwise buckle.

It has been demonstrated that the number of passes of a wheel before a predefined rut depth occurs can be increased by the sand filled grid. However, the amount of displacement of the sand as a function of the resistance of the grid elements to bending has not been quantified. Work has also not included design of grid elements based on their material properties, thicknesses, and braced lengths along with the distribution of vertical forces lessened by particle interlock.

The results of demonstration projects have also shown that heavy pavement construction equipment is not essential to the installation of the sand filled grid system and that the grids themselves are light and transportable. No details are known of any comparison in terms of initial and maintenance costs between the grid system and conventional designs for any one airport. Civilian application of this method may ultimately depend on cost considerations rather than on exigency.

VI. RECOMMENDATIONS

As a result of the investigation described in this report and the conclusions that were reached, the following recommendations are provided:

1. Existing data provided by field experimentation should be used to establish functional criteria for the use of sand filled grid systems for light aircraft pavements.

2. Develop a structural behavior model that can predict the state of primary stress and response of the pavement system.

3. Design a factorial experiment and construct models for laboratory testing under repetitive loads with a representative sampling of available grid types, sand types, and wearing courses of various thicknesses and Marshall properties.

4. Utilize the results of laboratory testing to correct and refine the predictive model.

5. Validate the predictive model by in-service field tests at three utility type airports.

6. Based on the methodology developed, a comparison of cost should be made between the design and construction requirements of a sand filled grid system and a conventional system for light aircraft pavement application.

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capacity to resist vertical loads from traffic. The problem of inelastic deformation of the walls due to excessive vertical loads can be overcome by a sufficiency of cover for the system. The lower the grid below the wearing course, the less likely it is to buckle from traffic loads.

Association[10] has published an information series with construction specifications and design curves for these units. Applications include cellular block paving for city streets and parking areas; paving block thicknesses are specified based on axle load, load repetitions and strength of the supporting soil, etc. The widest usage of these blocks (sometimes

University and prior experimental results collected by the Corps. Some agreement between theory and practice was obtained for only some failure modes

tilled grid system and that the grids themselves are light and transportable. No details are known of any comparison in terms of initial and maintenance costs between the grid system and conventional designs for any one airport. Civilian application of this method may ultimately depend on cost considerations rather than on exigency.

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