TITLE: Full-Scale Instrumented Testing of Multiple Airfield Matting Systems on Soft Soil to Characterize Permanent Deformation

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ABSTRACT

This paper presents results from full-scale testing of six airfield matting systems of various materials and designs that were evaluated on subgrades constructed to a California bearing ratio (CBR) of 6 and subjected to simulated aircraft loads. Mat breakage, deformation, and subgrade earth pressure were monitored during each test to determine the effectiveness of the airfield mats in reducing cumulative subgrade deformation and decreasing subgrade stresses. Based on test results, a simplified expression was developed to predict subgrade deformation on a CBR of 6 as a function of aircraft passes and airfield mat properties. The values predicted showed reasonable correlation with the measured data. The empirical equation can be used as an expedient tool for characterizing airfield matting behavior.

Keywords: Airfield mat; subgrade deformation; temporary surfacing; full-scale test; lightweight mat

1. INTRODUCTION

Expediently constructing temporary airfields and expanding existing airfields has a long history in the U.S. military (see airfield matting background section of this paper for more information) for the purpose of increasing maximum-on-ground capacity. Conventional construction techniques, such as asphalt and portland cement concrete paving, require considerable resources and time periods that usually inhibit rapid deployment for airfields. The ability to rapidly construct or expand airfield facilities enables the military to deploy supplies and materials quickly and stage aircraft at forward operating bases. Matting systems allow for rapid construction of airfields (and roadways) in areas where conventional methods are impractical.

Matting systems also have a wide range of commercial applications, in addition to their military uses, and have gained popularity as new designs, fabrication processes, and materials have been introduced. Modern matting system materials include fiberglass, light aluminum alloys, polymers, and composites, with varying assemblies that include rolls, folded mats, and individual panels. The sources listed in Table 1 provide comprehensive reviews of state-of-the-art products available commercially that were tested for military applications. For expeditionary airfield applications, however, available products are limited, but numerous efforts have been conducted over the last 70 years by the U.S. Army Engineer Research and Development Center (ERDC) to find suitable solutions. Early airfield matting system investigations in the U.S. date back to the 1940s. Since then, designs have evolved from heavy duty steel planks towards lightweight material panels, with efforts focused on finding matting solutions that are logistically optimal (i.e., lightweight, easy to transport and install), but strong enough to handle governing military aircraft.

Currently, the primary method used by the U.S. military for expedient airfield construction is preparing the natural foundation of an area and surfacing it with the AM2 mat system. AM2 is an aluminum mat system developed in the 1960s that has had success offering a short term solution for surfacing airfields. However, AM2 can be logistically cumbersome due to its weight and large panel dimensions. M19, a light-weight aluminum honeycomb core mat, was also developed in the 1960s, but

production ceased in the 1970s as performance problems led to vast procurements of the better performing AM2. Recently, renewed emphasis has been placed on investigating alternative materials and mat systems.

A variety of matting materials and matting configurations were studied in the investigation reported herein to determine their suitability for carrying modern fighter aircraft. A program was initiated and implemented by the U.S. Air Force to find lightweight alternatives to AM2. Key components of the investigation were full-scale tests conducted at ERDC over a period of several years and subsequent analysis of data from multiple studies to evaluate subgrade permanent deformation behavior.

This paper presents results of full-scale instrumented evaluations of AM2, M19 and four other matting systems. The evaluations conducted are described more fully in a series of reports (Rushing and Tingle, 2007; Rushing et al., 2011; Rushing et al., 2012). Each evaluation consisted of constructing a subgrade to a specific California Bearing Ratio (CBR), surfacing it with airfield matting, and applying simulated aircraft traffic on the mat surface while monitoring damage and deformation. The objective of this paper is to evaluate and compare the different mat types tested in terms of subgrade permanent deformation for constant support conditions and aircraft loads for the purpose of developing permanent deformation prediction relationships.

2. AIRFIELD MATTING BACKGROUND

Historical matting designs that have been investigated include light-duty types, such as flexible mesh, laminated wood, laminated fencing, and more robust materials such as steel and aluminum planks. For military airfield applications, specifically, the heavy duty steel and aluminum mat designs proved to be the most viable options. However, light-duty mats were continually sought to reduce the need for larger aircraft to transport heavy duty mats (Tolbert, 1945).

Rushing and Howard (2011) evaluated a variety of commercial matting systems to determine their effectiveness in carrying heavy military vehicle traffic over loose sands (beach access) and mudflats. Mat system designs included fiberglass-reinforced mats, plastic and aluminum hexagonal mats, and HDPE

mats, with installation methods ranging from continuous rolls of material to individual panel placement. Representative sections were constructed with either sand or clayey silt subgrades, surfaced with the individual matting systems, and continuously trafficked with a six-wheel truck carrying a 7-ton payload. Total earth pressure cells (EPCs) were installed in the sand subgrade, 30.5 cm below the surface of each tested mat, to provide insight into the relationship between mat breakage, surface deformation, and subgrade pressure. Deformation rates were predicted using two best fit equations (Equations 1 and 2), through the measured deformation points of mat systems tested, where D_{R-S} = depth of rut on sand subgrade, in., D_{R-W} = depth of rut on silty clay subgrade, in., P = the number of passes, and C_1 and C_2 are regression constants.

$$D_{R-S} = C_1[\ln(P)] + C_2 \quad (1)$$

$$D_{R-W} = C_1[P] + C_2 \quad (2)$$

Recommendations were presented for the use of each mat system based on rutting and mat breakage. The pressure data were used to show how the varying combinations of moduli and dimensional properties of the mat systems could affect confinement and stress states of the supporting material. The authors emphasized the value of instrumentation data for future modeling efforts that could help understand matting behavior.

For airfield applications, products readily available commercially are limited since some aircraft loads and tire pressures are much higher than conventional vehicle traffic, and there is considerable risk associated with operation of expensive aircraft and personnel. Substantial contributions were made from the 1940's through the 1970's as more sophisticated aircraft were added to the military's inventory. Table 2 lists important sources found in literature that discuss research on expedient surfaces during this period.

Since its development, AM2 has been the primary expeditionary airfield surfacing used by the U.S. military. However, its weight is a limiting deployment factor, where aircraft payload limits are exceeded without approaching their cubage limits. Thus, emphasis has been placed on finding lightweight solutions able to withstand the damaging effects of modern controlling aircraft. Examples of recent work dedicated to this field, apart from that described in this paper, are provided by Anderton and Gartrell

(2005), Gartrell (2007), and Gartrell et al. (2009), where full-scale evaluations were conducted on commercial matting systems intended to serve contingency airfield requirements to sustain C-17 and C-130 transport aircraft loads.

To evaluate the matting designs discussed thus far, the most common approach has been to build full-scale test sections with a controlled subgrade CBR overlaid by a matting surface that is then trafficked using simulated aircraft loads. The CBR is a measure of the subgrade strength, or bearing capacity, underneath the matting surface. Although full-scale testing has provided a realistic performance measure, it has proven to be costly. Therefore, a few more recent efforts have used full-scale data to develop various techniques for predicting airfield matting behavior. The following paragraphs summarize recent characterization activities relevant to this paper.

Gonzalez and Rushing (2010) used a stress-based approach to develop a mechanistic model for the purpose of predicting passes-to-failure for a mat system based on subgrade strength in terms of CBR. They used a simply-supported beam test setup described by Berney et al. (2006) and a finite element implementation of the Mindlin plate solution (Mindlin, 1951) for determining the unit section modulus ($E_c^{NJ(2)}$) of different mat systems. $E_c^{NJ(2)}$ is the overall material resistance to deflection not considering joint properties. An overall composite modulus including the joint ($E_c^{J(2)}$) was also determined and included in the analysis. Layered elastic analyses were performed to compute the maximum deviatoric stress in the subgrade, which was then related to known mat performance (i.e., passes to failure), to develop the design methodology's performance criteria. Full-scale instrumented test section data for two of the matting systems evaluated in this paper and mats tested by Anderton and Gartrell (2005) were included in the Gonzalez and Rushing (2010) data set.

Doyle et al. (2014) performed three-dimensional finite element analysis (FEA) on instrumented test sections described by Gartrell (2007) and Anderton and Gartrell (2005) using measured EPC data. Material property inputs for the mat systems evaluated included the composite modulus (E_c^{NJ}) as determined by the test setup and a FEA back-calculation procedure described by Berney et al. (2006).

Although FEA modeling provided reasonable predictions of soil response in some cases, it was considerably less effective for thin composite matting systems with the inputs available. FEA modeling was recommended as a preliminary tool to be used prior to full-scale testing.

Rushing and Howard (2015) developed an empirical method for characterizing rutting resistance of the AM2 mat system. Data collected from full-scale testing of AM2 over five subgrade strengths (CBRs of 6 to 100) were used to develop correlations between subgrade soil deformation rate, number of applied F-15E passes, and underlying soil's CBR. Earth pressure measurements were not used in their analysis. The expression developed is shown in Equation 3, where δ_s = the subgrade deformation, in., P = the number of passes, and CBR is the strength of the subgrade underneath the structural mat system.

$$\delta_s = \log_{10} P * 1.64 * CBR^{-0.61} \quad (3)$$

Of the methods discussed thus far, those by Rushing and Howard (2011; 2015) are the most directly applicable to this paper. Rushing and Howard (2011) developed an empirical technique for predicting surface deformation and furthered their analysis by using instrumentation measurements, but the study focused on matting for roadways. Rushing and Howard (2015) used full-scale data from simulated F-15E traffic tests, but limited their study to AM2 and did not incorporate measured earth pressure for relating mat modulus to confinement provided by the system. Components of both of these approaches were adopted for the analysis presented in this paper. Six different mat designs, including AM2 and M19, were tested over a CBR of 6 under simulated F-15E traffic conditions. Lightweight composite material prototypes, such as carbon fiber (Foster and Anderson, 2003), and new welding techniques recently introduced into the inventory of potential mat designs were evaluated. Total earth pressure was measured at different depths. The information collected was used to determine the rate of subgrade deformation for each mat design, and ultimately to develop a predictive deformation equation.

3. MATERIALS TESTED

Pertinent properties of all matting systems tested are shown in Table 3. The overall composite modulus in absence of a joint ($E_c^{NJ(2)}$) is currently the most reasonable measure available to the authors

for each mat's elastic properties. Rushing and Howard (2015) published flexural properties for Mat 1, but they were not used for the analyses presented in this paper for consistency with information available for the other mats. $E_c^{NJ(2)}$ was determined using the back-calculation procedure described by Gonzalez and Rushing (2010) and the test setup described by Berney et al. (2006), where a single panel was simply supported and loaded incrementally while deflection was measured at four locations (similar to a four point bending test). Note that E_c^{NJ} (Doyle et al., 2014; Berney et al., 2006) and $E_c^{NJ(2)}$, although determined using different back-calculation methods, are conceptually the same term and aim to characterize the matting panels' resistance to deflection. The remainder of this section describes each matting system separately.

3.1. Mat 1: AM2

AM2 Mod 5 is the primary expeditionary airfield surfacing used by the U.S. military. Each panel is fabricated from a single 6061-T6 aluminum alloy extrusion with end connectors welded to the short ends to form a complete panel. The core is comprised of vertical stiffeners in the longitudinal direction. Panels are: (1) joined at the two long edges by a hinge-type male/female connection, and (2) joined at the short end by an overlap/underlap connection secured by an aluminum locking bar.

3.2. Mat 2: M19

M19 aluminum matting has panels nearly square that consist of a honeycomb core made of 0.318-cm (0.125-in.) hexagonal cells of aluminum foil. The core is bonded to top and bottom rolled-aluminum sheets by an epoxy adhesive. Panels are joined along two edges by a hinge-type male/female connection. The other two edges consist of overlap/underlap end connectors secured by an aluminum locking bar.

3.3. Mat 3: Carbon Fiber Composite

The carbon fiber composite mat system panels are composed of carbon fiber top and bottom skins and a foam-filled carbon fiber core. The core is constructed with vertical carbon fiber stiffeners spanning

perpendicular to each other. Panels are connected on each edge by aluminum extrusions that are designed to accept an H-shaped nylon locking bar. The top and bottom skins of the individual panels are bonded by an epoxy adhesive to the aluminum extrusions.

3.4. Mat 4: Aluminum Honeycomb Composite

The aluminum honeycomb composite mat system panels have an aluminum honeycomb core made of 0.318-cm (0.125-in.) hexagonal cells of aluminum foil, similar to the M19 mat. The core is bonded to top and bottom skins by an epoxy adhesive. Both skins are composed of a carbon fiber sheet sandwiched between two aluminum sheets. Panels are framed with welded aluminum connector rails. The connection at the long dimension is a hinge-type male/female system. The short ends are connected by H-shaped nylon locking bars.

3.5. Mat 5: MLC-70 Trackway

The MLC-70 Trackway matting system is made from a single aluminum extrusion. When the panels are assembled in an array, they can be rolled up for storage and transportation. The connection system along the long dimension is a male/female t-slot. Shoot bolts are inserted into slots in the male edge of the panel to prevent lateral movement of the panels along each row. No connection system is included along short edges.

3.6. Mat 6: Aluminum Truss

The aluminum truss system is a second generation prototype. Mat panels were made from two aluminum extrusions with isosceles triangle cross sections that were friction stir welded together. The connectors along the short ends of each panel were hand welded to the extrusions. Panels were connected on the short end by a double-arrow-shaped locking key inserted into connector slots. The connection along the long dimension was a hinge-type male/female system.

4. EXPERIMENTAL PROGRAM

The following sections detail construction of the subgrade test sections, mat installation, traffic operations on each mat surface, data collection, and the criteria used to determine mat failure. Garcia (2015) provides additional experimental program information.

4.1. SUBGRADE CONSTRUCTION

Each test incorporated a high-plasticity clay (CH) subgrade constructed to a CBR of 6 ± 1 . The CH soil came from a local source in Vicksburg, MS. Moisture content-density and moisture content-CBR relationships were established through laboratory testing (ASTM D1557 and ASTM D1883) to determine the target moisture content and dry density required to obtain the target CBR of 6 ± 1 (Table 4). Although slight variations may have been present between soil procured for each test, the values shown in Table 4 are typical, representative properties of the soil.

The subgrade for each test was constructed at an elevation below the finished grade of a covered facility. A test pit was excavated to a specific size. The soil at the bottom of the excavated pit (i.e., below the subgrade) was a low plasticity silt (ML) having a CBR less than 20. The ML soil was leveled and compacted with pneumatic and vibratory steel-wheel rollers to ensure the remainder of the test section had a stable foundation. The bottom and sides of the pit were lined with impervious 6-mil polyethylene sheeting to minimize moisture migration from the CH subgrade.

Subgrade thickness varied from 0.61 m to 1.52 m between tests. The CH soil was processed by spreading to a uniform 0.31-m depth, pulverizing with a rotary mixer, adjusting the moisture content, and stockpiling. This iterative process continued until the target moisture content was reached. The CH was then placed in the test pit in 0.20-m lifts. Each lift was compacted with a pneumatic roller to a thickness of 0.15 m. Each compacted lift was subjected to in situ CBR tests in accordance with U.S. Army Corps of Engineers Standard CRD-C 654-95 (Handbook for Concrete and Cement, 1995) and nuclear moisture/density tests (ASTM D 6938) to verify target values were met. Average in situ properties of the constructed subgrades are shown in Table 5.

4.2. MAT INSTALLATION

The subgrade was surfaced with matting panels (Table 3) with the layout established by using stakes, strings, and measuring tapes to mark the centerline and data collection locations. Each mat system was installed by hand according to manufacturer guidelines. Once mats were installed, lead weights were placed on the section edges to represent the resistance to movement provided by a large expanse of matting. Steel or lead weights were used in the center of larger matting sections with more than one test lane. Lines were painted on the surface to mark data collection locations and to designate traffic areas for aiding in simulated traffic operations during testing. An example of a fully constructed test section is shown in Figure 1, and Table 6 provides test section geometry for each mat experiment.

4.3. SIMULATED AIRCRAFT TRAFFICKING PROCEDURES

A load cart designed to simulate a fully-loaded F-15E aircraft was used for trafficking each mat surfaced test section (Figure 2). The load cart was equipped with a single 91.4-cm by 27.9-cm, 30-ply tire inflated to an internal pressure of 2,240 kPa (325 psi) to represent the test tire. An F-15E aircraft loaded to its maximum capacity weighs 360 kN, with the main gear carrying 87% of that load (i.e., 313 kN). Therefore, the cart was loaded such that the test wheel was supporting half of the main gear load (i.e., 156 kN). The F-15E load cart was equipped with one outrigger wheel to prevent overturning and was powered by the front half of a U.S. Army transport truck.

Traffic on each mat surface was applied in a normally distributed pattern that simulated the traffic distribution, or wander width, of the main landing gear wheel of the F-15E aircraft when taxiing to and from an active runway (Figure 3). The traffic area was 114.3 cm wide and was divided into five lanes, where the width of each lane corresponded to the measured contact width of the F-15E tire when fully loaded (i.e., 22.9 cm). Application of traffic consisted of driving the load cart forward and then backward over the length of the mat test section and then shifting the path of the load cart laterally approximately one tire width on each forward path. For F-15E simulated traffic, one pattern of normally distributed

traffic is equal to 16 passes. A pass is defined as the crossing of a single point by the test vehicle, either forward or backwards.

4.4. DEFORMATION MEASUREMENTS

Data were collected throughout trafficking to determine the rate of deformation and the level of mat damage. Typically, traffic was paused for deformation measurements at 0, 16, 32, 48, 112, 240, 496, 1,008, 1,520, and so forth passes. Mat breakage was observed and recorded periodically as the tests proceeded.

Plastic deformation of the mat surface (δ_m) and subgrade (δ_s) was monitored at cross sections located near the quarter-points along the length of each test section. Data were collected at 0.3-m intervals along each cross section using either a robotic total station and prism or rod and level. These locations were chosen to characterize the average performance of the mat while avoiding potential effects associated with the boundary conditions at the edges of the test section.

δ_s was more difficult to monitor throughout trafficking for each test since observation holes were not drilled through the mats to collect physical measurements underneath the mat panels and since electronic instrumentation was not installed in the subgrade surface. One method attempted was taking rod and level readings at certain locations on the unloaded mat surface and then parking the load cart test tire at the same locations and taking rod and level measurements immediately adjacent to the tire (Figure 4a). The difference between the unloaded and loaded measurements was the elastic deflection of the mat and subgrade as the test wheel moved over the mat surface, as described by Rushing and Howard (2015). The sum of the average δ_m on the mat surface and the average elastic deflection was used to approximate δ_s and is given the term δ_{s-1} .

In addition to the δ_{s-1} approach, an attempt was made to monitor δ_s by adding a 26.7-kN load next to each cross section location by parking a forklift carrying 17.7 kN of lead blocks adjacent to each cross section. The purpose was to deform the mat panels just enough to contact the subgrade surface without causing plastic deformation of the subgrade. Survey data were then collected at 0.3-m intervals along

each cross section. This method was designated the “loaded deflection” procedure (Figure 4b), according to Rushing and Howard (2015), and the data collected at each cross section were averaged and used to approximate the term δ_{s-2} .

δ_s measurement methods varied for each test; however, enough data were collected so a direct comparison could be made between each mat type. For Mats 1 through 5, data were available to calculate δ_{s-1} ; and for Mats 3 through 6, loaded deflection measurements were obtained to determine δ_{s-2} .

The approaches used to determine δ_s are not without improvement potential. ERDC has attempted alternative approaches (e.g. embedded instrumentation) and is continuing to evaluate alternative approaches to those used herein. At present, however, the approaches utilized are preferred. One of the challenges faced for determining rutting profiles with internally embedded instrumentation is the matting systems are only affixed in the horizontal plane by small friction forces due to self weight and the lead blocks around the perimeter that are intended to simulate the weight of an additional expanse of matting around the test section. Therefore, horizontal movements of several centimeters occur in the lateral direction that vary considerably with mat type due to the load cart simulating fighter aircraft.

4.5. SUBGRADE INSTRUMENTATION AND DATA ACQUISITION

Mats 1 through 5 each had the subgrade instrumented with total earth pressure cells (EPCs) that were 22.9 cm diameter to monitor the stress distribution provided by the mat system (Table 7). Pressure values recorded are average values across the 22.9 cm diameter of the EPC face. EPCs were not installed beneath Mat 6. EPCs for Mats 1 through 5 were placed during subgrade construction beneath the centerline of traffic at different depths. The test sections for Mats 1 and 2 also had EPCs installed approximately 1.8 m offset from the centerline to capture the horizontal distribution of the subgrade stress away from the wheel path. Even though EPC locations varied between some mat tests, sufficient data were collected to make comparison for each mat. To minimize data processing, pressure was recorded at certain intervals at a sampling rate of 250 Hz. Typically, after each pass level where traffic was paused for collecting deformation data, pressure was recorded during the first 16 passes (one pattern).

4.6. FAILURE CRITERIA

The failure criteria established for simulated F-15E traffic were either (1) 10% mat breakage or (2) the development of 3.18 cm (1.25 in.) of permanent surface deformation. These failure criteria were developed based upon previous testing of airfield matting and U.S. Air Force requirements. The permanent deformation limit of 3.18 cm is based on roughness limitations for the F-15E aircraft. Mat breakage percentages were calculated by dividing the area of a failed panel (or half-panel) by the total area influenced by the simulated traffic application in the assembled test section. A panel was considered failed if the observed damage posed a significant tire hazard or caused instability of the load cart. A tire hazard was defined as any damage that could not be reasonably maintained by simple field maintenance procedures (e.g., skin delamination).

5. RESULTS

5.1. MAT BEHAVIOR

Results of full-scale testing are summarized in Table 8. Trafficking was typically continued after failure was established to capture additional information. With the exception of Mat 5, mat panel failures occurred at different levels for all mats. In some cases, panels had to be replaced to be able to continue traffic. In terms of passes to failure and δ_s at the end of the test, Mat 3 performed very well and better than any of the other matting systems. The drawback was that all mat breakage occurred quickly, without advanced warning, and created tire hazards that required panel replacement immediately. Although Mat 5 had no mat breakage, it failed to prevent δ_s and reached 7.6 cm (3 in.) of deformation after just 350 passes. Mat 5 was flexible enough to yield and plastically deform without causing tire hazards or prevent further operations from occurring.

For determining δ_m and δ_s , the survey data were re-evaluated using methods different than those applied for the originally funded work. For example, δ_{s-1} was not determined by Rushing and Tingle

(2007), Rushing et al. (2011), and Rushing et al. (2012), but is used for assessing mat system performance in this paper. Therefore, some differences relative to the original reports are present in this paper.

Figure 5 shows the progression of δ_m and δ_s (δ_{s-1} and δ_{s-2}) as a function of F-15E aircraft passes for each of the mat systems. The data were plotted on a logarithmic scale to increase the resolution of the deformation at lower pass numbers, especially for mats that were trafficked to less than 1,000 passes.

The rate of δ_s was generally higher than δ_m . δ_{s-1} increased more quickly than δ_{s-2} for Mats 3 through 5, which was expected, since δ_{s-1} is based on load-cart induced elastic deflection, a difference of nearly 130 kN from the weight applied by the forklift (see Figure 4). The rates of both δ_m and δ_{s-2} for Mat 3 were lower than the other mat systems, whereas the opposite is true for Mat 5. This can be explained due to the very stiff properties of carbon fiber (Mat 3) as compared to the lower modulus and dimensional characteristics of Mat 5. The panels for Mat 5 are merely 22.9 cm wide, preventing the assembled system from providing adequate bridging over any deformation on the subgrade compared to the other systems with much larger horizontal dimensions. This also explains the similarity between the rate of δ_m and δ_{s-2} for Mat 5.

It appears that the most relevant performance property is δ_s (as opposed to δ_m), since the rate of δ_s increase is higher than that of δ_m . From Figure 5b, the initial slope for the δ_{s-2} curves of Mats 3, 4 and 6 are closely related. The lower rate of increase in δ_{s-2} in Mats 3 and 4 may be largely attributed to the carbon fiber material in the composite cross section of both mats. For Mat 6, the internal support provided by the “truss-like” members appears to be a key contributor to preventing excessive subgrade deformation. The rate of increase in δ_{s-1} was very similar for Mats 1 through 4. The relationship between these curves may be a combination of the optimal dimensional properties of Mats 2 through 4 (i.e., larger width than Mat 1) and the increased stiffness of Mat 1. Although the stiffness of Mat 2 is the lowest of the systems tested, its performance was close to that of the stiffer Mat 1. Gonzalez and Rushing (2010) explained in their analysis that Mat 2 $E_c^{NJ(2)}$ determination was likely affected by the narrow and square geometry of the panel. The authors concluded that the rigid plate analysis used for backcalculating $E_c^{NJ(2)}$

was probably not suitable for determining Mat 2 stiffness, thus bringing its use into question for purposes of this paper.

5.2. EPC MEASUREMENTS

An example of the pressure recorded by an EPC placed under the centerline of Mat 4 is shown in Figure 6. Each of the spikes shown represents one forward/backward pass by the load cart during one pattern. The wander pattern used during trafficking (Figure 3) is evident from the spikes' increase as the load cart moved toward the gauge location at the centerline and their decrease as the load cart moved laterally away from the gauge. Load cart operations were operator dependent and precise position could not be documented, other than the assumption that the load cart was traveling along the appropriate lane. Therefore, each pair of spikes corresponding to two passes by the load cart along the same lane did not yield exactly the same value.

Data were reduced by selecting the maximum pressure value recorded by each pressure cell during each data collection interval (recording period), which was 450 kPa in Figure 6. Each of the values was normalized to only show the influence of the load cart on the subgrade by removing the effects of soil overburden pressure. The normalized pressure values for EPCs at the same offset distance and depth were averaged to report one value for each depth and offset distance. Figure 7 shows graphical summaries of the average maximum normalized vertical pressure values for data collection intervals in the instrumented test sections. Pressure distribution was relatively stable and didn't show considerable change throughout each test for Mats 1 through 5. It should be understood that this effort utilized relatively large diameter pressure cells so an average pressure over a relatively large area was obtained, which was desired for this effort. To truly obtain peak values, smaller diameter cells should be used.

6. ANALYSIS

6.1. PERFORMANCE PREDICTION

To remove any bias associated with structural failures of the mat panels for each mat system, the data shown in Figure 5b were revised so that δ_s was plotted until that point in which structural mat failures (or panel replacements) were judged to have affected the measurements (Figure 8). The data were plotted in terms of the logarithm of the pass number. For example, $\log_{10}$ of 16 is 1.20; therefore, the data for pass 16 were plotted 1.20 units from the origin of the x-axis.

With this data, linear trend lines were fitted to each curve and forced through the origin to determine whether the data is suitable for predicting δ_s . The results showed that the R^2 value was 0.84 or greater for all six mats tested, indicating acceptable prediction. The regression data provided in Figure 8 are to be used in Equation 4, where δ_s = the subgrade deformation, cm, P = the number of passes, and C = the regression coefficient. Note that trendlines were determined with Regression Through Origin (RTO) techniques, so the R^2 values reported should be interpreted accordingly.

$$\delta_s = C[\log_{10}(P)] \quad (4)$$

As noted by the regression coefficients for Mats 3 and 4, the rate of increase of δ_{s-1} was about twice the rate of δ_{s-2} . Although both measurements are useful for providing predictions of airfield matting behavior, δ_{s-1} seems to provide a more conservative approach. Using regression coefficients to calculate δ_{s-2} for Mats 3, 4, and 5 actually yields pass levels when the deformation criterion is exceeded that are outside of the test limits. Since these mat systems are typically used for aircraft operations, over predicting their capabilities is problematic and unsafe for aircraft and personnel. Therefore, curves developed using δ_{s-1} measurements were used for relating subgrade deformation to a given $E_c^{NJ(2)}$ and number of passes. Since δ_{s-1} and $E_c^{NJ(2)}$ were not determined for the Aluminum Truss system, it was not included in the following discussion.

To relate $E_c^{NJ(2)}$, δ_s , and number of F-15E passes, δ_{s-1} was calculated for Mats 1 through 5 using the regression coefficients in Figure 8 at 10 passes (i.e., $\log_{10}(10) = 1$). Values determined were plotted against $E_c^{NJ(2)}$. Different trends were fitted to the data and a power function proved to be the most

suitable. The simplified expression shown in Equation 5 was developed, where $\delta_{s-1-pred-1}$ = the predicted subgrade deformation, cm, P = the number of passes, and $E_c^{NJ(2)}$ = the composite modulus, MPa.

However, the relationship had a low R^2 value ($R^2 < 0.50$).

$$\delta_{s-1-pred-1} = \log_{10}(P) * 38.21 * [E_c^{NJ(2)}]^{-0.33} \quad (5)$$

The values used to develop Equation 5 were revisited and it became clear that data relative to Mat 2 had to be removed because they were affecting the regressions. A power function was fitted to the revised data and Equation 6 was developed, where $\delta_{s-1-pred}$ is the predicted subgrade deformation, cm.

$$\delta_{s-1-pred} = \log_{10}(P) * 686.26 * [E_c^{NJ(2)}]^{-0.63} \quad (6)$$

The equality plot shown in Figure 9 was developed with the same δ_{s-1} data set used to create the regressions in Figure 8. $\delta_{s-1-pred}$ was calculated for the same pass levels and associated $E_c^{NJ(2)}$ values of the mats. Note that data relative to Mat 2 were not used for this analysis. According to Figure 9, the R^2 value associated with Equation 6 is 0.91 and the computed standard error was 0.6 cm. All of the data is fully encompassed by equations $y=0.6x$ and $y=1.3x$, an envelope that is mostly driven by the outermost points in the plot. The regression with a slope of 0.93 is represented with a dashed line, whereas the slopes of the envelope and the line of equality are shown in solid lines. Additional information is provided by Garcia (2015).

To illustrate curves developed based on Equation 6, Figure 10 was created for arbitrarily selected passes. Figure 10 indicates that an increase in mat stiffness for weaker mats causes large decreases in δ_{s-1} . If there is an increase in stiffness at the stronger end of the spectrum, only minimal decreases in δ_{s-1} are observed.

Equation 6 and/or Figure 10 can be used to approximate the subgrade deformation for a given number of F-15E aircraft passes and $E_c^{NJ(2)}$ for a mat system that will be placed on a CBR of 6. To use these curves, $E_c^{NJ(2)}$ should be determined using the test method described by Berney et al. (2006) and backcalculated according to the approach used by Gonzalez and Rushing (2010). Any other method for

determining mat stiffness (e.g., laboratory four-point bending test) is not necessarily applicable to the approach presented above, in the absence of further investigation. The curves are also limited to mat systems with panels that have rectangular geometries.

To demonstrate the ability of Equation 6 to determine δ_{s-1} , data from the test sections for Mats 1, 3, 4, and 5 were investigated in terms of δ_{s-1} failures (i.e., $\delta_{s-1} \geq 3.18$ cm). The test results and solutions for P using Equation 6 are shown in Table 9 for comparison. The predicted values are conservative for weaker mat systems, but Equation 6 tends to over predict the performance of Mat 1. To gain some insight of the sensitivity of the relationship when solving for P , Equation 6 was solved for three levels of deformation: 2.92 cm (1.15 in.), 3.18 cm (1.25 in.), and 3.43 cm (1.35 in.). The results showed a wide scatter in the predicted P . Small changes in $\delta_{s-1-pred}$ yield large changes in the predicted P when using the inverse relationship. However, the overall tendency of Equation 6 is to yield more conservative results for weaker mat systems. Potential users of Equation 6 are advised to look at the relationship in order to predict a range of allowable passes since small changes in δ_{s-1} can result in large changes in P .

As discussed in the airfield matting background, Rushing and Howard (2015) published design curves and the expression shown in Equation 3 to determine δ_s as a function of F-15E passes and subgrade CBR, specifically for Mat 1. Curves developed by Rushing and Howard (2015) showed similar behavior to those shown in Figure 10, where small CBR increases for a weak subgrade cause large decreases in δ_s . As the CBR increases, the same increase in subgrade strength only provides minimal decreases in δ_s , similar to what is shown here for increasing mat stiffness. Interestingly, Rushing and Howard (2015)'s equation (Equation 3) raises CBR to an exponent of -0.61, while Equation 6 raises $E_c^{NJ(2)}$ to an exponent of -0.63. There isn't sufficient data at the present time to develop a more universal equation applicable to any mat $E_c^{NJ(2)}$ or soil CBR, but there does seem to be promise that such a universal equation could be developed in the future as more data becomes available.

It should be noted that the relationship developed is based on deformation rate analyses. Structural mat failures were not taken into account, and failure by exceeding the mat breakage criterion cannot be

determined from the analysis presented thus far. It is possible for a mat system to fail by mat breakage prior to δ_{s-1} failure. Therefore, further investigation into the available data would be needed to connect the two failure mechanism into one function (or series of functions) that can predict which failure component may occur first.

6.2. PRESSURE MEASUREMENTS

Pressure measurements were used as an independent assessment of the relationships presented thus far in the paper. The primary relationship investigated with pressure measurements was that of $E_c^{NJ(2)}$ and δ_{s-1} . Findings from pressure measurements are presented in the following paragraphs.

The data in Figure 7 show that Mats 1 through 5 worked well at distributing the applied load so that a fraction of it was experienced by the subgrade. To make a consistent comparison of the pressure distribution measured from large diameter cells, the average maximum normalized pressures determined for the first traffic pattern at different depths were plotted relative to the measured $E_c^{NJ(2)}$ of the mats (Figure 11a). Note that peak values for smaller areas could be larger than the values shown if smaller diameter cells had been used. As expected, mat systems with higher stiffness values were generally able to diminish pressure in the subgrade more than those with less stiffness. Although Mat 2 $E_c^{NJ(2)}$ is the lowest, discrepancies in the determination of mat properties due to its square geometry make it difficult to relate its stiffness to measured pressure. Based on a comparison of deformation rates, pressure distribution under Mat 2 should be comparable to that under Mat 4. The data shown in Figure 11a support this statement. The most notable differences in pressure are noted at the 15.2-cm and 30.5-cm depths, indicating that mat stiffness has more effect on the near surface pressure distribution, which is expected.

Figure 11b plots pressure at 30.5 cm (same pressure values shown in Figure 11a) relative to $\delta_{s-1-pred}$ at 10 passes. The purpose of Figure 11b was to determine if there was a correlation between pressure and δ_{s-1} that was similar in shape but opposite in magnitude to Figure 10. In Figure 10, the fundamental power fit relationship (Eq.6) related $E_c^{NJ(2)}$ and δ_{s-1} with an R^2 of 0.91 where higher $E_c^{NJ(2)}$ resulted in lower δ_{s-1} .

Higher $E_c^{NJ(2)}$ values should lower measured pressures, which did generally hold true in Figure 11b, but there was not a strong power fit relationship between pressure and δ_{s-1} . As such, Figure 11b only provides modest support for Figure 10.

7. SUMMARY AND CONCLUSIONS

Matting systems have been an expedient surfacing solution for rapid construction of airfields for many decades. Their primary purpose and essential features have remained fundamentally the same. However, mat materials, geometry, design, and assembly have changed. This paper aims at presenting data from six full-scale test sections of airfield matting systems to compare their performance in terms of accumulated subgrade deformation and to develop relationships that could help users make informed decisions when selecting an airfield matting system. A simple expression was developed to quickly estimate subgrade deformation, based on mat properties, for a given number of F-15E passes on a CBR of 6. The equation seems reasonable and follows the same general form of Rushing and Howard (2015), which looked at a constant matting systems and varied subgrade CBR. Since most of the data were revised and limited to the first 1,500 passes (or less) for use in the analysis, the predictive relationship developed should be used for estimating δ_s up to 1500 F-15E passes. Results determined for greater than 1500 F-15E passes may be misleading. Note, however, that this refers to 1500 F-15E passes, where the aircraft is fully loaded and is traveling in a narrow path. Realistically, take offs are usually much heavier than landings due to cargo being discharged and fuel burned while in service. Also, other, less severe aircraft that are not as damaging would also be expected to utilize the matting system. The efforts presented in this paper have provided potential users of matting systems and additional predictive tool, which are not prevalent in the current body of literature.

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Table 1. Review of modern matting systems tested for military applications

Reference	CBR of Subgrade	Military Application	Traffic Type
Rushing and Garcia (2013)	6	Aircraft maintenance hangars	F-15 Eagle fighter aircraft (standard weight)
Rushing and Howard (2011)	1-3, 5, and 15	Roadways	7 ton U.S. Marine Corps transport vehicle
Gartrell et al. (2009)	5-6, 8-10, and 40-50	Airfields	C-17 and C-130 cargo aircraft
Garcia (2015)	6	Airfields	F-15 Eagle fighter aircraft (maximum weight)

Note: CBR = California bearing ratio

Table 2. Historical research on expedient surfaces: 1940's - 1970's

Reference	Airfield Matting System
Greulich (1943); Tolbert (1945)	Pierced steel plank
WES (1951)	M8 steel and M9 aluminum
Garrett and Horsley (1957) Turner (1961)	T-mats
Burns and Barker (1967)	AM2 extruded aluminum
Carr and Ellison (1973)	M19 aluminum honeycomb

Table 3. Properties of mats tested.

Mat	Mat Name	Description	L , cm	W , cm	t , cm	D , N	$E_c^{NJ(2)}$, Mpa	Source of $E_c^{NJ(2)}$
1	AM2	Single aluminum extrusion with vertical stiffeners in longitudinal direction and welded end connectors.	365.8	60.9	3.81	647.2	27,372	Gonzalez and Rushing (2010)
2	M19	Aluminum honeycomb core bonded to aluminum skins with epoxy adhesive.	127.5	125.7	3.81	330.9	3,447	Gonzalez and Rushing (2010)
3	Carbon Fiber Composite	Foam filled core with carbon fiber stiffeners. Carbon fiber top and bottom skins bonded to extruded aluminum connection rails on each edge.	213.4	127.0	3.18	552.9	16,926	Rushing et al. (2011)
4	Aluminum Honeycomb Composite	Aluminum honeycomb core bonded to top and bottom skins by an epoxy adhesive. Skins were composed of a carbon fiber sheet sandwiched between two aluminum sheets.	264.2	106.7	3.18	541.8	16,685	Rushing et al. (2011)
5	MLC-70 Trackway	Single aluminum extrusion. Male/female connection in long dimension. Connected panels can be rolled for transport.	457.2	22.9	3.18	327.8	3,792	Rushing et al. (2012)
6	Aluminum Truss	Two welded aluminum extrusions with isosceles triangles cross section and welded end connectors.	264.2	53.3	3.18	383.4	--- ^a	--- ^a

L = length of one panel; W = width of one panel; t = thickness; D = Weight of one panel; $E_c^{NJ(2)}$ = composite modulus absent a joint.

Note: Mat 1 was evaluated in Rushing and Howard (2015); Mats 1 and 2 were studied in Gonzalez and Rushing (2010); and Mats 3 through 6 have not been used for mat behavior analyses in the journal articles cited.

^aMat 6 is a prototype. $E_c^{NJ(2)}$ was not measured.

Table 4. Typical properties of soil conditions tested.

Description	Vicksburg Buckshot Clay
Color	Gray
USCS Group Classification	CH
LL	77
PL	27
PI	50
Max DD, kg/m ³ (lb/ft ³) ^a	1,670 (104)
OMC, %	19
– 75 mm (%)	90
% Clay	46
Gs	2.74
MC for CBR of 6, %	34 ± 2
DD for CBR of 6, kg/m ³ (lb/ft ³)	1,377 (86)

Note: USCS = Unified Soil Classification Systems; LL = liquid limit,; PL = plastic limit; PI = plasticity index; DD = dry density; OMC = optimum moisture content;

CBR = California bearing ratio; Gs = specific gravity; MC = moisture content

^aASTM D1557

Table 5. In situ properties of the subgrade in each test section.

Mat	ASTM D 6938			CRD-C 654-95	
	Wet density (lb/ft³)	Dry density (lb/ft³)	Moisture (%)	Moisture, (%)	CBR (%)
1	118.5	90.8	30.6	33.5	6.0
2	118.0	90.6	30.4	33.0	6.0
3	119.5	92.5	29.6	32.3	5.9
4	118.9	92.0	29.3	32.3	5.9
5	119.8	92.3	29.8	31.1	6.2
6	116.8	90.2	29.6	31.6	6.1

Table 6. Test section geometry for each mat experiment.

Mat	Subgrade Depth, m	Dimensions	
		L, m	W, m
1	1.52	12.2	6.7
2	1.52	12.2	6.7
3	0.91	10.4	6.4
4	0.91	8.5	7.9
5	0.91	12.2	7.3
6	0.61	4.3	6.7

Table 7. EPC locations for each test section.

Depth ^a , cm	Offset ^b , cm	MAT					
		1	2	3	4	5	6
15.2	0	-	-	Y	Y	Y	-
30.5	0	Y	Y	Y	Y	Y	-
60.9	0	-	-	Y	Y	Y	-
76.2	0	Y	Y	-	-	-	-
137.2	0	Y	Y	-	-	-	-
76.2	182.9	Y	Y	-	-	-	-
137.2	182.9	Y	Y	-	-	-	-

Note: (-) means no EPC was installed

^aDepth from surface of subgrade; ^bOffset from centerline

Table 8. Results of full-scale testing.

Mat	$MB^a \geq 10\%$	$\delta_m \geq 3.18 \text{ cm}$	$\delta_{s-1} \geq 3.18 \text{ cm}$	$\delta_{s-2} \geq 3.18 \text{ cm}$	Pass level at end of test
	Pass level when criterion was met or exceeded				
1	1,536	N/A ^b	384	--- ^c	1,792
2	2,085	N/A ^b	192	--- ^c	2,085
3	3,404	N/A ^b	496	3,404	3,404
4	662	N/A ^b	240	N/A ^b	720
5	N/A ^b	124	16	48	350
6	752	N/A ^b	--- ^c	752	752

^aMB = Mat breakage; ^bCriterion not exceeded; ^cNot measured.

Table 9. Comparison of measured and predicted δ_{s-1} values.

Mat	$E_c^{NJ(2)}$ (MPa)	Test results		Pass level prediction at:			
		Pass level when $\delta_{s-1} \geq 3.18$ cm	δ_{s-1} (cm)	δ_{s-1} = value from test results	δ_{s-1} = 2.92 cm	δ_{s-1} = 3.18 cm	δ_{s-1} = 3.43 cm
1	27,372	384	3.35	1,118	454	783	1,322
2	16,926	496	3.18	137	92	137	202
3	16,685	240	3.40	184	88	131	193
4	3,792	16	4.88	19	6	7	8

LIST OF FIGURES

Figure 1. Test section surfaced with Mat 1.

Figure 2. (a) F-15E load cart and (b) close up of load cart test wheel on Mat 1.

Figure 3. Typical normalized traffic wander pattern of F-15E load cart.

Figure 4. (a) Elastic deflection measurement corresponding to δ_{s-1} and (b) loaded deflection procedure corresponding to δ_{s-2} .

Figure 5. Rate of (a) δ_m and (b) δ_s for each mat system.

Figure 6. Example pressure response during one pattern (16 passes).

Figure 7. Average maximum normalized pressure under matting systems.

Figure 8. δ_s predictions using data prior to structural mat failures.

Figure 9. Equality plot of predicted vs measured δ_{s-1} .

Figure 10. Predictions of δ_{s-1} for a given $E_c^{NJ(2)}$ and pass number.

Figure 11. Avg. max normalized pressure during first 16 passes (a) related to $E_c^{NJ(2)}$ and (b) related to δ_{s-1} .

pred.

Figure 1 - Color for Web

Figure 1 - Gray for Print

Figure 2 - Color for Web

Figure 2 - Gray for Print

Figure 3 - Color for Web

Figure 4 - Color for Web

Figure 4 - Gray for Print

Figure 5 - Color for Web

(a)

(b)

Figure 6 - Color for Web

Figure 7 - Color for Web

(a) Mat 1

(b) Mat 2

(c) Mat 3

(d) Mat 4

(e) Mat 5

Figure 8 - Color for Web

Figure 9 - Color for Web

Figure 10 - Color for Web

Figure 11 - Color for Web