Extreme Cold Weather and Field Strength Testing

of

Engineered Material Arresting Systems (EMAS)

By

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Presented for the

2010 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Atlantic City, New Jersey, USA

April 2010

ABSTRACT

The Engineered Material Arresting System (EMAS) was jointly developed by the Federal Aviation Administration (FAA), The Port Authority of New York and New Jersey (PANYNJ), and Engineered Arresting Systems Corporation (ESCO-ZA) in the 1990's as an alternate means of providing overrun safety when the mandated 1,000-foot-long Runway Safety Area (RSA) could not be economically achieved [1]. The current EMAS system, EMASMAX®, manufactured (ESCO-ZA), is currently the only system that meets the requirements of FAA Advisory Circular AC150/5220-22A [2] and is installed at 30 airports in the U.S. To date, the system has successfully arrested six overrunning aircraft, and has proven to be a reliable, efficient remedy for length-deficient runway end safety areas.

Due to a lack of historical data, there have been some questions regarding EMAS' long-term durability. In particular, there was of a lack of data regarding the ability of the system to maintain performance and survive for up to 20 years in extreme cold environments, or any quantitative method to evaluate the condition of the installed systems.

This paper discusses two studies conducted by the FAA and ESCO-ZA to answer these questions: Extreme Cold Weather Testing and Development of a Field Strength Test Method. The results of the cold weather study have shown that EMAS is unaffected by extreme cold and temperature cycling, and can be expected to be durable for up to 20 years or more in extreme cold climates, while the development and certification of a field test method now provides a way to test the viability of installed beds. Combined, these studies result in a higher confidence that properly-maintained EMAS systems can survive harsh runway environments for up 20 years.

INTRODUCTION

Every year, tens of millions of commercial airline landings occur at airports around the world. Almost always, these aircraft land without incident. However, in a few instances, the aircraft is unable to stop on the runway after landing, resulting in an accident. This type of accident is called an aircraft "overrun". Each year there are an average of 43 commercial aircraft overruns worldwide, accounting for almost 30% of all major commercial aircraft accidents involving fatalities [3].

To help reduce the possibility of an overrun becoming an accident, runways are required to have escape areas called Runway Safety Areas, (RSA) at their ends to provide additional space for an aircraft to stop. To be effective, the RSA should be 1,000 feet long or more [4]. However, many airports do not have the space to provide adequate RSAs due to natural (such as waterways) or man-made (such as buildings, roadways, etc.) obstacles which either cannot or would be too costly to remove.

While increasing the length of the RSAs at airports might not be practical, there is a technology available which can provide the same, or even greater, protection in far less space than a standard RSA. This FAA-approved technology is called the Engineered Material Arresting System, or EMAS.

EMAS is a soft concrete material encased in a protective coating. The JBR (jet-blast resistant) coating provides durability in all climates and weather conditions, and shields the material against damage due to jet blast. The system is installed on the pavement at the end of the runway in the RSA. When an aircraft enters into the EMAS, the material crushes and the landing gear of the aircraft sinks into the material. The interaction between the crushed material and the airplane tires causes the aircraft to decelerate. The properties of the material are engineered to provide efficient deceleration while minimizing the potential for damage to the aircraft or injury to the passengers and crew.

EMAS was developed in the early 1990's through a joint effort between the U.S Federal Aviation Administration (FAA), the Port Authority of New York and New Jersey (PANYNJ) and Engineered Arresting Systems Corporation (ESCO–ZA) of Aston Pennsylvania. After extensive testing, the system was certified by the FAA in 1996, and the first system was installed later that year at JFK International Airport in New York City. As of January 2010, there are 48 systems installed at 32 airports in the USA and abroad. To date, six overrunning aircraft have been successfully saved by the EMAS. In all cases, there was minimal damage to the aircraft and no significant injuries to the passengers or crew.

While EMAS has proven to be a cost-effective, efficient, and successful way to protect against overrun accidents, there have been questions regarding its long-term durability. In particular, there was of a lack of data regarding the ability of the system to maintain performance and survive for up to 20 years in extreme cold environments. Further there was no quantitative method to evaluate the condition of installed systems. As a result, the FAA conservatively decided that all EMAS systems may need to be replaced after 10 years of service [5].

To answer these questions, and ultimately to provide a level of confidence to extend the useful life of the EMAS, two (2) studies were conducted. First, cold weather testing was conducted by the FAA in coordination with the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire and ESCO-ZA. Second, ESCO-ZA, in coordination with the FAA, developed and certified a field-strength testing method for evaluating the condition of installed systems. Combined, these two efforts have provided the data and methodology necessary to validate the viability and condition of EMAS systems in all weather conditions, and offer a level of confidence to extend the installation life beyond the current 10 year replacement assumption.

EXTREME COLD WEATHER DURABILITY TESTING

ESCO-ZA's EMAS system, EMASMAX®, consists of nominally 4 foot by 4 foot cellular cement blocks with depths varying from 5 inches to 28 inches. The cement blocks are covered on the top and bottom in plastic, with the sides covered with a polyester scrim or mesh. A typical EMAS block is shown in Figure 1.

An EMAS installation, as shown in Figure 2, consists of the arrangement of the individual blocks in the RSA, with the exposed sides of the bed and the seams between the blocks sealed with an extruded silicone sheet. The silicone seal is adhered to the blocks with silicone caulk.

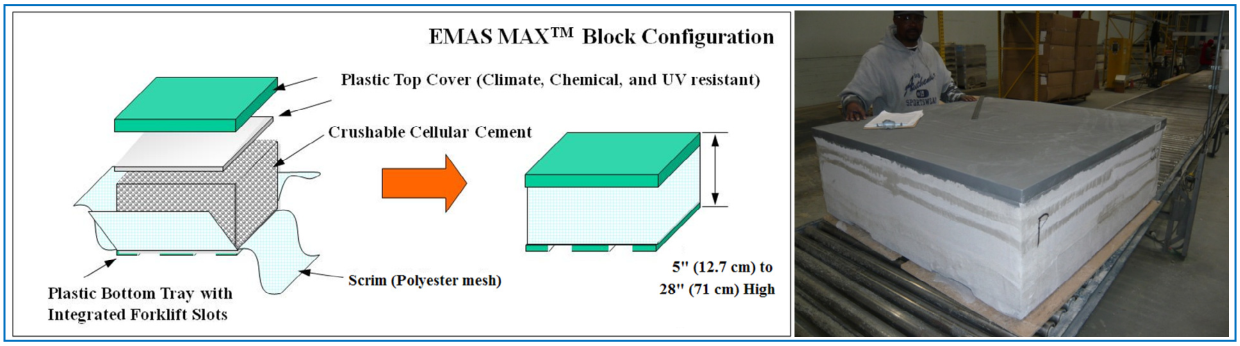

Figure 1. Typical EMAS Block Configuration.

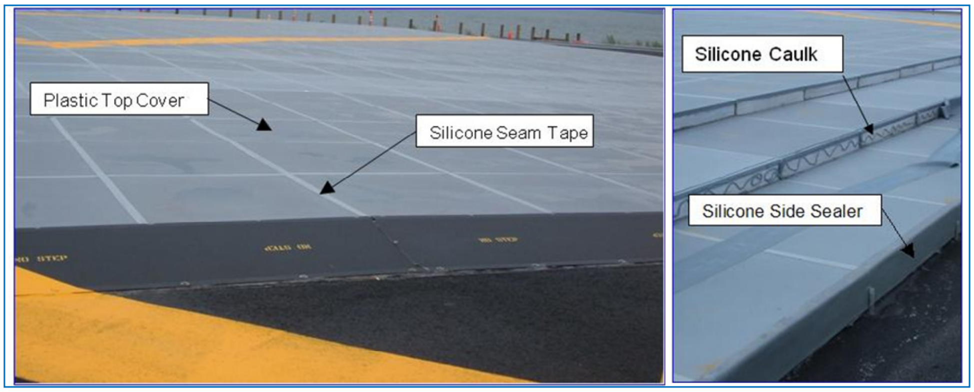

Figure 2. Typical EMAS Installation Showing Silicone Joint and Side Seals.

The extreme cold weather testing conducted by CRREL had four (4) major objectives [6]:

1. Evaluate the long term durability of the EMAS through twenty (20) years of simulated cycling from extreme cold to warm temperatures.

2. Evaluate the effect of temperature and humidity cycling on EMAS material strength.

3. Evaluate the effect of extreme cold on silicone seal durability and adhesion.

4. Evaluate the effect of extreme cold temperature on plastic top durability.

Long Term Durability

To evaluate long-term durability, an 11 by 20 block (44 feet by 80 feet) EMAS bed was installed in one of CRREL's large environmental chambers, as shown in Figure 3. The bed was then subjected to temperature cycling from -20^{o}F to ambient temperature (typically +60^{o}F to +80^{o}F). A total of twenty (20) cycles were performed over a 9-month period, each cycle approximately 14 days in length (7 days at cold temperature, 7 days at ambient temperature). Thermocouples and humidity gauges embedded in selected blocks, as shown in Figure 4, recorded the core temperature and humidity of the EMAS. In addition, qualitative condition assessments were performed during the cycling and quantitative post-cycling strength measurements of the core material were performed and compared to pre-test measurements.

Figure 3. Long Term Durability Test Bed Installation in CRREL Environmental Chamber.

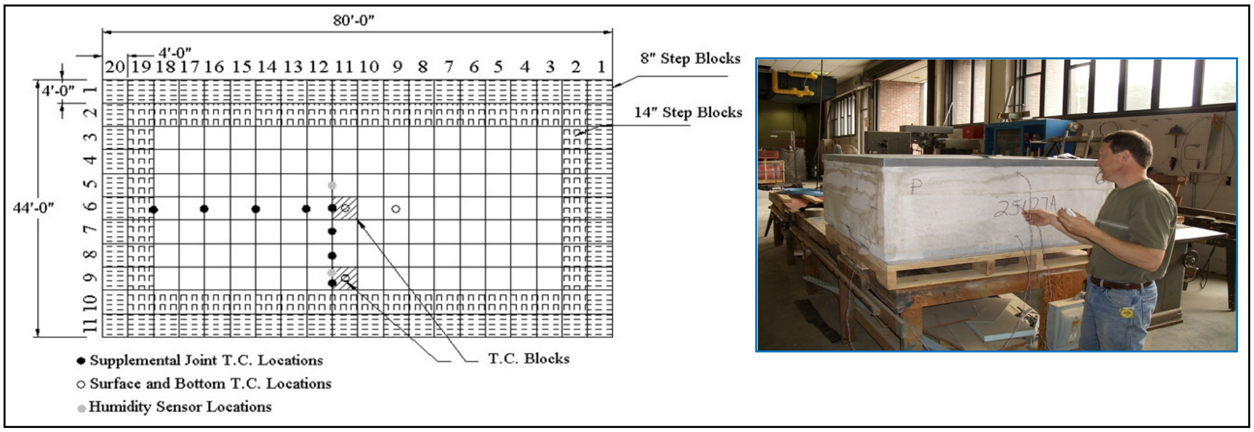

Figure 4. Thermocouple/Humidity Gauge Locations within EMAS Test Bed.

Typical temperature readings during a typical thermal cycle are shown in Figure 5 [6]. The results throughout the bed were consistent and showed that, as expected, the EMAS core material is a good insulator with temperatures within the blocks generally lagging the ambient temperature by an average of 30^{o}F.

Qualitative Inspection of the bed during the cycling showed some frost formation within the gaps between the blocks in the air vents, as shown in Figure 6. However, this frost was only on the surface of the material, and would not cause any change in the properties or performance of the EMAS material. No deterioration of the extruded silicone side and seam seal, or loss of adhesion was evident after the completion of the 20 thermal cycles [6].

To ascertain if there was any effect from the temperature cycling on the block strength, and subsequently the performance capability of the EMAS, block punch tests were performed on nine (9) blocks before and after temperature cycling. The pre-cycling punch tests were performed by ESCO-ZA on the newly-manufactured blocks before the plastic tops were installed. These blocks were then randomly placed into the test bed. After temperature cycling, the tops of these blocks were removed and they were tested by CRREL using a method that mimicked and was calibrated to the patented ESCO-ZA Compressive Gradient Strength (CGS) system [7].

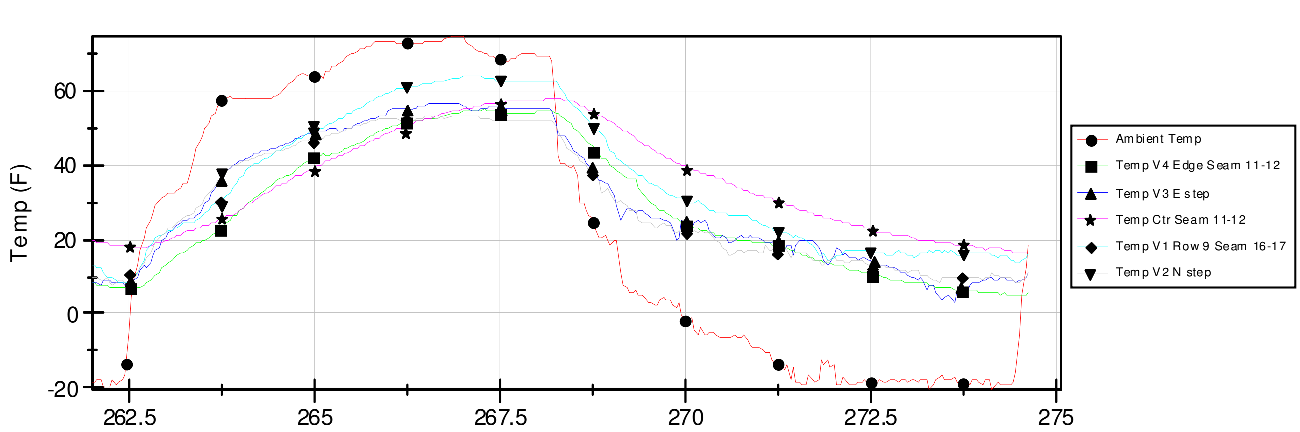

Figure 5. Typical Temperature History for One 14-Day Hot/Cold Cycle.

Figure 6. Typical Frost Concentrations Within the Vents (Top Left), Sides of the Blocks (Bottom Left) and Under the Plastic Top (Right).

The results of the punch tests in CGS Units are given in Table 1 [6]. As can be seen, six of the nine tests showed little change, while three showed some variation. However, the average pre- and post-cycled results for the nine blocks as well as their standard deviations are virtually identical. It is thus concluded that the 20 hot-cold thermal cycles had no effect on the strength, and conversely the performance capability, of the EMAS.

Temperature/Humidity Cycling

To explore the effects of temperature and humidity on EMAS core material strength, one cubic foot samples were cycled in an environmental chamber with temperature cycled from -50^{o}F to room temperature (typically 60^{o}to 80^{o}F) and relative humidity ranging from 20% to 100% for 20 cycles. A sample of the test temperature and humidity data is given in Figure 7.

Table 1. Summary of Pre-and Post-Thermal Cycling Punch Test Results.

Block Number	Pre-Test Measurement	Post-Test Measurement
22302	62.55	60.2
22303	59.35	73.45
22319	65.3	59.35
22320	72.8	74.65
22321	66.75	78.00
22322	73.75	69.8
22381	83.46	68.9
22324	55.75	56.25
26322	70.25	72.15
Average	***67.77***	***68.08***
Std. Deviation	***8.39***	***7.66***

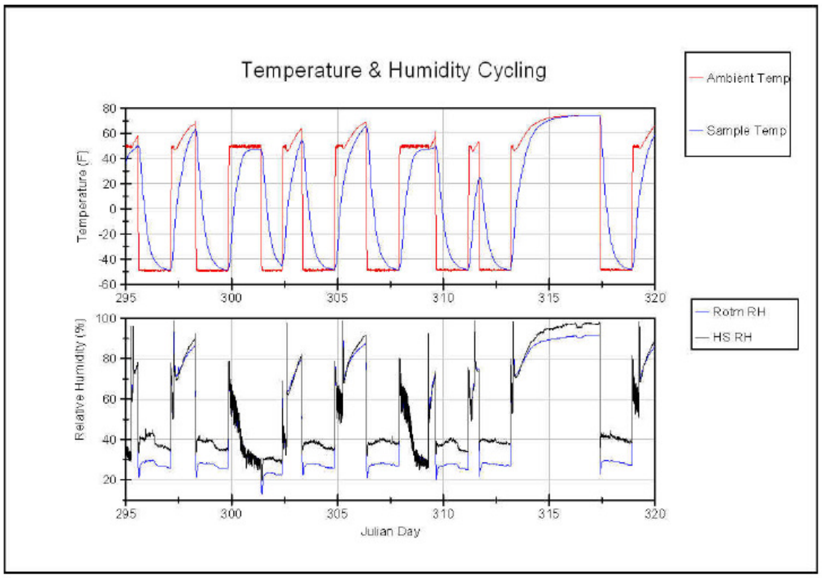

Figure 7. Temperature and Humidity Data for EMAS Core Material Environmental Conditioning.

After completion of the temperature/humidity conditioning, three (3) sets of samples were punch tested for strength. The sample groups were:

- Group 1. Control Group – No environmental conditioning
- Group 2. Thermal cycled only.
- Group 3. Thermal and Humidity cycled.

Samples were punch tested at room temperature, 0°F, -20°F, and -50°F. The results of the punch tests are given in Figure 8. As can be seen from the figure, there was little difference in the average or range of strength values obtained within and between groups, and as such it is expected that temperature and humidity will have little effect on overall EMAS performance.

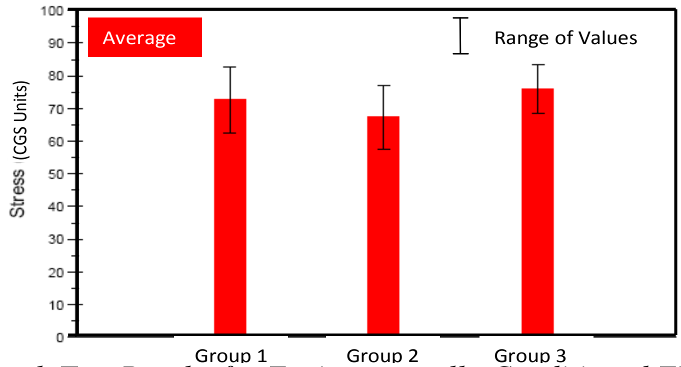

Figure 8. Punch Test Results for Environmentally-Conditioned EMAS Samples.

Silicone Seal Durability

To evaluate the durability at cold temperature of the extruded silicone seam and side seal material, and the integrity of the silicone caulk used to install the seals, test specimens were fabricated which consisted of coupons of the silicone material bonded between two pieces of the plastic lid material. The coupons were tensile tested to failure at various temperatures to record the load required. The test and specimen arrangements are shown in Figure 9.

Figure 10 contains the results of the tensile tests. The strength of the silicone increased with decreasing temperature, but not by an amount that would impact performance or durability. The material remained pliable throughout the tested temperature range. In all cases, the material failed before the bond between the silicone and the plastic lid material. These results verify that the extruded silicone seals are durable under extreme cold temperature conditions.

Figure 9. Test Specimens and Experimental Arrangement for the Extruded Silicone Seal Tensile Tests (Left) and Typical Post-Test Result (Right).

Lid Durability

One final concern addressed by the CRREL testing was the durability of the plastic lids at extreme cold temperatures, specifically that the lids would become brittle and easier to damage when cold. To test the effect of cold on the lid material, lids were cooled to -17^{o}F and weights dropped from several heights to assess the damage inflicted. The volume of the damaged area at the various test conditions was measured, and qualitative examination of the cracking was recorded for each test condition. The results at temperature were then compared to those obtained at room temperature (nominally 70^{o}F)

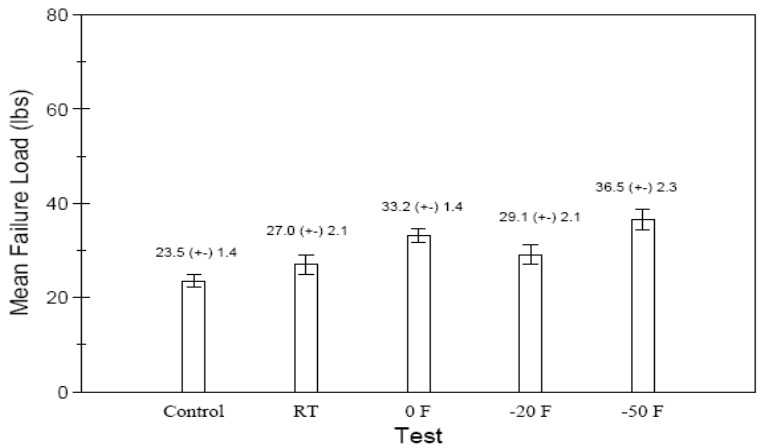

Figure 10. Tensile Test Results for the Extruded Silicone Seal Material at Various Temperatures.

A sample drop weight and typical lid damage are shown in Figure 11. Typical results are shown in Figure 12. Based on the examinations, it was determined that no significant changes occur to the plastic lid material at extreme cold temperatures, and that the material should provide adequate protection and durability throughout its expected operating temperature range.

Figure 11.
Sample Drop Weight and Typical Damage Inflicted on the Plastic Lid Material.

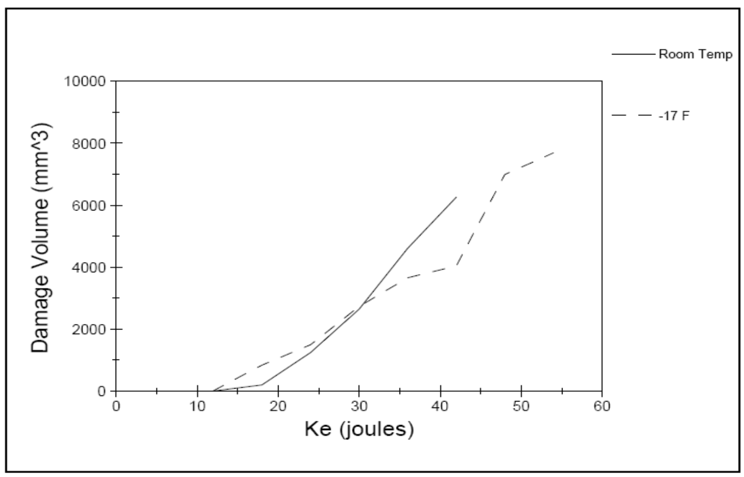

Figure 12. Typical Results for the Plastic Lid Drop Testing.

Extreme Cold Weather Testing Summary

In general, the CRREL testing showed that the EMAS system tolerated the cold cycling well, with little change in strength and subsequently little or no change in expected performance. The silicone seals, adhesive, and lid materials also showed little change in durability and performance. Based on these results, it was concluded that the current EMAS configurations durability, performance, and expected life will not be significantly impacted if installed in an extreme cold weather location and properly maintained.

EMAS FIELD STRENGTH TESTING (FST) METHOD

The current generation of the ESCO-ZA EMAS product, JBR-502 (Trade name: EMASMAX®), was engineered to provide long term durability with minimal maintenance. Environmental testing performed on this configuration, including the extreme cold weather testing detailed above, has shown that an installation life of up to 20 years or more can be expected with proper maintenance.

While these evaluations have confirmed the durability of the EMASMAX® in a laboratory environment, there were still questions regarding the effectiveness after years of exposure in a real-world runway environment, especially given variability in the level and frequency of preventive maintenance performed on each system. Because of this uncertainty, the lifecycle cost calculations from FAA Order 5200.9 [5] assume that the EMAS material will require replacement at 10 years.

The performance of EMAS depends highly on the material properties of cellular concrete (CC). In order to determine that installed EMAS systems have maintained designed arresting capability, a Field Strength Test (FST) was needed to measure the strength of CC blocks, which should fall within a certain range. An R&D program performed by ESCO-ZA, in cooperation with the FAA, developed the FST method, which uses principles similar to those used for in-house testing on the Punch Test Machine (PTM). An FST tolerance band is defined, along with the FST test method to provide an indication of strength and confirm viability of EMAS installations at airports.

Field Strength Test (FST) Method Tolerance Band Development

Test Apparatus and Instrumentation

The FST apparatus, shown in Figure 13, is a hand-held instrument that consists of a punch tip attached to a shaft that is mounted to a load cell. The operational temperature range is between 32^{o}F and 122^{o}F. Distance is measured using ultrasonic sensors. The FST apparatus records force and distance data that can later be downloaded for analysis. The resolution of the penetration force measurement is about 0.2 lbs. In addition, the FST records data discretely in increments of penetration depth.

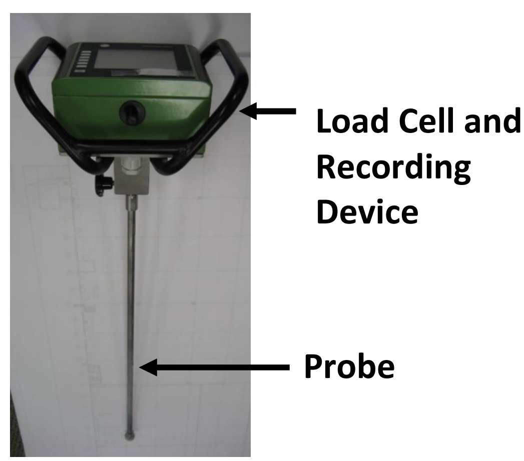

Figure 13. ESCO-ZA's Field Strength Test Apparatus.

ESCO-ZA uses a proprietary Compressive Gradient Strength (CGS) [7] to qualify block strengths. The approved strength tolerance band for CGS was based on the PTM. The new tolerance band discussed in this paper for the FST method is comparable to the CGS tolerance band for the PTM. Due to the unique material properties of cellular concrete, a study has been fully conducted to establish this one-to-one correlation.

Material Selection

Many tests were conducted over a two year period to understand the strength characteristics of the fielded EMAS systems, the measurements obtained with the equipment, and the correlation to PTM values. The final test sequence consisted of forty 60-strength EMAS blocks tested between in 2007 and 2008. The block heights vary in a wide range to cover various block sizes used at airports. Therefore, the block strength from this sample should closely represent the actual strength of all the blocks produced during this period. The block strengths were collected using both the FST and PTM at symmetrical locations on each block so they can be compared side by side.

Correlation between Measurements on FST and PTM

To numerically compare block strengths obtained by the two different test apparatus, FST and PTM, *dimensionless block strength* is defined and used hereafter in this paper. Figure 14 shows the correlation of the dimensionless strengths measured on the PTM and FST. Each data point represents two strengths measured on the same block. The linear regression line of the strengths is also given in Figure 14.

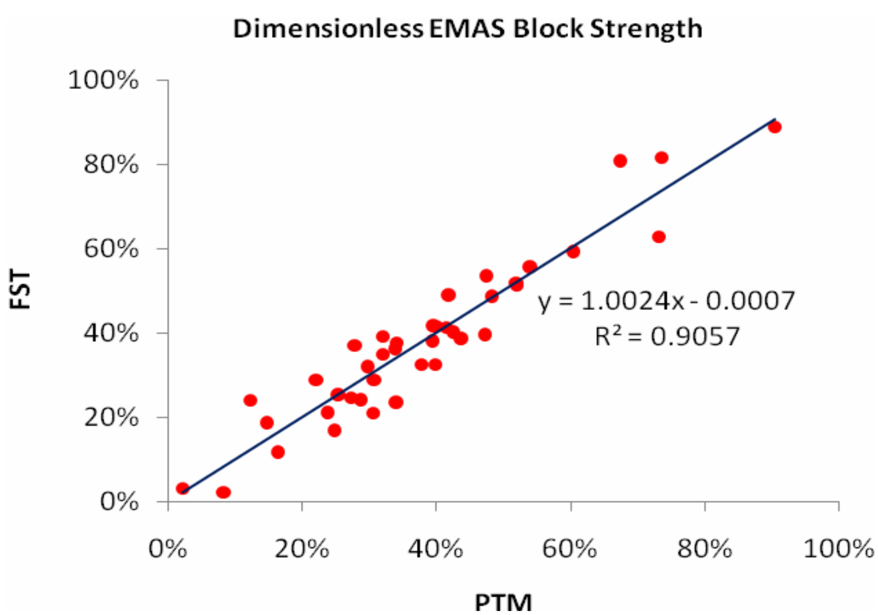

Figure 14. Strength Correlation Between FST and PTM.

Table 2 summarizes the statistics of the strength correlation. The coefficient of correlation r is 0.952, and the coefficient of determination R^2 is 0.905. The results indicate that the strengths measured on the FST correlate strongly with those measured on the PTM.

Table 2. Parameters of Linear Regression of Dimensionless Strengths.

Parameter	Value
N	40
DOF	38
b_1	1.002
b_0	-0.000
R	0.952
R^2	0.905
Total sum of squares	142.8%
Residual sum of squares	13.5%
Residual mean square	0.4%
Root mean square error	6.0%

The results presented a high coefficient of correlation between the measurements on the FST and the PTM. The critical value of correlation coefficient is 0.304 at the level of significance of 0.05. The calculated r value is much higher than the critical value. A t-test was also performed to further check the significance of the coefficient of correlation between the strengths measured on the FST and the PTM. The results suggest that the correlations are significant.

Dimensionless Strength Difference

The difference in dimensionless strengths measured on the FST and the PTM for each block was calculated. Figure 15 shows the histogram of the strength difference between the FST and the PTM. The new tolerance band has the same mean strength as the one used on the PTM, and the standard deviation of the strength difference is 5.9%. Normality of the dimensionless strength difference between the FST and the PTM was checked, and the results indicate that the normal distribution is a good model for the data. The majority of the strength differences are within ±10. This suggests that the measurements on the FST are close to those obtained on the PTM.

The margin of error E can be calculated with a given level of confidence using Students' t-distribution,

$$E = t\frac{s}{\sqrt{N}} \tag{1}$$

where N is the sample size, t is the critical t-value, and s is the standard deviation of the sample. The confidence interval of the mean strength difference is calculated using the data in Figure 15. The results show that the margin of error of the strength difference is very low, within ±1.9% for 95% level of confidence. This suggests that the measurements with the FST are basically equivalent to those on the PTM.

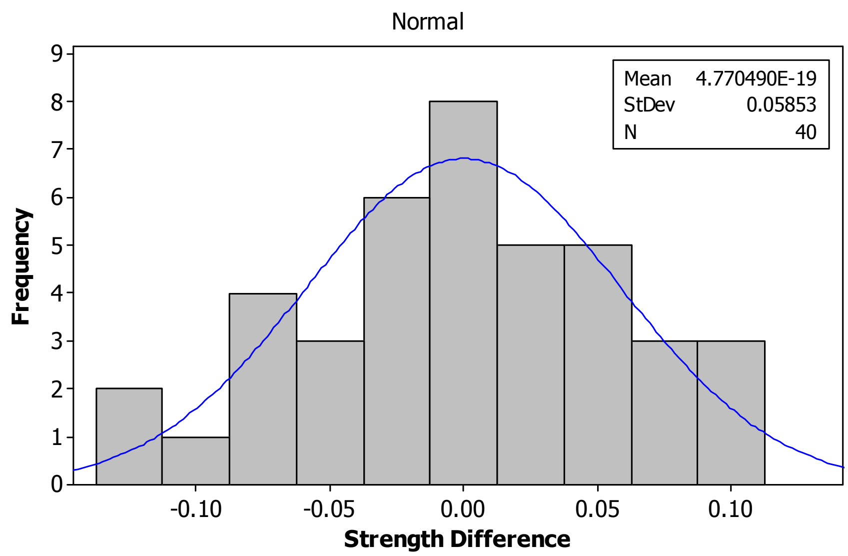

Figure 15. Histogram of Dimensionless Strength Difference Between the FST and PTM.

FST 60-Strength Tolerance Band

Based on the data analysis discussed in the previous sections, the 60-strength tolerance band for EMAS blocks was developed and is presented in Figure 16. Due to the strength characteristics of the CC on the FST, the strength tends to level off when reaching a certain penetration depth, as shown in Figure 16. This tolerance band is used in the FST method to indicate the strength of installed EMAS beds.

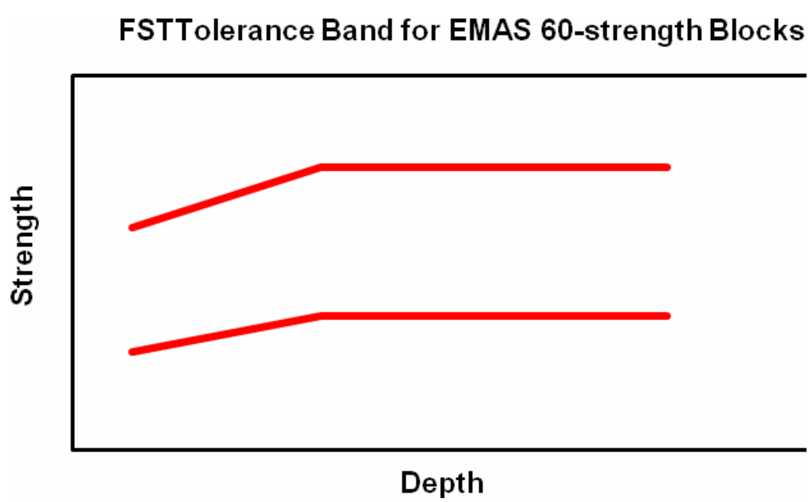

Figure 16. FST Tolerance Band for 60-Strength EMAS Blocks.

Test Method

Sample Size Determination

Determining the sample size is very important because a sample size that is too large wastes time and resources, while a sample size that is too small may lead to inaccurate results. This section discusses sample size determination based on the level of precision, the confidence level, and the degree of variability in the EMAS block strength. The analysis focuses on the mean strength of installed EMAS and assumes that the strength of produced EMAS blocks closely follows a normal distribution.

Although the size of installed EMAS beds varies considerably, ranging from about 1,100 blocks to 5,600 blocks, it should not drive the sample size determination. Using the total number of blocks in each individual EMAS bed as the total population, the sample size will unlikely exceed a few percent of the population. The sample size selected should be appropriate for the largest possible bed size. The level of precision is the sampling error between the sample mean and the true mean of the population. Often expressed as a percentage, a 10% precision level is reasonable based on the variability of the block strength. The confidence level needs to be selected to calculate the confidence interval, which includes the true mean of the population on the selected level of confidence. A 95% confidence interval is calculated here based on the selected 10% precision level. Note that the confidence interval cannot be relied on if the samples are not random.

The natural variability of the EMAS block strength also contributes to the sample size determination. The less variation in the block strength, the smaller the sample size needed. With a "good" estimate of the population variance based on the EMAS production data, the degree of variability is therefore defined. The sample size N can be calculated by rewriting Equation (1). With a selected margin of error of 7 strength units and the estimated standard error of 10 units in EMAS block strength, the sample size is 10. If the degree of variability in the block strength of the total population is higher, a sample size larger than 10 should be used to meet the requirement on precision level.

Random Sampling Method

It is important to use random sampling in order to reliably determine the mean bed strength within a desired confidence interval. Therefore, the location of samples for the FST will be determined using ASTM D 3665-07 [8]. A block layout should be obtained for the specific EMAS bed to be tested. The following criteria will define the effective arrestor bed area in which the FST will be conducted.

- *All testing will take place at least 100 feet from the effective runway end.* This is the standard setback for repairs made to the JBR coating.
- *All testing will take place in blocks that are 12 inches in height or greater.* Shorter blocks will not provide enough data to make a reasonable determination of block strength.

Once the setback for testing has been determined, the effective arrestor bed area will be marked on the block layout.

Test Procedure

Once the number of samples and test locations has been determined using the method described in the previous section, the test locations are marked on the bed. A cordless drill with a 6" diameter hole saw attachment or a cordless circular saw may be used to cut through the JBR coating to gain access to the cellular concrete material at each sample location in the arrestor bed to be tested.

Before the FST can be taken out into the field, it is calibrated and pre-programmed with a test plan. The FST is assembled in the field before testing can commence. The machine operator can conduct the tests when they are ready while observing the penetration load and depth readings, and keeping the machine stable. The test data is saved to the FST so that it can later be downloaded for analysis.

FST Data Presentation

The FST method has been used in the field throughout its development stage. Test data was collected from several installed 60-strength EMAS beds, including Rochester, Baton Rouge, Fort Lauderdale, Boston, and Binghamton between October 2007 and May 2008. The strength curves were plotted together with the FST tolerance band, and the results indicated that all the tested EMAS beds were still within the band. Figure 17 shows the sample data collected on the EMAS bed at Binghamton RW16 departure end.

The dimensionless strength can also be provided with a confidence interval. For example, the mean strength in Figure 17 is 48.2%, which is very close to the mid-point target. The 95% confidence interval that includes the true mean strength of the Binghamton EMAS bed is (31.1%, 65.4%).

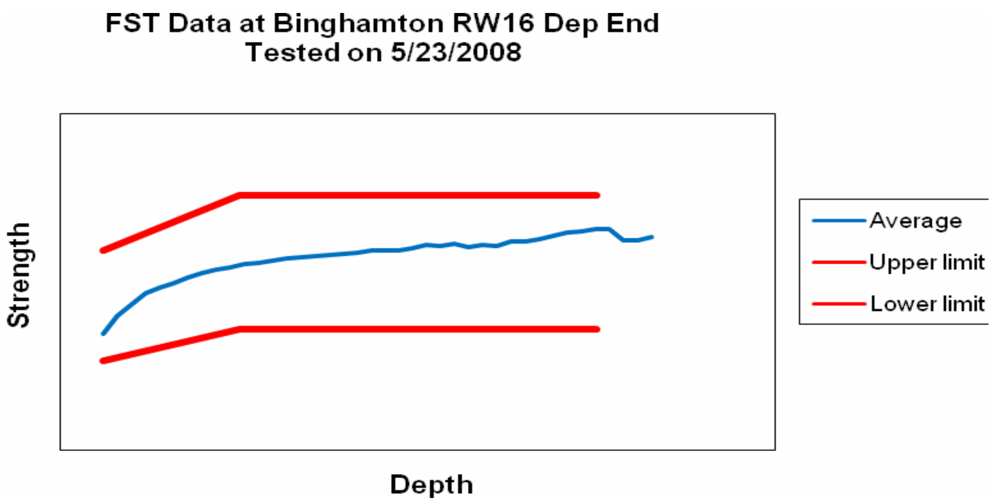

Figure 17: Sample data from field test at Binghamton RW16 Departure.

FST Discussions and Conclusions

With the development and FAA-approval of the FST, a quantitative method now exists to evaluate the condition of installed EMAS systems. This system can be used to periodically test the strength of the EMAS, and verify that the core material is still within acceptable strength ranges. The results of the FST testing can now be used to indicate when a system is nearing the need for replacement, rather than depending solely on a universal 10-year replacement criteria.

The strength indicator of EMAS beds should be based on the FST punch data collected from randomly selected blocks. The number of blocks to be tested on each bed needs to be determined, depending on desired accuracy of test results. The selected blocks should be tested by the FST with a depth at least 65% of the block height whenever possible. The dimensionless strength should be used as a strength indicator associated with a certain level of confidence, for example, 95%. The overall strength curves need to be evaluated. The distribution of the data is important for understanding the strength variation.

Multiple variables, including moisture content, ambient temperature, wind speed, operators, and weather conditions, may affect the readings on the FST. Therefore, these variables should be considered in the analysis of FST results. It is believed that the appropriate operator for the field strength test is someone who is fully-trained and certified in the use of the equipment and the methods and procedures for conducting testing. This operator should be supervised by an engineer who is ultimately responsible for the data analysis and reporting the results.

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