INNOVATION IN CEMENT STABILIZATION OF AIRFIELD SUBGRADES

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ABSTRACT

The Washington Dulles International Airport (IAD) is located in Loudon and Fairfax Counties in northeastern Virginia, approximately 26 miles northwest of Washington, D.C. The Metropolitan Washington Airports Authority (the Authority) reconstructed the original 10,000 feet of Runway 12-30 at IAD with Portland cement concrete pavements. The geotechnical investigation concluded that extensive areas of the runway subgrades are weak and needed to be addressed. The three main options to address the weak subgrades were:

i. Undercut the poor subgrades and replace them with good quality borrow materials with a minimum CBR value of 20.
ii. Crush the demolished concrete pavement structure and use it as crushed recycled concrete base to improve the subgrade support conditions.
iii. Addition of small amounts of ordinary Portland cement to the top 12 inches of the existing subgrades.

The Authority, in conjunction with the design team, chose Option iii as it gave them the most realistic chance of completing the project within budget and on schedule. This paper presents the mixture design process of the cement stabilized subgrade soils for the reconstruction of Runway 12-30 at IAD. This paper describes a laboratory study aimed at designing cement stabilized subgrade soils that satisfy the following:

i. Optimal shrinkage and durability in addition to strength.
ii. Early opening to construction traffic within 3-days of curing.
iii. Innovative acceptance criteria to ensure that good quality is obtained in an accelerated construction schedule.

INTRODUCTION

The Washington Dulles International Airport (IAD) is located in Loudon and Fairfax Counties in Northern Virginia, approximately 26 miles northwest of Washington, D.C. The airport elevation is about 313 feet above sea level. The Metropolitan Washington Airports Authority (the Authority) owns and operates the facility. Three concrete runways serve the airport. These runways are designated 1L-19R, 1R-19L and 12-30. Runways 1L-19R and 1R-19L are each served by two parallel taxiways, and one parallel taxiway serves Runway 12-30. The IAD was originally designed to accommodate up to six million passengers annually. The airport is currently serving more than three times the number of passengers it was designed for, as reported in the Design Report prepared by the team led by Michael Baker Jr., Inc. [1].

To continue servicing the needs of the public, new facilities are being built at the airport by the Authority through their Dulles Development (d^2) Program. This program is designed to provide the much needed new concourses, taxiways, runways, automated people mover system, new air traffic control tower and other facilities required to expand the infrastructure. This program also provides for the upgrading of existing facilities at the airport. As part of the d^2 program, the Authority planned to reconstruct the original 10,000 feet of Runway 12-30 at IAD with Portland cement concrete. The reconstruction included removal of the existing Portland cement concrete pavement and the underlying granular aggregate base or cement stabilized base materials. The project area is shown on the Project Location Map presented as Figure 1. The reconstruction was planned to begin 500 feet from the Runway 30 threshold since the pavement in this 500-foot extension was reportedly in good condition, as reported in the Michael Baker, Jr., Inc. Design Report [1].

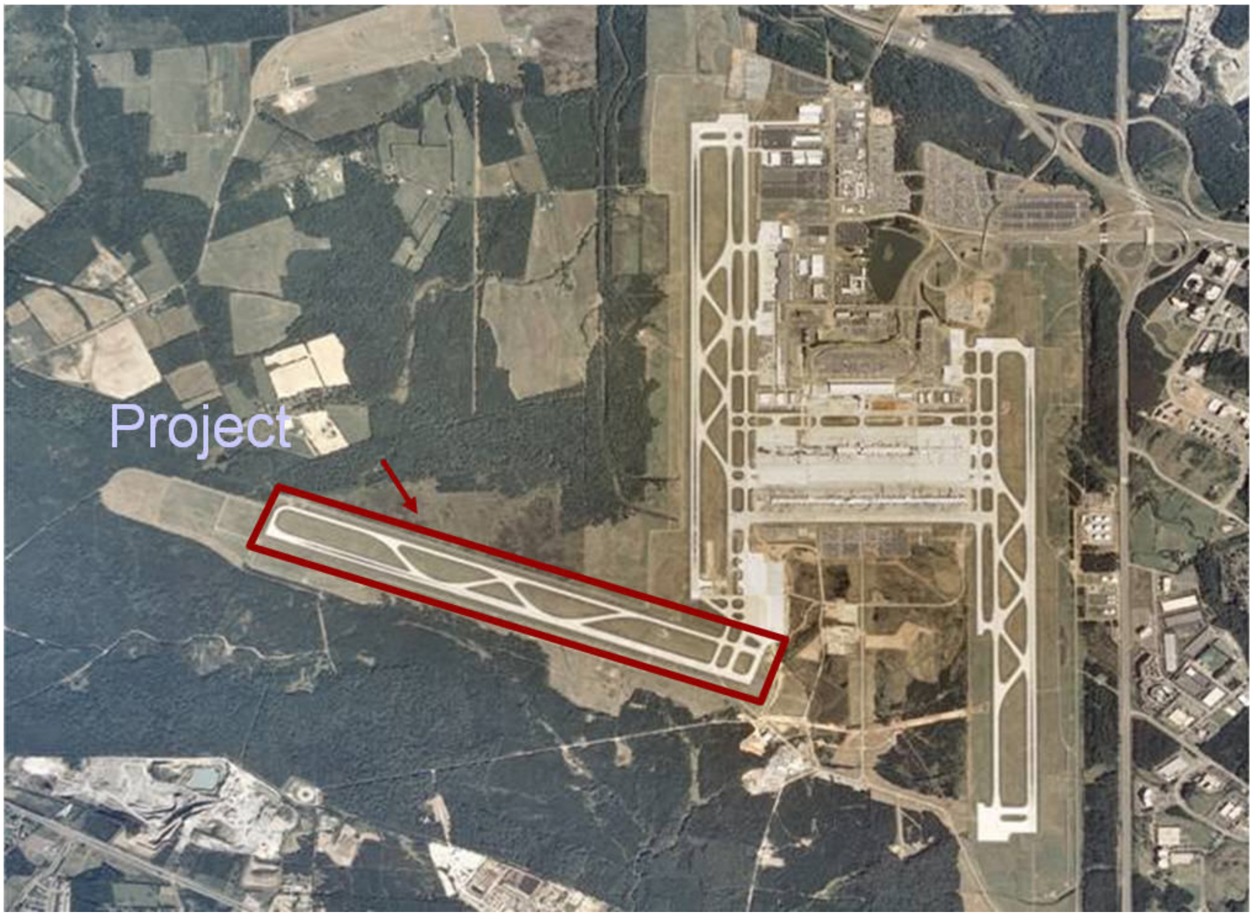

Figure 1. Project Location Map.

GEOTECHNICAL INVESTIGATION

The initial geotechnical investigation was performed in accordance with the Federal Aviation Administration (FAA) Advisory Circular (AC) 150/5320-6D [2]. The investigation concluded that extensive areas of poor subgrade support conditions exist along the length of the runway in addition to poor drainage beneath the runway surface. The soaked California Bearing Ratio (CBR) values determined on the subgrade soils underneath the existing runway pavement varied between 0.7 and 36.8 percent, with an average value of 8.5 percent, at 0.1-inch penetration and 95% compaction based on the respective maximum dry densities for the untreated materials. The samples increased in volume upon completion of the CBR test and swells varying from 0.2 percent to 9.1 percent were recorded in the test samples. Although, the average CBR value was 8.5, the standard deviation was 9.2. Hence, the recommended FAA procedure of using the average value minus one standard deviation, which roughly corresponds to the 85th percentile subgrade design CBR value, does not apply. The subgrade soils were significantly weak to support the cement stabilized base and the Portland cement concrete airfield pavement surface.

Perched/trapped ground water was encountered in thirteen (13) out of fifty (50) boring locations at depths varying between 0.75-ft. to 10.0-ft. below the existing pavement surface. At more than half of these locations ground water was encountered in the pavement structure and seemed to be running into the borings. Also, water was observed to be spilling out from the light cans at several locations along the runway centerline and near the outer edge of the runway at the touchdown lights in a few locations. Another significant observation was that out of the twenty (20) samples that were subjected to Modified proctor tests, seventeen (17) of those samples had in-situ moisture contents that were significantly higher than the optimum moisture content that was determined from the modified proctor tests, as reported in the Geotechnical Investigation Report [3].

To address the issue of poor subgrade support conditions, the following options were considered:

i. Undercut the poor subgrades and replace them with good quality borrow materials with a minimum CBR value of 20.
ii. Crush the demolished concrete pavement structure and use it as crushed recycled concrete base to improve the subgrade support conditions.
iii. Addition of small amounts of lime, fly ash and / or ordinary Portland cement to the top 12 inches of the existing subgrades.

Lime stabilized subgrades require 7-days or more of curing to develop the desired strength. There were some concerns about the long term performance of lime stabilized subgrade in a transient moisture environment due to the high solubility of the calcium hydroxide and leaching effects described by McCallister and Petry [4]. Similar concerns were also expressed with the use of lime-fly ash as the stabilizer. Primarily due to the fast track nature of the project, the Design Team was requested by the Authority to explore the options of opening the stabilized subgrade within 72-hours to construction traffic. Therefore, ordinary Portland cement was evaluated as the candidate stabilizer in view of the high early strength provided by cement stabilized subgrade soils [5].

The merits of each option were explored with respect to technical viability, cost effectiveness and time required. In-situ stabilization of the existing subgrades with small amounts of ordinary Portland cement turned out to be the preferred option, as reported in the Michael Baker, Jr., Inc. Design Report [1].

PROJECT OBJECTIVES

The objective was to design a cement stabilized subgrade that would provide adequate subgrade support to the runway pavements. The Authority instructed the design team to perform a mixture design for the subgrade cement stabilization and develop appropriate specifications. Some of the salient features considered in the mixture design process were as follows:

i. The cement stabilized subgrades shall have optimal shrinkage and durability in addition to strength.
ii. Conventional specifications required 7-days of curing. In view of the fast track nature of the project, the Authority instructed the design team to explore options that could allow the stabilized subgrades to be opened to construction traffic within 3-days.
iii. Develop an acceptance criterion for the cement stabilized subgrades so that a good quality product is obtained without sacrificing the fast track nature of the construction work in meeting the project deadlines.

PRELIMINARY CEMENT CONTENT

The natural moisture content of the subgrade soils was measured as per ASTM D 2216 [6]. The general index tests on untreated soils included Atterberg limits – ASTM D 4318 [7], Gradation analysis including hydrometer – ASTM D 422 [8]. The untreated soils were classified in accordance with ASTM D 2487 [9]. The preliminary cement content was estimated with the pH test in accordance with ASTM D 4972 [10]. Based on the results of the pH test, cement contents of 3 percent, 4 percent and 5 percent by weight was selected for further evaluation, as reported in the Mixture Design Report [11].

MIXTURE DESIGN METHODOLOGY

The field testing consisted of collecting additional soil samples from the ten (10) boring locations that were identified as having poor support conditions during the first phase of study. Borings were drilled at offsets of 5.0-feet from the original locations to better ensure the similarities of the samples. The next step was to perform the mixture designs for stabilizing the subgrades with ordinary Portland cement. Mixture designs were performed on samples from the ten (10) locations identified as having poor support conditions in the Phase 1 study, and on three (3) locations identified as having better support conditions in the Phase 1 study. The three (3) samples from better support locations are defined as MIX 1, MIX 2 and MIX 3. Each of these samples was a composite of subgrade soils that had CBR values in excess of 7 from different boring locations. The mixture design process aimed at optimizing both shrinkage and durability in addition to maximizing strength.

The first step in the process was to characterize the subgrade soils as per ASTM D 2487 [9] followed by the moisture density relations test as per ASTM D 558 [12] to determine the optimum moisture contents and maximum dry density for molding the samples. The moisture density test was performed on all the subgrade samples stabilized with 3%, 4% and 5% ordinary Portland cement.

The durability tests (wet-dry tests – ASTM D 559 [13] and freeze-thaw tests – ASTM D 560 [14]) were used to establish the optimum cement content. As stated in the PCA document [5], the durability tests were designed to determine whether the soil-cement would stay hard or whether expansion and contraction on alternate freezing-and-thawing and moisture changes would cause the soil-cement to soften. The samples that produce low soil-cement weight losses in the freeze-thaw and wet-dry tests resist volume changes or hydraulic pressures that could gradually break down bonds of cementation. The least amount of cement needed to pass the durability test is typically considered the optimum cement content. These tests were performed on soil samples from the ten poor support locations and the three better support locations, blended with 3%, 4% and 5% ordinary Portland cement. Because of the large number of tests that failed the wet/dry tests (ASTM D 559) at 3% cement addition and in the essence of time, it was not necessary to perform the freeze/thaw tests (ASTM D 560) at 3% cement content. Freeze/thaw tests were performed at 4% and 5% cement content, as reported in the Mixture Design Report [11].

Upon completion of the durability tests, the optimum cement content was determined. The strength and shrinkage measurements were performed on samples molded with optimum cement content. The unconfined compressive strength test per ASTM D 1633 [15] was used to evaluate the feasibility of 3-day curing for the construction of cement stabilized subgrades. Typically cement stabilized subgrades are cured for 7-days. However, in view of the tight time schedule, strength gain in the first 72-hours was evaluated for consideration to open the cement stabilized layers to construction traffic and further pavement construction work earlier than 7-days. Unconfined compressive strength (UCS) of one specimen of each mixture design molded at optimum cement content was measured after a curing period of 3-days, 7-days and 28-days as per ASTM D 1633 [15]. Unconfined compressive strengths were also measured on untreated subgrade samples, as reported in the Mixture Design Report [11].

The shrinkage test was performed to ascertain if excessive shrinkage might occur within the cement stabilized subgrades. Cement treated subgrades typically shrink upon hydration of the ordinary Portland cement. This shrinkage builds up tensile stresses and strains within the pavement structure that, in turn, produces transverse cracks. Generally, when the stress in the cement stabilized subgrades exceeds the strength of the material, cracking begins. To perform the shrinkage measurements, 3 in. x 3 in. x 11¼ in. beam specimens were prepared in accordance with the procedure suggested by George [16] to perform shrinkage measurements at the optimum cement content. Shrinkage measurements were taken for 28-days.

TEST RESULTS

Index Properties and Classification

Laboratory test results for the soil index properties, gradation, Unified Soil Classification and Moisture Density Relations are presented in Tables 1a and 1b. They indicate that the existing poor subgrade soils are comprised of low plasticity clays and clayey sands, as partially exhibited by soils that had an average plasticity index (PI) of 18 along the 12-30 Runway. The average in-situ moisture content of those subgrade materials was mostly higher than their average optimum moisture content, as reported in the Mixture Design Report [11].

Moisture-Density Relations

Moisture-Density relations as per ASTM D 558 [12] were conducted on all the bagged samples from various borings with 3%, 4% and 5% cement. Those results presented in Tables 1a and 1b indicate that the maximum dry density for the cement stabilized subgrades varied from 105.0 pcf to 126.2 pcf with an average value of 114.0 pcf. The optimum moisture content varied from 10.8 percent to 18.5 percent with an average of 14.8 percent, as reported in the Mixture Design Report [11].

Table 1a.
Index Properties, Gradation and Classification.

Boring No.	Moisture Content, %	Atterberg Limits			Gradation Analysis Percent Passing		USCS Classification[a]
		LL	PL	PI	#4	#200	
B-18	16.0	32	14	18	93	71	CL
B-22	16.0	34	14	20	85	57	CL
B-31	20.7	36	20	16	90	70	CL
B-36	25.0	32	16	16	94	72	CL
B-39	33.3	37	15	22	74	47	SC
B-48	23.0	32	16	16	91	69	CL
B-49	21.8	36	16	20	93	76	CL
B-102	10.5	31	16	15	88	49	SC
B-108	14.0	34	17	17	32	13	SC
B-109	27.3	46	16	30	96	88	CL
MIX 1	-	25	12	13	81	36	SC
MIX 2	-	37	14	23	86	64	CL
MIX 3	-	23	11	12	86	43	SC

[a]USCS: United Soil Classification System (ASTM D 2487)

Table 1b.
Moisture Density Relations

Boring No.	Moisture Density Relations ASTM D588 Cement Content					
	3%		4%		5%	
	MCC[a]	OMC[b]	MCC[a]	OMC[b]	MCC[a]	OMC[b]
B-18	112.8	14.2	113.7	15.8	113.2	14.2
B-22	112.3	14.4	117.0	14.6	116.4	14.8
B-31	108.6	18.2	107.8	17.2	106.6	17.8
B-36	110.9	17.0	107.2	13.8	111.6	17.7
B-39	111.6	14.9	111.8	16.4	110.3	16.8
B-48	118.2	15.5	114.5	16.4	115.2	16.6
B-49	111.7	15.0	110.2	15.0	111.7	15.0
B-102	105.0	13.0	116.2	11.8	115.3	12.5
B-108	113.0	15.0	111.6	14.5	112.7	16.6
B-109	-	-	107.3	17.5	-	-
MIX 1	124.7	11.8	125.0	12.7	123.5	11.7
MIX 2	111.0	15.2	106.2	20.0	109.7	16.7
MIX 3	126.2	12.4	123.9	10.6	124.4	11.1

[a]MDD = Maximum dry density [b]OMC = Optimum moisture content

Durability Tests

Results of durability tests are presented in Table 2. Durability tests as per ASTM D 559 [13] for wet/dry tests were performed on all the subgrade samples stabilized with 3%, 4% and 5% cement while freeze/thaw tests as per ASTM D 560 [14] were performed on subgrade samples stabilized with 4% and 5% cement. The criteria used for evaluating the test results were as per recommendations contained in American Concrete Institute Committee 230's State-of-the-Art Report on Soil Cement [17]. Seventy-five percent (9 out of 12) of the samples stabilized with 3 % percent cement failed the wet/dry durability tests, as reported in the Mixture Design Report [11].

Sixty-nine percent (9 out of 13) of the samples stabilized with 4% cement passed the wet/dry tests and ninety-two percent (12 out of 13) passed the freeze/thaw tests. Eighty-three percent (10 out of 12) of the samples stabilized with 5% cement passed the wet/dry tests and all passed the freeze/thaw tests, as reported in the Mixture Design Report [11].

Table 2.
Durability Measurements.

		Durability Tests				
		Wet/Dry ASTM D 559			Freeze/Thaw ASTM D 560	
	USCS	Cement Content				
Boring No.	Classification	3%	4%	5%	4%	5%
B-18	CL	Fail	Pass	Pass	Pass	Pass
B-22	CL	Fail	Pass	Pass	Pass	Pass
B-31	CL	Fail	Fail	Pass	Pass	Pass
B-36	CL	Fail	Fail	Fail	Pass	Pass
B-39	SC	Fail	Fail	Fail	Pass	Pass
B-48	CL	Pass	Pass	Pass	Pass	Pass
B-49	CL	Fail	Pass	Pass	Pass	Pass
B-102	SC	Fail	Pass	Pass	Pass	Pass
B-108	SC	Fail	Pass	Pass	Pass	Pass
B-109	CL	-	Fail	-	Fail	-
MIX 1	SC	Pass	Pass	Pass	Pass	Pass
MIX 2	CL	Fail	Pass	Pass	Pass	Pass
MIX 3	SC	Pass	Pass	Pass	Pass	Pass

Unconfined Compressive Strength

Unconfined compressive strength measurements presented in Table 3 were obtained from cylindrical samples for the untreated subgrade soils and on cement stabilized subgrade soils. The cement (4%) stabilized subgrade soils were subjected to strength measurements after 3-day, 7-day and 28-day curing. Compressive strengths for the untreated (raw) soil varied between 23.6 psi and 59.9 psi, with an average value of 45.4 psi. The compressive strength for cement stabilized soils after 3-day curing ranged between 80.2 and 370 psi, with an average of 173 psi. Upon 7-day of curing the compressive strengths ranged between 85 and 529 psi, with an average of 186 psi. After 28 days of curing, the compressive strengths ranged between 149 and 592 psi, with an average of 256 psi. The average strength gain within 3 days of adding cement to the subgrade soils was 127.6 psi (173-45.4), while the strength gain in 7 days was 140.6 psi (186-45.4), as reported in the Mixture Design Report [11].

Table 3.
Unconfined Compressive Strength Measurements.

Boring No.	USCS Classification	Unconfined Compressive Strength, psi (ASTM D 1633) Age Raw	3 days	7 days	28 days
B-18	CL	60	161	172	195
B-22	CL	50	146	112	239
B-31	CL	39	151	148	244
B-36	CL	49	80	85	179
B-39	SC	51	99	124	161
B-48	CL	44	154	203	216
B-49	CL	60	104	129	208
B-102	SC	24	220	203	257
B-108	SC	47	239	202	318
B-109	CL	-	-	-	-
MIX 1	SC	39	370	529	592
MIX 2	CL	43	151	123	149
MIX 3	SC	39	205	203	313

Shrinkage Measurements

The shrinkage measurements presented in Table 4 were performed on subgrade soils stabilized with optimum cement content of 4% (determination process described later in this paper). The shrinkage strains measured on the subgrade samples stabilized with 4% ordinary Portland cement varied from 34 to 407 micro strains (μs) in 3 days, between 100 and 550 μs in 7 days and between 1783 and 5988 μs in 28 days. The average strain after 3 days of curing was 174 μs, 266 μs after 7 days of curing and 3,840 μs after 28 days of curing, as reported in the Mixture Design Report [11].

OPTIMUM CEMENT CONTENT

Mixture design standards typically recommend that the optimum cement content be based on the results of the Durability Tests as specified in ASTM D 559 [13] and ASTM D 560 [14]. Based on the results summarized in Table 2, 69 percent of the subgrade samples with 4 percent cement passed the wet-dry tests, while 92 percent passed the freeze-thaw tests. Upon closer examination of the data, it was observed that the subgrade samples from Boring B-109 failed both the durability tests. Subgrade samples from Borings B-36 and B-39 stabilized with 3%, 4% and 5% cement failed the wet-dry test but passed the freeze-thaw test. The samples from Boring B-31 stabilized with 3% and 4% cement failed the wet-dry test but passed the freeze- thaw test.

Table 4.
Shrinkage Measurements.

Boring No.	USCS Classification	Shrinkage Measurements, 4% Cement[a] 3 days, μS	7 days, μS	28 days, μS
B-18	CL	407	550	2600
B-22	CL	68	200	4445
B-31	CL	110	200	5611
B-36	CL	280	347	5010
B-39	SC	60	100	5988
B-48	CL	101	211	4226
B-49	CL	80	100	3181
B-102	SC	34	102	1947
B-108	SC	181	275	1783
B-109	CL	-	-	-
MIX 1	SC	70	160	1810
MIX 2	CL	288	465	4568
MIX 3	SC	400	450	2331

[a]per George [16]

Hence, the optimum cement content selection criterion was slightly modified. The optimum cement content was based partially on the following:

- Durability Test Results specified in ASTM D 559 [13] and ASTM D 560 [14].
- Unconfined Compressive Strength of the mixture.
- Impact of Shrinkage on increasing the cement content.
- Pragmatism.

In a study conducted for the Portland Cement Association (PCA), George [16] recommends that the 7-day unconfined compressive strength of cement stabilized soils shall be within 350 psi and 450 psi. However, the average 7-day unconfined compressive strengths on the subgrade soils across the runway were lower than the limits suggested by the PCA study [16].

Caltabiano and Rawlings [18] suggested that the drying shrinkage of cement-treated material should not exceed 250 μs after 20 days. Based on a research study performed by George [16] for PCA, drying shrinkage values varying between 310 μs and 525 μs are suggested for cement stabilized soils. Excessive shrinkage in the cement stabilized subgrades is undesirable as that causes shrinkage cracking in the cement stabilized subgrades. The shrinkage cracks deteriorate over a period of time as the cracks become larger causing secondary durability problems. The subsequent pavement layer is typically placed after the recommended curing period. Therefore, from the data presented in Table 4, it was clear that the shrinkage measurements after 3-days and 7-days curing were in agreement with the criterion suggested by the PCA study [16].

Increasing the cement content would increase the shrinkage observed in the mixtures. Subgrade samples from Boring B-109 were only stabilized with 4 % cement. The cement stabilized samples from Boring B-109 failed about half-way through the test. In the previous investigation [3] this material exhibited 6.2 percent of swelling upon completion of CBR test for a sample stabilized with 4 percent cement.

Per Little [19], subgrade soils are reactive with lime if the soil and lime mixtures achieve an appreciable improvement in unconfined compressive strength (increases greater than 50 psi) following the addition of lime and curing for 48 hours. Since cement stabilized soils also rely primarily on the Calcium Oxide for the long term reactions and product development, a similar logic was adopted in reviewing the test result obtained in this study. The sample from Boring B-36 exhibited an increase of 31 psi (80-49) and 36 psi (85-49) after 3-day and 7-day curing respectively. Since the increase in unconfined compressive strength was less than 50 psi, the soil was considered non-reactive. Boring locations B-31 and B-39 indicated marginal results. The samples from these areas failed one of the durability tests, but had good unconfined compressive strength. It was considered prudent to undercut and replace these materials found in a localized area rather than add excessive amount of cement to stabilize this material. The extent of undercutting poor soils and replacement with select fill materials were defined after the runway had been demolished and the subgrades were exposed.

Based on the above criteria, 4 percent by weight was chosen as the optimum cement content for stabilization of the subgrade soils. The top 12 inches of the in-situ subgrade material was stabilized with 4 % ordinary Portland cement.

SUBGRADE CURING

The average strength gain within 3 days of adding cement to the subgrade soils was 173 psi, while after 7 days curing was 186 psi. Since the strength gain after 3 days was nearly equal to the strength gain after 7 days, it was concluded that the strength developed in the subgrade soils within 3 days is sufficient to permit the movement of construction equipment on the subgrades to facilitate construction of the remaining pavement layers. This study touched this important aspect in a peripheral manner due to time and budgetary constraints. This important topic should be studied further.

Acceptance Criterion

The acceptance criterion was based on the typical in-place field density and moisture determined at random locations in accordance with ASTM D 1556 or ASTM D 2922 at one (1) test per 1,000 square yards of the constructed cement stabilized subgrade soils. For an acceptable cement stabilized subgrade, the density had to be 95 percent or better. The project team was concerned that in case of non-acceptance, the Contractor needed clear guidance on the next step so as to meet the project schedule.

Therefore, if the field density of the compacted mixture was less than 95 percent of the maximum density, the compacted mixture in those areas was removed and replaced with bituminous concrete backfill material. The bituminous concrete backfill material was chosen as the replacement material due to fast track nature of the project. The cement content of the hardened cement stabilized subgrades was determined as per ASTM D 806. If the cement content was found to be less than 4.0 percent by weight of the cement stabilized subgrades, the Contractor was responsible for the remedial measures. If the cement content was 4.0 percent or higher, the Contractor was reimbursed for the remedial measures.

The undercut quantity was estimated on the basis of the poor results of Borings B-31, B-36, B-39 and B-109. For each boring location, the undercut quantity was estimated as 200-feet long by 150-feet wide over a maximum 2-feet depth. The actual undercut quantities during construction were close to the estimate.

CONCLUSIONS

The existing weak subgrade soils were inadequate to support the reconstruction of the airfield pavements. The purpose of this of this study was to develop a methodology that would be technically viable, cost-effective and timely to meet the aggressive project deadlines. This study was performed to characterize the subgrade soils and develop a mixture design for the cement stabilized subgrades to be used in the reconstruction of the airfield pavements for Runway 12-30. Laboratory tests were performed on subgrade soil samples stabilized with small amounts of ordinary Portland cement to determine the optimum cement content while ensuring that the cement stabilized subgrades had adequate strength and durability while minimizing excessive shrinkage.

The various test procedures and brief discussion on the test results have been narrated in the preceding sections of this paper. The study focused on balancing the strength, shrinkage and durability of the cement stabilized subgrade soils. The study concluded that stabilizing the in-situ subgrade soils with small amounts (4 percent by weight) of ordinary Portland cement is a technically viable, cost effective and speedy way to prepare the subgrades for the reconstruction of the airfield pavements for Runway 12-30.

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