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IMPROVING RUNWAY STRIP PERFORMANCE TO FULFILL INTERNATIONAL REQUIREMENTS THROUGH ECO-EFFICIENT SOIL TREATMENTS: CASE STUDY OF A MAJOR ITALIAN AIRPORT

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Abstract

The paper presents a case study of a significant intervention conducted on a major Italian airport for improving the structural and functional properties of the runway safety STRIP in order to fulfill specific national and international standards.
The STRIP had to accomplish strict requirements in terms of the maximum longitudinal and transversal terrain slope and minimum values of bearing capacity; in particular, soil bearing capacity was identified as the main lack and thus the most urgent action to be carried out in the airport. However, the STRIP itself is located in a very critical area due to its closeness to the runway and several constraints were therefore identified during the design stage. The optimal strategy was identified as the one that minimized the intervention timing and costs, reducing the handling of construction material to/from the airport, avoiding delays to the air traffic, and maximizing the performance of the treated soils in terms of bearing capacity. In this framework, an energy-controlled stabilization technique of in-situ soils was developed.
Several measurements, in both laboratory and field environment, were also conducted at different stages: *i)* before the intervention took place, *ii)* during the construction stage, and *iii)* at the conclusion of the work to monitor and validate the expected results.
The intervention was able to provide the STRIP areas with a smooth surface presenting terrain slopes and bearing capacity in accordance with the standards. The illustrated methodology could also be applied to other airports saving time, costs, materials, and limiting air traffic delays.

Key words: airport pavement, cement-treated soil, recycling, soil bearing capacity

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1. Introduction

Aircrafts maneuvering is strictly regulated by international standards from the International Civil Aviation Organization (ICAO); governments and airport authorities must therefore rigorously comply with the standards. ICAO's recommendations are mandatory adopted in Italy following the current regulation enforced by ENAC, namely the governmental Italian agency for civil aviation.

Particular consideration is also required for all the areas, both paved and unpaved, in the very close proximity of the main airfield infrastructures - runways, taxiways, and aprons - usually deputed to the aircraft ground maneuvering. Those areas are usually unpaved, and must guarantee a solid and smooth surface to allow potential veer-off aircrafts to safely stop without reporting major damages to the aircraft structure and gears (ICAO, 2011). They are usually named Runway Safety STRIPs, and they have the precise role of: 1) reduce damages to potential veer-off aircrafts thereby ensuring specific longitudinal and transversal terrain slopes and bearing capacity; 2) provide a safety area, clear from obstacles, to the aircrafts during flight operations (landing, take-off, aborted landing and take-off etc.). The Runway STRIP

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is symmetrical with respect to the runway center line and its geometry is established by the ENAC national standards (ENAC, 2011) and the ICAO regulation (ICAO, 2004, 2006). The width of the STRIP for major airports is 150 m from the runway center line, symmetrically. The inner part of the STRIP, in the closest proximity of the runway is identified as the CGA (Cleared and Graded Area); the geometry of the CGA is also reported in the previously cited regulations.

It should be pointed out that the CGA technical requirements in terms of bearing capacity and terrain smoothness are more stringent than the ones demanded to the outer part of the STRIP, since the CGA represents the inner safety surface a veering-off aircraft interacts with, at first. Airport authorities are demanded by ICAO to adjust their STRIPs according to the above-mentioned criteria.

The present paper reports about the design and construction methodologies that brought to the structural and functional adaptation to standards of the runway STRIPs of a major Italian airport located in the northern part of Italy. The methodology described in the present manuscript was already adopted for fixing STRIPs of other two major airports in Italy.

2. Objective

The main goals of the project were 1) to provide the airport with a new STRIP surface able to comply with the international standards, 2) limiting the overall intervention timing to avoid delays, 3) maximizing the productivity of the construction site, and 4) reducing the total amount of non-renewable material (i.e.; virgin aggregates) to be provided.

The intervention area was about 440′000 m^2 (≈ 526’235 yd^2) and a *controlled* stabilization of in-situ soils with hydraulic binders was specifically developed to guarantee the appropriate (but not excessive) bearing capacity; this was required to not damage veering-off aircrafts and provide a solid and smooth surface for emergency vehicles to drive over. The soil stabilization allowed minimizing delays in airport operations and drastically reducing the soil handling to/from the construction site, thus providing both economic and environmental benefits.

The functional intervention, instead, consisted in grading the STRIP surfaces for an estimated area of almost 192′000 m^2 (≈ 229’630 yd^2); standard graders and loaders were used for handling soils. The following section describes the preliminary analyses conducted on the STRIP soils to evaluate their current compliance with technical requirements.

3. Preliminary analysis

The main requirements established by the international ICAO standards and accepted by the national Italian authority for civil aviation (ENAC, 2011) are described in Table 1.

The airport authority and the Road Research Laboratory of the Polytechnic Institute of Milan developed an accurate investigation plan to characterize the actual properties of the STRIP soils and their compliance with the national and international standards; in particular, the analysis was mainly conducted in the portion of the STRIP (CGA) closest to the runway paved shoulders. The inner stripe of lawn, parallel to runway center line and having a width of 35 m, was therefore investigated since that area was assumed as the zone demanded to stop veering-off aircrafts with the highest probability. The preliminary investigations aimed at characterizing the real in-situ conditions in order to provide the designers with an up-to-date snapshot of the airport STRIP.

The bearing capacity of soils, strictly dependent on the soil type and water content, was investigated through twelve measurements (Fig.1). For each measurement point, although several other non-destructive methods are also available, it was analyzed:

- the deformation modulus (M_d) with the Plate Load Test (PLT) (AASHTO T 221-90, 2008) and the relative soil humidity (ASTM D2216, 2010; UNI EN ISO/TS 17892-1, 2005) at 10 cm beneath the surface. This assumption was made to conservatively consider the superficial part, mainly composed by grass and turf, as not providing any bearing support;
- the classification of the in-situ soil at different depths (20 cm, 50 cm, and 80 cm below the surface) according to the AASHTO M 145-91 (2008) and UNI EN 13242 (2008).

Table 1. Technical requirements for the inner (CGA) and outer part of the STRIP

		BEARING CAPACITY	***GRADING***
CGA	< 75 m (Runway Heads)	**Average sinking of the nose landing gear < 15 cm**	***Longitudinal terrain slope < 1,5%***
		CBR index between 15 and 20% (soil sample taken at 15 cm below the surface)	Transversal terrain slope < 2,5%
	< 105 m	Minimum thickness of grassy topsoil ranging between 10 cm up to 15÷17 cm	Maximum allowable terrain slope within 3 m from the runway paved shoulder 5%
	> 75/105 m	Minimum bearing capacity for safety vehicles to drive over during all-weather conditions	Longitudinal terrain slope < 1,5%
		Gradually decreasing soil bearing capacity	Transversal terrain slope < 2,5%
STRIP (> 105 m)		Minimum bearing capacity for safety vehicles to drive over during all-weather conditions eventually specifying suitable paths	Transversal terrain slope growing up to 5%

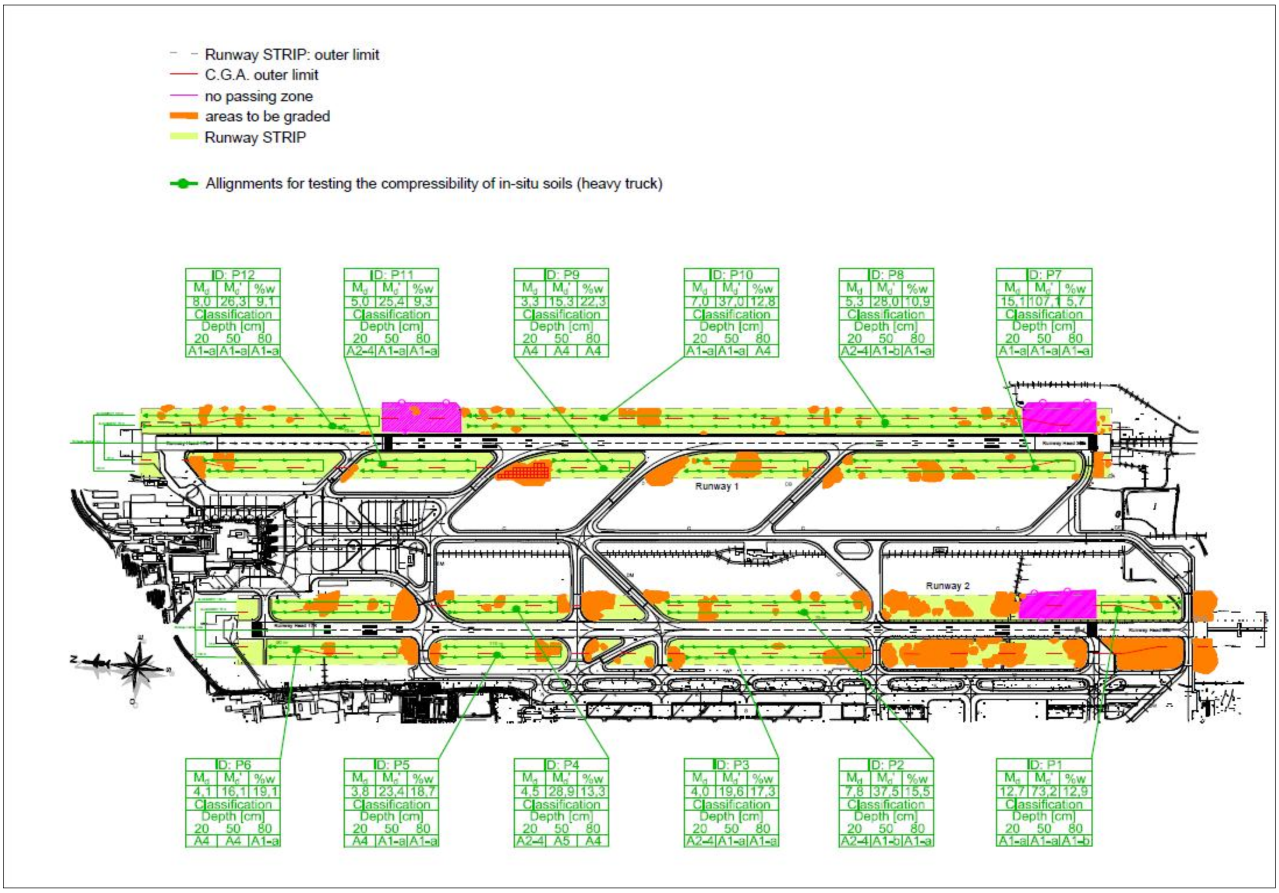


Fig. 1. Investigation campaign on the airport STRIP areas

In addition, it was evaluated the vertical displacement produced in 179 measurement points by the heaviest emergency vehicle adopted in the airport (an heavy 4-axel truck from the Fire Dept. at its maximum load weight) circulating on the STRIP soils. The total weight of the truck, as given by the weight station, was 405 kN (almost 40.5 tons) and the tire pressure was 0.8 MPa. The objective of this analysis was to compute the sinking of the STRIP soils under a controlled weight and specific conditions of relative humidity; successively, the analysis was extended to the sinking caused by the critical aircraft. Finally, a topographic survey of the entire area was performed in order to characterize portions in need of leveling, filling or excavated material, to comply with the standards reported in Table 1. The investigation areas, the twelve measurement points, and a summary of the investigation campaign results are illustrated in Fig. 1.

Outcomes were identified as follows:

- the deformation modulus (M_d), to be considered as an actual value of the bearing capacity of the soil, resulted in an average value of 6.7 MPa (standard deviation of 3.7 MPa) with an average relative humidity in the measurement points equal to 13.9%;
- going from the inner parts to the outer portions of the STRIP (transversally respect to the runway center line) no relevant differences in the bearing capacity of the soils were shown;
- the classification of the in-situ soils mainly included three soil categories according to the UNI EN standard 13242 (2008) and AASHTO M 145-91 (2008): A_1, $A_{2\text{-}4}$, and A_4; unfortunately, a casual spot-distribution within the STRIP areas was identified;
- soils mechanical characteristics considerably improved with growing depth of investigation;
- the vertical displacements caused by the passage of the emergency vehicle showed an average value of 2.57 cm at the natural moisture conditions of the soil (17.78% of relative humidity);
- the vertical displacements caused by the passage of the emergency vehicle showed an average value of 4.86 cm at soil moisture conditions close to saturation (26.44% of relative humidity was measured after several rainy days);

Table 2 summarizes results obtained in the preliminary investigation phase. The following section describes how the preliminary results were considered in the design stage of the intervention.

4. Mechanical modeling of *in-situ* soils

A modeling phase was then needed to estimate the vertical displacement produced by the critical aircraft (Boeing 777-300ER) on the STRIP since no full scale test using a real aircraft gear was affordable during the preliminary investigations. In particular, the vertical displacements coming from the passage of the emergency vehicle were to be converted into vertical displacement of the critical aircraft for the determined moisture soil conditions; the technical

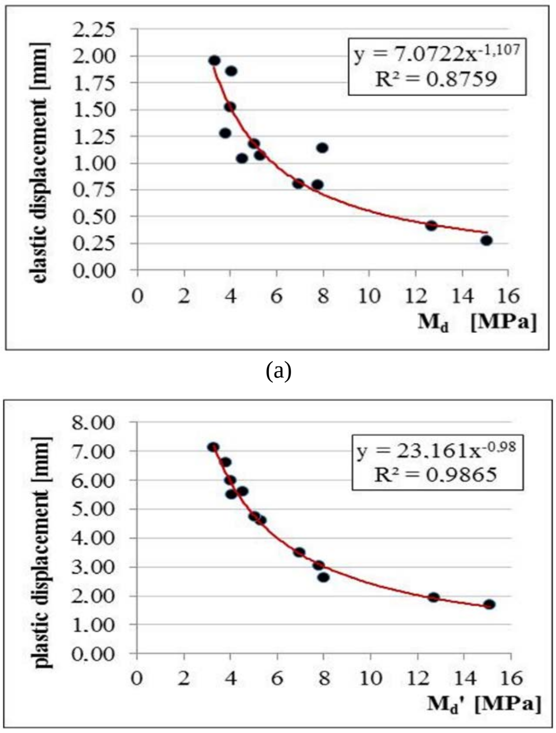
regulations, indeed, imposed a maximum sinking value into the soil of 15 cm at the nose landing gear to avoid significant damages to a veering-off aircraft.
The maximum sinking (total admissible displacement) was assumed to be the sum of two contributions: an elastic deformation totally recoverable after the passage of the load plus a plastic not-recoverable deformation due to the resiliency of the soil.
The methodology adopted for the estimation of the soil theoretical displacement basically reflected the test types performed during the preliminary stage: plate load tests (PLTs) and passages of the emergency vehicle at different moisture conditions. The PLT was useful to determine the elastic and plastic portion (since the two-cycle standard procedure was adopted) of the total displacement for an incremental pressure of 0.1 MPa (PLTs were indeed performed measuring the vertical plate displacement at pressure values of 0.05 and 0.15 MPa according to the standard); on the other hand, the second test was used to evaluate the plastic portion of displacements but induced by a tire pressure of 0.8 MPa. The methodology is explained below. The calibration of the model was performed adopting the values obtained from the PLTs. In particular, it was possible to estimate the recoverable (elastic) and unrecoverable (plastic) portion of the displacement for each measurement point because of the two load cycles (load – unload – reload). Fig. 2 illustrates the two contributions to the total displacement and their interpolation, evaluated at the twelve measurement points.

The average deformation modulus (M_d) measured in the field among the twelve points at an average humidity of 13.91% was equal to 6.7 MPa; according to the regressions in Figure 2 a M_d value of 6.7 MPa will correspond to an elastic displacement of 0.86 mm and a plastic displacement of 3.59 mm. The total vertical displacement caused by a pressure of 0.1 MPa was thus equal to 4.45 mm (= 0.86 mm + 3.59 mm).

Table 2. Average values obtained in the preliminary investigations

					Average value	*Standard Dev.*	*Min*	*Max*
Plate Load Test	**Deformation Modulus (M_d) [MPa]**				6.7	3.7	3.3	15.1
	Deformation Modulus - second load cycle (M_d’) [MPa]				36.5	27.0	15.3	107.1
	Relative soil humidity [%]				13.9	4.8	5.7	22.3
Soil Compressibility Tests (heavy truck)	**Runway 1 (35R-17L)**	**Alignment**	**120 m EAST**	**Vertical displacement [cm]**	2.4	0.6	3.8	1.5
				Relative soil humidity [%]	18.0	1.0	18.7	17.3
			75 m EAST	**Vertical displacement [cm]**	2.4	0.5	3.3	1.5
				Relative soil humidity [%]	17.8	1.8	19.1	16.5
			75 m WEST	**Vertical displacement [cm]**	2.8	0.5	3.8	2.0
				Relative soil humidity [%]	18.1	0.8	19.3	17.0
			120 m WEST	**Vertical displacement [cm]**	2.7	0.6	3.8	1.0
				Relative soil humidity [%]	17.4	0.9	18.4	16.2
	Runway 2 (35L-17R)		**120 m EAST**	**Vertical displacement [cm]**	5.0	0.7	6.8	4.3
				Relative soil humidity [%]	25.3	0.9	26.0	24.0
			75 m EAST	**Vertical displacement [cm]**	4.6	0.9	6.5	3.5
				Relative soil humidity [%]	26.2	1.9	28.4	23.8
			75 m WEST	**Vertical displacement [cm]**	4.6	0.7	6.0	3.8
				Relative soil humidity [%]	27.5	3.2	31.0	24.8
			120 m WEST	**Vertical displacement [cm]**	5.3	0.8	6.8	3.5
				Relative soil humidity [%]	27.2	1.7	28.9	25.5

This value was adopted in the following step of the model where the soil was assumed as a homogenous and linearly elastic layer; the elastic displacements produced by the nose landing gear of the critical aircraft were indeed evaluated according to the multi-layer elastic theory using the mechanical parameters (elastic modulus E and Poisson coefficient υ) of the real in-situ soil. A back analysis was performed to compute E and υ starting from the PLT displacements previously computed. The outcomes showed that the in-situ soil could be modeled as a semi-infinite space having an elastic modulus of 30 MPa and Poisson coefficient equal to 0.35.



(a)

(b)

Fig. 2. Deformation modulus at the: (a) first (M_d), (b) second (M_d') loading cycle (PLT)

4.1. Analysis of vertical displacements produced by the critical aircraft

In relationship to the elastic part of the total displacement induced by the critical aircraft, the multi-layer elastic theory was used to introduce in the model the mechanical soil parameters previously computed (E = 30 MPa, υ = 0.35).

The load characteristics such as the tire pressure and the footprint radius of the nose gear were assumed according to the manufacturer specifications. It should be noted that two modeling conditions were taken into account distinctly separating the different moisture conditions of the soil, 17.8% and 26.4% of relative humidity; safety conditions must be indeed guaranteed even after long periods of rain taking the soil moisture proximal to saturation.

The plastic portion of the total displacement induced by the critical aircraft was estimated correlating the plastic displacements obtained from the PLTs and the ones from the passages of the emergency vehicle. In particular, since 1) the plastic displacement caused by the plate pressure of 0.1 MPa was equal to 3.59 mm and the plastic displacement caused by the vehicle was 31.1 mm (tire pressure of 0.8 MPa), 2) the tire footprint radius were similar among the two test procedures, and 3) a ratio almost equal to 8 was identified within the plastic displacements (31.1 mm / 3.59 mm = 8.6) and the load pressures (0.8 MPa / 0.1 MPa = 8), then the plastic displacements induced by the aircraft were estimated linearly amplifying the values obtained during the preliminary analyses.

Outcomes, summarized in Table 3, showed that the total displacement due to the nose gear load of the Boeing 777 was higher than the maximum (15 cm) provided by the technical standards. A structural intervention on the STRIP soil was therefore required to increase the bearing capacity.

5. The design project

The lack of proper bearing capacity of the STRIP was restored treating the in-situ soils with cement and adopting a controlled-energy approach during the compaction stage (Crispino et al., 2010; Giustozzi et al., 2012); in particular, 20 cm of effective soils, below the superficial layer of lawn and turf and within the inner stripe of 35 m, were stabilized with cement. The new STRIP structure is highlighted in Table 4.

Table 3. Elastic, plastic, and total displacements caused by the passage of the critical aircraft

Aircraft	*Landing Gear*	*Load Condition*	*Tire Pressure [MPa]*	*Tire Load [kg]*	*Tire Footprint Radius [cm]*	*Elastic Displacement [mm]*	*Plastic Displacement [mm]*	*Total Displacement [mm]*
B777-300ER	rear	static	1.55	27155.67	23.61	AVERAGE HUMIDITY CONDITION =17.8%		
						29.2	55.6	84.8
						HIGH HUMIDITY CONDITION = 26.4%		
						22.0	54.9	76.9
	front	dynamic*	1.53	22335.00	21.56	AVERAGE HUMIDITY CONDITION = 7.8%		
						75.9	109.5	185.4
						HIGH HUMIDITY CONDITION = 26.4%		
						58.0	108.0	166.0

* *because of the braking effect*

Table 4. The new STRIP layer structure and mechanical characteristics of materials adopted in the model

STRIP structure		***Material Mechanical Parameters***	
Material	***Thickness [cm]***	***Average humidity condition [17.8%]***	***High humidity condition [26.4%]***
Grassy Topsoil	15	E = 30 MPa ; υ = 0.35	E = 10 MPa ; υ = 0.40
Cement treated in-situ soil	20	E = 250 MPa ; υ = 0.30	E = 250 MPa ; υ = 0.30
Subgrade	-	E = 30 MPa* ; υ = 0.35	E = 20 MPa ; υ = 0.40

**precautionary value*

The main decision factors that brought to the final design solution were:

- reduction of the total volume of soil handled;
- maximization of the construction site productivity;
- lower amount of construction machineries and related emissions;
- economic advantages;
- zeroing the use of non-renewable resources such as virgin aggregates.

The design solution was further analyzed according to the methodology described in the previous sections in order to quantify the elastic, plastic, and total displacements caused by the critical aircraft after the proposed intervention in the above mentioned two moisture conditions. Results are summarized in Table 5.

5.1. The construction phase

Unfortunately, the majority of the construction works took place during the autumn-winter season because of contingent needs of the airport authorities. Therefore, several rainy days and showers were experienced and high-water content was retained by the in-situ soil.

Full scale test areas were consequently set up in order to develop a stabilization and compaction methodology depending on the soil type, cement content, and soil relative humidity. Eleven full scale test areas were built each one having rectangular-shape geometry (40 m x 5 m).

Four cement contents (1.5, 2, 2.5, and 3% by weight of the dry soil), four stabilization thicknesses (20, 25, 30, and 40 cm), and different compaction sequences were tested. In particular, a single drum roller weighting 220 kN (almost 22 tons) was adopted for compaction; two sequences of compaction were tested: a *light compaction* which performed 4 passages in vibrating mode (the vibration frequency was adjusted depending on the stabilization thickness) and 2 finishing passages in static mode, and a *medium compaction* which included 6 passages in vibrating mode and 2 finishing passages in static mode.

Outcomes from the full scale tests are summarized in Table 6. The medium compaction sequence was preferred by the airport authorities. It should be noted (Table 6) that the deformation modulus M_d, representative of the mechanical performance of the in-situ soil after 7 days of curing, was required to range from 80 to 120 MPa; the final surface had therefore to guarantee a sufficiently high bearing capacity without showing an excessively rigid behavior. For that purpose, the compaction did not aim to reach the maximum relative density of the soil, as it is usually required, but to control and optimize the compaction energy depending on the cement content and stabilization thickness.

Finally, the construction steps were identified as follows (Fig. 3):

- harrowing of the superficial lawn and turf to break up roots and consequently remove the surface soil to be re-used afterwards;
- measure of the relative humidity of the in-situ soil and implementation of the most appropriate stabilization treatment (thickness and cement content) as identified in the full-scale tests;
- spreading of the cement powder on the soil surface;
- stabilization of the in-situ soil using a pulvimixer (recycler);
- compaction of the resulting surface (compaction sequence as identified during the full-scale tests);
- backfilling with the lawn and turf soil previously removed;
- hydro-seeding.

The productivity of the construction site was around 3′000 m^2 per night (1 night = 5 hours of effective work).

Table 5. Design project: elastic, plastic, and total displacements

Aircraft	***Landing gear***	***Load condition***	***Tire pressure [MPa]***	***Tire load [kg]***	***Tire footprint radius [cm]***	***Elastic displacement [mm]***	***Plastic displacement [mm]***	***Total displacement [mm]***
B777-300ER	rear	static	1.55	27155.67	23.61	AVERAGE HUMIDITY CONDITION = 7.8%		
						21.9	41.7	63.6
						HIGH HUMIDITY CONDITION = 26.4%		
						33.1	82.1	115.2
	front	dynamic*	1.53	22335.00	21.56	AVERAGE HUMIDITY CONDITION = 7.8%		
						15.6	41.2	56.8
						HIGH HUMIDITY CONDITION = 26.4%		
						26.7	81.0	107.7

Table 6. Full scale test areas - optimization of stabilization and compaction methodologies

Soil classification [UNI EN 13242, AASHTO M 145-91]	*Optimum water content [ASTM D698] [%]*	*In-situ soil humidity before the intervention [%]*	*Soil Stabilization*		*Compaction methodology*	*Minimum requirements after 7 days of curing [MPa]*
			Thickness of stabilized soil [cm]	*Cement content [%]*		
A1	8	8 ± 3	20	1.5	22 tons single drum roller: 6 passages in dynamic mode + 2 passages in static mode	$M_d \geq 80 \div 120$
A2-4	12	12 ÷ 15	20	1.5		
		16 ÷ 19	30	2.5		
		20 ÷ 22	40	3		
A4	18	18 ± 5	20	1.5		

In particular, the finishing hydro-seeding treatment was firmly needed to avoid dust and rubbles on the runway due to strong winds; the runway, indeed, had to be re-opened in the early morning after every nocturnal working shift. A synthetic hydro-colloid was therefore adopted to guarantee a sticky action on the soil (Fig. 4).

Fig. 3. Construction steps

5.2. Controlling activities during and after construction

Inspection activities during the construction phase were carried out to check:

- the soil type (ASTM M 145-91, 2008; UNI EN 13242, 2008);
- determination of the CBR index (ASTM D1883, 2007; UNI EN 13286-47, 2012) on laboratory prepared samples having the same cement content and relative humidity of the in-situ soil; samples were cured 24 hours in a climate chamber (relative humidity = 95% and T = 20°C) and 24 hours soaked in water (T = 20°C);
- measure of the deformation modulus M_d (PLT) after 7 days.

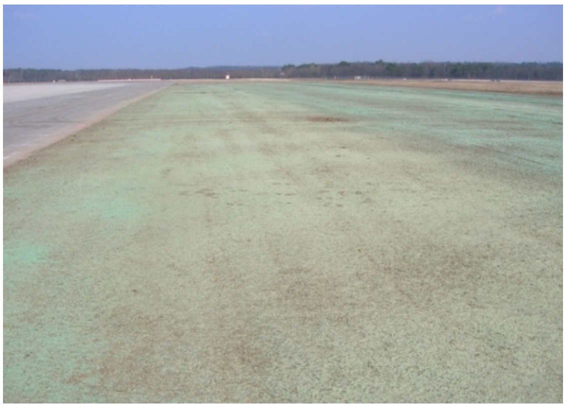


Fig. 4. The final STRIP treated soil (in particular, the hydro-seeding finishing treatment)

In addition, the bearing capacity of the soil was tested at the end of the construction phase. The total displacement due to the passages of the emergency vehicle already adopted during the preliminary analysis stage, was measured again in 46 measurement points spread all over the STRIP.

Outcomes both from the deformation modulus analysis and the truck passages showed that the new STRIP provided a total compliance with the national and international standards; the maximum displacement observed was always below 5 cm at standard moisture conditions and below 9 cm in proximity of soil saturation (for further details in Table 7).

6. Conclusions

The present paper described the overall procedure from the preliminary analysis, initial evaluation, design, construction, and final verification and monitoring of a functional and structural intervention conducted on a runway STRIP of a major Italian airport.

Table 7. Deformation modulus and vertical displacements after the intervention

	Runway 1 (35R-17L)		Runway 2 (35L-17R)	
	Deformation Modulus [MPa]	Vertical Displacement Super DRAGON X8 [cm]	Deformation Modulus [MPa]	Vertical Displacement Super DRAGON X8 [cm]
Mean	**111.5**	**0.6**	**93.7**	**1.1**
Dev. Stand.	**30.8**	**0.4**	**8.5**	**1.7**
Min.	**83.2**	**0**	**85.7**	**0.0**
Max.	**187.5**	**2**	**111.1**	**5.0**

The intervention aimed to make the STRIP comply with national and international standards in terms of bearing capacity and leveling requirements. Although representative of a specific case study, the intervention methodology could be adopted by other airport authorities in order to conform their runway STRIPs to standards. In addition, similar interventions could be also adopted to enhance the bearing capacity of other critical areas in airports, such as the Runway End Safety Area (R.E.S.A.) for instance.

Several advantages were indeed experienced: the soil handling to/from the construction site was greatly minimized (this aspect assumes a main importance when huge areas have to be treated) saving a valuable amount of non-renewable resources and landfill, the productivity of the construction site was maximized limiting delays for users and complications in the airport capacity.

The intervention adopted a particular soil stabilization technique with cement; controlled compaction energy was thus provided to end up having a final surface with sufficient bearing capacity to sustain veer-off aircrafts from sinking but, in the meanwhile, guaranteeing a specific and limited deformation to let the aircrafts naturally brake.

Emergency vehicles are now also able to reach every portion of the STRIP, and during all-weather conditions (water content of the soil), without getting stuck. Finally, the case study demonstrated as the correct approach for design, especially within critical areas such as airports, is considerably based on a multi-stage approach, from preliminary investigations to full scale tests and final construction.

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