RECYCLING PRACTICES FOR ACHIEVING ENVIRONMENTAL SUSTAINABILITY IN AIRPORT PAVEMENTS

Authors:
Giustozzi F., Ph.D, P.E. (corresponding author)
Research Associate – Politecnico di Milano/Virginia Tech – filippog@vt.edu
P.zza Leonardo Da Vinci 32, 20133, Milan, Italy
Office:+39-02-23996605
and
3500 Transportation Research Plaza, 24060, Blacksburg, Virginia, USA
Mobile: +1-(540)505-6861

Crispino M., Ph.D, P.E.
Professor – Politecnico di Milano – maurizio.crispino@polimi.it
Director, Infrastructure Section – DIIAR

Flintsch G., Ph.D, P.E.
Professor – Virginia Tech – gflintsch@vt.edu
Director, Center for Sustainable Transportation Infrastructure - CSTI

ISBN 978-88-902409-0-4

ABSTRACT

Both the design and the construction of airfield pavements have to be consistent with strict requirements and constraints and also higher safety standards due to their particular setting. In addition, maintenance and construction times must be minimized in order to avoid delays and limitations on airport capacity. Maintaining or constructing airfield pavements also entails working during all-weather conditions (e.g.; winter time and heavy cold conditions); materials adopted therefore play a major role in the success of the maintenance or construction activity.

Environmental management plans and eco-friendly policies and strategies are increasingly being adopted by airport directors. Noise reduction plans through improved air traffic management techniques, emissions control for aircraft engines and ground maneuvering vehicles, reuse of water for washing airfield pavements, use of renewable energies, and use of photocatalytic materials are only some of the numerous ways of achieving a sustainable airport.

The paper focuses on construction techniques and the development of innovative materials for the achievement of environmental sustainability on airfield pavements. In particular, the authors present how a long lasting and well performing airport pavement can be built if more than 85 % of the materials used are recycled materials. The environmental analysis of a case study on a major Italian airport shows that the release of almost 35 % of emissions could be avoided if recycling practices are taken into account. Furthermore, pavement performance is analyzed and monitored as well in order to show that recycling does not necessarily result in lower performance.

Outcomes clearly suggest that the recycled airport pavement has a comparable performance and less of an environmental impact on standard airfield pavements. Moreover, results can be implemented into an Airport Pavement Management System to assess the best strategy, considering the environmental footprint in addition to the traditional performance analysis and cost effectiveness.

Keywords: recycling, sustainable airport pavements, life cycle assessment, carbon footprinting.

INTRODUCTION

The global aviation community is continuously studying and increasingly adopting sustainable practices into their airport management plans. Sustainability in aviation has been consistently enforced over recent decades through various practices: engine emissions reduction, curfew acts for low noise departing and landing procedures, recycling practices and waste management, renewable resources utilization, and electric vehicles for ground maneuvering, for instance.

Moreover, pavement structures represent a major asset in airport facilities. A massive amount of non-renewable resources is therefore consumed for maintenance and rehabilitation related projects in an attempt to cater to this asset. Despite this concern, very little has been done to achieve environmental sustainability while constructing and preserving these assets. In particular, airport pavement management systems (A-PMS) do not include environmental impacts as a decision factor among different alternatives. Lack of funding was mentioned as the first reason for not implementing sustainability practices into the A-PMS (Berry et al., 2008) although several references (i.e.; Giustozzi et al., 2012; Pittenger, 2011; GTAA, 2010) demonstrate that applying the right treatment on the right pavement at the right time can significantly provide cost and environmental savings. Sustainable practices should therefore represent a way to develop more efficient solutions while planning both short and long-term strategies.

Airfield pavements in major airports usually have 24 hour operating periods in all-weather conditions; maintenance and rehabilitation activities must therefore respond to various needs: traffic (delays and airport capacity reduction), safety conditions (avoid Foreign Object Damage), time of intervention (short re-opening to traffic), and effectiveness of materials used (performance and durability).

OBJECTIVE

The paper presents a case study of a taxiway pavement construction on a major Italian airport adopting almost 85 % of recycled materials. The presented solution optimizes the eco-efficiency while preserving high performance.

The first section of the paper shows the methodology adopted and materials qualification while the second section provides the reader with an environmental assessment of the different stages that lead to the pavement construction.

Results clearly show that high performance and durability, usually demanded by airport pavements, can be achieved with higher environmental benefits through the adoption of recycled aggregates and in-situ soils valorization.

ASSESSING SUSTAINABILITY ON AIRPORTS: A CASE STUDY

The paper presents the construction of a pavement in a major Italian airport (Milan area). The work was carried out in three months during the fall and winter seasons. The aim was to improve the airport capacity to allow the new large aircrafts (NLAs) such as the Airbus 380 and the Boeing 777 to taxi on the new infrastructure. The area involved was approximately equal to 60,000 square meters. Considering that airport pavements usually have a standard thickness between 70 cm and 110 cm, the amount of material involved was therefore significant. Virgin aggregates and bitumen represented a significant quantity of non-renewable resources to be provided. Waste materials, mainly in-situ soil, substantially contributed to landfilling and dumping. Therefore, sustainability and environmental impacts had a main weight during the design stage; the final solution led towards the re-use and valorization of in-situ soils and the use of recycled aggregates as much as possible. In addition, since performance is a main feature of airport pavements, the following section investigates the mechanical characteristics of the pavement layers. A particular effort was made to test and characterize the recycled material used.

PERFORMANCE ASSESSMENT

Material mix-design and construction techniques were optimized to ensure a long lasting and well-performing pavement, in addition to the environmental benefits. The resulting pavement consisted of: an innovative surface layer made of open-graded asphalt filled with hyperfluid cement mortar (6 cm), a recycled cement bound layer as an intermediate layer (30 cm), and a cement stabilized soil adding recycled aggregates as a foundation layer (40 cm).

Materials adopted in the construction of the airport pavement were selected considering both the winter construction conditions and the environmental benefit with the main purpose of saving valuable non-renewable resources. The most notable feature, and also the most challenging aspect, was to build such an important structure composed of almost 85 % recycled resources. Material handling was in this way minimized, thus reducing greenhouse gasses emissions due to construction machineries and hauling, therefore lowering the pavement's embodied energy. Virgin aggregates and bitumen consumption was also minimized since they were used only on the surface layer of the pavement. Finally, hauling and its related environmental impact were significantly reduced since almost all of the construction material came from the airport area.

Materials selection and characterization were accomplished through laboratory, on-site, and full scale investigations. The new taxiway was opened to air traffic after four months from the beginning of construction activities and seven days after the placement of the surface layer. The pavement classification number (PCN) was also computed according to the ICAO standards (ICAO, 2004) through falling weight deflectometer testing. The average PCN was equal to 120.

Surface layer: open graded asphalt filled with hyperfluid cement mortar

The use of what can be still considered an innovative material on airfields was suggested for enhancing both the structural capacity and the resistance to particular surface actions (i.e.; chemical actions due to brake fluid loss from aircrafts landing gears).

Indeed, the bituminous surface layer consists of an open-graded asphalt mixture, modified bitumen, and high-quality aggregates filled with a specific hyperfluid cement mortar (Crispino et al., 2007a). The binder content and type had to be defined for assuring the best structural performance of the mixture when in-service. In the case study presented 50/70 penetration grade (EN12591, 2009) polymer modified bitumen was chosen; the optimal amount was equal to 3.5 % by weight of dry aggregates.

The void content was equal to 25-30 % in order to allow a correct filling when pouring the cement mortar. Indeed, the mortar is hand-applied on the surface using scrapers to allow its full-depth penetration into the voids. The quick placement and hardening favor a swift re-opening to traffic and high compression resistance to heavy loads.

The main structural and functional characteristics of the surface layer can be summarized as follows (Table 1).

Table 1 Open graded asphalt filled with hyperfluid cement mortar

Index	Standard	Value
Density [g/cm^3]	ASTM 2726/88	2.32
Stiffness @5 °C [MPa]	EN 12697-26	12,326
Stiffness @20 °C [MPa]	EN 12697-26	7,560
Stiffness @40 °C [MPa]	EN 12697-26	4,324
ITS @20 °C [MPa]	EN 12697-23	1.53
BPN	EN 13036-4	65
Macrotexture depth [mm]	EN 13036-1	0.52

Intermediate layer: recycled cement bound layer

Since the thickness of the surface layer, although stiffer than usual bituminous mixtures, was consistently reduced when compared to standard airport pavement structures, a high bearing capacity and favorable durability characteristics were consequently demanded to the layers below.

An experimental investigation was therefore conducted to optimize the aggregate selection and the design and construction procedures of the recycled cement bound base layer (Crispino et al., 2007b).

Aggregates were recycled from the disposal of runway head concrete slabs inside the airport area; material handling and hauling were therefore strongly reduced in addition to the lower consumption of non-renewable resources.

The analysis was conducted according to laboratory and on-site tests. The laboratory investigation stage was aimed towards the water and cement content optimization of the recycled mixture. Mechanical properties and rheological behaviour during the compaction stage were also highlighted. The optimal water/cement ratio was finally established and the proper mixture was chosen. In addition, a full scale test section was performed within the airport area. The aim was the optimization of the laying and compaction methodology, and the monitoring of the bearing capacity evolution during the curing process.

According to the laboratory investigation (Crispino et al., 2007b) based on aggregate characterization (EN1097-2, 2010), modified Proctor test (EN13286-2, 2010), unconfined compression stress test, and indirect tensile test, the 4 % cement and 8 % water mixture was selected for the following on-site full scale investigation. A full scale test section (400 square meters) was used inside the airport area to optimize construction techniques and evaluate the curing process. The dynamic modulus (E_d) was measured using a light weight drop tester (Teil-B-8.3, 2003) to assess the optimal number of passes during compaction. Six passes of a 15 tons single drum roller were identified as providing the optimal compaction (Crispino et al., 2007b).

Foundation layer: cement stabilized in-situ soil with recycled aggregates

The stabilization of in-situ soils was developed to reduce materials supplied and to limit handling throughout the construction site, a time consuming and massive activity when operating on a very large scale like airport areas. Re-use and valorization of existing soils, enhancing their properties through stabilization treatments, allows the reduction of virgin aggregate consumption and waste production (Bahar et al., 2004). Recycled aggregates from crushed concrete slabs were added to the existing in-situ soil (classified according to AASHTO as A1a soil) to improve the mechanical performance of the layer and enhance the bearing capacity of the pavement. Recycled aggregates were initially cleaned from impurities (e.g.; pieces of steel wire fabric) and then sieved.

Besides technical and economic advantages (higher productivity during construction, lower cost of materials supplied, higher independence from climatic factors such as rain, etc.), a massive savings of non-renewable resources was achieved when compared to standard foundation layers.

The amount of hydraulic binder added to the mixture of soil and recycled aggregates to achieve the required performance was again established based on laboratory and on-site investigations (Toraldo, 2007).

Recycled aggregates obtained from concrete slab disposal were selected and sieved through a plug mill. The maximum size was 70 mm, coarser than the aggregates used in the recycled intermediate layer previously described. According to the laboratory investigation (Toraldo, 2007) based on aggregate characterization (EN1097-2, 2010) and modified Proctor test (EN13286-2, 2010), the optimal water content for providing the best compaction properties of the soil mixture was identified. A range between 6 % and 8 % of water content was therefore selected for the following on-site full scale investigation. A full scale test section (almost 12,000 square meters) was installed inside the airport area to optimize both the type and content of hydraulic binders for the in-situ stabilization process and construction techniques. Six different areas (almost 200 square meters each) were investigated adopting different contents and types of hydraulic binder, while keeping the optimum water content defined during laboratory tests constant. In particular, two different binders were used: Portland cement for enhancing strength and resilient properties, and lime for reducing plasticity and improving the mixing efficiency. Finally, the 3.5 % of cement and no lime was adopted as the final design mixture.

ENVIRONMENTAL ASSESSMENT

The eco-effectiveness of the project has been evaluated through the analysis of the emissions released in the atmosphere due to the manufacture of materials, use of construction equipment, and processes (hauling of materials, recycling, etc.). The functional unit is therefore represented by the entire process of paving the airport taxiway; materials quantities, densities, and taxiway dimensions are provided in Table 2.

The boundary conditions adopted in the environmental assessment (ISO-EN14044, 2006) make the analysis useful for comparison between similar construction projects. In particular, the manufacture of materials was computed within a cradle-to-gate approach; emissions were therefore computed from the manufacturing of raw materials to the point where the product was ready to use. Moreover, emissions from the fuel consumption of machines and processes included only the construction stage, omitting computations for the maintenance phase and the use phase over the life cycle. The time horizon of the analysis consequently ended with the start of the service life of the pavement.

The following sections provide a detailed investigation of the material consumption, the equipment used, and the processes involved. Finally, a comparison with a standard airport asphalt pavement, in terms of emissions produced was conducted.

Materials

Environmental analysis of materials was conducted through a comprehensive carbon footprinting assessment, the calculation of the total amount of greenhouse gasses emitted for a product. Processes, and their related emissions, involved for manufacturing the initial raw material up to the final product as ready-to-use, have been considered into the carbon footprint assessment. A single footprint refers to the six greenhouse gasses identified by the Kyoto Protocol (Oberthür and Ott, 1999). It is common use to combine them into an equivalent unit of carbon dioxide (CO_2e). The conversion method is based on the global warming potential (GWP) of a certain gas over a specific time interval (Alley, 2007). A time span of 100 years was adopted in the paper for evaluating the GWP of the different gasses. For instance, the GWP of nitrous oxide is established equal to 298 (Solomon, 2007): one unit of nitrous oxide released in the atmosphere has the potential to trap the heat and warm up the planet equal to 298 units of carbon dioxide, whose GWP is standardized equal to 1.

The airport taxiway measured almost 2 km in length and 30 m width. Layers' mix-design was designed as follows:

- Open-graded asphalt with cement mortar: 66.5 % virgin aggregates, 30 % hyperfluid cement mortar, 3.5 % bitumen;
- Recycled Cement Bound Layer: 88 % recycled aggregates, 4 % cement, 8 % added water;
- Cement Stabilized In-situ Soil: 94.5 % soil and recycled aggregates mixture, 3.5 % cement, 2 % added water (the total amount of water added should also take into account the relative humidity of the in-situ soil when stabilization occurred).
- Asphalt emulsion was also used for ensuring a good bond between the intermediate layer and the surface layer.

Emissions related to materials production and manufacture were computed according to PaLATE database (Horvath, 2004) (Table 2). Several literature sources are available on the topic but a global inconsistency between the data provided still represents a major issue in LCA for road/airport pavements and related materials (Giustozzi et al., 2012).

Table 2 Inventories of emissions related to materials

Material	**CO_2** [g/ton]	**CO** [g/ton]	**NO_2** [g/ton]	**SO_2** [g/ton]	**PM10** [g/ton]	**Hg** [g/ton]	**Pb** [g/ton]	**Water Use** [g/ton]
Sand and Gravel	10,922	14.4	22.0	10.7	156.5	4E-07	3E-03	21.5
Bitumen	1,121,978	4,736.4	6,239.0	5,653.1	1,057.5	4E-02	2E+00	8,292.2
Cement	715,000	1,131.9	3,185.9	3,158.2	596.7	3E-03	3E-01	1,870.5
Concrete Additives	2,302,229	11,804.5	9,373.6	6,929.6	3,370.8	7E-02	5E+00	35,885.3
Asphalt Emulsion	969,318	4,091.9	5,390.1	4,883.9	913.6	3E-02	1E+00	7,163.9
Water	0.497	0.002	0.003	0.003	0.001	4E-10	9E-07	0
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh
Electric services (utilities)	1,243.97	0.37	3.56	6.97	0.24	4.7E-08	1.9E-04	0.08

The following table provides data about the quantity of materials involved in the project. Those values were also useful for computing impacts related to transportation of materials.

Table 3 Carbon footprinting related to materials

Layer	Density [kg/m^3]	Width [m]	Length [m]	Thickness [m]	Volume [m^3]	Carbon Footprint [ton CO_2e]
Open Graded Asphalt with Cement Mortar – surface	2,320	30	2000	0.06	3,600	1,213.97
Recycled Cement Bound Layer – intermediate	2,300	30	2000	0.30	18,000	940.35
Cement Stabilized In-situ Soil with Recycled Aggregates - foundation	2,200	30	2000	0.40	24,000	850.90
			Total	**0.76**	**45,600**	**3,005.22**

Construction processes and equipment

This section presents, from an environmental standpoint (fuel consumption and related emissions), a detailed description of the processes involved for:

- the production of the recycled aggregates obtained from the disposal of concrete slabs;
- the construction of the foundation (in-situ stabilization), intermediate layer (cement bound layer), and surface layer (open graded asphalt filled with cement mortar) of the airport pavement previously described.

Emissions related to machines and on-site plants were computed to find the carbon footprint due to the construction process and equipment. In particular, recycled aggregates were produced by crushing concrete slabs into conveyable blocks, sorting out the steel of slab reinforcements, milling and sieving the blocks through a plug mill and a screening plant to come out with smaller particles having specific sizes.

Machines involved in the recycling process included:

- excavators with a rock-breaker bucket for crushing concrete slabs;
- loaders for loading up dumper trucks;
- trucks for transferring concrete blocks to the plug mill;
- loaders for supplying material unloaded from trucks into the plug mill;
- a screening movable plant for sieving particles into homogenous sizes and removing steel elements.

The cement stabilization of in-situ soil for building the foundation layer was performed using a grader for spreading recycled aggregates, a cement spreader, a soil stabilizer with a water tank to achieve the optimal soil humidity, and a single drum roller for the final compaction.

The recycled cement bound layer was made using the recycled aggregates and a mobile mixing plant installed inside the construction site; a standard paver was adopted for laying and a single drum roller was used for the final compaction. An asphalt spreader was used for applying the bonding coat between the intermediate and the surface layer.

The surface layer was then laid adopting the standard methodology for asphalt layers (paver and roller application); the hyperfluid cement mortar was finally hand-applied to fill the voids.

It should be noted that all the machines previously described used diesel except the plug mill, the mixing and the screening plant, which were all electric-power based. The analysis of fuel consumption for machines and movable plants was conducted by investigating the average fuel, mainly diesel, usually spent during their activity (i.e. loading 1 m^3 of soil, milling 3 cm of pavement, etc.). Technical specifications were used to ascertain, for standard working conditions, the maximum speed, the common operational speed, and their typical performance. Fuel consumption varies depending on the amount of power provided by the engine and on the working conditions of machines (temperature, altitude, etc.).

Several assessment methods for construction equipment fuel consumption are available (U.S. Environmental Protection Agency, 2008; Wang, 2007), however, coefficients from “Construction Equipment Ownership and Operating Expense Schedule” (U.S. Army Corps of Engineers, 2009), unique for each type of equipment, were used in the calculations to obtain the fuel consumption.

The methodology adopted and results obtained are presented as follows:

1. The power-torque engine curve for every unit of equipment was analyzed and the value of the maximum power (brake horsepower - bhp) at a specific speed (revolutions per minute – RPM) was computed.
2. A fuel factor in gallons per brake horsepower-hour (gal/bhp*hr) was used (U.S. Army Corps of Engineers, 2009). Diesel fuel factor (FF) is computed using the following formula:

$$FF\left[\frac{gal}{bhp\cdot hr}\right]=\frac{HPF*lbs\ Fuel\ per\ bhp\cdot hr}{lbs\ Fuel\ per\ gal} \qquad (1)$$

Where:

HPF is the horsepower factor and represents an average percent of full-rated horsepower being used by the engine, it is an estimate of the engine load under average working conditions. It is necessary to modify the rated horsepower as engines and motors in actual production do not work at their full-rated horsepower at all times. Periods spent idling, traveling in reverse, traveling empty, close maneuvering at part throttle, and operating downhill are examples of conditions that reduce the HPF.

Pounds (lbs) of fuel per bhp·hr is an average based on a variety of engine applications from manufacturer engine data.

Pounds (lbs) of fuel per gallon is the factor that determines the weight of the fuel consumed.

3. The fuel consumption (FC) for a specific unit of equipment was then obtained by multiplying the maximum power developed by the engine (from the power-torque engine curve), the fuel factor previously described, and a conversion factor for converting gallons into liters.

$$FC\left[\frac{l}{hr}\right]=\max Power[bhp]\cdot FF\left[\frac{gal}{bhp\cdot hr}\right]\cdot\gamma\left[\frac{l}{gal}\right] \qquad (2)$$

4. Given the amount of material being handled and the productivity of a specific type of machine, the working time (WT) for carrying out a certain activity (i.e.; stabilizing 0.4 m of soil over 100 m^2) was computed using the formula that follows:

$$WT\ [hr]=\frac{\text{Volume of material }[m^3]\cdot\text{Density }[ton/m^3]}{\text{Productivity }[ton/hr]} \qquad (3)$$

5. The final quantity of fuel for developing a certain activity with a specific unit of equipment was therefore computed as:

$$F\ [l]=FC\ \left[\frac{l}{hr}\right]\cdot WT\ [hr] \qquad (4)$$

In addition, the Code of Federal Regulations (Code of Federal Regulations, 2005) provides values for carbon content per gallon of diesel fuel: 2,778 g.

The Intergovernmental Panel on Climate Change guidelines (IPCC, 2007) for calculating emissions inventories require that an oxidation factor be applied to the carbon content to account for a small portion of the fuel that is not oxidized into CO_2. For all oil and oil products, the oxidation factor used is 0.99 (99 percent of the carbon in the fuel is eventually oxidized, while 1 percent remains un-oxidized (U.S. Environmental Protection Agency, 2005). Moreover, to calculate the CO_2 emissions from a liter (or gallon) of fuel, the carbon emissions were multiplied by the ratio of the molecular weight of CO_2 (m.w. 44) to the molecular weight of carbon (m.w. 12): 44/12.

$$CO_2 \text{ from 1 gal diesel} = 2{,}778 \text{ g} \times 0.99 \times (44/12) \approx 10.1 \text{ kg/gal} = 2.6639 \text{ kg/l} \qquad (5)$$

Outcomes from the fuel consumption analysis related to equipment are summarized in the table 5.

Transportation

Transportation provides a variable contribution to the emission assessment depending on the distances involved. Whenever material handling requires long distances, emissions related to hauling become a main producer of pollutants; thus, minimizing transportation of material for a construction project can therefore produce a substantial environmental benefit.

In the case study hauling was largely reduced by recycling aggregates and using them as construction material. Only a small amount of resources (virgin aggregates, bitumen, and cement), mainly imputable to the surface layer, was transferred from outside the airport area.

In particular, transportation distances can be summarized as follows:

- virgin aggregates: 25 km (average distance from the nearby quarries)
- hot mix asphalt and asphalt emulsion: 30 km (average distance from the nearby asphalt plants)
- cement and cement mortar: 25 km (average distance from the nearby suppliers)
- recycled aggregates: 6 km (distance from the concrete slabs of the runway head to the new taxiway construction site); in particular, 1.5 km was the distance between the runway head and the plug mill-screening plant while 4.5 km was the distance between the plug mill-screening plant and the construction site.

According to the U.S. Department of Energy (Davis et al., 2010) the average fuel efficiency for a truck in severe working conditions is 0.414 l/km (2.41 km consuming one liter of diesel). Furthermore, a capacity factor was added to the formulation to take into account the different amounts of fuel consumed depending on the loading conditions. A maximum loading capacity of 20 tons was assumed for trucks, almost 12-15 m^3 of sand-gravel materials. The formula adopted is expressed as follows.

$$CO_2[g] = \frac{Effective\ Load\ [ton]}{Capacity\ [ton]} \cdot Distance\ [km] \cdot Fuel\ Efficiency\left[\frac{l}{km}\right] \cdot CO_2\ per\ liter\ of\ diesel\left[\frac{g}{l}\right] \qquad (6)$$

The amount of emissions related to hauling is summarized below. The following section presents an environmental comparison between the pavement presented in the case study and a common asphalt pavement for airport applications (no recycling practices adopted).

Table 4 Emissions related to hauling

Hauling	**CO_2** [kg]	**NO_x** [g]	**PM_{10}** [g]	**SO_2** [g]	**CO** [g]	**Hg** [g]	**Pb** [g]
Virgin aggregates	9,087	491,262	95,796	29,476	40,938	0.09	4.09
Bitumen	574	31,027	6,048	1,862	2,586	0.01	0.26
Cement	4,220	228,140	44,490	13,688	19,012	0.04	1.90
Cement mortar	3,058	165,304	32,222	9,918	13,775	0.03	1.38
Asphalt emulsion	161	8,691	1,694	521	724	0.00	0.07
Recycled aggregates	31,688	1,713,007	335,605	102,780	142,751	0.31	14.25
Total CO_2e [kg]				**49,594**			

Recycled vs. Standard airport pavement: an environmental comparison

An environmental assessment of a common asphalt airport pavement was conducted to compare its carbon footprint with the eco-benefits of the solution adopted in the case study. A standard pavement thickness and common materials were assumed according to the Airport practices (other pavements within the airport area have this structure): 30 cm of hot mix asphalt for surface, intermediate, and base layers altogether; 25 cm of cement bound layer as the subbase; 35 cm of in-situ soil cement stabilization as the foundation layer. No recycled aggregates were to be used. It should be noted that if a granular layer was adopted as foundation then much more virgin aggregates had to be provided, increasing the total emissions coming from hauling and material handling.

Emissions were computed according to the methodologies previously described for materials production and manufacturing, the equipment used for construction, and hauling distances. The same transportation distances were assumed for both pavements. Results clearly suggested that recycled aggregates and low hauling distances provided massive environmental savings, especially when high quantities of materials are involved.

Table 5 summarize the findings.

Table 5 Comparisons – recycled vs. standard airport pavement

Recycled Airport Pavement	**Layer**	**Material**	**Quantity [t]**	**Thickness [cm]**	**Emissions CO$_2$e [kg]**		
					Materials	**Hauling**	**Construction**
	Open Graded Asphalt with Cement Mortar	Virgin aggregates	4,069.80	6	49,237	9,238	770
		Bitumen	214.20		269,017	583	
		Hyperfluid cement mortar	1,369.44		858,118	3,108	
		Asphalt emulsion	60.00		37,598	163	0.197
		Total Quantity - surface layer	**5,713.44**		**1,213,970**	**13,092**	**770.2**
	Recycled Cement Bound Layer	Recycled aggregates	28,512.00	30	141,276	15,532	28,022
		Cement	1,008.00		799,069	2,288	
		Water	1,440.00		0.802	negligible	
		Cement bound layer production	30,960.00		-		
		Total Quantity - intermediate layer	**30,960.00**		**940,346**	**17,820**	**28,022**
	Cement Stabilized In-situ Soil with Recycled Aggregates	Recycled aggregates	30,618.00	40	151,711	16,679	14,786
		Cement	882.00		699,185	2,002	
		Water	360.00		0.20	negligible	
		Total Quantity - foundation layer	**31,860.00**		**850,896**	**18,681**	**14,786**
	TOTAL EMISSIONS - RECYCLED AIRPORT PAVEMENT				**3,005,212**	**49,593**	**43,578.2**
Standard Airport Pavement	**Layer**	**Material**	**Quantity [t]**	**Thickness [cm]**	**Emissions CO$_2$e [kg]**		
					Materials	**Hauling**	**Construction**
	Hot Mix Asphalt layers	Virgin aggregates	27,740	30	355,324	73,357	5,150
		Bitumen	1,637		2,176,999	4,354	
		Asphalt emulsion	180		113,203	490	0.58
		Total Quantity - surface layer	**29,557**		**2,645,526**	**78,201**	**5,151**
	Cement Bound Layer	Virgin aggregates	23,760	25	287,447	53,930	4,281
		Cement	840		665,891	1,907	
		Water	1,200		0.67	negligible	
		Total Quantity - intermediate layer	**25,800**		**953,339**	**55,837**	**4,281**
	Cement Stabilized In-situ Soil	Virgin aggregates	25,515	35	308,679	57,914	12,214
		Cement	735		582,654	1,668	
		Water	300		0.16	negligible	
		Total Quantity - foundation layer	**26,550**		**891,333**	**59,582**	**12,214**
	TOTAL EMISSIONS - STANDARD AIRPORT PAVEMENT				**4,490,198**	**193,620**	**21,646**

Summing up the emissions related to the entire projects and dividing them by the total area of the new taxiway (almost 60,000 m^2) then a specific amount of equivalent CO$_2$e equal to 51.6 kg/m^2 and 78.4 kg/m^2 can be computed for the recycled and standard pavement, respectively. A comprehensive environmental saving of almost 35 % can therefore be estimated. Landfill saving, although not studied in the present paper, can also represent an effective eco-advantage to list.

Transportation of virgin aggregates represented a high-impact activity; emissions related to hauling in the standard airport pavement became in fact almost 3.5 times higher if compared with the recycled pavement. Construction equipment and related practices were almost similar in terms of pollution produced; this aspect was mainly due to the additional activities for processing and obtaining the recycled aggregates from concrete slabs (disposal, milling, screening, etc.).

CONCLUSIONS

The case study presented in the paper suggests a different way of designing and building airport pavements taking into account performance but also environmental impacts related to the materials used, the construction equipment and practices, and material handling.

A similar, and sometimes better, performance can be achieved by using recycling aggregates coming from demolition activities of obsolete infrastructures. However, laboratory and on-site preliminary investigations are strongly recommended since recycled material can vary greatly in its mechanical and structural behaviour.

In addition, significant environmental savings, in terms of lower emissions released in the atmosphere, can be provided. Limiting hauling can increase the productivity among the construction site and therefore shorten the working times, avoiding air traffic delays and airport safety issues.

Finally, costs can be significantly reduced by adopting recycled aggregates already available on site. Maintaining high performance while reducing costs and environmental impacts can represent a complementary way to achieve sustainability on airports. Comprehensive and multi-attribute approaches are therefore recommended for evaluating different design strategies.

REFERENCES

Alley R. 2007. “Climate Change 2007: The Physical Science Basis - Summary for Policymakers”. *Intergovernamental Panel on Climate Change*.

Bahar R, Benazzoug M, Kenai S. 2004. “Performance of compacted cement-stabilised soil”. *Cement and concrete composites*. Volume 26, Issue 7 :811-20. ISSN: 0958-9465

Berry F, Gillhespy S, Rogers J., 2008. “Airport sustainability practices”. *Project 11-03*, Topic S02-02. ISBN: 0309098092

Code of Federal Regulations, 2005. “Fuel economy calculations.” *Title 40 - Protection of the Environment*, Part 600 - Fuel Economy of Motor Vehicles. Report n°40, U.S.40 CFR 600.113

Crispino M, Toraldo E, Pozzi M., 2007a. “An innovative rehabilitation technique for airport concrete pavements.” *RILEM - International Conference on Advanced Characterization of Pavement and Soil Engineering Materials*. Athens, Greece.

Crispino M, Toraldo E, Pozzi M., 2007b. “The use of crushed concrete slabs in base layers of airport pavements.” *Proceedings of the Fifth International Conference on Maintenance and Rehabilitation of Pavements and Technological Control*. Park City, Utah, USA.

Davis SC, Diegel SW, Boundy RG., 2010. “Transportation energy data book: Edition 28”. *Oak Ridge National Laboratory*. Center for Transportation Analysis, United States. Dept. of Energy. Office of Energy Efficiency.

EN1097-2, 2010. “Part 2: Methods for the determination of resistance to fragmentation Tests for mechanical and physical properties of aggregates.” *CEN/TC 154 - Aggregates: ICS 91.100.15 - Mineral materials and products*.

EN12591, 2009. “Specifications for paving grade bitumens.” *Bitumen and bituminous binders: BSI*. p. 36.

EN13286-2, 2010. “Part 2: Test methods for the determination of the laboratory reference density and water content - Proctor compaction.” *Unbound and hydraulically bound mixtures*: ICS 93.080.20 (Road construction materials). p.34.

Giustozzi F, Crispino M, Flintsch G., 2012. “Multi-attribute life cycle assessment of preventive maintenance treatments on road pavements for achieving environmental sustainability.” *The International Journal of Life Cycle Assessment*:1-11. DOI:10.1007/s11367-011-0375-6

GTAA Greater Toronto Airports Authority, 2010. “Outside, Inside, Upside: A Three-Dimensional Look at Corporate Social Responsibility.” http://www.torontopearson.com/en/gtaa/corporate-social-responsibility/#

Horvath A., 2004. “Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE).” *Recycled Materials Resource Center*, Department of Civil and Environmental Engineering, University of California, Berkeley.

ICAO, 2004. “Aerodromes: international standards and recommended practices: Annex 14 to the Convention on International Civil Aviation.” *International civil aviation organization*.

IPCC, 2007. “4th Assessment Report (AR4).” In: *Change IPoC*, editor. 2007. p. 104. http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html

ISO-EN14044, 2006. “Life Cycle Assessment: Requirements and Guidelines.” *Environmental Management*. ICS: 13.020.60; 13.020.10. p. 46.

Oberthür S, Ott H., 1999. “The Kyoto Protocol: international climate policy for the 21st century.” *Springer Verlag*. ISBN: 354066470X

Pittenger DM., 2011. “Evaluating Sustainability of Selected Airport Pavement Treatments with Life-Cycle Cost, Raw Material Consumption, and Greenroads Standards.” *Transportation Research Record: Journal of the Transportation Research Board*, 2206:61-8.

Solomon S., 2007. “Climate change 2007: the physical science basis: contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.” *Cambridge University Press*. ISBN: 0521705967

Teil-B-8.3., 2003. “Dynamischer Plattendruckversuch mit Leichtem Fallgewichtsgerätes. Forschungsgesellschaft für Straßen und Verkehrswesen.” Technische Prüfvorschriften für Boden und Fels im Straßenbau: Arbeitsgruppe Erd und Grundbau.

Toraldo E., Mariani E., 2008. “Experimental Investigation On The Use Of Crushed Concrete Slabs For Subbase Layers In Airport Pavements.” *VARIREI International Conference*, Italy.

U.S. Environmental Protection Agency, 2005. “Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel.” *Office of Transportation and Air Quality (OTAQ)*.Report n° EPA420-F-05-001. www.epa.gov/otaq/greenhousegases.htm

U.S. Environmental Protection Agency, 2008. “NONROAD Model 2008a: nonroad engines, equipment, and vehicles.” http://www.epa.gov/otaq/nonrdmdl.htm

U.S. Army Corps of Engineers, 2009. “Construction Equipment Ownership and Operating Expense Schedule.” *EP 1110-1-8*. http://www.nwa.usace.army.mil/html/offices/ed/c/ep_current.asp

Wang M., 2007. “Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model”, Version 1.8 b. *Argonne National Laboratory*.