ISSN: 2581-4311
DOI: doi.org/10.30967/IJCRSET/Abdel-Latif-GAL-Younes/223

URF PUBLISHERS
connect with research world

International Journal of Current Research in Science, Engineering & Technology

https://urfpublishers.com/journal/ijcrset

Vol: 9 & Iss: 4

Research Article

Integrating Modern Technologies and Sustainable Pavement Materials into Airport Airside Infrastructure during the Construction Phase: Structural, Environmental and Economic Assessment for Carbon Neutrality

Abdel Latif G.A.L. Younes*

Housing Department, the Egyptian Syndicate of Engineers, Cairo, Egypt

Citation: Abdel Latif G.A.L. Younes. Integrating Modern Technologies and Sustainable Pavement Materials into Airport Airside Infrastructure during the Construction Phase: Structural, Environmental and Economic Assessment for Carbon Neutrality. *Int J Cur Res Sci Eng Tech* 2026; 9(4), 619-627. DOI: doi.org/10.30967/IJCRSET/Abdel-Latif-GAL-Younes/223

Received: 19 August, 2026; **Accepted:** 31 August, 2026; **Published:** 24 October, 2026

***Corresponding author:** Abdel Latif G.A.L. Younes, Egyptian Syndicate of Engineers, Cairo, Egypt

Copyright: © 2026 Abdel Latif GALY., This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

ABSTRACT

This research presents an integrated quantitative framework for developing sustainable airport airside infrastructure by integrating Building Information Modeling with Geographic Information Systems, the use of smart construction equipment and sustainable pavement material technologies, alongside evaluating the environmental and economic impacts of carbon emission reduction strategies during the construction phase, aiming to reduce Greenhouse Gas Emissions (Scope1). The methodological scope comprises three main pillars: The first focuses on leveraging Building Information Modeling and Geographic Information System to achieve an optimal cut - and - fill balance within the airport boundary and the deployment of equipment guided by 3D GPS technology and Artificial Intelligence during the execution of excavation, backfilling and fine grading of the subgrade, as well as during the spreading of the subbase course and base course, achieving a high level of elevation accuracy ranging between ±3: ±5 mm. The second pillar involves using Warm Mix Asphalt in paving, produced via mechanical water injection to lower mixing temperature by 20: 40 °C. The third pillar focuses on capturing carbon dioxide and reinjecting it into fresh concrete during central mixing, a processing called carbon mineralization. Using equipment's guided by 3D GPS technology and Artificial Intelligence reduces directly equipment operating hours by 30: 50% during earthworks, subgrade / base layer preparation and fine grading. Carbon mineralization is using in rigid paving for runway thresholds and aircraft aprons, this technology permanently sequesters carbon as calcium carbonate, boosting the concrete's early compressive strength and reduces cement consumption. As a baseline model, assuming 1000 direct equipment operation hours, this reduction yields a direct fuel savings 10000 liters of diesel, which translates to a direct fuel cost reduction of $10000. Cumulative operational savings reach $ 24000 including labor and maintenance, while abating 26.8 tCO_2 e in scope1 emissions. Concurrently, Warm Mix Asphalt cuts plant burner fuel consumption by 20 % and reduces site level volatile organic compounds by 50%. Regarding carbon mineralization technology, it permanently sequesters up to 15kgCO_2/m3 in concrete pavement without compromising structural integrity or flexural strength under heavy aircraft gear loadings. Consequently, the approach presented in this study offers airfield infrastructure engineers and aviation authorities a validated, scalable pathway toward achieving carbon neutrality during airside infrastructure construction.

Keywords: Warm mix asphalt; Carbon mineralization; Direct machine Operating hours; Greenhouse gas; Carbon neutrality

Introduction

Global aviation infrastructure is undergoing a fundamental paradigm shift driven by the imperative to reconcile expanding operation capacities with stringent decarburization mandates. While historical mitigation strategies have predominantly focused on aircraft operation efficiency and fleet electrification, airside civil infrastructure encompassing runways, taxiways and aprons represent important elements, yet underdressed, source of embodied carbon and the Greenhouse Gas (GHG) during construction phases. The construction phase of heavy-duty airside infrastructure is particularly energy intensive, characterized by massive earthwork operations, heavy equipment fuel consumption, high temperature binder true production and cement dense concrete manufacturing. Achieving true Carbon Neutrality (CN) across airport airside infrastructure necessitates a systemic, multi tear integration of digital spatial planning, intelligent construction machinery and low carbon materials engineering.at the preconstruction and early design phase, the optimization of mass haul operations remains a critical lever for environmental abatement. Integrating Building Information Modeling (BIM) with Geographic Information Systems (GIS) enables high precision spatial modeling, cut – and – fill volume balancing and 3D terrain simulation. This digital synergy minimizes earthwork miscalculations and eliminates the superfluous off- site transport and disposal of excavated soils, thereby curtailing Scope3 transport emissions and site logistic overheads. Transitioning into site execution, the deployment Automated Machine Guidance (AMG) and telematics driven smart construction equipment optimizes grader, excavator and compactor passes during earthwork preparation and subbase / base layer placement. This automated precision directly lowers engine idle time, optimizes fuel burn rates, accelerates construction schedules and enhances structural compaction uniformity.

Concurrently, decarbonizing airside pavement systems requires a dual material strategy targeting both flexible and rigid pavement. For asphalt runways and taxiways, Warm Mix Asphalt (WMA) technology allows for significant reductions in production and compaction temperatures relative to traditional Hot Mix Asphalt (HMA). This thermal reduction yields immediate fuel savings at asphalt plants, diminishes localized volatile organic compound emissions and lower the overall operational carbon footprint while preserving asphalt rheological performance. For rigid pavement segments subjected to extreme static loads, carbon dioxide CO_2 mineralization technology presents a disruptive pathway for structural and environmental optimization. Injected during concrete batching, CO_2 reacts with hydrating cementitious phases to form nano – scale calcium carbonate ($CaCO_3$) crystals. This refinement enhances earl age compressive and flexural strength for rigid pavement. This research presents a holistic structural, environmental and economic frame work to evaluate the synergy of digital planning tools, AMG, WMA and CO_2 mineralized rigid pavement. This study quantifies the net carbon abatement potential and capital cost savings, offering a road map for zero – emissions airside infrastructure construction.

Research Objectives

The primary objective of this study is to formulate and empirically evaluate an integrated construction framework that combines digital spatial planning, automated equipment execution and sustainable materials to achieve decarburization and low cost during the construction of airport airside infrastructure. The specific sub - objectives are:

- To evaluate the efficiency of integrated BIM / GIS platforms in optimizing cut - and - fill mass haul operations during early-stage airside design.
- To evaluate the operational efficiency, fuel consumption rate and structural compaction uniformity of AMG equipped heavy construction machinery during subgrade, subbase and base course placement compared to conventional construction method.
- To characterize the mechanical performance, thermal production savings and microstructural enhancement of WMA and CO_2 mineralization concrete.

Research Problem

The construction phase of airport airside infrastructure remains heavily carbon intensive due to fragmented execution strategies. Current airside engineering practices suffer from three critical inefficiencies as follow:

- Unoptimized excavation, backfilling and grading operations relying on 2D design methods, causing cut - and - fill volume discrepancies and excessive off – sits transport emissions.
- Conventional heavy machinery execution during subgrade, subbase and base layer placement, leading to high fuel burn rates and machine idle times.
- Reliance on thermal dense HMA and high binder Ordinary Portland Cement (OPC) concrete, which significantly inflates the embodied carbon footprint of runways, taxiways and aprons.

While individual advancements exists, there is a district lack of unified, empirical framework evaluating the combined structural, environmental and economic synergy of integrating BIM/GIS, AMG and low carbon pavement materials (WMA and CO_2- mineralized concrete) within a single construction workflow. Without the implementation of this framework, the airport construction sector will remain lacks a proven roadmap for zero – emissions airside construction.

Research Methodology

To evaluate the structural, environmental and economic impacts of BIM/GIS, AMG and sustainable paving materials into airside infrastructure construction, this study adopts a four - stages empirical and theoretical methodology.

Stage 1: Digital Spatial Planning (BIM & GIS) Integration

It is important to precise terrain data acquisition in early airside design via advanced LIDAR scanning and 3D models. Coupling these spatial models with runway, taxiway and apron pavement profiles designs optimizes cut – and – fill balance and eliminates superfluous off- sites earthwork hauling (illustrates with a numerical example).

Stage 2: Execution Using Automated Guided Machines

Executing construction via sensor - equipped, AI- guided machinery alongside comparative analysis against conventional equipment. Key metrics demonstrate reduced construction timelines (schedules), minimized Daily Operating Machinery

Hours (DOMH), decreased fuel and maintenance expenditures, optimize labor cost and reduced carbon emissions.

Stage 3: Sustainable Pavement Materials (Characterization)

Flexible pavement – WMA: Evaluating and characterizing WMA technologies to identify optimal manufacturing methods and quantify their primary engineering and environmental benefits. Key performance outcomes include lowering asphalt mix production temperature, reducing burner fuel consumption at asphalt batching plant, mitigation carbon emissions and enhancing site workability and increasing compaction efficiency.

Rigid pavement - CO_2 mineralization in concrete: This stage encompassing the optimal dose of gaseous CO_2 which in - site injection during fresh concrete mixes in addition to the mechanical evaluation and the mix design optimization. It further quantifies the multifaceted benefits of the technology without compromising the target structural design strength of the concrete.

Stage 4: Research Findings, discussion and actionable roadmap

The final stage encompasses the analysis and discussion of the research findings, outlining an actionable and practical execution roadmap.

Airport Infrastructure Elements

The airport infrastructure consists of the following elements[1] as shown in **(Figure 1)**:

- Airside Infrastructure (Includes: Runways; Taxiways; Aprons/ Ramps; Navigational and Light Aids; Aircraft Rescue and Firefighting).
- Terminal Infrastructure (Includes: Passenger Terminals; Boarding Gates and Passenger Boarding Bridges; Cargo Terminals; Air Traffic Control).
- Landside Infrastructure (Includes: Access Roads and Interchanges; Multimodal Transport; Parking Facilities).
- Utility and Support Infrastructure: (Includes: Chilled Water Plants; Storm Water Management; Maintenance, Repair and Overhaul).

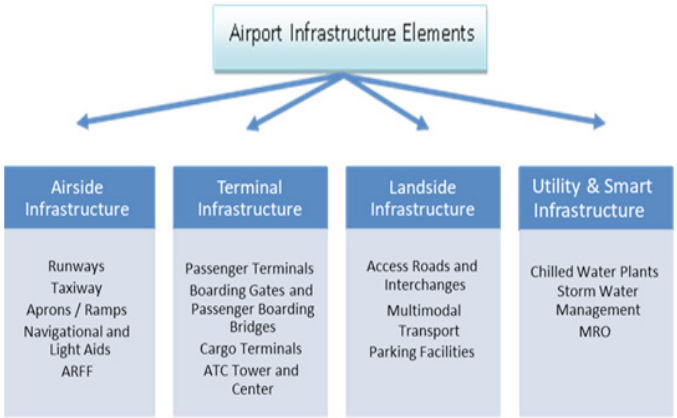

Figure 1: Airport Infrastructure Elements.

Airside Infrastructure and Its Construction Phases

Airside infrastructure is the specialized civil, structural, electrical and systems engineering framework within the security restricted boundary of an aerodrome, specially engineered to support aircraft ground movements, takeoffs, landings and airside processing operations as shown in **(Figure 2)**.

Figure 2: Airside Infrastructure Elements.

The construction of airside infrastructure involves phased engineering workflows within a highly regulated, active operational environment. The major steps include: Site preparation and demolition; Earthwork and subgrade stabilization; Subbase and base course layering; Pavement surfacing (Flexible/Rigid); Airfield drainage infrastructure; Airfield ground lighting and utility integration; Marking, grooving and friction testing; and Commissioning and safety inspection[2].

Greenhouse Gas (GHG) Emissions

The GHG Protocol categorized carbon footprint and atmospheric warming emissions into three operational boundaries[3]:

Scope 1 Emissions (Direct Emissions)

On - site emissions from sources owned or directly controlled by an organization.

Examples: Fuel combustion in heavy machinery / equipment, boilers, fleet vehicles and Chemical leaks.

Scope 2 Emissions (Indirect energy emissions)

Emissions associated with the generation of purchased electricity, steam, heating or cooling consumed by an entity.

Examples: Off - site power grid generation consumed by airside lighting, terminal facilities or manufacturing plants.

Scope 3 Emissions (Value Chain /Indirect Emissions)

All other indirect emissions (occur upstream and downstream across the supply chain).

Examples: Embodied carbon in purchased materials (asphalt / concrete / steel), supply chain logistics, aircraft (landing and take - off) cycles and waste disposal. **(Figure 3)**, shows the three operational boundaries carbon emissions scope1, 2 and3. The following **(Table1)** is an applied example from airport paving project which illustrates the difference between Scope1 and Scope 2 emissions.

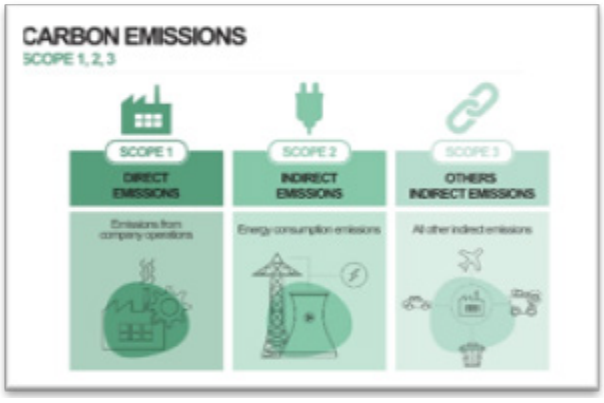

Figure 3: Types of Carbon Emissions

Table 1: The Difference between Scope1 and Scope 2 Emissions.

On – Site Activity Type	Environmental Classification
Operating a grid connected central concrete batching plant.	Scope2 (since fuel is combusted off – site at the power generation plant).
Operating the same concrete batching plant using on – site diesel generator.	Scope1 (since fuel combustion occurs directly on - site).

Transitioning Airside Infrastructure toward Zero – Emission Operations through

Sustainable construction

Airside infrastructure development faces mounting pressure to mitigate life cycle GHG emissions. Transitioning construction projects toward zero - emission frameworks through automated grading, WMA and concert CM systematically minimizes embodied carbon while preserving structural integrity under heavy aircraft gear loadings. The study encompasses the construction of main, secondary and auxiliary runways, taxiways and rigid pavement areas at runway thresholds, aprons and dispersal points, extending from the runway threshold to aircraft stands at gates. The construction phase focuses on minimizing the carbon footprint of construction, reducing thermal radiation and maximizing material recycling, this is summarized in the following procedures:

Smart Earthworks, grading and zero emission construction

Optimization of Mass – Haul Balance and Cut – Fill Volumes for on – Site Carbon Mitigation (CM): Off -site earthwork transport can be minimized by leveraging BIM and GIS to achieve an optimal cut - and - fill balance within the airport boundary[4]. There are specific, internationally recognized scientific equations and empirical ratios for calculating emission resulting from soil transport, based on Life Cycle Assessment (LCA) methodology, the GHG protocol standards and standards ISO. 14083 – 2023.

$$E_{Haulage} = (V * Ƥ / C_{truck}) * (2 * D) * SFC * Ef_{diesel} \quad \ldots\ldots\ldots\ldots (1)$$

The above equation is called Earth Hauling Formula[5], Where V = the volume of soil in m^3 - Ƥ = loose bulk density in ton/m^3 - C_{truck} = truck payload in ton /truck – 2*D = round trip distance in km – SFC = specific fuel consumption L/Km - Ef_{diesel} = direct diesel equipment emission factor.

Numerical application: earthwork haulage carbon model

The following are the baseline input parameters:

Bulk density of excavated soil Ƥ = 1.8 t/m^3 - Truck payload capacity C truck = 20 ton/ trip

Round – trip distance 2*D = 24 Km - Specific fuel consumption SFC = 0.45 L / Km (heavy duty damp truck)

Standard diesel emission factor Ef_{diesel} = 2.68 Kg CO_2 / L (Scope 1 direct emission)

Optimized cut and fill volume V = 100000 m^3

Total soil mass = V * Ƥ =100000*1.8= 180000 ton

Number of trips = total soil mass / C_{truck} = 180000 / 20 = 9000 haulage cycle

Total distance saved = Trips * 2 * D = 9000 * 24 = 216000 Km

Fuel saved = Total distance * SFC = 216000 * 0.456 = 97200 Liters

$E_{Haulage}$ = Fuel saved * Ef_{diesel} = 97200 L * 2.68 Kg CO_2/L = 260.5 t CO_2 e

AI - Driven smart construction equipment and 3D GPS automated machine guidance (AMG)

It represents an advanced earthwork automation framework; Includes automated Heavy equipment, such as grader, loader and excavator using real time satellite positioning and AI algorithms. By linking machine controls directly to 3D BIM/GIS models, it enables millimeters accurate earthwork, eliminates rework, cuts equipment idle time and significantly reduces fuel consumption and carbon emissions[6].

Figure 4: AI – Driven Smart Construction Equipment and 3D GPS AMG.

Operational mechanism of AI – driven smart construction equipment and 3D GPS AMG[6]

- **Digital twin integration:** The 3 D design model of the project is loaded into the equipment's onboard computer, including the target elevation along with longitudinal and transverse slopes.
- **Real – time perception and sensing:** LIDAR sensors, cameras and Inertial Measurement Units (IMU) mounted on the excavator arm or motor grader blade scan the terrain in real time, determining the precise position of the blade / bucket with millimeter level accuracy.
- **Autonomous and automated control:** AI algorithms continuedly compare the real – time ground elevation against the target design profile. The system automatically adjusts the hydraulic controls to regulate digging depth or grading angles with extreme precision, eliminated the need of manual intervention.
- **Soil - adaptive machine learning:** The system dynamically identifies soil resistance and strength characteristics, whether (rocky, clay or sandy) and automatically adjusts cutting force or compaction levels to prevent engine strain and minimize fuel consumption.

Calculation of DEOH resulting from using AI - driven smart construction equipment and 3D GPS AMG

To calculate the reduction in DEOH resulting from the development of AI – driven and 3D GPS enabled equipment, the following equations are applied[7-9]

$$H = V / P_{eff} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where V is the total volume of soil – P_{eff} is the equipment product rate

$$P_{eff} = Q * E * S * A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where A is the guidance optimize factor - S is the rework and pass factor - E is the operational efficiency and idle factor – Q is the theoretical equipment productivity. **(Table 2)** listed below represents Parameters Comparison between Conventional and AI - AMG earthmoving operations.

Table 2: Parameters Comparison between Conventional and AI- AMG.

Factors / Parameters	Convention Method	AI–AMG Integration	Operational and Technical Impact
E	40 working min / hr = 0.67	50 – 54 working min / hr = 0.85	Minimizing delays, set up times ,and grade checking pauses
S	0.75 Requires 1.33 passes	0.9 Requires 1 pass / min	Eliminates unnecessary grading passes and rework
A	0.8 Depending on operator skill and path overlap	0.98 Algorithmic path with optimized overlap	Optimizes haul / grading paths and eliminates path variance

Operating hours reduction percentage equation $\Delta H = (1 - H_{AMG} / H_{conv}) * 100$

$\Delta H\ \% = (1 - P_{eff.\ conv} / P_{eff\ AMG}) * 100$ …….. (4)

$\Delta H\ \% = (1 - Q * E_{conv} * S_{conv} * A_{conv} / Q * E_{AMG} * S_{AMG} * S_{AMG}) * 100$

Assume Q (theoretical equipment productivity – assume bulldozer) = 200 m^3 / hr and V (the volume of soil) = 100000 m^3

$P_{eff.\ conv} = Q_* E_{eff\ conv} * A_{eff\ conv} * S_{eff\ conv} = 200 * 0.67 * 0.75 * 0.8 = 80.4\ m^3$ / hr

$P_{eff\ AMG} = Q_* E_{eff\ AMG} * A_{eff\ AMG} * S_{AMG} = 200 * 0.85 * 0.9 * 0.98 = 149.94\ m^3$ / hr

$H_{conv} = 100000 / 80.4 = 1243.78$ hr

$H_{AMG} = 100000 / 149.94 = 631.83$ hr

$\Delta H\ \% = [1 - (631.83 / 1243.78)] * 100 = 49.2\ \%$ = taken from 40 – 50%.

Mathematical calculation of direct fuel and cost savings

The financial and operational assumption: Assuming airport runway earthwork and subgrade fine – grading project that requires 1000 baseline equipment operating hours – using conventional grading equipment (e.g., standard motor grades and bulldozers) – equipment diesel consumption = 25 L/hr – diesel fuel price = $1.0 /L.

Saving DOEH = 1000 hr * 40% = 400 hr

Total volume of saved fuel = 400 hr * 25 L/ hr = 10000 Liters

Direct financial fuel saving = 10000 L * $ 1 = $ 10000

Mathematical calculation of indirect cumulative financial savings

- Equipment wear and tear reduction

Eliminating 400 operating hours' delays scheduled maintenance cycle, extends equipment lifespan and reduces wear on ground engine tools (blades, edges and tires).

- Operating and maintenance savings

Estimated equipment operating and maintenance cost excluding operator labor and fuel

= $15 * 400 hr = $ 6000

Estimated blended label rate = $ 20/hr, so additional labor savings

= 400 hr * $ 20 /hr = $ 8000

The following **(Table 3)** presents the total reduction in direct and indirect costs resulting from a 40% saving in DEOH.

Table 3: Reduction Costs Resulting from a 40% Saving in DEOH.

Indirect Cost Component	Operation and Engineering Description	Estimated Unit Rate $ / hr	Total Cost Savings 611.95 hr
Operations and Maintenance (O&M)	Reduced engine wear, hydraulic fluid consumption, tire/track degradation and routine maintenance	$ 25 / hr	$ 15298.75
Indirect Field Labor	Saving in equipment operator wages, grade – checking staff and land surveying team hours	$ 20 / hr	$ 12239.0
Site Supervision and Overheads	Reduction in quality assurance and quality control, site engineering supervision and health, safety and environmental monitoring	$ 10 / hr	$ 6119.5
Total Indirect Cost Savings	Cumulative indirect financial abatement achieved via hours reduction	$ 55 / hr	$ 33657.25 / hr

Scope 1 Carbon Emission Quantification Reduction: To evaluate the localized environmental sustainability benefits of AI – driven and 3D GPS enabled equipment automated earthmoving operations; the net mitigation in GHG emissions was quantified using standard carbon accounting guidelines[10] from the Intergovernmental Panel on Climate Change and U.S. Environmental Protection Agency.

Direct emissions equation (Scope 1) as a function of operating hours[11] is:

$E_{scope1} = H * SFC * EF_{diesel}$ …….. (5)

Where E scope1 is the total equivalent carbon dioxide emissions ($kgCO_2e$) - H is the DEOH –SFC is specific fuel consumption rate (L / hr) - EF_{diesel} is the approved fuel consumption factor (kg CO_2e/L) which is equal approximately 2.68 for diesel.

$E_{scope1.conv} = H * SFC * EF_{diesel} = 1243.78$ hr * 25 L / hr * 2.68 kg CO_2 e

$= 83333.3$ kg CO_2 e = 83.33 t CO_2 e

$E_{scope1.AMG} = H * SFC * EF_{diesel} = 631.83$ hr * 25 L / hr * 2.68 kg CO2 e

= 42332.6 kg CO_2 e = 42.33 t CO2 e

Net direct carbon abatement ΔE_{scope1} = 83.33 -42.33 = 41.0 t CO2 e

Sustainable airside pavement: Evaluating benefits and carbon footprint reduction of WMA

WMA refers to a suite of technologies that allow the mixing, hauling, placement and compaction of asphalt concrete paving mixtures at significantly lower temperatures than Hot Mix Asphalt[11] (HMA). while HMA is typically produced at 150 °C: 180 °C, WMA technologies lower the production temperature by 20 °C to 40 °C, operating typically between 110 °C to 140 °C see table1.WMA additives and processes work by reducing the viscosity of asphalt binder or increasing the workability of the mixture at lower temperature. They are categorized into three main production mechanisms.

Table 4: Comparison Parameters between WMA and HMA.

Aspect of Comparison	Hot Mix Asphalt (HMA)	Warm Mix Asphalt (WMA)
Production Temperature	From 150 °C: 180 °C	From 110 °C: 140 °C
Lower production temperature	----------	From 20 °C to 40 °C

The Main Production Technologies of WMA: There are three main production technologies of WMA as shown in figure5.

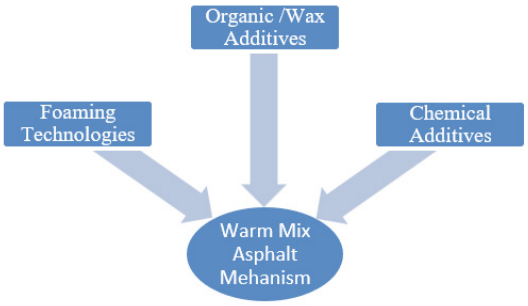

Figure 5: Main Production Technologies of WMA.

Foaming additive technology: **(Table 5)** below presents the WMA production technologies utilizing foaming additive technology[12].

- **Chemical additive technology:** WMA can be produced using various chemical additives for example, Amidoamines, Fatty Amines and Polyamines).
- **Organic /wax additive technology:** There are three types of them, as listed in the following **(Table 6)**.

Engineering advantages of using WMA

Mechanical water injection foaming system for producing WMA: The technology exploits the rapid thermodynamic phase change of liquid water into steam. When 1 cm of water evaporates at high production temperature, it expands into approximately 1.7 cm^3 of steam. Pure water is injected at a precisely metered rate of 1.25% to 2.0 % by weight of the liquid asphalt binder (bitumen). Mixing and compaction temperatures are lowered by 20 °C to 40 °C, bringing production down to 110 °C to 140 °C. The foamed state lasts for a few minutes- sufficient time to coat all aggregate particles inside the mixing drum, after which the steam dissipates, resorting the bitumen to its original structural properties without permanent chemical modification[14].

Comparative environmental and fuel energy assessment: HMA vs.WMA production: For airport airside pavement volume of 100000 m^3 = 240000 metric tons at a standard compacted density of 2.4 ton / m^3, transitioning from HMA to WMA via water foaming technology yields significant thermodynamic and environmental efficiency.

Assuming a standard water - injection rate of 1.5 % by weight of bitumen (out of 5 % binder content) and 30 °C production temperature reduction and burner fuel requirement HMA 8.0 L / ton. **(Table 8)** listed below illustrates the percentage of reduction in fuel consumption and the corresponding Scope1 emissions abatement resulting from the production 240000 tons of WMA.

Table 5: Methods for Producing WMA via Foaming Additive Technology.

Foaming Additives		
Mineral and Chemical Foaming Additives		**Mechanic Water Injection Foaming System**
Hydrated Minerals For example: Hydrated Lime – Synthetic Hydrates	Synthetic Zeolites For example: Aspha – Min; Advera WMA	It is considered one of the most efficient and widely used technologies for producing WMA in the modern asphalt plants; this is due to its direct reliance on thermal physics of water, eliminating the need for expensive chemical or wax additives.

Table 6: Types of Organic / Wax Additives.

Organic /Wax Additives		
Fischer – Tropsch / F – T Waxes For example: Sasobit	Fatty Acid Amides For example: Licomont BS100	Montan Waxes and Modified Petroleum Waxes For example: Romonta; Montan Wax; Luchemo WMA

Table 7: Environmental and Construction Advantages of WMA.

Engineering Advantages of Using WMA	
Environmental and Energy Advantages	**Construction and Operational Advantages**
Reducing the temperature differential by 20 °C to 40 °C directly lowers fossil fuel consumption (diesel or natural gas) in the asphalt plant[13] burner by 15% to 35%.	Longer haul distance: WMA cools much more slowly than HMA relative to ambient air temperatures because the difference between the mix and environment is smaller (Δ T) is lower, this allows longer transmit time to remote sites or heavy traffic corridors[13].
Combustion of lower fuel volumes to achieve reduced production temperatures directly decreases stack emissions from the asphalt plant: Total carbon dioxide emissions (scope 1) are reduced by 15% to 30% during the manufacturing process of asphalt; Emissions of all other gases lowered[13] by up to 50%.	Mechanical water injection reduces interfacial tension, enabling complete aggregate coating and effortless field compaction to the target density at lower temperatures. Reduces the required number of field roller passes and DEOH, thereby lower fuel consumption and associated tailpipe emissions from paving machinery[13].

Table 8: Reduction in Fuel Consumption and the Corresponding Scope1 Emissions of Using (WMA).

Parameter	Hot Mix Asphalt	Warm Mix Asphalt	Net Direct Saving	Percentage Reduction
Total Production Mass	240000 tons	240000 tons	----------	----------
Burner Fuel Consumption	1920000 liters	1536000 liters	384000 liters	20 %
Direct Plant CO_2 Emissions	5145.6 t CO_2 e	4116.48 t CO_2 e	1029.12 t CO_2 e	20 %

Sustainable Airside Rigid Pavement: Evaluating Benefits and Carbon Footprint of Mineralization

Carbon storage and sequestration methods: It is the process of capturing and security trapping carbon dioxide CO_2 to prevent it from remaining in or entering the Earth´s atmosphere[15], this process aims to prevent the accumulation of GHG in the atmosphere, thereby mitigating its impact on global climate change and reducing overall carbon footprint of industrial, transport and infrastructure (e.g., airport airside infrastructure) operations. In environmental engineering and sustainable science, carbon sequestration is categorized into three primary pathways:

- **Biological sequestration:** The natural storage of carbon vegetation, forests, soils and marine ecosystems (blue carbon) through photosynthesis and organic matter accumulation.
- **Geological sequestration:** The technological capture of CO_2 from point sources (e.g., power plants, industrial facilities or asphalt / concrete batching plants) followed by its high-pressure injection and permanent trapping within deep underground porous rock formations or depleted hydrocarbon reservoirs.
- **Mineral technological sequestration:** The chemical fixation of CO_2 through reactions with alkaline minerals or its permanent mineralization into durable building materials, such as concrete, aggregate composites or industrial byproducts.

Carbon dioxide mineralization: It is an inorganic chemical sequestration process in which gaseous carbon dioxide CO2 chemically reacts with alkaline metal oxides, primary calcium Ca 2+ or magnesium Mg 2+ to form thermodynamically minerals (such as calcium carbonate, CaCO3).In civil and environmental engineering, particularly regarding concrete and rigid pavements, this technology permanently traps captured carbon dioxide within the hydrated cement matrix or industrial byproducts (e.g., slag and fly ash). The process converts CO2 into structural mineral phases, effectively achieving permanent geological scale carbon storage while simultaneously enhancing the early age compressive strength and microstructural density of the concrete substrate[16].

- Direct Carbon Dioxide CO_2 Mineralization during Concrete Batching (Process Mechanism)
  - **Automated dosing:** Liquid CO_2 is metered and delivered into the central batch mixer via an automated control system calibrated per cubic meter[17].
- **In - Site Injection:** The gas is injected at low pressure converting into a subzero micro snow gas mix directly into aggregate and cement slurry during the initial mixing phase.
- **Rapid chemical reaction:** CO_2 reacts instantly with dissolved calcium ions (Ca^{2+}) released during cement hydration.
- $CO_2 + Ca(OH)_2 = CaCO_3 + H_2O$
- **Nano crystallization:** This reaction synthesizes insoluble Nano scale calcium carbonate ($CaCO_3$) crystals that serve as nucleation sites, refining the pore matrix and increasing microstructural density.
- Standard Dose Rates
  - Optimal range 0.1 % to 0.3 % by weight of cementations materials for a standard 400 Kg / m3 binder design[18].
  - Dosages below 0.1 % yield negligible structural benefits, while dosages exceeding 0.5 % risk excessive[18].
- **Applied example:** Quantified Carbon Footprint Reduction for Airside – Rigid Pavements via CO_2 Mineralization
  - Baseline data

Scope of work: Construction of an airside taxiway and apron rigid pavement.

Total concrete volume = 50000 m^3.

Reference cement concrete = 400 Kg /m^3.

Cement production emission factor = 0.85 t CO_2 e

- Engineering application

Gas injection rate: CO_2 was injected at a rate of 0.15 % by weight of cement (0.6 $KgCO_2$ /m^3).

Mix optimization: due to earl age strength gain from Nano – calcium carbonate crystal nucleation, cement content was reduced by 5% (20 Kg /m^3), while fully maintaining design stress requirements.

Direct carbon sequestration:

Sequestration gas volume = 50000 m^3 * 0.6 Kg / m^3 = 30000 Kg. (Permanent trapping and mineralization of 30 tons of CO_2 within the airside concrete matrix).

Avoid scope 3 emissions

Total saved cement = 50000 m^3 * 20 Kg / m^3 = 1000000 Kg = 1000 tons

Emission abatement = 1000 tons * 0.85 = 850 tons of CO_2

Total carbon footprint reduction = 850 + 30 = 880 tons of CO_2

Results and Discussion

The utilization of modern technologies such as BIM and GIS, during the planning and design phase of airport airside infrastructure, achieving an optimal cut and fill balance and provides high accurate volumetric quantities. This minimizes excess soil transport, resulting in reduced fuel costs for off – site haulage and a corresponding decrease in CO_2 emissions (Scope1). This sustainability gain is primarily driven by optimizing mass hauling diagrams, minimizing haul distances and eliminating unnecessary rework caused by volumetric estimation errors during conventional survey operations.

The empirical studies of this research state that AI – Driven Smart Construction Equipment and 3D GPS AMG reduces DEOH by 40%: 50% during the construction phase of airport airside infrastructure.

Using AI – Driven Smart Construction Equipment and 3D GPS achieve a 49.2 % reduction in direct scope1 carbon dioxide emissions compared to conventional construction method. For baseline earthwork volume of 100000 m^3, direct emissions dropped significantly from 83.33 t CO_2 e under conventional operations to 42.33 t CO_2 e with AI – Driven Smart Construction Equipment and 3D GPS deployment. This yields a net operational carbon abatement 41.0 tCO_2 e, driven directly by 611.95 hours reduction in running time and corresponding saving of 15298.75 liters of diesel fuel.

Total direct and indirect operational cost savings resulting from 611.95 hours reduction in DEOH of $ 48956 (15298.75 * $ 1 + $ 33657.25).

In an airside paving project 100000 m3 (240000 tons) of WMA produced via 1.5 % water foaming technology, mixing and compaction temperature are reduced by 30 °C relative to HMA. This thermal efficiency lowers burner fuel consumption from 8.0 L/ton to 6.4 L/ton, yielding a direct 20% energy saving equivalent to 384000 liters of fuel. Utilizing a standard combustion factor of 2.68kg/liter, the process abates scope1 plant emissions by 20%, reducing total carbon output from 5145.6 tons to 4116.48 tons for a net reduction of 1029.12 t CO_2 e.

The quantitative analysis demonstrates that the primary environmental leverage of CO_2 mineralization in airside rigid pavements stems not only from direct chemical trapping (30 tons) but significantly from the microstructural optimization that enables binder reduction. This synergy achieves an overarching net abatement of 880 tCO_2e, a 5% reduction in concrete cement content without compromising structural integrity or pavement durability.

Conclusion

This study validates an integrated framework combining BIM/GPS spatial optimization, AI – Driven Smart Construction Equipment and 3D GPS deployment, WMA and CO_2 – mineralization concrete for airside infrastructure construction. The study demonstrates: Reduced in DOMH = 40%, lowered in cost savings (direct and indirect) for earthmoving (excavation, backfill and fine grading) and a 49.2 % reduction in Scope1 carbon emissions. Lowering the asphalt mix production temperature by °C resulted in 20% carbon emissions scope1 and burner fuel consumption. Furthermore, injection 0.15% CO_2 by weight of cement resulted in reduction in carbon emissions, alongside enabling a 5% reduction in total cement binder content. Additionally, enhancing the workability of both concrete and asphalt mixture achieved accelerated early – age strength development and improved field compaction efficiency.

Abbreviations

BIM Building Information Modeling
GHG Greenhouse Gas
CN Carbon Neutrality
GIS Geographic Information System
AMG Automated Machinery Guidance
WMA Warm Mix Asphalt
HMA Hot Mix Asphalt
OPC Ordinary Portland Cement
DOMH Daily Operating Machinery Hours
CM Carbon Mitigation
LCA Life Cycle Assessment

Author Contributions

Abdel Latif Younes: Conceptualization, Methodology, Data cu ration, Formal analysis, Writing – original draft, Writing – review & editing.

Conflicts of Interest

The authors declare no conflicts of interest.

References

1. Subbotin AV. Airport infrastructure status and development perspective. IOP Conf. Ser.: Earth Environ. Sci 2021;666(3):032062.
2. Sharma RK, Singh SP. Assessment and optimization of airside infrastructure pavement performance. IOP Conf Ser Mater Sci Eng 2021;1110(1):012018.
3. Davies MR, Turner JH. Quantification and mitigation strategies for greenhouse gas emissions in infrastructure civil engineering. IOP Conf Ser Earth Environ Sci 2022;1078(1):012015.
4. Zhang HL, Wang XM, Chen YF. Integration of GIS and 3D modeling for infrastructure spatial optimization and management. IOP Conf Ser Earth Environ Sci 2023;1152(1):012022.
5. Petrov SM, Ivanov VA, Sidorov ON. Optimization of earthmoving and haul distance operations using integrated spatial algorithms. IOP Conf Ser Earth Environ Sci 2021;868(1):012041.
6. Liu JM, Zhang KW, Chen HR. AI- driven autonomous earthmoving equipment and 3D GIS spatial integration for smart construction site operations. IOP Conf Ser Mater Sci Eng 2022;1215(1):012034.
7. Miller RT anderson KL. Quantification and optimization of direct machine operating hours in earthwork construction projects. IOP Conf Ser Earth Environ Sci Eng 2022;1042(1):012019.
8. Park DW, Lee SH, Kim JH. Impact of automated machine guidance on direct equipment operating hours and fleet productivity. IOP Conf Ser Mater Sci Eng 2021;1180(1):012045.
9. Kuznetsov EV, Popov MA. Evaluation of direct machinery operation efficiency and fuel consumption in airfield site preparation. IOP Conf Ser Earth Environ Sci 2023;1125(1):012030.
10. AI-Mulla FA, Evans TR, Popov MA. Quantification of scope1 GHG emissions reduction in civil earthworks using intelligent 3D machine guidance systems. IOP Conf Ser Earth Environ Sci 2023;1208(1):012027.
11. Al Qahtani HM, Sterling JR, Martine A. Empirical modeling of Scope1 carbon emissions relative to heavy equipment operating hours in civil construction sites. IOP Conf Ser Earth Environ Sci 2023;1184(1):012015.
12. Al - Mansoori MR, Williams DJ, Chen SK. Performance evaluation of foaming additive technologies for warm mix asphalt production and pavement sustainability. IOP Conf Ser Mater Sci 2021;1145(1):012028.
13. Al - Mansoori MR, Williams DJ, Chen SK. Mechanical performance and engineering advantages of warm mix asphalt technologies in airfield pavements. IOP Conf Ser Mater Sci Eng 2021;1145(1):012028.
14. Chen SK, Al - Mansoori MR, Zhao YL. Thermodynamic mechanism and mechanical water injection foaming system for warm mix asphalt production. IOP Conf Ser Mater Sci Eng 2022;1210(1):012014.

15. Martinez AK, Al - Qahtani HM, Sterling JR. Comparative analysis of carbon storage and mineralization pathway for sustainable infrastructure. IOP Conf Ser Earth Environ Sci 2023;1195(1):012042.

16. Sterling JR, Martinez AK, Al -Qahtani. Carbon mineralization mechanisms and performance evaluation of CO2- injection concrete systems. IOP Conf Ser Earth Environ Sci 2023;1205(1):012019.

17. Al - Ahmadi, Evans TR, Al - Mulla FA. Dosing protocols and carbonation kinematics of gaseous CO_2 injection in fresh concrete mixing. IOP Conf Ser Mater Eng 2023;1240(1):012033.

18. Evans TR, Al - Ahmadi MK, Sterling JR. Optimal and threshold dosage limits of gaseous CO2 injection in fresh concrete: mechanical and microstructural evaluation. IOP Conf Ser Mater Sci Eng 2023;1245(1):12018.