IBRACON Structures and Materials Journal
Revista IBRACON de Estruturas e Materiais
ISSN 1983-4195 ismj.org

ORIGINAL ARTICLE

Feasibility of pervious concrete as engineered material arresting system for airport runway safety areas

Viabilidade do concreto permeável como material delineado como sistema de detenção para áreas de segurança de pistas de aeroportos

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Received 10 February 2023
Revised 28 March 2023
Accepted 28 May 2023
Corrected 27 March 2024

Abstract: From the late 1960's airport engineers developed special paving material for arresting aircraft gears in event of overrun as a partial extension of a runway end safety area. Such pavement surface material, inverting a general concept, should be crushed over the first pass of gear wheels resulting the aircraft to sink and being promptly arrested resulting in abrupt loss of velocity, preferability avoiding loss of lives and injuries as well as with minimum risks for the airplane structural integrity. Herein is analyzed and discussed the possible application of pervious concrete for such a task by simulating an actual situation (Congonhas airport) and understanding the structural effects on the crushable concrete surface layer, pointing out stresses, deflections and required strengths for the material. Simulations regarded the critical aircraft A 320-200 as well as fire-fighters cars over the pavements. Analysis complied to Federal Aviation Administration requirements for non-standard pavement structures as well simulation of stresses trough the finite element method for medium-thickened plates. Compressive stresses along with flexural excessive stresses, besides predictable punching shear stresses allowed to conclude by the feasibility of using low strength pervious concrete as alternative for engineered material to be built as arresting system.

Keywords: aircraft arresting systems, concrete pavements, pervious concrete, finite element method.

Resumo: Em finais da década de 1960 engenheiros aeroportuários desenvolveram materiais de pavimentação especiais para reter trens de pouso de aeronaves em caso de avanço sobre a extensão final da área de segurança da pista. Tal material da superfície do pavimento, invertendo um conceito geral, deve ser esmagado na primeira passagem das rodas resultando no afundamento da aeronave que é prontamente retida, resultando em perda brusca de velocidade, de preferência evitando perdas de vidas e ferimentos, bem como riscos mínimos para a integridade estrutural do avião. Nesse estudo é analisada e discutida a possível aplicação do concreto permeável para tal tarefa, simulando uma situação real (aeroporto de Congonhas) e compreendendo os efeitos estruturais na camada superficial do concreto permeável, indicando tensões, deflexões e resistências requeridas para o material. As simulações consideraram a aeronave crítica A 320-200 bem como veículos de combate a incêndios sobre o pavimento. A análise atendeu aos requisitos da *Federal Aviation Administration* para estruturas de pavimento não padronizadas, bem como a simulação de tensões pelo método dos elementos finitos para placas medianamente espessas. Tensões de compressão juntamente com tensões excessivas de tração na flexão, além das tensões de cisalhantes (punção) previsíveis, permitiram concluir pela viabilidade do uso de concreto permeável de baixa resistência como alternativa para material de engenharia a ser construído como sistema de retenção de aeronaves.

Palavras-chave: sistemas de retenção de aeronaves, pavimentos de concreto, concreto permeável, método dos elementos finitos.

How to cite: J. T. Balbo, "Feasibility of pervious concrete as engineered material arresting system for airport runway safety areas," *Rev. IBRACON Estrut. Mater.*, vol. 17, no. 3, e17305, 2024, https://doi.org/10.1590/S1983-41952024000300005

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Financial support: National Council for Scientific and Technological Development (CNPq) Process #304391/2019-0.
Conflict of interest: Nothing to declare.
Data Availability: Data-sharing is not applicable to this article as no new data were created or analyzed in this study.
This document has an erratum: https://doi.org/10.1590/S1983-41952024000300011

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1 BACKGROUND AND PROBLEM RELEVANCE

1.1 Transportation infrastructure safety arresting systems

Concept of arresting system for vehicles moving on wheels at high speed in roads and highways is not a new subject for Transportation engineers. For instance, regards to trucks losing control where effectively taken as an emphatic design concern during the 1960s after AASHTO Road Tests and its extension studies. Deacceleration and arrester beds are strategically built in road locations with steep ascending ramps to permit the escape of runaway trucks; arrester beds are also placed laterally in dangerous curves in racetracks. In general, the safety containment facilities for trucks runaway are the combination of a gravity ramp (ascending grade), an arrester bed with a certain thickness of small round gravel or sand, and a dragnet with energy absorbing poles [1], [2]. Studies for arresting facilities in highways have been developed main during years 1970s to 1980s [3], consolidating such systems on codes and design guides [4], [5].

Arresting systems for airplanes are connected to Runway End Safety Areas (RESA) what is an extension of an airport runway besides its required runway take-off and landing lengths (defined as primary functions of airport site altitude as critical aircrafts as well its weight and load – [6]) with the primary function and serviceability to mitigate runway excursions due to aircraft overrun. Overruns can be consequence of an aborted take-off as well as an advance of the aircraft over the runway end due to mechanical or human failure. Summarizing, FAA [6] defines RSA as "*a defined surface surrounding the runway prepared or suitable for reducing the risk of damage to airplanes in the event of an undershoot, overshoot, or excursion from the runway*". Depending on overrun conditions the accident can lead to loss of lives, grave injuries to passengers and crew as well as severe damage to the aircraft, as reported in several events [7].

RESA areas are required to be built following engineering criteria to ensure smooth surface (not uneven ones) and appropriate support to the aircraft gears. Drainage issues also must be addressed in geometric design and material used for paving. Also, its dimensions shall be designed to provide easy access to rescue teams and fire-fighting equipment and trucks. The design length of the RSA is the length from the runway end or from the stopway end when it is to be present [8] in view of that the RSA can be the only extension of the runway.

1.2 Engineered materials arresting systems for airports

FAA [9] suggests the RESA lane to have a minimum of 200 m (Figure 1) with a conventional resistant pavement to support the aircrafts in case of touch down before the runway end (undershoot). According to FAA [8] the use of Engineered Material Arresting System (EMAS) for RESA can reduce its length as such systems are concepted to forcibly stop the aircraft surpassing, (both in take-off and landing operation) arresting it, that means, a forced halt, considering its velocity by 70 knots (130 km/h).

EMAS are dedicated to improving safety when land is not available for runway extension, or the required standard RESA length is not feasible [10]. EMAS standard lengths are fixed by FAA [11] basic guidance for planning purposes, as show in Figure 2 based on a general aircraft gross weight while in Figure 3 one can see the relation between EMAS bed and the entering velocity for several commercial aircrafts. The weight of the airplane has the greatest impact on its stopping distance [12] (wheels friction to the pavement surface and reverse thrust are other relevant factors during stops).

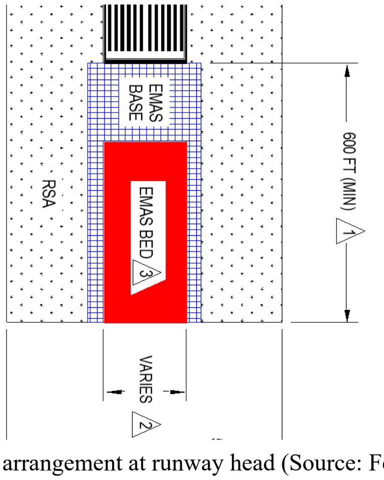

Figure 1. RESA and EMAS general arrangement at runway head (Source: Federal Aviation Administration [9])

Military systems arrestors are an old concern to the landings of war airplanes over aerocarriers (very short runway length) and could be taken as an initial concept; however, the use of hooks and cable are extremely difficult to be though in RESA for civil airplanes. Primordial research on pavements arresting systems for airport were done in UK during the late 1960's [7]. In 1984 after an accident with a landing Scandinavian Airlines DC-10 at JFK (New Your) the Port Authority studies concluded that the use of a foamed plastic over the RESA would be effective to mitigate overrun consequences [13]. Federal Aviation Administration then sponsored a full-scale study employing successive foamed plastic layers and developed a mathematical model for the prediction of material crushing and gear wheels sinking and arresting of a B-727.

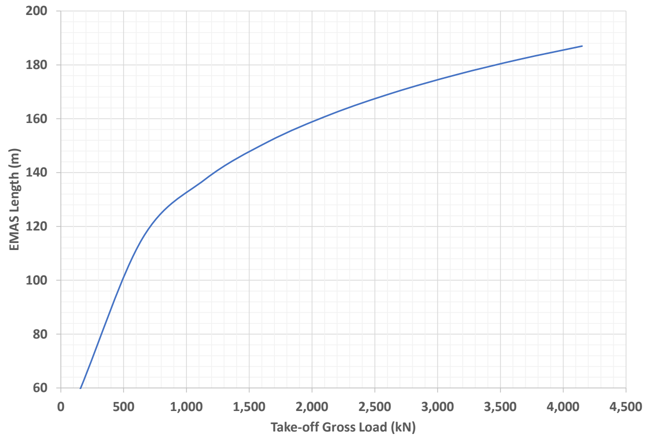

Figure 2. EMAS length as function of load (adapted from Federal Aviation Administration [11])

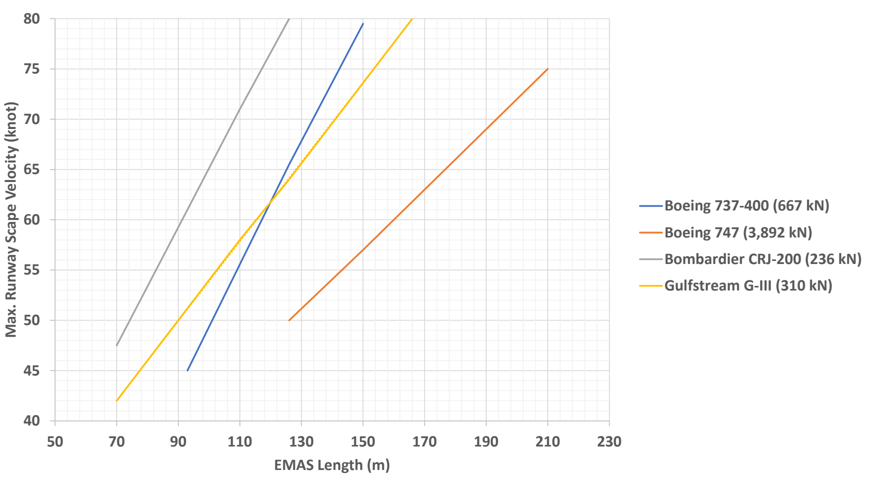

Figure 3. EMAS length as function of scape velocity (adapted from Federal Aviation Administration [11])

EMAS is an idea applied from the 1990s to mitigate the overrun situation; official efforts in research and development for EMAS began in 1993 [14]. Evidently, a long enough RESA would be effective to deaccelerate the aircraft avoiding accidents. However, the airport site cannot have available area for a due long RESA extension. For such situations the EMAS are installed within the RESA after the runway limit allowing a quick stop for the moving aircraft since provided an abrupt deacceleration. Rolling resistance offered by the EMAS material affects its length in the RESA. The greater the rolling resistance (for instance, using only aggregates), shorter the EMAS length could be. The use of aggregate (19/50 mm range [15]), gravel or crushed, is a common feature for truck arrestor beds, when the wheels must displace well the material and sink inside it, with more favorable results for round aggregates due to its small friction angle [16], [17]. Round aggregates cause a high and quick deacceleration [18]; recent studies for passengers' vehicles have shown values of 0.3 g and 0.9 g for, respectively, coasting vehicles and in braking action [19].

However, in opposite to traditional and efficient use of round gravels in truck arrestor, aggregate spray launched to dissipate energy can be a major concern since one can foresee the aircraft fuselage damage risks due to gravel launchings during an overrun, besides the unavoidable risks for the gears systems. Several materials have been employed in recent airport technology history around the world and must be considered as modern and advanced technology expected by aircraft and airport operator as well by pilots and passengers since its existence can improve drastically the survival of human's life in cases of overrun as observed in recent aviation history. FAA [10] reports that from 1999 to 2021 eighteen overruns arresting occurred in US airport salving 419 crews and passengers' lives.

1.3 Typical EMAS solutions

Such engineered materials, of course, shall be of ease maintenance/restoration after an overrun event since they are design to arrest the aircraft gears, what is feasible through and insufficiency of bearing the compressive contact pressures of gear wheels. Therefore, the wheel line until the arrest results in progressive and large vertical plastic deformation induced by material microstructure rupture. Thin cellular (low density) concrete plates and blocks (*circa* 1.2 m x 1.2 m), silica (glass) foam block elements [20], foamed concrete [21], even poor asphalt mixtures [22] with unchangeable stiffness, (over well compacted and resistant aggregate bases covered are possible solutions) since the carpet layer is a crushable material. The idea is clear: refrain the aircraft gears from continuing its movements as pavement surface crushes and sinks and eventually holds the wheels, causing abrupt reduction of velocity and eventually stopping the ship. Note that the classical concepts for pavement bases, sub-bases and subgrades are not altered.

In 1991 there existed strong consensus among engineers to favor the employment of EMAS with low-density and weak strength materials, as the cellular concrete with foam, although non-recyclable [14]). In foamed cellular concrete energy absorbed from crushing is due to elastic buckling combined to plastic yield as well as to brittle fracture of the cured mixture microstructure [23]. Several in situ tests were performed during the 1990s by the Federal Aviation Administration and industry partners at some runways in: William J. Hughes Technical Center (Atlantic City, NJ); JFK Airport (NY); Tyndall Air Force Base (FL – fire tests); La Guardia Airport (NY).

Tests with heavy and light airplanes, as well as with nose and main gears, resulted favorable permitting the establishment of memorandums and guides for EMAS design since then. Most regular research is also directed for the improvement of light density cementitious precasted materials [17], [22]-[24]. An interesting proposal for the arrestor pavement bed is laying two beds; the superficial one for the arresting of light airplanes while the underneath bed, stiffer, in charge to stop heavier aircrafts [24].

There are cost issues to be connected to geometric solutions for using both RESA and EMAS. Such a case allows some decreasing velocity beyond the runway end through a conventional strengthened pavement and the completion of the RESA with the EMAS using a shortened extension; all of that shall be considered in view of conditions such as airport design of a runway extension or a RESA safety improvement, by the design engineer. Also, EMAS option inflicts different mechanical analysis consideration based on the gear-pavement dynamics crushing interaction. FAA (2014) defines EMAS as "*high energy absorbing materials of selected strength, which will reliably and predictably deform under the weight of an aircraft*". When stated "*high energy*" one must comprehend as non-recoverable deformation work, i.e., plastic rupture.

One should note that there are two engineering aspects on considering EMAS beyond runway ends. Firstly, as mentioned, and clear, after an incursion of aircraft over the EMAS pavement it will be locally destroyed and, hence, must be readily restored. Airport pavement maintenance (at air side) cannot be done while the airport is open for operation; as well restoration requires time. Especially intervention at the runway line because obstacles are forbidden by the approaching surfaces. However, to not intervene soon means a RESA without EMAS over its final length what discontinues the arresting warranty for aircraft safety at extreme excursion from runway end. Secondly, it looks like improbable to be common sense to build EMAS from the runway end since aircrafts maneuvers are essential over this area. Therefore, it is expected to build the RESA with partial employment of EMAS far from the runway end.

As RESA can be so understood as a beyond runway safety length destined to comprise a twofold function, by one hand allowing some extended speed reduction lane and braking allowance, and on the other hand, if still insufficient, a final lane purposed to definitively (hopefully) arrest the aircraft, stopping it. This extra length with EMAS, when territorially available, implies in paving, what is normally understood as a waterproofed soil area, that can be mitigated by using a compensatory system with advantages of increasing albedo in urbanized areas, among other benefits, including the possibility of avoiding completely the rains and storms runoff in a safety paved area, improving even more safety at the final aircraft movements, in combination with very rough texture of surface [25]. The options are clear: using thin carpet layers of open graded asphalt mixture or pervious concrete, both over not at all packed aggregate and poor compacted base (traditional gravel with no fines and very poor graded as well poor graded construction rubbles).

Another relevant aspect of EMAS for partial RESA is the concept reversal in terms of pavement design. Pavements (anyone) are designed by engineers using codes that considers the requirements of static and dynamic (fatigue) resistances for the materials and pavement layers. Asphalt and concrete layers are commonly designed nowadays to endure under mechanical responses in tensile for a long period, as 40 years in airport runways, taxiways, taxi lanes and aprons. Opposite to the conventional pavement design concepts, EMAS (surface layer only) shall be designed to break up at the first load! It is expected the base and underneath layer of the pavements are preserved from damage.

Concrete slabs are designed to resist fatigue under cyclic loads in flexure; it is valid for any type of cement concrete. However, such a principium is not sustainable because here one is looking for a breakup under compressive vertical strength to crush the material while rupture in tensile implies in transversal cracks within slabs. Also, high tensile strengths (or modulus of rupture) results generally in high compressive strengths.

Moreover, EMAS are not designed to afford maintenance equipment (common carriage) over its surface [9], what turns almost full-manual requirements for maintenance. This is a very restricting condition even for the access of equipment for aircraft rescue; possible damages caused by such equipment must be considered during EMAS selection. That means when restoration is needed the trucks and cars entering the RESA covered with EMAS will possibly be damaged as well by this rescue traffic. This is a very restricting fact for the use of most kinds of asphalt mixtures with more high concerns to hot mixes. Pervious concretes can easily overcome this shortcoming by using manual equipment and manual cars during restoration services. Pervious concrete is laid by light equipment and does not require compaction rolls. There are even possible resources to quickly bring the concrete to the damaged areas without walking over the EMAS to avoid increasing damages.

Besides all the aforementioned characteristics, FAA [9] requires EMAS to be water-resistant, not chemically or physically attacked by grubs, birds etc., resistant to plant growth, susceptible to sparking, not flammable, not favorable to combustion, exempt from fume emissions (toxics), to keep strength and elasticity under any climate condition, resistant to aircraft mechanical fluids, among others. One can note that for the last four mentioned required patterns, asphalt mixes shall be restrictive sometimes. Pervious concrete meets all the general conditions required by FAA [9]. It is comprehensible that EMAS material must be a design decision based on the aircraft types, remembering that the more weighted the ship it takes more distance to be halt [26], [27].

Along this paper are discussed (preliminary) the pervious concrete requirements for EMAS fulfill its role for arresting a typical aircraft in operation by the greater Brazilian companies in regional main airports. Based on the maximum requirements in terms of concrete compressive strengths (to allow pavement breakup) it was verified later the pavement capacity to support fire-fight cars in case of required rescue. The analysis comprises the discussions about thicknesses limits and concrete strengths to permit aftermost technical-economical evaluation for decision-makers as well. Finite element analysis was used for the prediction of stresses due to aircraft main gear wheels. It is supposed the use of light weighted aggregates for the pervious concrete.

2 AIRCRAFT CHARACTERISTICS FOR EMAS ANALYSIS

The chosen aircraft for the analysis is the Airbus A320-200. This ship is common to the Brazilian air companies' fleets and is taken for the feasibility analysis of the design of a pervious concrete pavement that will be subject to compressive/tensile rupture at the first operation of such aircraft over its surface, arresting the gears.

2.1 Main gear geometry

The jackets of main gears are connected to wheels rim axles through a towing fitting (Figure 4) and manufactures specifies distance between the lower point to the pavement surface, when tires are flat in contact to the surface and not inflated. When front tire is deflated this high is still less, 130 mm. Hence, to keep a EMAS bed with maximum thickness of 100 mm is safe to keep gear enough far from floor to avoid gear axle damages as hinging. Therefore, 100 mm thick pervious concrete is the adopted value for the present analysis.

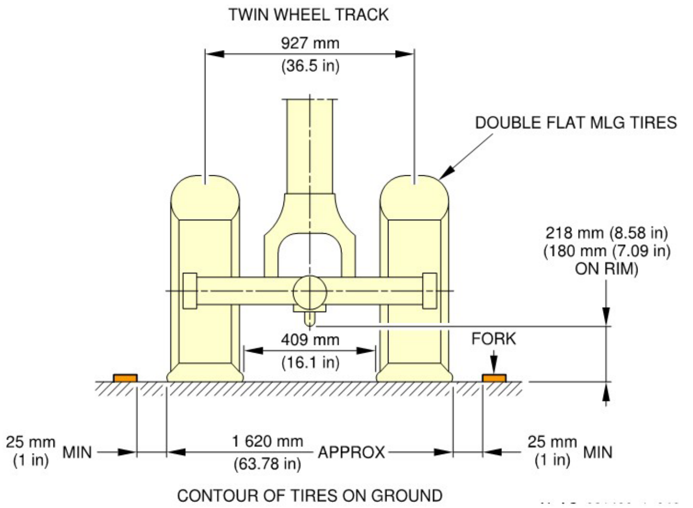

Figure 4. Minimal height from floor to towing fitting in main gear of A320-200 [28]

2.2 Loads and gears configuration

The maximum take-off design weight for A320-200 is 780 kN. Circa 95% of gross weight can be ascribed over the main gears under wings. Tires pressures are 1.23 MPa at nose tire and 1.44 MPa at main gear tires. Front (nose) tires are distant 0.5 m each other while in a main gear them are far 0.93 m each other. Geometric center of main gears is distant 7.59 m (AIRBUS, 2020) as shown in Figure 5.

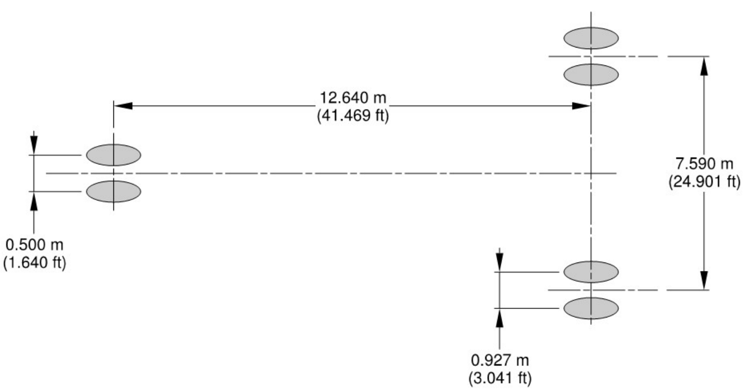

Figure 5. Distances between wheels and gears of A320-200 [28]

3. ANALYZING PERVIOUS CONCRETE AS EMAS

3.1 Parameters search for low strength pervious concretes

Pervious pavements saw extensive use in European countries in the 1970s, with American experiences going back to the 1980s [25]. The dosage of concrete to achieve the characteristic of offering high permeability implies very little or no fine aggregate in the mixture, seeking a void index (porosity) ranging from 15% to 35% of the total volume of concrete, which gives free passage to the surface waters that come through it [29]–[31]. When the subject become the EMAS for RESA in airports, the traditional way of defining a permeable pavement is not mandatory; for instance, EMAS may not have necessarily the function of capturing and storing storm water at all. In highways, open graded friction courses as surface layers are laid over non permeable bases, whatever granular or cement stabilized ones. In such a case the water will flow laterally within the pervious concrete layer to be discharged to adjacent areas of the RESA. In Table 1 are consolidated some range for parameters commonly found in pervious concrete mixture as can be found in extensive literature.

Table 1. Parameters patterns for pervious concrete mixtures [25]

Parameter/index	Range	Comments
Hydraulic conductivity (cm/s)	0.1 to 1.5	Also recognized as permeability; depends on the type of test
Porosity (%)	15 to 35	Also recognized by void ratio
Flexural tensile strength (MPa)	1.5 to 4	Permeable concrete can be dosed for even higher values
Static modulus of elasticity (MPa)	6,000 to 18,000	Values in the laboratory and in the field (backcalculated)
Specific weight (kN/m^3)	17 to 21	-
Percentage (by weight) of grains less than 4.8 mm	6 (maximum)	Usually zero or only fines (powders) adhered to coarse aggregates
grain shape	Preferably angular	-

The null or very little content of fine aggregate along with the unpacked coarse aggregate (little variation of sizes) imposes the high void index in the previous concrete grain structure. Cement paste will wrap all the aggregates surface to ensure the optimization of contact points with hard crystal bridges to ensure a certain resistance (in flexure and compression) and stiffness. Reasonable amount of such paste volume can be called as lost sacrifice paste volume since to ensure maximization of linking points between coarse aggregates will be adhered to the surface without serviceability. Both parameters, strength, and modulus of elasticity, differs drastically from conventional concretes for paving purposes. Light-weighted aggregate used must be crushable.

As presented for the considered aircraft A 320-200 configuration the maximum tire pressure is 1,44 MPa what does not have significant variation as the ship is moving. It is well established that for pervious concretes the flexural strength is function of both maximum diameter of aggregate and its porosity. A previous relationship study between modulus of elasticity and strength, both in compression, was obtained for a set of permeable concretes [32], as follows (Equation 1):

$$Ec = 4,880 \cdot \left(f_c\right)^{1/2} + 2,800[MPa] \tag{1}$$

The above relation led to a modulus of elasticity of 7,680 MPa (for 1 MPa strength) in accordance with range show in Table 1. The low value for *Ec* is related to the high porosity of the pervious concrete (in this case could be even over 35%).

3.2 EMAS design for A 320-200 aircraft

Pavement design for alternative porous concrete surface like EMAS was carried out according to Airport Design software FAARFIELD 2.0 [33]. Design followed non-standard selections since it was required to consider the layer parameters for pervious concrete as aforementioned (*Ec*= 7,680 MPa; coefficient of Poisson 0.25). Also, one should consider that minimum design period taken by FAA is 20 years and the deal is to design a pavement able to bear only one aircraft passage, no covers considered for that (relation pass/coverage=1). Albeit design is one pass fixed for the concrete layer, other layers shall be resistant to aircraft loads to avoid damage of base and subgrade stratum. The design option for concrete slabs was carried out; it considers the critical load as the main gear is close to the transversal or longitudinal joint. Concrete slabs are assumed 6 m by 6 m (squared), a common feature for airport concrete slab pavements. No dowel bars neither tie bars were supposed to exist for EMAS solution due to evident reasons (not to reduce stress at joint locations).

As for feasibility analysis let us take the case for Congonhas airport (in São Paulo) operating c. 600 aircrafts per day. Herein the traffic mix is not considered even because there are lighter aircrafts; for the design the A 320-200 is taken as the critical case. Therefore, the annual number of take offs is to be 219,000 but limited by FAA to a hundred thousand for individual airplanes for 20 years design life. Another important feature to be observed on design is the low resilient modulus of the pervious concrete what implies in high level of vertical pressure over granular bases and subgrades; if one opts for the design using a slab model, stress over underneath layers shall be undervalued jeopardizing the thickness design. One should note that the modulus of elasticity of the pervious concrete is close to modern stiff asphalt mixtures, making coherent to follow a design structural model using the multi-layer theory as asphalt pavements requires.

Subgrade conditions at the São Paulo city spike (like Congonhas area) is typically a tropical lateritic clay with resilient modulus over 150 MPa and California bearing ratio (CBR) of 8%. The EMAS at the RESA shall be built using a well graded crushed granular base specified by FAA as "P-209 crushed aggregate" on the design model. Surface layer is limited to 10 cm thickness as required taking the main gear dimensions patterns as discussed in section 2.1. Following the structural design of the pavement according to FAA [33] criteria and based on the traffic and material parameters as explained, it resulted 43 cm of granular base over the subgrade, covered by the 10 cm surface layer.

3.3 Analysis of mechanical responses of pervious concretes at RESA

Strain-stress analysis for the pavement loaded by the aircraft was carried out taking the slab geometry and simulation of the main gear over only one slab, coherent to the spacings shown in Figure 5. Wheels load and pressures were simulated as defined in section 2.2. Finite element software RIGIPAVE [34] was used for the stresses and deflection computations for a 100 mm pervious concrete slab, and the Winkler model for treating the underneath layers bearing capacity was assumed 75 MPa/m (granular base over moderate subgrade). No temperature gradients were considered due to high concrete porosity.

Computational simulations of stresses and deflections comprised A 320-200 main gear load conditions at the longitudinal edge and the center of slabs, for both top and bottom critical stresses (maximum principal stresses) and the load positioned from a central line to the transversal edge (where the wheels cross perpendicularly the joints), as shown in Figure 6. In Figure 7 and 8 are presented the simulation results describing variations of maximum top and bottom stresses for each load position considered as well as the deflections variations, respectively.

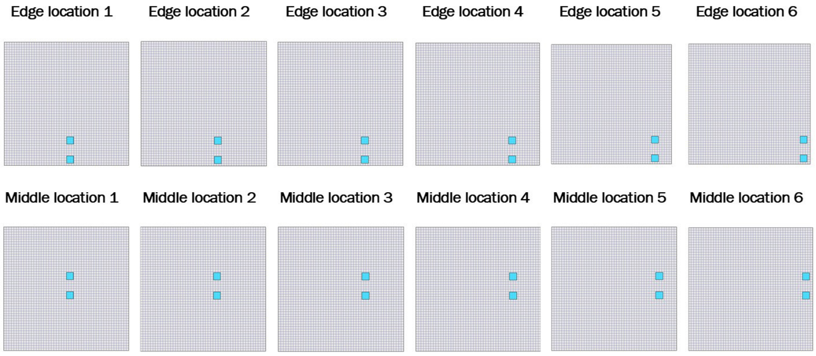

Figure 6. Main gear A 320-200 positions over pervious concrete slabs.

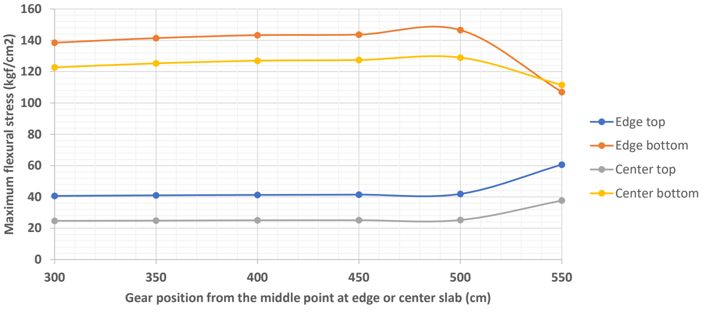

Figure 7. Maximum flexural stresses for main gear A 320-200 on concrete.

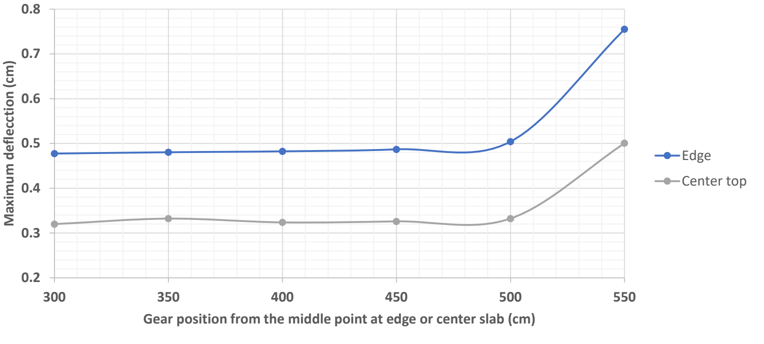

Figure 8. Maximum deflections caused by main gear A 320-200 on concrete.

4. DISCUSSION

4.1 Resistances of pervious concrete to ensure prompt rupture

From the stress analysis the comments are extracted as follows. The thin cross sections of pervious light-weighted concrete slabs are full in tensile and horizontal compressive stresses do not command slabs responses for such a situation. The flexural stresses values, for top and bottom slabs, are high and times superior to the concrete modulus of rupture, let us say $f_{ct,f}$. Center line top stress varies from 2 to 4 MPa whilst edge top stress varies from 12 to 11 MPa. Edge top stress are not critical ones as neither center top stresses.

The flexural resistance of the pervious concrete for the design is not to exceed 1 MPa (0.5 to 1 MPa are ease to fix with moderate light-weighted aggregates); for this condition, even the main gear line of movement during an overrun, passing close to the slab center or edge lines ensure the concrete rupture by flexure, and kept the compressive strength of the pervious concrete under 1.4 MPa, the vertical crushing shall be ensured.

One advantage for the required strengths, both in tensile and in compression, is that the pervious concrete dosage will require possibly no more than 150 kg/m^3 (like a rolled concrete without fines) of hydraulic binder consumption, resulting in low-cost material compared to regular 300-380 kg/m^3 requirements for light automobiles, bikeways, and pedestrian sidewalks.

Besides that, the airport area counting with large dimensions terrains, it is possible to consider the pervious concrete with some amount of fine aggregates although less permeability (void index close to 15% instead from 25 to 35% as in urban solutions), making the concrete more workable and requiring possibly no viscosity modifying agents to avoid fresh paste precipitation to the bottom of the layer during construction, eventually avoiding in-built clogging of the pervious concrete.

4.2 Excessive deflection levels

The good news is on the fact that transversal joint deflections are high (0.5 to 0.75 cm) and over the transversal joint. For a road concrete slab expectation for deflections are less than 10x0.01 mm while in heavy airports, 5x0.01 mm [35]. Results in Figure 8 point out that at the first joint crossing by the main gear the deflection level will be 500x0.01 mm for the central line case and 750x0.01 mm for the longitudinal edge case (in such case close to the slab corner). For concretes those level of vertical deformation is very high and incompatible to avoid fracture.

4.3 Regards concerning punching shear

Concrete pavement slabs are so far designed through some numerical or analytical tool. Nowadays solutions are largely based on finite element analysis of plate elements as well using combination of neural networks for modeling and stress-deflection prediction. However one must keep in mind that, in general, medium thick slabs theories (Kirchoff-Poisson) are employed considering an ideal stresses distribution in the slab domain, what sounds at least a little suspect for a material full of voids like pervious concrete: it is not homogeneous and some deviation from isotropy will not surprise; its elastic behavior, even in tensile, differs from elastic-linear; who knows whether it obey to generalized Hooke law?

Under the point of view of mechanical responses of such a slender plate, the second hypothesis for plates can differ a lot; it says that the normal stresses perpendicular to the mean plane of the plate are negligible compared to other (plane) stresses, what cannot be a full reality for thin plates. Moreover, theories consider the medium surface, although flexure, presents no deformation. Therefore, with the gotten results, positive stresses (tensile) at bottom and top, there shall be relevant vertical stresses to develop shear stresses especially at the wheels contours, causing punching ruptures in the thin slabs. Moreover, the discussion herein included light-weighted aggregates.

It is wise to remember that traditionally abandoning vertical shear computations is reasonable for relations between thickness and width of slabs from 1/20 to 1/25 or 1/30, depending on the concrete element's geometry. As such a relation in this study is 1/60 (could be also 1/50 or 1/40) due to maximum thickness of material to avoid wheels to sink without striking the gear higher mechanism. Therefore, shear stress will play large role associated to high tensile stresses and the vertical comprehensive stress, all of them acting to crush the light-weighted pervious concrete.

4.4 Substantial parallel aspects for EMAS design decision

During the design of EMAS is important to consider the airplane distances of arresting will be shortened if the engineered material thickness is increased by the single fact that the drag forces are increased [36]. Thickness decision are therefore function of possible many factors besides some herein discussed. Construction costs is one of them and will depend on the RESA length and the runway width as well. Compensation can be done by analyzing simultaneously material volumes for each possible case of thickness. However, the volume of EMAS bed within the RESA final configuration shall encompass aircraft stopping distances [37], all the aircraft traffic mix (it affects the thickness for the base to protect the subgrade), as well the costs for some material formulation [11], what can be achieved positively for a light-weighted pervious concrete as discussed in this paper, by reducing cement content on the mixture.

4.5 The use of the EMAS pavement by fire-fight cars

While push-back (cars) are not expected to operate over the EMAS (hitch with chains are used to remove the aircraft from the area), obviously, fire-fight cars and other light vehicles (ambulances and operational vehicles) may be required roll over EMAS and stop by the airplane in case of required rescue. This is situation must be considered for any material case, as well as for pervious concrete.

Dual tandem rear axle with eight wheels shall then be analyzed for the consideration of its damage potential. The tire pressure remains not a critical problem as regular air inflation results in 0.6 MPa, inferior to the possible the concrete compressive strength. The total maximum weight for such an axle is 170 kN and its effects in tensile are show for the critical case, namely, close to the transversal joint of the pavement (Figure 9) without load transfer between side-by-side slabs.

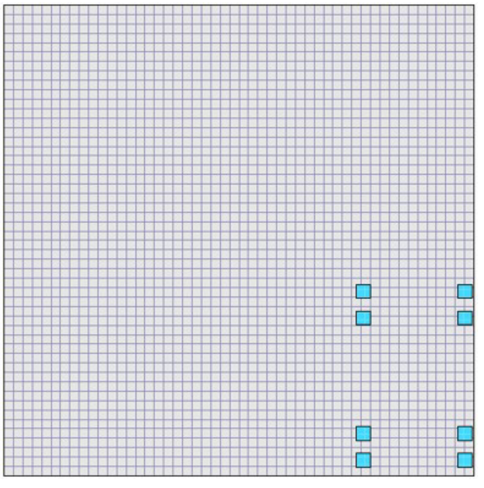

Figure 9. Position of a tandem axle of the fire-fighter car over the pervious concrete slab

Simulation of RIGIPAVE was then performed for tandem rear axle of the fire-fighter truck over the same designed EMAS pavement. Tandem axles are like two parallel axles spaced by 130 cm. Each axle has three wheels; twin wheels are distant 34 cm while the center of gravity of two twin wheels are distant 181 cm. The results achieved where: maximum deflection at the corner position 258x0.01 mm; maximum top stress of 2.92 MPa and maximum bottom stress of 3.61 MPa.

Even thrice times less than the airplane gear case, deflection due to the truck still is high due to the thin thickness of the plate. This imposes the full transversal section of the slab to be in tensile, both top and bottom. Tensile stress of 3 to 3.5 MPa requires pervious concrete with circa 16-20 MPa in compression [38], common for other applications of the material to ensure durability to fatigue, and not the case here.

Results indicate that the moderate tensile stress will not be a determinant factor to crush the slabs because is not conjugated to an excessive compression stress (the surface pressures are little in this case). Therefore, it is supposed, like in conventional concrete pavement, that after the truck passage over the thin slabs, it presents corner cracks as well as transverse and diagonal cracks. Since after the event no expectations of immediate overrun can be statically forecast, it is possible to avoid any maintenance service to recover the simple isolate cracks.

4.6 Sustainable solution for water runoff during storms?

Such point deserves some considerations to be addressed. Pervious concrete pavements are worldwide studied under the point of view of controlling storm water runoff due to its infiltration capabilities in field. New previous concrete surfaces allow high infiltration tax, even more for 35% voids that can be easily used for EMAS that requires mandatorily low strength.

It shall be considered that, during its service life, close to the position for the aircraft departures, even not impossible, it is difficult to think how and when the large should be cleaned by using vacuuming cars and strong pressure water equipment. The fact is that, besides air pollution, combustion dusts from the aircraft turbojet engines will be launched over the RESA surface causing, even slow, clogging the porous concrete structure. Although the issue of doing or not (the difficult) maintenance to clean the pervious concrete, sometime in the future the infiltration rate will reduce drastically.

One point is clear: while the permeable concrete surface will have enough infiltration tax, runoff will be satisfactorily controlled ensuring more safety in the case of overrun compared to other non-permeable surfaces, reducing skidding risks if the event happens during a rainy period.

To take advantage of such a concrete permeability, lateral edges of the EMAS area shall not be locked with concrete gutters. Pervious concrete shall be laterally finished as a slope ensuring the border is free to drain the collected storm water over the pavement surface.

It was clarified that the pavement bases, sub-bases, and subgrades must be preserved during the airplane overrun, avoiding any requirement of underneath layers reconstruction. Just the surface pervious concrete, solely at damaged areas, shall be removed and quickly replaced. Due to the huge loads over aircraft gears open-graded crushed stones are forbidden, therefore, to be used as pavement layers under the surface.

CONCLUSIONS

Building RESA with EMAS has become a strong concern for airport engineers in the 1990's due some aircraft runway end accidents in large airports. This article focused on a preliminary analysis of the possible application of pervious concrete to a specific area of the airport connected to the runway head called EMAS that can be built for safety improvement in the RESA areas.

For, conventional parameters for pavement design including the concrete surface were taken for the design an EMAS pavement section according to Federal Aviation Administration procedure. Although pavements are required to be designed for a minimum service life of 20 years, the surface course of the pavement was kept with 10 cm and the method adjusted the base thickness for compensation. Case study considered Congonhas airport characteristics.

Stresses and deflections were computed through linear finite element method software for pavement concrete slabs for several positions of the A 320-200 main gear moving over the pavement. It was concluded that conventional pervious concrete admixtures (used for bikeways, for instance) can serve as EMAS because both in flexure (very high stresses) and in compression (stresses higher than 1.4 MPa) will damage promptly the surfaced, crushing it (including its light-weighted aggregates) and allowing the airplane gears to sink and be arrested.

According to the results it is probable the intense rupture can begin exactly at the first free transversal edge perpendicular to de airplane direction due to very high deformation level; this condition is even more clear for an airplane gear approach close to the longitudinal edge joint.

Considered the analysis conditions and models, somewhat limited for all the mechanical responses expected for a thin concrete plate, it is possible to assume that important punching shear vertical action will add up the crushing mechanism event during the arresting of the aircraft (pavement full cross section in tensile).

Movements of fire-fight cars over the thin concrete slabs will more likely result in corner and diagonal or transverse cracks since its wheel pressure is not able to crush the concrete by compression.

Last, as generally required, the EMAS must be stocked in the airport area for immediate substitution after an overrun event causing the surface layer crushing of any material, even because in this case maintenance engineers are dealing with precasted materials available under previous request to industry. Pervious light-weighted concrete (produced in read-mix plants) can be manually removed from the crushed area and be laid quickly again; local works can by use manual wheelbarrows to carry the new concrete from the concrete-mixer trucks, requires no additional compaction unless smoothing service using a light metallic roll or rule.

Discussion leads to conclude that pervious concrete may comply several requirements [39] for EMAS to be used in runway head RESA. Its ease of execution and the low requirement for cement consumption can even lead to lower costs per square meter of pavement surface compared to asphalt plates, cellular concrete plates and overlays with foamed plastic blankets. As for any concrete pavement, strength and thickness shall be defined by the designer in view of specific airport operation characteristics. Thicker pervious crushable concrete can be used under more detailed studies about impacts for aircraft gears. Hence, values herein discussed are not to be taken as rules or universal.

ACKNOWLEDGEMENTS

Author recognizes the Ministry of Science, Technology, and Innovations and National Council for Scientific and Technological Development (CNPq) by the granted support.

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Author contributions: JTB: literature review; computer simulation; analysis and writing.

Editors: Luís Oliveira Santos, Guilherme Aris Parsekian.