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Original citation:
Amin, S., & Heweidak, M. (2022). Phenolic Foams: The Insulating Materials to Reduce the Frost Penetration, Skidding, and Flooding Risk of Road and Airfield Pavements. In P. K. Sandhya, M. S. Sreekala, & S. Thomas (Eds.), Phenolic Based Foams: Preparation, Characterization, and Applications (pp. 359-369). (Gels Horizons: From Science to Smart Materials (GHFSSM)). Springer, Singapore. https://doi.org/10.1007/978-981-16-5237-0_20

Publisher: Springer

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Abstract: The cell morphology of polymer foam shows an essential role in its functional attributes and its lightweight and thermal dependency cause diverse applications in building, utility lines and road structures. The most used polymer materials are flexible, structural and speciality foams. Phenolic foam, a member of speciality foam family, is produced through curing and expanding process with a composition of phenolic resin, surfactant, curing catalyst and blowing agent. The characteristics of phenolic foams (PF) in absorbing liquids and dissipating energy through collisions and shocks urge its application in road construction and airfield pavements. This chapter discusses the physical properties and the usages and benefits of PF for road and airfield pavements in the cold regions. The PF provides thermal efficiency and soft ground arrestor in pavements avoiding the overrunning of vehicles and aircraft. The open cell PF, as a geotextile layer in the permeable pavement systems (PPS), has also potential to retain and harvest rainwater. The PF layer under the porous friction asphalt of PPS delays the peak flow of rainwater during the extreme rainfall events and minimises the flooding risk.

Notion

PF	Phenolic foam	tetrafluoroethane	CFC-114
PPS	Permeable pavement system	Density	D
CACO3	calcium carbonate	Thermal conductivity	K
HCFC-141b	aliphatic hydrocarbon	Engineered Material arrestors systems	EMAS
HCFC-22	fluorocarbons	Extruded Polystyrene	XPS
CH2O	formaldehyde		
PFCs	fluorocarbons		

1. Introduction

The polymeric foams (PF) are formed using distinctive techniques including injection and extrusion moulded foam process and the use of supercritical fluids over solid counterparts and the moulding process made it light with enhanced structural stability [1-4]. The PF are classified into three groups based on the potential end-user applications such as structural, flexible and speciality foams. The structural or rigid foams, for example, rigid polyvinyl chloride and polyurethane foams are used in both construction and appliances as these have higher stiffness modulus and low thermal conductivity resulting in higher energy efficiency. The flexible foams including flexible polyurethane and polystyrene foams are used in cushion packaging and energy absorption applications for their low stiffness modulus and open-cell structure [5]. Speciality foams including PF are designed to meet predetermined cellular size and specific properties to perform functions in various applications.

The applications of PF in polymeric industries observe a growth from 5% to 6.5% during last five years for their better performance in fire resistance, thermal insulation, filtration, absorbing practices and environmental safety and cost [5,6]. The ability to dissipate the kinetic energy makes the PF as a soft ground arrestor in airfield pavement to avoid overrunning of aircraft and ensure safety. In addition, the PF has a potential as a geotextile layer in permeable pavement systems (PPS) to minimise the flooding risks and a thermal insulation layer in tunnels and pavements to avoid frost damage. The PF can improve the mechanical properties of foamed tar pavement optimising its stability and resilience. This chapter discusses the applications and benefits of PF in materials of roads and airfield pavements.

2. Physical properties of phenolic foams

The cell morphology is crucial for the functionality of PF as its cellular structure provides versatile applications in market areas such as thermal insulation, absorbent materials, safety applications and fresh flower support. The chemical process and constituents employed to produce PF determine two significant cellular structures: (1) open-cell foam with high liquid absorption and retention capacity within its structure and (2) closed-cell foam used as thermal insulation material in construction [7].

The main constituents to manufacture the PF are phenolic resins, acid catalyst, inorganic filler and blowing agents [8]. Phenolic resins comprise of approximately 80% solid and a combination of volatile components including phenol, water and formaldehyde [7]. The catalyst component stimulates the process of converting phenolic resins to foam. Sulfonic acids such as phenol and xylene have proven efficiency in foam curing over inorganic acid catalyst where corrosion problems exhibited. Inorganic fillers enhance PF properties, for example, calcium carbonate produces PF with densities over 50 kg/m^3 [7]. The blowing agents such as aliphatic hydrocarbon and fluorocarbons (HCFC-141b and HCFC-22) are the principal materials for defining the properties and morphology of PF [7,9]. The closed-cell PF has the ability to maintain its properties for long periods as long as blowing agents are confined within the foam structure while water evaporation and formulation of formaldehyde (CH2O) primarily control the production of open-cell PF such as floral foam [10,11]. Utilization of fluorocarbons (PFCs) as the blowing agents in closed-cell PF exhibit poor performance in terms of mechanical properties such as density and thermal conductivity comparing to the tetrafluoroethane blowing agent (CFC-114) [7,11].

Each product of PF has identical physical properties that allow its utilisation for a particular function (Table 1). Closed-cell PF with low thermal conductivity (0.018-0.02 W/mK) and high compression strength (2.8-7 kg/cm^2) is suitable for insulation applications [7,10]. The open-cell floral or absorbent foams possess an excellent ability in absorbing and retaining liquids within the foam structure for long periods but with lower compression strength and friable structure (Table 1).

Table 1: Physical properties of PF [7,53]

PF applications	Density (kg/m^3)	Compression strength (kg/cm^2)	Thermal conductivity W/mK	Closed/opened cell content	Water Absorption
Insulation	32-50	2.8-7	0.018-0.02	More than 90% closed	Very low

Floral and Absorbent	16-32 0.4	0.7-1.2	0.02-0.025	Less than 5% closed	Very high
Orthopaedic	8-12	0.2-0.3	Low thermal conductivity	Open/closed	Low
Foamed concrete for ground arrestor systems	200-800	4.2-5.6	0.1-0.66	Up to 75 % open	Very low

3. Airfield soft ground arrestor, skid resistance and safety

The highest rate of aircraft accidents (more than 25% of all commercial aircraft accidents annually) occurred due torunway excursion [12]. The runway excursion mainly occurs during aircraft take-off or landing in the form of runway overruns resulting from inappropriate aircraft handling techniques, aircraft malfunction, poor visibility and airfield pavement condition. The Ascend World Aircraft Accident recorded 141 runway excursion accidents (85% of these accidents occurred during landing) during the period 1998 to 2007 that led to 550 casualties [13]. A total of 28 overrun aircraft accidents were occurred in the United States of America during the period 2008 to 2017 and four of those accidents resulted in 17 casualties [14]. The aircraft overrun accidents have had a long history which urges the aviation industries to find out the best practices eliminating the disastrous consequences of aircraft overrun.

The International Civil Aviation Organization (ICAO) recommends 305m length safety area beyond the runway. Some airports find difficulty to comply with the ICAO standard due to the topographical locations and urge for alternative solutions to overcome this problem. The runway arrestor systems are widely used technique to effectively decelerate aircraft speed and ensure safe stopping. There are two techniques commonly used in the runway arrestor systems, active arresting system and passive ground system. The active arresting systems such as deck cables and large net barriers are mostly developed for jet aircraft [15-17]. Active arresting systems are not adequate for passenger aircrafts as deck cables are not economically feasible and the large net barrier obstructs aircraft passengers from using emergency egress. In addition, the net barrier adversely affects the aircraft wing flaps due to the applied load by the net barrier system. The passive ground system applies engineering materials to prevent the aircraft overrun and eventually reducing the length of runway safety area [16].

Several studies in the United Kingdom tested soft ground materials including gravel, sintered fuel and aerated concrete during the period from 1968 to 1971 [18,19]. The urea-formaldehyde foam was used as ground arrestor material and the trial was proceeded by Comet 38 aircraft in 1974. There was no damage in aircraft engine turbine due to the efficiency of foam in reducing the predictable peak drag force acting over leading and trailing wheels [16]. Cook et al [20] compared various materials such as, water, gravel, soft soil (clay and sand), PF and foamcrete to determine the advantages and disadvantages of materials in terms of workability, maintenance cost, resistance to erosion. Cook et al [20] recommended the PF as a ground arrestor material for its stable mechanical properties and its ability to decelerate the commercial aircraft with a coefficient of friction equals to 0.4 denoting a good braking action. Cook et al [20] examined the performance of PF as a ground arrestor with compressive strength of 380 kPa and 50 cm depth. The analytical models estimated the stopping distance of aircraft entering the PF arresting system with 50 knots and 60 knots speed. The Boeing 727 safely stopped at 128 meters and 165 meters distance with 50 knots and 60 knots speeds, respectively [20].

The aircraft stopping distance inside the bed arrestor subjects to deceleration rate, materials strength and thickness, aircraft weight and landing gear loads [21]. The increase of foamed concrete bed depth can significantly offset the aircraft load but landing gears subjects to additional loads. The rebounding force over landing gear wasn't evidently defined by Cook et al [20]. Cook et al [20] argued that PF had rebounding properties that might exhibit additional force over landing gear resulting in the damage of landing gear [22]. The Federal Aviation Administration (FAA) and Engineering Arresting Systems Corporation (ESCO) jointly worked on improving the rebounding characteristics of PF employing the crushable lightweight concrete to disperse the energy instead of returning to aircraft body [23]. The bed arresting system consists of precast blocks formed from closed cell concrete foam that is bonded by silicon sealer [22]. A protective layer is provided as a waterproof paint to improve the durability of material subjected to severe weather conditions [24]. The crushable concrete foam is the only engineering material arresting system (EMAS) that accredited and recommended by FAA and is used in 59 runways at forty airports [25]. However, the bed arrestor system with concrete foam requires at least 4 to 12 weeks to install and is expensive [22, 24]. The concrete foam causes a cloud of dust during aircraft landing that enter inside the aircraft engine risking the aircraft operation [26]. Moreover, the humid weather adversely impacts the foam reducing its long-term performance and requires maintenance for moisture infiltration and membrane peeling [22]. The foamed concrete arrestor does not perform safely for all types of aircrafts, for instance, the landing gear of puddle jumper aircraft may experience fatal damage when crash into the ground arrestor system [27].

Several studies examined the application of alternative materials for improving the ground arrestor system [21,22,26,27]. Yang et al. [26] investigated the use of polyurethane foam as a ground bed arrestor due to its low strength and energy dissipation capacity. Yang et al. [26] asserted the importance of ground arrestor material's strength on aircraft crash ignoring other factors such as material durability, cost and maintenance as well as stopping distance of aircraft inside the arrestor bed. A study examined the performance of tire-honeycomb material as a ground arrestor against the friction between the material and aircraft undercarriage and compared the results with traditional EMAS [27]. Yang et al. [27] argued that the manufacturing tire-honeycomb material was more environment friendly due to low haze production and effective in stopping overrunning aircraft. The FAA approved EMASMAX® and greenEMAS® as the EMAS. The EMASMAX® is nontoxic and composed of lightweight blocks made from cellular cement material with higher durability and fire and extreme weather resilient. The greenEMAS® is manufactured from recycled glass, bonded together with high strength plastic, covered by cement layer and treated by topcoat sealant [12]. The Zodiac Aerospace has installed EMASMAX® bed arrestor at 112 runways in 67 airports in the USA [12,54]. There were 15 incidents recorded in U.S airports until April 2019 where overrun aircrafts safely stop within EMAS with almost no passengers injured and undamaged aircraft body [28].

4. Frost penetration below highways and airfield pavements

Frost penetration, which occurs due to seasonal freeze-thaw cycles, reduces the life service of highways and airfield pavements [16,29,30]. The freeze-thaw cycles saturate the subgrade soil with excessive water and affect the mechanical properties of subgrade soil beneath the pavement structure without the existence of a proper drainage system [31]. During the cold season, the formation of ice lenses in the unbounded layer increases the bond between the particles of subgrade soil and subsequently improves the bearing capacity of the soil. The fine particles in subgrade soil, high thermal conductivity, the moisture content in pavement and ice formation in the pavement subsurface are the main factors of frost heave. However, the workability of pavement may be weakened due to thermal cracks and uneven frost heave [31]. The increase of temperature causes ice thawing resulting in soil saturated with water. The impact of ice thawing may cause potential settlement of pavement structure under heavy traffic loads due to poor drainage system and structural inadequacy [31]. In northern Sweden, around 40% of road network was inaccessible during the frost thawing period in the year 1994 and the Swedish national road administration estimated that the annual maintenance and reconstruction cost was approximately 25% of the road construction budget [31].

Several studies measured the frost penetration depth in the pavement structure [16,32-34]. Equations 1-4 show that soil thermal conductivity is one of the major determinants of frost penetration.

$$X = \sqrt{\frac{48K(FI)}{L}} \quad \text{Freitag and McFadden [33]} \tag{1}$$

$$X = \lambda\sqrt{\frac{48K(FI)}{L}} \quad \text{Aitken and Berg [35]} \tag{2}$$

$$FI = \frac{diLi}{24n\lambda} + R \quad \text{Bianchini and Gonzalez [34]} \tag{3}$$

$$X = a(FI)^{b} \quad \text{Baladi and Rajaei [32]} \tag{4}$$

Where *X* is the frost penetration depth; *FI* is the freezing index; *K* is the thermal conductivity; *n* is the factor transfers air *FI* to surface *FI*; *λ* is the correction coefficient; *d* is the layer depth; *R* is the thermal resistance; *L* is the latent heat; *a* and *b* are constant.

During the late 1960s, several studies in cold regions examined the application of insulation materials including polymeric foams to reduce the frost penetration depth in pavement foundation [36-37]. Penner [36] examined the impact of installing extruded polystyrene and polyurethane foams between the subsoil and gravel base to evaluate the pavement performance in Ontario, Canada. Penner [36] observed that the insulation foams reduced the frost heave at a significant level. In Alaska, Esch [37] investigated the usage of 5 cm of urethane foam and 8 cm of styrofoam as the subgrade insulation layer and identified that the frost penetration depth was reduced by 48.5% and 81%, respectively. However, Esch [37] observed that the polyurethane foam, a mixture of urethane and styrofoam in liquid state, had lower structural strength and thermal conductivity. A recent study monitored the impact of extruded polystyrene foam on the frost heave for three years in France and asserted its ability to reduce the frost penetration [38].

The application of polyphenolic foam in reducing the frost damage at Galongla tunnel located in China was experimented applying the finite element method (FEM) [39]. Thermal sensors were installed at ten sections along the tunnel axis at depth 370 cm. Tan et al. [39] compared the polyphenolic foam and concrete as insulation layers to study temperature distribution in rock surrounding tunnel lining. The polyphenolic foam performed better in sustaining very low temperature in rock layer for one year and thus avoid freezing-thawing damage. Li et al. [40] examined the thermal conductivity of three insulation foam materials such as polyurethane, phenolic and floquet in dry, wet and freezing conditions using the hot disk thermal physical property analyser. The relationship between thermal conductivity and gray volume moisture content ratio (*Gv*) was applied to evaluate the impact of water content on insulation foams. The average thermal conductivity for phenolic and polyurethane materials under dry condition was 0.040 W/(m.K) and 0.029 W/(m.K), respectively [40]. The experiments revealed that thermal conductivity increased with the increasing of iced mass moisture content. Although the PF is applied in wider range as the thermal insulator, the application of extruded polystyrene foam to reduce the freezing-thawing damage is more advantageous. For example, in Norway, polystyrene foam is one of the common insulation materials used in pavements [41]. The insulation materials such as foam glass aggregate are used as the alternative materials to extruded polystyrene foam in cold regions of Europe since the materials are economical and have been manufactured as an environmentally friendly solution [42].

5. Permeability and sustainable drainage system

Impermeable pavement surfaces hinder the infiltration of stormwater runoff and cause surface runoff of pollutants such as nutrients, heavy metals and motor oil to the waterbodies resulting in risk to marine life and human health if untreated [43-45]. Impermeable pavement surfaces also increase the volume of stormwater runoff that overburdens the capacity of drainage networks and eventually causing floods particularly in urban areas [44-45]. Sustainable drainage system (SuDS) is a contemporary challenge that considers permeable pavement system (PPS) as the environmentally and economically beneficial approach for minimising flood risks [46]. The most practised PPS in the United Kingdom is a geotextile layer beneath the pavement structure because geotextile materials retain stormwater pollutants and enhance the process of biodegradation within the pavement structure [47-49]. Several materials such as polyethylene, polypropylene and polyester are used to manufacture the geotextile layer that acts as the filtration or separation layer of PPS [48-50]. The three-dimensional structure of OASIS® PF can increase the material ability to absorb and attain stormwater up to a saturation limit [49,51].

Nnadi et al. [49] examined the hydraulic properties of OASIS® material with 1.3 cm and 2 cm thicknesses under rainfall intensities of 100 mm/ hr, 200 mm/hr and 400 mm/hr and stated that OASIS® material retained stormwater. Nnadi et al. [49] identified that one-centimetre increase of depth in OASIS material would increase its stormwater storage capacity by 37%. A similar study was conducted by Heweidak and Amin [52] examining the infiltration rate and steady-state behaviour, water storage capacity of different thicknesses of OASIS® material, and the effect of OASIS® material in deferring the water peak flow during rainfall intensities of 100mm/hr, 243mm/hr, 400mm/hr, and 563mm/hr. Heweidak and Amin [52] stated that a 35-mm thickness of OASIS® layer could absorb approximately stormwater with rainfall intensity of 100mm/hr for 15-mins duration and a 10-mm increase of OASIS® layer thickness can increase the water storage capacity by 12%. The PF can effectively retain rainwater delaying water peak flow that minimises the flooding risk (Table 2). The PF materials have structural strength bearing static loads, but pavement surface is subjected to both dynamic and static loads [52]. The PF layer may increase the probability of void clogging that affect the performance of PPS [55].

Table 2: properties of absorbent PF [5]

Material	Density (kg/m$^{3)}$	Polymer density(kg/m$^{3)}$	Expansion ration	Cell diameter (microns)	Void fraction %	Volume of foam In^3	Volume of solid In^3
Absorbent PF	32.04	1188.57	37.1	250	97.3	64	1.73

6. Conclusions

The low thermal conductivity, effective energy-absorption and liquid absorption of PF provide a wider range of its application in building and infrastructure materials. This chapter discusses the applications and benefits of PF in materials of roads and airfield pavements. The PF as a EMAS in airfield pavements demonstrates an efficient material to safely stop the aircraft within the PF bed arrestor system. However, the drag force generated from the aircraft undercarriage leads to serious damage of landing gear. The EMASMAX, approved EMAS by FAA, improves the rebounding properties of the bed arrestor in the airfield pavement. The EMASMAX is composed of cementitious cellular foam with sufficient capacity to dissipate the energy instead of returning to aircraft and the cellular cementitious foam is recyclable and environment friendly. The commercial availability of EMASMAX is very limited causing higher cost of installation and maintenance. Foam glass could be an alternative EMAS but it possesses high strength. The cementitious foams are subjected to moisture infiltration, membrane peeling and freeze-thaw effects.

The PF has the low thermal conductivity but the XPS are commonly utilised as an insulation layer in pavement structure in Nordic countries and Canada. The XPS has some technical difficulties such as weak joints due to geometry and possible loss of material efficiency over time as a result of XPS chemical decomposition. The application of PF to reduce frost penetration in pavement structure can be a sustainable solution as PF reduces the environmental impacts through recycling waste materials.

The experimental results of PF application in PPS argue its efficiency in minimising flood risk, however, further studies require to understand its performance under dynamic traffic loads with extreme rainfall intensities. The manufacturing process and residual after life cycle of PF hinder its applicability in road and airfield pavements. The contaminated waste of PF is non-recyclable and send to the depot. Future studies require to addressing the material durability, response to vehicles and aircraft loads and speed, the environmental impacts and the installation and maintenance costs.

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