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Review

Causes of Asphalt Pavement Blistering: A Review

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Abstract: No theoretical model effectively explains the blistering process, which provokes functional distress in asphalt pavements worldwide. This study focuses on the possible causes of blistering, the physical processes that drive blistering, the role of asphalt properties, and the uncertainties and gaps in the current knowledge. This paper analyzes peer-reviewed studies on pavement blistering published between 1959 and 2022 retrieved in a systematic literature review to justify and model this distress observed on sidewalks, airports, and bridges. According to the scientific literature, high surface temperatures due to solar radiation are the common factor responsible for uplifting, but several causal mechanisms have been investigated. Indeed, chemical reactions, evolutionary materials, thermal buckling, and physical reactions are the generally recognized causes. Their effects on pavement smoothness vary according to the various interdependent geometrical, physical, and mechanical properties of asphalt mixtures and the boundary conditions. Both the mix design and construction processes can hinder the blistering process that occurs during daytime hours of the hot season, right after the work is finished or a few years later. Further research should identify measures to prevent bulges whose management after uplift is difficult but necessary to avoid safety and functional issues.

Keywords: blistering; buckling; air voids; permeability; solar radiation; bulges

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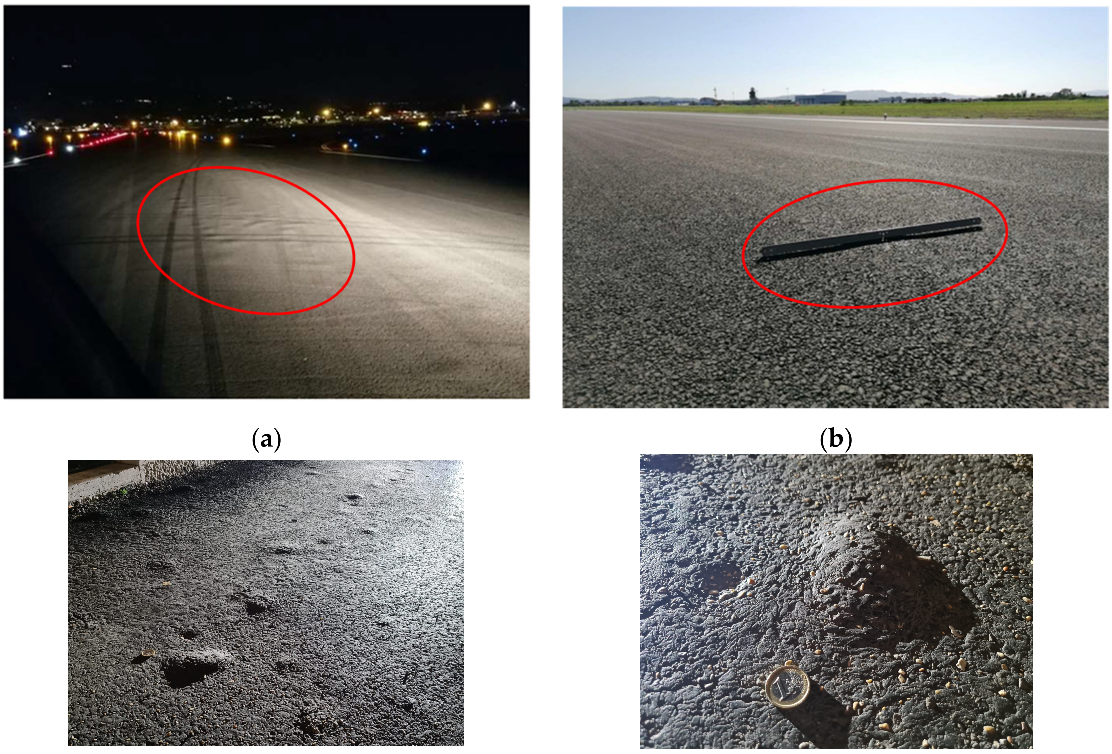
1. Introduction

The design and construction of road and airport pavements aim to meet structural and functional requirements [1] that ensure regular and safe service. Functional properties of a horizontal surface to be ridden require smoothness and adherence to allow for safe and comfortable vehicle mobility [2]. Several distresses (e.g., cracks, potholes, rutting, and raveling) have been recognized and investigated in the literature to counteract their appearance and manage their effects [3]. However, blistering negatively affects surface flatness and integrity [4], but it is still not fully understood [5]. It is frequent in hot climates and often appears upon exposure to rain, fog, or other water sources [6]. It is an irreversible (or partially reversible) process that consists of nonlinear blister growth dynamics that can start at the interface between two layers or within the upper layer and can have different consequences [7]. Indeed, blisters can reach a stable state, break, or lead to delamination, depending on the mechanical and adhesion properties of the materials [8,9]. The uplifts have a circular shape with extremely variable dimensions: their diameter can reach 1 m, and their maximum elevation is usually a few centimeters over the ideal and initial flat surface [10]. It often affects asphalt mixtures on asphalt roof shingles [11], pipelines [12], pipes for drinking water supply [13], Portland cement concrete bridge decks [14,15], steel deck bridge pavements [16], dams [7], pumped-storage power stations [7], runways [17], sidewalks [18], carriageways [5], waterproofing membranes [19], and asphalt-covered concrete structures [20] in south- and west-facing areas. According to the literature, the main physical mechanisms that drive blistering are temperature fluctuation [21], bottom-up pressure [22], loss of adhesion [23], peeling fracture [20], thermal expansion, and buckling [24]. Moreover, the blister failure mode has a direct relationship with the air void content, air and water permeability [25], stripping [23], the tensile/bond strength of the asphalt mixture [26,27], and the surface roughness [28]. The properties of the lower layer play a pivotal role: asphalt over granular or permeable layers does not suffer from blisters [29]. Moreover, a rough lower surface (e.g., milled binder) ensures a higher bonding performance between the tack coat and the upper layer [30]. Additionally, subsurface void detection with ground penetrating radar allowed for the identification of cavities filled with water [31].

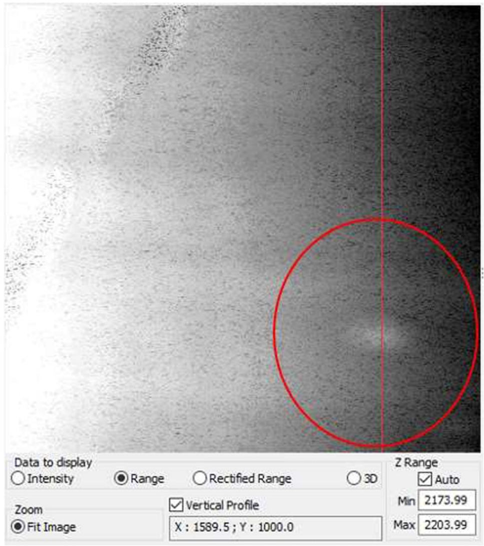
The complex mechanisms damage the surface of pavement, requiring maintenance and rehabilitation work. Indeed, neglecting the problem causes further distress with the onset of cracks, the infiltration of water, and removal of the bulge surface [32]. Cracks, potholes, raveling, surface wearing, and stripping affect pavement use when a low tolerance for out-of-flatness has to be applied (e.g., for airport runways where blistering can cause foreign object debris) [33]. Figure 1a,b shows night and day images of two runway pavements where blisters are in the red circles. Figure 1c,d shows the effects on sidewalks whose surface has numerous bulges; both images present a 1 euro coin (23.2 mm diameter).



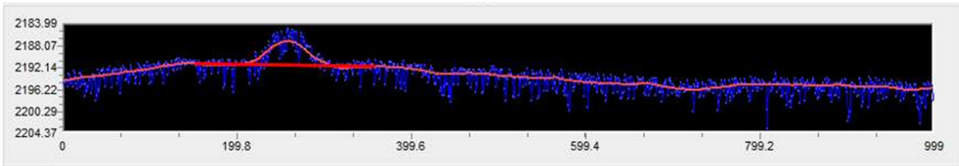
(**a**) (**b**) (**c**) (**d**)

Figure 1. Blisters. (**a**) On runway pavement; (**b**) on runway pavement; (**c**) on sidewalks; (**d**) on sidewalks.

Moradi et al. [34] proposed a machine vision system to detect and grade the blistering defects of coatings according to [35]. Although there is a lack of standardized assessment methods to classify the severity and impact of pavement blisters, bulges higher than 3 mm prevent aircraft movements [36], and vertical differences in elevation higher than 1.25 cm are hazards for sidewalks and crosswalks [37]. Figure 2b shows the surface laser profile of the red alignment in Figure 2a and highlights the blister profile. The red circle in Figure 2a highlights the position of a blister.



(**a**)



(**b**)

Figure 2. Blister. (**a**) Surface image; (**b**) surface laser profile.

This paper aims to present and discuss the causes of blistering according to the state of the art. The examined literature is useful for identifying the potential causes and the physical processes of blistering. In particular, this manuscript takes into account two conflicting hypotheses based on the laws of thermodynamics and the buckling theory of plate elements.

2. Method

Despite decades of experience with blistering, its origin and evolutionary mechanisms are not yet fully understood. The difficulty of understanding it stems from the low frequency of occurrence compared to other well-known pavement distresses and the real challenge of reproducing the conditions in which it has been observed. The current research methodology for bulging bubbles mainly relies on experience and case studies. This study aims to discuss the existing knowledge critically and answer the following research questions:

- What are the potential causes of blistering?
- What are the physical processes that drive blistering?
- What roles do the asphalt properties play in blistering?
- What are the uncertainties and gaps in the current knowledge?

A systematic literature review (SLR) was carried out to answer these questions according to Kitchenham [38]. It is composed of planning (i.e., identification of the state of the art that justifies the SLR), conduction (i.e., implementation of a search strategy to pursue the goals), and reporting results (answers to the questions and discussion of the results) [39].

Peer-reviewed primary studies on blistering in road and asphalt pavements, published between 1959 and 2022, were included in the analysis. The main search strategy was automated and involved the Web of Science and Scopus databases. The keywords used for the search were “blister” + “asphalt” or “blistering” + “asphalt” or “blistering” + “pavement” or “blister” + “pavement”. A manual search completed the process. It involved documents published since 1990 and cited by the previously found works. This activity involved both peer-reviewed and non-peer-reviewed documents. The work selection strategy identified 45 primary studies (i.e., peer-reviewed indexed research papers), 7 conference proceedings, and 15 books, theses, and technical reports. These works allowed the authors to conduct a critical study on the state of the art to answer the research questions.

3. What Are the Potential Causes of Blistering?

Over the years, it has been possible to observe blistering on many asphalt pavements, collect information related to the specific contexts of its occurrence, and formulate hypotheses on the potential causes. Blisters (or bulges) occur during daytime hours and have regular circular shapes whose diameters range from a few centimeters to more than 1 m. Sasaki et al. [40] identified two blistering processes: primary blistering is observed just after the completion of the pavement and is usually caused by water trapped within the layers during laying [41]; secondary blistering occurs in hot periods following the end of the work and has been attributed to chemical, physical, and organic reactions within the asphalt surface, buckling effects, or moisture intrusion into upper layers. Whatever period they appear in, the necessary conditions for uplift occurring are high surface temperatures and an imperfect bond between the upper and lower layers (e.g., wearing and binder courses, or overlay and existing wearing layer) [42] or low tensile strength of the asphalt mixture [43].

3.1. Chemical Reactions within the Asphalt Surface

In 1984, blistering appeared on Runway 14–32 of the Marine Corps Air Station in Beaufort, South Carolina. In summer, secondary blisters involving a thin asphalt overlay two years after its construction occurred during the cold period. The bubbles were observed in limited areas of the pavement, and chemical reactions between the pavement materials and/or the biological activity of organisms present have been investigated as the causes of blistering [44]. A complex bacterial composition was found in blisters on asphalt concrete linings in the Czech Republic [45]. Both chemical reactions and biological activities can lead to the production of gases that are responsible for the observed distress. Hironaka and Holland [44] came to rule out such a possibility. Firstly, they noticed the fast occurrence of high surface temperatures of the surface due to solar radiation. Daytime blister behavior occurs at the upper layer of asphalt pavement because the maximum daily temperature range occurs within the topmost 5 cm of the surface. This condition suggests a close and reasonable correlation with the climatic conditions to which the pavement was exposed. The bubbles raised when the temperature increased, receded when the temperature decreased, and deflated when punctured. Therefore, the blisters contained pressured gases and were not caused by buckling effects. Due to the deep (more than 3 m) groundwater table and the sandy subgrade, steam from the groundwater or soil could not cause gas pressure beneath the wearing layer. Four gas samples from the blisters were analyzed to investigate their composition. However, the chemical approach was incorrect:

- According to [44], it is unlikely that chemical activity was responsible for the gas production since the materials used in the production process were chemically stable. The inversion of a chemical reaction requires a certain amount of energy and a catalyst, which were unavailable within the pavement considering the daily cyclicity. Finally, the amount of gas generated by reactions over time would have decreased due to the progressive consumption of available resources until exhaustion. Therefore, the daytime increase in gas pressure and the sudden appearance of blistering would not have been possible after many cycles;
- The chemical analyses of the gases contained under the surface uplifts revealed a high concentration of carbon dioxide and a low methane content, which is the main product of anaerobic activities. Such conditions suggest the presence of aerobic biological activities, which need a continuous oxygen supply. Blister gases do not differ from those in the normal air, and no other found gases could be responsible for the bubbles.

However, the low void content of the asphalt and the lack of interaction of the latter with the outside make aerobic activities unlikely [45].

A finite element analysis was implemented to estimate the pressure necessary to develop bubbles under a thin asphalt layer [44] and compare the numerical results with those from the thermodynamic equations of gases [46]. ADINA 1.0 software was used to develop a three-dimensional model of a blister with no bonding of the asphalt layer except at the blister perimeter. The calculated pressures were higher than those from the thermodynamic analysis due to the boundary conditions and the thermal–mechanical properties of the modeled materials. The field measurements, laboratory tests, and numerical results confirmed that the blistering was caused by the thermal expansion of air- and water vapor-trapped gases in the asphalt voids [44]. Voids and cracks in the asphalt allow gases to move into the pavement until the pavement matrix expands due to the diurnal temperature changes, trapping air and moisture. Blisters arise where the bonding between the asphalt layers or the tensile strength is deficient, and the gas pressure overcomes the adhesion forces.

3.2. Unsuitable Aggregates

Potentially harmful materials in aggregates caused blisters in two pumped-storage power stations built in Poland and Germany in the 1970s [47–49]. In Germany, after 3 and 20 years of operation, a multi-layer facing of asphalt laid and rolled to seal the upper reservoir had bulges. The long interval time between the construction and the appearance of the blisters reveals that the cause was a ratchet process driven by progressive decay due to evolutionary materials whose properties evolved during their service life. In particular, petrographic investigations and electron microscopy proved the presence of weak cracked basalt and marl within the asphalt mixtures exposed to severe cyclic weather conditions. In semi-arid or arid climates, improper aggregates can modify the skeleton of the upper layer during its service life. Materials with more than 0.2% soluble salts [50] allow for the growth of salt crystals within the road pavement that cause blisters due to water fluctuations and steam [51]. In Botswana, detrimental salts ($NaHCO_3$) caused the loss of adhesion between the aggregates and bitumen [5] of road and airport pavements. In Algeria, salt whiskers of halite (NaCl) caused blisters up to 10–15 cm high on the runway of Adrar [52]. Other studies have investigated salt contamination due to sodium chloride as the cause of pavement blistering [53,54].

3.3. Inside Overpressure

The currently most accredited hypothesis explains blistering with the following theory: during scorching summer days, exposure to solar radiation leads to high surface temperature values [55]. High air temperatures contribute to such conditions because the cooling capacity of the air is reduced. This heating process also affects any gas and/or water within the wearing layer or at the interface with the lower layers [56]. Changes in the water–heat regime in the base and lower layers of the pavement and the subgrade cause blistering as a deep process [57]. Soil moisture retention properties for unbound materials modify the water content during the seasonal drying and wetting cycles [58]. Increases in moisture inside the granular layers due to rainy and humid periods change the volume and strength of the granular soils [59] and contributes to blister development inside the upper dense layers [49] (Figure 3).

Volumetric expansion and evaporation can be countered by the wearing course avoiding interaction with the atmosphere and by the tack coat preventing downward expansion. Thus, gas and water vapor trapped under the surface break the interface bonding between layers [60]. The pressure causes bulges when it overcomes the opposing forces [57] (Figure 4).

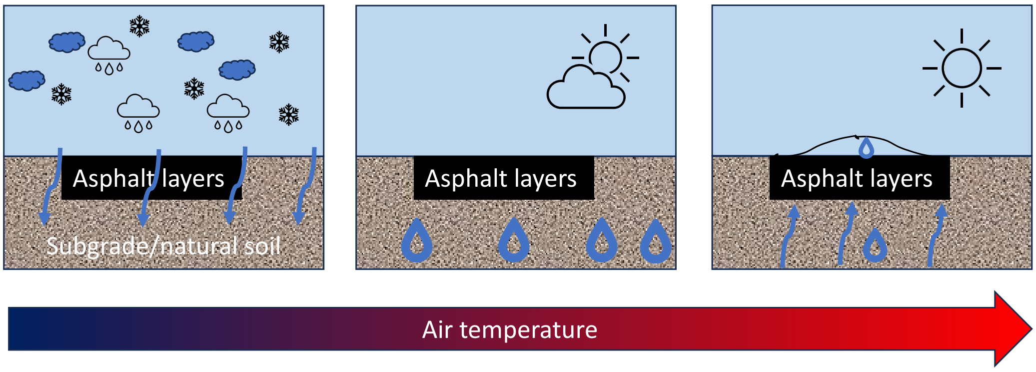


Figure 3. Blister deep process.

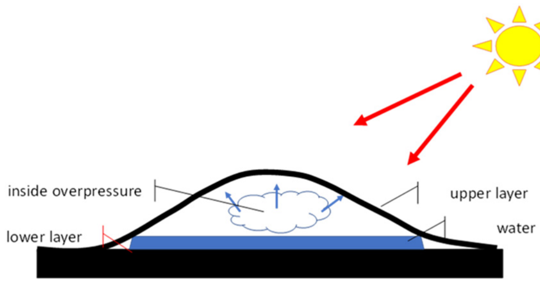


Figure 4. Blister mechanism.

A surface bulge depends on a pressure increase that lifts the wearing layer to a stable condition. According to these hypotheses, exposure to solar radiation and inside overpressure are the driving variables behind blistering [57]. When solar radiation reaches the pavement surface, some is absorbed, some is reflected, and the remaining is transmitted [61]. The asphalt reflection coefficient depends on several factors (e.g., the age of the material, type of aggregates, and surface color). Since traffic erosion leads to lightening of the pavement color and increases the albedo (e.g., from the initial values of 0.04–0.06 to 0.09–0.18), the increased reflective capacity slows down the heating and decreases the pavement peak temperature on a summer day [62]. Therefore, higher temperatures reached by a recently laid layer lead to a higher probability that secondary blistering will occur in the first hot season of a pavement laid in cold months.

3.4. Thermal Buckling

In 2008, Croll [18] studied the blisters on the asphalt sidewalks on Gower Street that required several maintenance works and led to hazardous potholes for pedestrians. In [40], the surveyed surfaces involved a secondary blister process. According to Croll [18] and Castaing et al. [63], thermodynamic models cannot determine the process or predict gas pressure under the upper layer. Therefore, they did not consider the hypothesis that the pressure increase in the trapped gases determines the appearance of bubbles as sufficiently explanatory. Indeed, according to the theory of plates in flexure [64], the underlying pressure would deform the surface into the highest wavelengths. Given the deformation shape, the pressure is inversely proportional to the fourth power of the characteristic wavelength. Pavement blisters overcome this condition. The upward expansion is inversely proportional to the second power of the plane radius, and the pressure is inversely proportional to the fourth power of the plane radius: the energy required for a volume change is inversely proportional to the sixth power of the plane radius. Finally, the gas law [40] requires that expansion reduces the pressure beneath the bulge, while the growth of incremental blistering needs increases in both the pressure and deformation. In the examined sidewalks, some blisters were drilled without the evidence of pressured gases and uplifted after drilling, and others were not drilled. Thus, Croll [18] investigated an alternative thermal source as a cause of blistering. Cyclic thermal stresses induce expansion and contraction constrained at the surface, as confirmed by concentric ridges and furrows around the bubbles. Thus, asphalt slabs can be compared to heavy elastic sheets affected by a temperature increase. However, asphalt does not behave linearly or elastically because it depends on the time and temperature [65], but Croll [18] believes that the structural model of an elastic plate constrained and subjected to in-plane compression supports the hypothesis of asphalt blistering and pingos within permafrost [66]. Indeed, daily temperature ranges cause the expansion and contraction of asphalt, giving rise to traction and compression cycles that generate instability and the appearance of bubbles when geometric imperfections of the lower pavement layer cause upward curvature of the upper layer [67]. Deformation steps of the asphalt surface cause a ratchet process and lead to incremental plastic deformation. Indeed, part of the elevation generated at hot temperatures is not recovered in the subsequent cooling phase, and over time, this leads to the gradual growth of a generic bubble. The asphalt body cannot recover uplifts despite the restoration of the initial conditions due to the variation in stiffness caused by the changing temperature.

4. Physical Processes

Leaving aside the hypotheses about chemical and/or biological reactions and improper materials as factors that cause blistering, the current state of the art bases its discussion on the laws of thermodynamics and the buckling theory of plate elements.

4.1. Thermodynamics Approach

The laws of thermodynamics can support the hypothesis that blistering originates from thermal overpressures of the gases contained in the pavement. Assuming that only air is inside the asphalt and considering it is an ideal gas, Equation (1) for isochoric transformations allows for the calculation of the pressure variation in the gas contained in a given volume for an increase in temperature [46]:

$$\mathrm{P}_{\mathrm{g},2} = \mathrm{P}_{\mathrm{g},1} \frac{\mathrm{T}_2}{\mathrm{T}_1} \frac{\mathrm{V}_1}{\mathrm{V}_2} \tag{1}$$

where P_g is the air pressure, T is the air temperature, V is the air volume, and 1 and 2 refer to the initial and final conditions, respectively.

According to Equation (1), Stene [57] demonstrated it is possible to reach a volume increase of 30% with a 45 °C temperature increase. Beijers [68] produced a laboratory blister between a concrete surface and a waterproof asphalt layer, but there was not always enough air pressure to justify blistering. This result showed that the surface blister extension and the number of bubbles depended on the air volume initially trapped in the pavement. However, in some cases, a high trapped air volume and severe distress are difficult to justify when low-void-content asphalt is considered [69]. Hironaka and Holland [44] demonstrated the pivotal role of vapor pressure with a thermodynamic analysis. Assuming that water is in the pavement voids, it can be stated that the steam generated by water heating contributes to the increase in pressure. If water vapor and air are ideal gases according to Dalton's law [70], the respective partial pressures can be added to determine the total pressure (P) in a blister (Equation (2))

$$P = P_g + \varphi P_{sv} \tag{2}$$

where φ is the relative humidity, and P_{sv} is the saturated vapor pressure.

Therefore, Equation (3) describes the equilibrium between vertical stresses [71]:

$$\sigma_{VT} = P_g + P_w + P_r - P \tag{3}$$

where P_w is the weight per unit area of the asphalt, and P_r is the tensile strength or the bond strength of blisters within the layer or at the interface between two layers, respectively.

Using Equations (1) and (2), Hironaka and Holland [44] demonstrated for temperatures from 25 °C to 60 °C that the increase in pressure overcomes the uplift resistance and can cause blistering even with an extremely modest amount of water. In the literature, blister tests have investigated the sealants and asphalt materials' bond strength [72]. Stene [57] developed a pressurized blister test composed of a container partially filled with water and an asphalt slab laid on a perforated aluminum plate to verify whether the Norway climatic conditions caused the observed damage. Two slabs were investigated: they differed in width (3 cm and 4 cm, while their size in the plan was 30 × 30 cm) and void content (2–5%). The results demonstrated that the expansion of air and steam under the slab allowed for the formation of a surface bubble. The pressure model cannot overlook the surface tension of the water because it prevents outflow through the interconnected voids if their diameters are less than 4×10^{-3} cm [40]. Under such geometrical conditions, and with modest hydraulic loads, the water in the accessible voids remains trapped in the narrow interconnecting channels, obstructs the passage of gases, and generates the conditions for blistering to start. The results from [57] demonstrate that water in asphalt voids contributes to the phenomenon.

For thin slabs and small deformation, Equation (4) describes the vertical uplift:

$$d(r) = \frac{3pa^4(1-\nu^2)}{16Eh^3}\left(1-\frac{r^2}{a^2}\right)^2 \tag{4}$$

where *d*(r) is the vertical uplift at distance *r* from the center of the blister, *p* is the pressure inside the blister, *a* is the radius of the debonded area, *h* is the asphalt thickness over the bulge, and *v* and *E* are the Poisson's ratio and Young's modulus of the material, respectively.

However, deformations on sidewalks do not agree with the hypothesis of a thin membrane because the maximum uplift is even more than the asphalt thickness. Therefore, shear forces significantly contribute to the phenomenon according to Equation (5) [8]:

$$d(r) = \frac{3pa^4(1-\nu^2)}{16Eh^3}\left(1-\frac{r^2}{a^2}\right)^2 + \frac{3pa^2(1-\nu)}{5Eh}\left(1-\frac{r^2}{a^2}\right) \tag{5}$$

In many cases, the volume of the bubbles increases throughout the day as a consequence of a process that allows more air to enter the bubble than go out. The blister can expand until rupture, leaving a pit that allows water to enter the pavement [73]. Lai [74] supposed that the pavement begins to warm up in the morning, creating a top-down thermal gradient and reducing the asphalt stiffness. In the meantime, the air and water in the voids increase their temperature and begin to expand and evaporate, respectively, with a consequent increase in the total pressure. The gas thrust can lead to lifting, with a new condition of equilibrium between the gas pressure, the asphalt bulk density, the adhesion or indirect tensile strength, and the resistance to deformation. At sunset, the asphalt temperature decreases, and the stiffness modulus increases. Cooling occurs in the same direction as the heating process (i.e., from top to bottom). The cooling asphalt cannot recover the original configuration, thus maintaining the acquired deformation, although the gases no longer exert the outward thrust [75]. This volumetric deformation determines the onset of negative pressure inside the bubble and the air suction inside the cavity. Micro-cracks that thermal shrinkage could have caused on the pavement materials contribute to this process [74]. Through repetition over the days, accumulation of the air in the bubble, an increase in the lift, and its surface extension occur.

4.2. Buckling Approach

The buckling theory of plate elements can support the hypothesis that blisters come from critical thermal in-plane loads. In particular, the circadian variation in the surface temperature implies residual stresses at each starting cycle that cause a ratchet process and lead to incremental plastic deformation. The smallest value of the critical load that causes instability implies the formation of only one half-wave in the direction perpendicular to the load application. Due to the circular geometry of the bubbles, the problem is symmetric in the horizontal plane, and it is possible to assume that the aspect ratio (i.e., a/b) is equal to 1. Equation (6) gives the bending stiffness of a thin uniform plate:

$$D = \frac{Eh^3}{12(1-\nu^2)} \tag{6}$$

where E is the Young's modulus, ν is the Poisson's ratio, and h is the uniform thickness of the plate.

In such conditions, the buckling coefficient k_{cr} is equal to 3.670 for stiffened elements. Equation (7) gives the critical stress for a uniaxially compressed sheet resting on a rigid underlying subgrade:

$$\sigma_{cr} = 3.670D\frac{\gamma\, h}{\overline{w}} \tag{7}$$

where γ is the specific weight of the material of the sheet, and $\overline{w}$ is the uplift deformation.

In asphalt pavements, discrete imperfections and continuous supports under the upper asphalt layer can trigger buckling [24]. Under such conditions, Equation (7) can be applied to Equation (8) due to the amplitude of the initial bulge-type imperfection ($\overline{w_0}$):

$$\sigma_{cr} = 1.835\mathrm{D}\frac{\gamma\, h}{\overline{w_0}} \tag{8}$$

Imperfect foundation layers and low friction coefficients can contribute to the uplift buckling distress [76,77] of the surfaces exposed to seasonal temperature variations. Therefore, the system develops a thermally induced buildup because of a small out-of-flatness of the lower layer (e.g., a protruding aggregate of the foundation layer or an irregular surface laying) [18]. However, while asphalt pavement is an elastic sheet, its self-weight is significant [26], which cannot be overlooked to model pavement subject to biaxial in-plane compression [78]. Moreover, Croll recognizes that the uplift of asphalt blisters is not sudden [18], which a buckling phenomenon would require.

5. Concurrent Causes and Discussion

The thermal conditions of asphalt and air drive the blistering phenomenon because they cause gas overpressure under or within the wearing layer and critical compressive stress in the plane of the initially flat plate. Nevertheless, the asphalt properties and boundary conditions can contribute to blistering:

- The asphalt thickness over the bubble plays a pivotal role in whether or not distress occurs. The wearing layer acts as a deformable membrane that retains gases and prevents their expansion into the atmosphere [57] or suffers from buckling effects due to a ratchet process [18]. The opposing weight force and the bending stiffness of the membrane depend on its thickness: the higher the thickness of the material that covers the bubble, the greater the weight force that the upheaving gas pressure or the temperature compressive stress will have to exert on the surface. Assuming the wearing layer is a flat plate, the greater its thickness, the greater the stiffness against the flexural deformation outside of the plane. Thin layers [57] make the appearance of blistering more probable;
- Bitumen affects the complex constitutive law of asphalt and determines a variable viscous-elastic response depending on the surrounding conditions. The response of a rheological mixture depends on the load application method, delivery timing, and temperature [65]. Asphalt inherits variability in its deformation behavior from the binder. Thus, when a load is applied, it has a mixed viscous-elastic and plastic response by varying the boundary conditions [57]. Since the growth of bulges requires at least a few hours, the pressure generated by the expansion of the gases translates into a load applied slowly and a mixture whose surface temperature can reach 65 °C. At hot temperatures, creep behavior is dominant, the equivalent elastic modulus decreases, and the critical stress to create a buckling effect reduces;

- The adhesive bond strength of asphaltic material and aggregates prevents failures due to stripping [27,28];
- Waterproof upper layers promote membrane behavior, and waterproof lower layers prevent overpressure from dissipating when thermodynamic processes cause or contribute to bubbles. The greater the quantities of gas trapped inside the pavement that are unable to interact with the outside due to the presence of waterproof membranes, the more likely blistering is to happen [68];
- The permeability of both water and air of asphalt plays a pivotal role in the blistering process: water is necessary for gas overpressures that contribute to buildup, while air voids make possible dynamic equilibrium conditions among the air, water, and bitumen. In particular, high surface temperatures can lead to leaking, which closes the voids and contributes to the impermeability of the wearing layer and its membrane effect [25];
- Concerning water permeability, Awadalla et al. [79] demonstrated for void content values higher than 8% that the greater the void, the higher the water permeability. On the other hand, mixtures with a void content below 3% have the opposite condition because the voids are not interconnected and avoid filtration paths. Therefore, an air void content below 3% and a water permeability coefficient lower than 1×10^{-8} m/s are assumed to be the impermeability indices [7]. The analysis of the role of water permeability therefore indicates that the prediction of the possibility or otherwise of blistering in a given superstructure can be trusted for the evaluation of hydraulic conductivity [40];
- Concerning air permeability, Sasaki et al. [40] identified the threshold for the air permeability coefficient (i.e., 10^{-9} m/s) below which blistering is observed;
- A proper mix design using bitumen with a high softening point can help prevent blistering, which can delay the loss of consistency of the asphalt mixture. Additionally, the grading of aggregates, the bitumen content, and the compaction temperature affect the presence of gases in mixtures;
- The construction process (e.g., the weather conditions during roadwork, the procedures and machines used to lay the pavement) can lead to gases being trapped along the separation plane between the wearing and binder layers (or the two upper ones). Meader et al. [80] suggest working after the daily maximum surface temperature has been reached;
- Whatever the physical process, construction defects (e.g., imperfect plane surfaces or an initial debonding aperture) [81] or damage of the layers (e.g., cracks where water enters) increase the chances of a blister occurring [3,32,67];
- The surface roughness of the lower layer and the tack coat counter blistering: overlays on the smooth layers and not enough or an absent tack coat promote surface buildup [28]. Furthermore, the tack coat can play contrasting roles because it ensures the continuity between the two upper layers of the pavement and allows for waterproofing of the lower layer [65].

According to the scientific literature, blistering is an asphalt distress phenomenon whose origin and development mechanisms still need investigation due to its low frequency compared to fatigue and rutting. Blistering consists of local uplifts that are essentially circular with variable dimensions: their diameter can reach 1 m, and their maximum height is usually a few centimeters above the ideal and initial flat surface [10]. It is an irreversible (or partially reversible) process consisting of non-linear blister growth dynamics, which can start during daytime hours at the interface between two layers or within the upper layer and can have different consequences [7]. It is common in hot climates when surface temperatures rise due to solar radiation and often occurs after exposure to rain, fog, or other water sources [5]. Table 1 summarizes the most significant hypotheses about blistering's main and concurrent causes and boundary conditions.

Table 1. Main and concurrent causes and boundary conditions of blistering.

Variables	Main Cause	
	Buckling [18]	Thermal Expansion [44,57,60]
Necessary variables	Thin layers [24,57,64]	Water and voids within the asphalt [40]
Boundary conditions	Hot temperatures [18,63]	Hot temperatures [74,75]
Physical processes	Instability [64]	Overpressure, evaporation [70]
Concurrent causes	Construction defects [66,81] Imperfect foundation layers [76] Low friction coefficients [77]	Imperfect bond between layers [42] Low tensile strength of the asphalt [43] Air void content and water conductivity [40,79] Membrane behavior [68] Stripping [27,28]

6. Conclusions

Blistering on asphalt pavements is a complex mechanism governed by several boundary conditions. Its behavior is diurnal, and the solar radiation and heat transmission within the upper pavement layers drive the phenomenon. Despite decades of research about this phenomenon, its origin and development mechanisms are unclear. Thermal conditions seem necessary but do not raise the pavement surface enough for safety and functional consequences.

According to the scientific literature, two physical–mechanical processes drive the distress evolution: bottom-up pressure induced by gases trapped under or within the upper layer and buckling conditions. Intensive moistening of the structure in rainy periods and solar radiation in hot periods can contribute to blistering. Indeed, high asphalt temperatures cause decreases in the asphalt tensile stiffness and adhesion strength, the thermal expansion of entrapped gases in the asphalt voids, the evaporation of water under or within the upper layer, and out-of-plane deformation. According to the buckling theory of plate elements, critical thermal in-plane loads lead to instability and cause blisters. Both chemical and geometrical bonds between the upper and lower layers can reduce the risk of surface blistering. Further analyses should investigate the relationships among the void content, the water and air permeability, and the variation in the water/air permeability and void content/distribution due to cyclic temperature variations. In addition, the surface and gradient temperatures of asphalt varying the thermal performance of its components, the weather conditions, the shear friction between the wearing and binder layers, the adhesion bond between the wearing and binder layers, the influence of traffic, and the role of the smoothness and permeability of the lower layers are worthy of investigation. Due to the increasing extreme heat events, blistering occurrence may increase, and highly reflective materials and the physical properties of non-permeable-to-water but permeable-to-air mixtures could be ideal solutions. On the other hand, in roadworks, attention should be paid to cold and hot joints, the roughness of the lower layer, the tolerance for out-of-flatness, and the quantity and performance of the tack coat.

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