Assessing Hazardous Spills Impact on Road Surface Performances by 3D High Resolution Surveying Techniques

Published Version:
Girelli, V.A., Cotignoli, L., Ghasemi, N., Lantieri, C., Tini, M.A., Vecchione, R., et al. (2023). Assessing Hazardous Spills Impact on Road Surface Performances by 3D High Resolution Surveying Techniques. Springer International Publishing [10.1007/978-3-031-20241-4_18].

Availability:
This version is available at: https://hdl.handle.net/11585/906126 since: 2022-11-23

Published:
DOI: http://doi.org/10.1007/978-3-031-20241-4_18

Assessing Hazardous Spills Impact on Road Surface Performances by 3D High Resolution Surveying Techniques

Valentina Alena Girelli[1], Luca Cotignoli[1], Navid Ghasemi[1], Claudio Lantieri[1], Maria Alessandra Tini[1], Rossella Vecchione[1], Gabriele Bitelli[1] and Valeria Vignali[1]

[1] DICAM Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Viale del Risorgimento, 2 – 40136, Bologna, Italy,
valentina.girelli@unibo.it; luca.cotignoli2@unibo.it; navid.ghasemi3@unibo.it; claudio.lantieri2@unibo.it; mariaalessandra.tini@unibo.it; rossella.vecchione95@gmail.com; gabriele.bitelli@unibo.it; valeria.vignali@unibo.it

Abstract. Surface texture of a road pavement is recognized as one of the most relevant parameters in driving safety. Spillages on the highway can lead to dangerous conditions for road users and cause damage to the road surface. Hazardous substance spills caused by traffic accidents threaten the safety road and request a specific clearance operation to reduce the risk of asphalt surface degradation. The aim of this paper is to evaluate the effect of usual hazardous liquids spilled during traffic accidents from vehicles on the asphalt properties and related safety parameters. The experimental application is performed via digital photogrammetry. The application of 3D geomatic techniques allows to calculate new texture indicators through geometric and colorimetric information more accurate than traditional survey techniques. The proposed approach can constitute a new useful investigation method, in addition to traditional surveys, which are slower and less precise. The texture reading by using three-dimensional analysis is an innovative way to obtain and compare the traditional performance indicators used to measure friction with new proposed indicators. In particular, the described experience evidences the mechanical behaviour and the structural damage of asphalt samples related to different exposure times treated with five hazardous liquids. Both traditional and innovative techniques are carried out to evaluate roughness (British Pendulum Number, BPN). The obtained results show how the various substances affect in different way the samples asphalt surface.

Keywords: road pavements, texture, geomatics, digital photogrammetry, hazardous spills.

1 Introduction

Pavement surface texture is one of the most relevant contributing elements to satisfy users driving safety, noise pollution and environmental sustainability. Nowadays, multiple parameters are used to evaluate and classify the surface layers performance. Surface texture influences many road features as skid resistance, ride quality and tire-pavement noise [1].

It is important for road authorities to guarantee sufficient skid resistance level, monitoring the surface pavement condition and developing methodologies of road texture analysis to define the optimal maintenance for infrastructure trough preventive activities [2, 3]. It is clear that the knowledge of the frictional properties and the awareness of the measurement methods are particularly important for the safety of road users [4]. In order to assess the pavement surface characteristics, texture indicators are measured and they can be grouped into three main classes. The first category includes geometrical parameters related to the microstructure of the specimens. The second category takes into account statistical parameters that are also referred to the geometry of the profile. The last class is composed by performance indicators, which are close to the issue of skid resistance [5]. Both national and international standards regulate the evaluation of the aforementioned indicators. The tests most frequently used to provide significant outcomes about the skid resistance of a pavement surface is the British Pendulum test (EN 13036-4) [6].

Road safety issues can occur during road accidents due to the possibility of hazardous substances spillages. After road accidents, vehicular fluids are released on pavement surface contributing to increase the risk of road surface material damage during vehicles trafficking. It is well known the importance of efficient spill management programs to prevent secondary accidents and to guarantee the safety of road users and responders [7]. If the hazardous substances are not removed quickly, they can lead potentially to worsening of skid resistance condition and to structural damage of bituminous materials. Few researches investigated the behaviour of liquid spills on pavement surfaces. A linear relationship between spill area and spill volume was demonstrated for plane and inclined surfaces in both asphalt and concrete [8]. Baldwin at all. [9] evaluated pavement strength simulating normal loading condition and traffic effects by means of two tests – resilient modulus and wheel tracker.

The texture properties of the pavement surface can be assessed analysing the 3D models of asphalt samples obtained by means of high-resolution geomatic techniques [5]. The implementation of 3D geomatic techniques allows to calculate, through geometric and colorimetric data, new texture indicators more precise than traditional survey techniques. The advantage of using instruments capable of producing and processing three-dimensional data makes possible to calculate superficial and volumetric indicators.

Referring to surfaces and volumes, this kind of survey permits a more stable and complete texture characterization, providing further possibilities of evaluating the pavement surface performances. The 3D documentation methods can be divided into two main categories, Range-Based and Image-Based approaches. In the first case, an active sensor such as a 3D laser scanner is employed for the raw data acquisition to develop the 3D model of the object. In Image-Based modelling, the same result is obtained through a digital camera with appropriate lens, which can make this approach more affordable [10]. In recent years, the aforementioned methods were used also to investigate surface texture data. Pavement surface friction and texture data were analysed to assess the influence of effective texture depth [11] and the prediction of asphalt friction [12]. In both studies, a three-dimensional analysis was carried out using a portable ultra-high resolution laser scanner. Moreover, a friction contact test was conducted to reproduce tyre-pavement friction process and to observe the real rubber-contacted area by means of 3D laser camera [13]. An automatic close-range photogrammetry system (ACRP System) based on three cameras photogrammetry technology was furthermore applied to realize image acquisition and 3D reconstruction of asphalt pavement surface texture [14]. This research demonstrated a good correlation between the Mean Texture Depth MTD values obtained with ACRP system and Sand patch method.

This research aims to evaluate the effects on the asphalt properties and related safety parameters of five hazardous liquids typically spilled from vehicles. As mentioned, asphalt road surfaces are degraded over time by liquid spillages and it can contribute to irreversible material damage during trafficking. Therefore, the exposure time become a fundamental parameter that is considered in this survey to evaluate the different behaviours of contaminated asphalt samples. The experimentation compares the specimens characteristics before and after the spillages. Moreover, the behaviours of specimens are analysed related to different exposure time to determine how hazardous liquids affect bituminous conglomerate and how road surface performances change over time.

The experimentation is carried out in laboratory constructing 3D models based on photogrammetric methods and performing skid resistance test on asphalt samples cored from an existing pavement. The three-dimensional models are created for both uncontaminated and contaminated samples to determine a volumetric indicator, which relevance will be explained later. The surveys and the comparisons of road surfaces are carried out at different epochs. This procedure requires a redundant number of photos from a wide array of positions for images acquisition, then a “Structure for Motion” (SfM) approach is applied to obtain a raw 3D model, which is implemented through dense image matching and model georeferencing. The pavement friction in both dry and contaminated conditions is evaluated by means of British Pendulum test.

The proposed approach can constitute a useful investigation method for fast surveys, in addition to traditional ones. The possibility of obtaining texture information from three-dimensional data involves a series of advantages in monitoring the paving quality, detecting texture characteristics with high accuracy and reliability of results. Three-dimensional parameters are in fact more representative of a portion of road paving in respect to single profiles.

2 Geomatic Methods for High Resolution 3D Modelling

Many engineering and industrial applications find advantages in accurate 3D measurements and modelling. In the Architecture, Engineering and Construction industry, in the last 25 years, the need of acquiring 3D data for building and civil infrastructures has increase more and more in many applications, hand in hand with the technological development of sensors and surveying techniques [15]. In every phase of a project life, the availability of reliable 3D data support and facilitate the work of designing, impact estimating, checking the progresses, sharing, reporting, programming the future interventions, etc. One thinks, for example, of the revolutionary impact that the adoption of Building Information Modelling (BIM) has had in the construction sector [16].

For the 3D surveying and modelling of infrastructures as buildings, bridges, roads and rails, the geomatic techniques that have now become a standard are the laser scanner systems (terrestrial or mobile) and the digital photogrammetry (terrestrial or by UAV), thanks to their capabilities to record 3D data in a fast and accurate way. Point clouds and models obtained by these techniques, alone or in integration, also with other surveying techniques and sensors, can be exploited for many different purposes, from the digital documentation to geometrical studies, as a fundamental support for restoration, monitoring and structural analysis, or for HBIM applications [17, 18].

Next to these applications, are nowadays emerging sensors and methodological solutions aimed at very high-resolution 3D modelling of objects, specifically oriented to the geometrical characterization and monitoring of surfaces and objects with sub-millimetric precision [19, 20].

For these particular case studies, 3D scanning using Triangulation or Structured-Light Projection and SfM photogrammetry are the most suitable surveying techniques to obtain reliable and very accurate 3D models.

Scanner systems directly acquire the 3D model of the object. The workflow is well known: the point clouds describing the object surface, measured from different positions, are aligned in the same reference system and triangulated to generate meshes. The scans are fused together in one final mesh, which is furthermore edited to fix problems like noise and holes, to reduce the resolution or to optimize the whole surface. The final step is usually the application onto the mesh of the RGB images acquired contextually with the geometric survey, to obtain the photo-textured 3D model.

SfM digital photogrammetry permits nowadays to obtain in an automatic way, by means of the images of the object acquired from different positions, a similar raw product, which is a dense point cloud of the object surface. After the generation of the point cloud, the processing follows the same steps previously described. One of the differences between the two techniques is that photogrammetry requires some reference data: at least a distance on the object, known with great precision, to correctly scale the 3D model, or a certain number of points of known coordinates to orient the model itself in a specific reference system.

Each of these two approaches presents peculiar potentialities and limitations: the choice of the most appropriate technique depends on many factors, such as type of object or scene, material, purpose of the survey, required detail, budget, logistic constraints. Seen all these considerations, it is today well proved that the integration between these two approaches is often the best answer.

In the described case study, the initial idea was to use both techniques in order to analyse their performances and compare the obtained results. Unfortunately, this was not possible because, after the spill, the samples surface was too wet, consequently too shiny and dark to be acquired by a Structured-Light Projection scanner. For these reasons, it was decided to use only photogrammetry. Given what was said above, a Structured-Light Projection Scanner was used to establish the absolute reference system in which all the 3D models of the samples surfaces were then inserted.

The surveying and data processing operations will be described in the paragraph 3.2.

3 Experimental Program

The purpose of the experimentation is to create three-dimensional models of asphalt samples spilled with five hazardous substances in order to assess the consequential mechanical and physical behaviours by means of volumetric indicator. As mentioned, the survey was carried out in laboratory through a traditional method and digital photogrammetry. The photogrammetric survey was carried out to observe the roughness of road surfaces at different epochs by analysing the volumetric variation. The British Pendulum test (BPT) was performed to assess the damage due to the hazardous spill on asphalt specimens measuring the skid resistance. The standard procedure was applied to evaluate the asphalt properties in accordance with CNR 105/85 standard, which is transposed by UNI EN 13036-4 where it is calculated the Pendulum Test Value (PTV). The British Pendulum Number (BPN), i.e. the average of the five obtained results, was calculated for each sample and it was corrected by specific coefficients depending on the temperature of the sample. All the samples were tested at a temperature of 25°C.

3.1 Test Preparation and Spill Procedure

When traffic accident occurs, several hazardous material spills can be released. The types of hazardous material spills that result from road accidents can be classified in vehicular fluids and cargo spills [21]. The most frequently spilled types of substances are those used in the operations that guarantee the locomotion of the vehicle. In addition to the type of liquid spilled, many variables can influence the road surface performances such as exposure time, liquid volume, temperature and traffic condition.

This research investigates the behavior and the impact of the most common hazardous vehicle fluids: fuel, oil and battery acid. Five liquids were selected and analyzed, according to the quantity present in vehicles and heterogeneity in terms of behavior, composition, and toxicity. Each substance has been spilled on two samples to get more meaningful results. The five hazardous liquids spilled were: diesel, petrol, engine oil, brake oil, sulphuric acid.

Moreover, due to the unforeseeability of traffic incidents and the handling time for the clearance operations, the tests were performed related to a specific timeline. The surveys were performed: 5 min, 30 min, 1h, 2h, 4h, 6h, 1d and 2d after the spillage. The acceptable volume of spilled liquid was evaluated in a preliminary phase to cover homogeneously the specimens after the spill. The optimal quantity considered was about 60 ml. This survey analyzed pavement skid resistance without considering the actions of traffic flow, in order to assess, above all, the behaviors of asphalt samples spilled with hazardous substances. Since high traffic volume can lead with a reduction of skid performances, future research will consider the presence of traffic. As this survey reflected the real environmental condition and material properties, the experimentation temperature was fixed at 25°C, which is a meaningful average temperature value in Italy.

In the light of the previous considerations, the variables influencing the effect of road surfaces and the assessments made in this survey for each of the parameters were summarized in Figure 1.

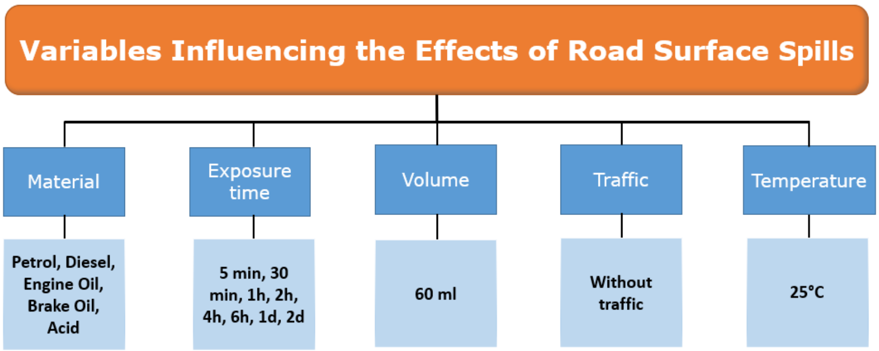


Fig. 1. Experimentation variables

Asphalt samples were cored from an existing road pavement. The final specimens had cylindrical shape with a nominal internal diameter of 150 mm and a height of 100 mm. The specimens are constituted by a commonly used wearing course layer realized on a binder layer. The US25 wearing course, which represents the surface layer, used in the current experimentation was realized with traditional unmodified bitumen (50/70) and aggregate passing at 8 mm sieve. The characteristics of the asphalt mixture, shown in Table 1, are related to bitumen content, density, voids and degree of thickening.

Table 1. Wearing course characteristics

Bitumen content	**Weight/Volume**	**Voids**	**Degree of thickening**
%	g/cm^3	%	%
5.76	2.174	10.52	97.21

The various specimens were cleaned of any residual sand and debris caused by coring procedure that would have compromised the experiment. Then, they were placed and confined in a flat container, around which two types of coded targets were attached related to two different photogrammetric packages: Agisoft Metashape and Bentley ContextCapture. However, only Metashape targets were used in the processing here described.

All samples were analyzed before the spill and subsequently at the aforementioned time periods. The external surface was sealed with a plastic film investigating the worst case scenario in which the liquid is not allowed to drain via surface texture.

Fig. 2. Experimental procedure and pouring operation

3.2 Photogrammetric Survey and Data Processing

For each combination of sample and exposure time reported in Figure 1, in order to obtain an accurate 3D model by photogrammetric processing, eight photos were taken with a compact camera (Sony Cyber-shot DSC-RX100 VII, 20 Megapixel) from different positions and angles. Of these eight shots, six were taken with an optical axis converging to the specimen surface and two with a perpendicular optical axis (nadiral photos) (Figure 3a). In this way each photo contained the entire surface of the specimen and those targets positioned around it were easily identifiable.

Before proceeding with the spillage of hazardous substances, each sample was also scanned using a high-resolution structured-light projection 3D scanner, based on blue light technology (3D Artec Spider, accuracy up to 0.05 mm). Thanks to the size and shape of the specimens it was possible to complete the survey with a unique scan, in order to reduce the incidence of alignment errors among different scans. For each scan, the frame registration was performed with the highest accuracy level available for the adopted scanner model.

Finally, it was obtained a 3D photo-textured optimized mesh of each sample with respective targets, characterized by a resolution of 0.1 mm. These models were used to establish the absolute reference system of the specimens: each Cartesian tern was defined with the XY plane coincident with the best-fit plane of the top surface of the corresponding specimen in such a way that the Z-coordinate represents the surface roughness. The target coordinates measured on these meshes were used during the photogrammetric processing and to scale and insert the 3D models in an absolute reference system. Thanks to the technical characteristics of the scanner and the way in which the scanning and its subsequent processing was carried out, the coordinates of the targets were assumed to have an accuracy in the order of 0.1 mm.

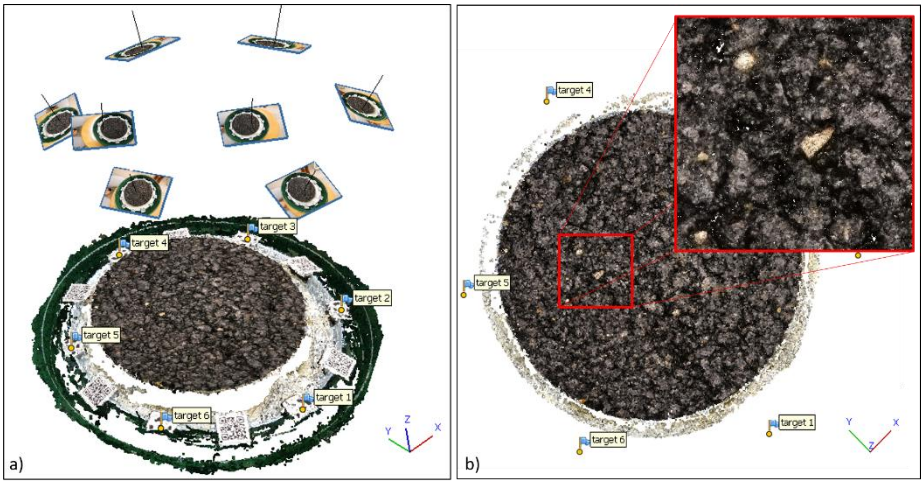


Fig. 3. 3D modelling of the asphalt surface: a) images acquisition scheme, target distribution and orientation of the absolute reference system; b) density and descriptive quality level of the obtained point clouds.

Photogrammetric processing was performed using the Structure from Motion approach, obtaining for each set a high dense point cloud composed by more of 8 million points in the specimen top surface, with a density of about 180000 points per cm^2 (Figure 3b). The average reprojection error of the points was estimated in 0.7 pixel with an estimated Ground Sample Distance of about 0.06 mm/pixel.

Each point cloud was then cleaned and cropped removing the outer circular ring, obtaining a disc with a diameter of 12 cm. In this way, it was possible to remove external disturbances considering only core samples with same size, to perform the comparisons analysis between models related to different exposure times.

The analysis was carried out in two different ways: by comparing the surfaces of the specimens in different epochs and by comparing the roughness parameter extracted from the 3D models.

In order to make it easier to compare the Z-coordinate of different models and consequently to estimate whether the surface has been worn or swollen, both analyses were carried out on regular grids obtained from each point clouds by means of a Natural Neighbor algorithm, keeping the original data obtained by photogrammetric processing as pure as possible. The grids are the same for all specimens in terms of both limits and spacing.

The surface comparison was performed, for each sample, by subtracting the surface grid at different exposure time from the corresponding surface without hazardous substances at time 0, that is before the spillage. The obtained difference values were used to realize a classed post map for the surface comparison and to extract some statistical parameters (maximum and minimum value, average, standard deviation). Based on the precision of the photogrammetric survey, and applying variance propagation to the differences, the maps were constructed considering a tolerance limit of ±0.2 mm: differences within this range of values are to be considered not significant.

The roughness parameter was extracted for each exposure time from the 3D model of the specimens top surface. As mentioned before, the roughness is traditionally expressed by a characteristic parameter calculated on profiles. Whereas, in the present case, it was calculated with a three-dimensional approach directly on the whole surface. To this aim, the average of the Z-coordinate values was first identified. Then the positive and negative volumes of the surface were calculated, with respect to the plane of this average value and the corresponding plane areas. Finally, the roughness parameter was calculated as the ratio between the sum of the volumes and the sum of the areas (Figure 4).

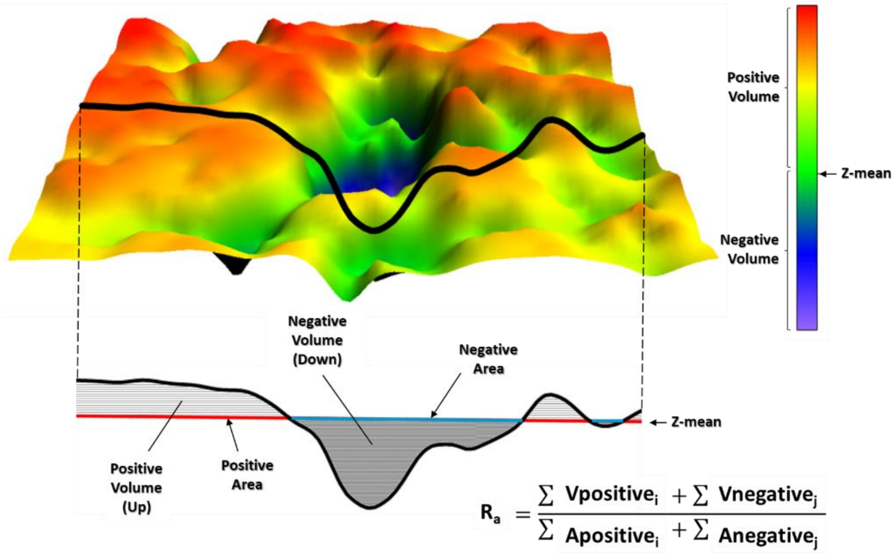


Fig. 4. Definition of the surface roughness parameter on a volumetric basis

4 Results

The analysis of the 3D model generated by photogrammetry and the skid test results are shown and discussed. The results are reported in relation to the macro-categories of hazardous substances tested and the main observations concern:

- the temporal trend of skid resistance;
- the state of liquid absorption and the structural response over time;
- the comparison between the surface maps of the spilled samples in a specific time interval;
- the relative roughness trend.

The results, concerning the BPT, were analysed to investigate the skid resistance characteristics of the spilled samples over time (Figure 5). Figure 6 shows the development of the relative surface roughness value over time. In order to compare the results, in this survey it was considered the average of BPN and the roughness parameter of the different type of spills related to the samples tested. As mentioned, the test was carried out on two specimens for each type of substance.

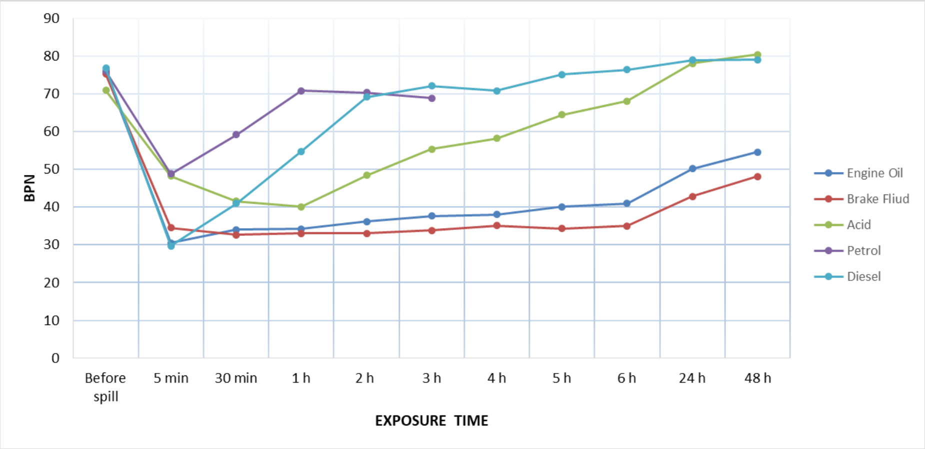


Fig. 5. Temporal trend of skid resistance (British pendulum test)

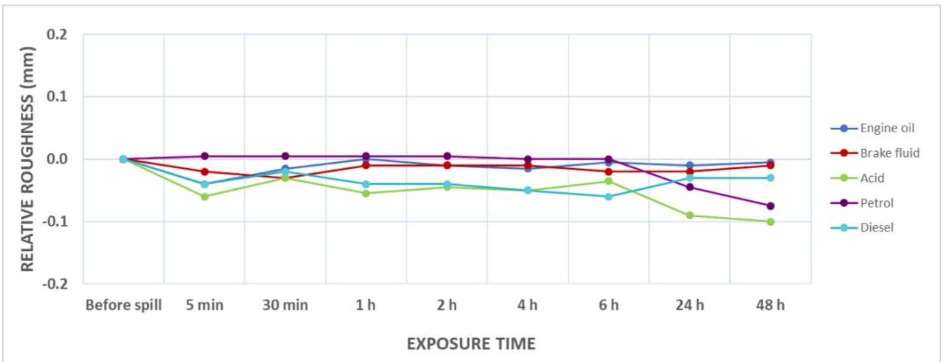
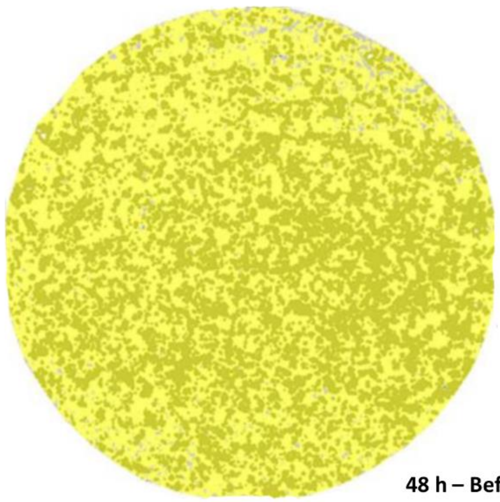


Fig. 6. Temporal trend of relative roughness

The oily liquids (engine oil and brake oil) revealed the worst skid resistance recovery over time, leading to critical surface performances even after 48 hours from the spill. This type of hazardous liquids generated an abruptly decrease of skid resistance, about 60%, immediately after the contamination. In the first period of the test, until six hours, the skid resistance was halved, about 40 BPN for engine oil and 35 BPN for brake oil. The contaminated asphalt samples partially recovered their skid resistance only 24 hours after the spill. After 2 days, the skid resistance was recovered up to 64% for brake oil and 73% for engine oil compared to the initial value.

The relative roughness trend of all the specimens treated with oils was almost unchanged. These results can be linked to the persistence of oils on samples surface, which creates a smooth layer on the specimens inducing a bulk smoothness of the surface.

All samples showed as well a slightly swelling of the difference surface maps. This behavior is particularly evident for the specimens treated with engine oil, due to its higher viscosity. As an example, Figure 7 shows the results obtained by comparing the surface of one of the specimens treated with engine oil before spill and after 48h.



Minimum	Maximum	%
-1	-0.5	**11.7**
-0.5	-0.2	**55.0**
-0.2	0.2	**32.1**
0.2	0.5	**0.9**
0.5	1	**0.3**

Minimum	-4.9
Maximum	3.3
Mean	**-0.3**
Standard deviation	0.2

Fig. 7. Specimen treated with engine oil: map of the differences between the 3D models of the surface before the spill and after 48 hours (mm).

The fuel liquids (diesel and petrol) showed a rapid recovery of skid resistance in the short-period, demonstrating a better reaction in terms of adherence compared with oils. Increasing the exposure time, it was registered a gradually and linear restoration of skid resistance in the range 5 min – 2 hours. After 2 hours, the skid resistance value was recovered up to 90% for both diesel and petrol.

All the samples treated with fuel liquids showed a swelling of the surface, two days after the spillage, resulting from dissolution of the bitumen causing an increase in voids and a release of stresses within the specimens (Figure 8). The relative roughness showed a slight decrease over time, which became particularly noticeable after 6 hours in the case of petrol. The observed time delay in roughness variation can be related to liquid high volatility which increases the time required to modify the asphalt samples structure. However, both the fuel liquids slightly reduced asphalt roughness of the specimens by smoothing them surface.

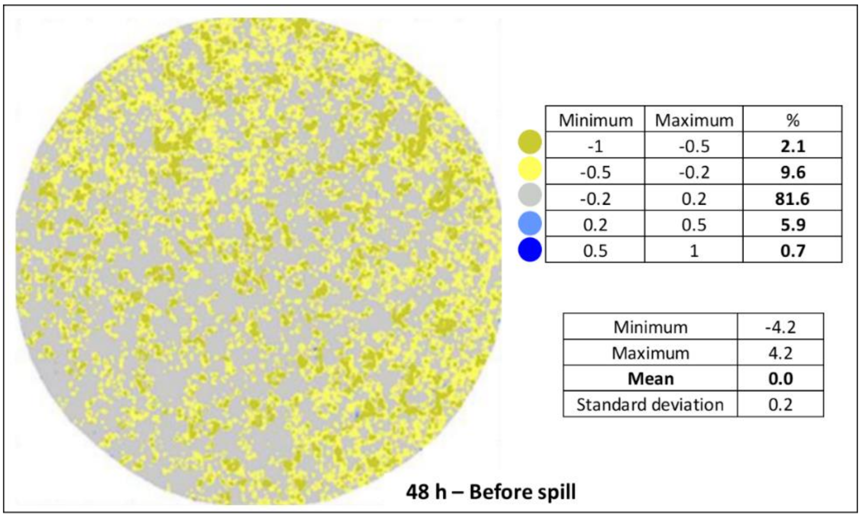


Fig. 8. Specimen treated with diesel: map of the differences between the three-dimensional models of the surface before the spill and after 48 hours (mm).

The samples, contaminated with sulphuric acid, demonstrated an intermediate trend compared to the fuels and oils tested. The skid resistance increased gradually over the exposure time and after one day from the spill the samples recovered the initial skid resistance. The BPN average values revealed that the skid resistance further rose compared to the initial value with a recovery of 112%. This particular condition was due to the chemical reaction between the contaminant and the asphalt surface.

The corrosion mechanism of the sulphuric acid on samples surface is much more visible than for other liquids. Indeed, both samples initially showed a lowering of the upper surface (Figure 9), but 48 hours after the spill the difference maps are characterized by consistent swellings (Figure 10). The relative roughness trend is characterised by a clear decrease.

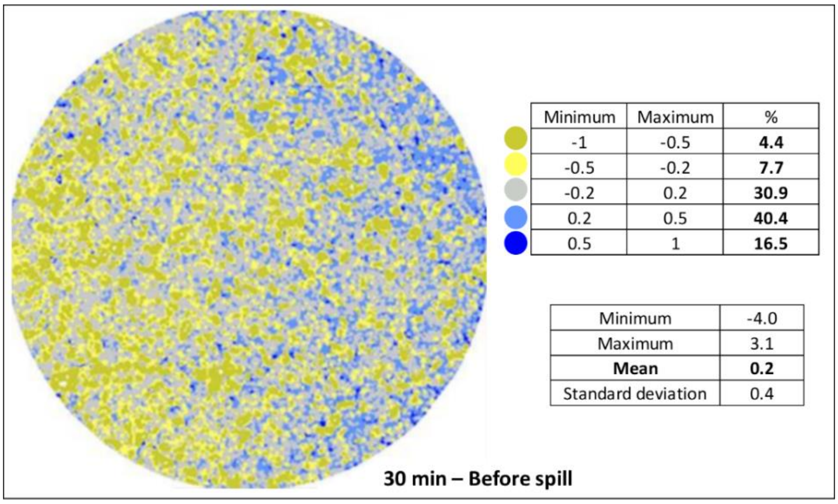


Fig. 9. Specimen treated with sulphuric acid: map of the differences between the three-dimensional models of the surface before the spill and after 30 minutes (mm).

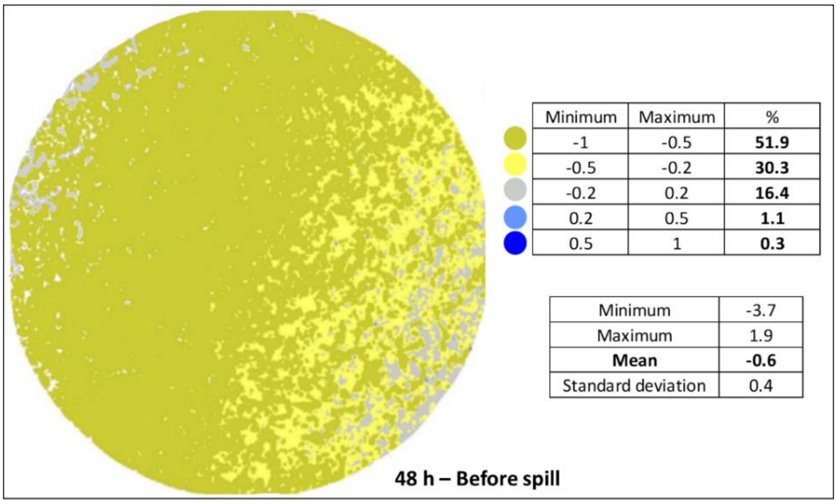


Fig. 10. Specimen treated with sulphuric acid: map of the differences between the three-dimensional models of the surface before the spill and after 48 hours (mm).

The structural response of the samples was different for each category of substances because of their physical-chemical characteristics. In particular, the viscosity and the volatility of contaminants strongly influenced the absorption time. Oils, due to their high viscosity, required much time to be fully absorbed. For example, the engine oil took more than 2 days to be absorbed into the asphalt samples, forming patches that persisted on the specimens throughout the test (Figure 11a). On the other hand, fuels were immediately absorbed by the asphalt samples because of their low viscosity and high volatility. Diesel and petrol completely penetrated the asphalt specimens, causing the asphalt softening in the short period. The bituminous conglomerate specimens, spilled with petrol, showed severe structural damages 30 minutes after the spillage (Figure 11b). It is important to underline that 3 hours after the spillage, no test has been performed due to the fading of asphalt bituminous component and the total degradation of the samples. In the sulphuric acid spills, the corrosion mechanism occurred on the samples surface due to the chemical reaction between the contaminant and the asphalt components, which modified the structural aggregation of the asphalt particles. After 6 hours from the acid treatment, a white film was formed on the samples surface because of the chemical reaction (Figure 11c).

Fig. 11. Appearance of samples 48 hours after spillage of hazardous liquids: a) engine oil; b) petrol; c) sulphuric acid.

5 Conclusion

The study evaluates the effects of hazardous liquids, spilled from vehicles, on the asphalt properties and related safety parameters by means of innovative and traditional methods. The survey results suggest that specific hazardous substances as fuels, oils and acids accidentally released from vehicle components on road pavement strongly affect the asphalt properties and its related safety parameters.

The digital photogrammetry employed in this research resulted appropriate for the characterization of asphalt texture and structural properties. The brightness and reflectivity of the spilled asphalt surface represents in fact a serious problem for the use of an active triangulation instrument. Thus, digital photogrammetry has successfully overcome the problem providing reliable asphalt surface texture for both uncontaminated and contaminated conditions.

All the substances used in this survey have a chemical and physical potential capacity to modify the structural composition of asphalt particles. It was demonstrated that all the spills, except engine oil, caused a reduction of relative roughness leading to a slight smoothness of the surface.

The laboratory results, performed via BPT, have highlighted a relevant reduction of adherence for all the hazardous substances in the short-period (0-30 min). The spillages of brake and engine oil revealed that the adherence properties of contaminated asphalt samples were not recovered also in the long-period. The spillages of petrol and diesel have caused to the tested samples irreversible structural damages which have strongly influenced the performance of the test in the long period.

Future research prospective will aim to obtain further outcomes by means of additional analysis performed under traffic conditions to complement this preliminary survey.

Acknowledgments

The authors wish to thanks the company Zini Elio s.r.l., in particular Carlo Versari, for the support in the development of this research project.

References

1. Woodward, D., Millar, P., Lantieri, C., Sangiorgi, C., Vignali, V., The wear of Stone Mastic Asphalt due to slow speed high stress simulated laboratory trafficking, Construction and Building Materials, 110, 270-277, (2016). https://doi.org/10.1016/j.conbuildmat.2016.02.031
2. Pranjić, I., Deluka-Tibljaš, A., Cuculić, M., Šurdonja, S., Influence of pavement surface macrotexture on pavement skid resistance, Transportation Research Procedia, Volume 45, 747-754, (2020). https://doi.org/10.1016/j.trpro.2020.02.102
3. Lantieri, C., Lamperti, R., Simone, A., Vignali, V., Sangiorgi, C., Dondi, G., Mobile laser scanning system for assessment of the rainwater runoff and drainage conditions on road pavements, International Journal of Pavement Research and Technology, 8, 1-9, (2015). http://hdl.handle.net/11585/519188
4. Mataei, B., Zakeri, H., Zahedi, M., Moghadas Nejad, F., Pavement Friction and Skid Resistance Measurement Methods: A Literature Review, Open Journal of Civil Engineering, (2016). http://dx.doi.org/10.4236/ojce.2016.64046
5. Bitelli, G., Simone, A., Girardi, F., Lantieri, C., Laser Scanning on Road Pavements: A New Approach for Characterizing Surface Texture, Sensors, 12(7), 9110-9128, (2012). https://doi.org/10.3390/s120709110
6. Boscaino, G., Praticò, F.G., Vaiana, R., Spectral Texture Indicators Significance in Relation to Flexible Pavements Surface Performance. In *Proceeding of XXII World Road Congress*, Durban, South Africa, 19–25 October 2003.
7. Daniell, J. N., Traffic Incident Management in Hazardous Materials Spills in Incident Cleaning, Federal Highway Administration, Office of Transportation Operations, Washington, DC, (2009).
8. Simmons, C.S., Keller, J.M., Hylden, J.L., Spills on Flat Inclined Pavements, Pacific Northwest National Laboratory, Washington, DC, (2004).
9. Balwin, B., Carmody, O., Collins, T., Degradation of asphalt due to diesel spills on roads, Road System & Engineering Technology Forum, (2005).
10. Katsichti, V., Kontogianni, G., Georgopoulos, A., 3D documentation of frail archaeological finds using low-cost instrumentation, Int. Arch. Photogram. Rem. Sens. Spatial Inf. Sci., 157–163, (2019). http://dx.doi.org/10.5194/isprs-archives-XLII-2-W17-157-2019

11. Shihai, D., Kelvin, C.P.W., Enhui, Y., You, Z., Influence of effective texture depth on pavement friction based on 3D texture area, Construction and Building Materials, Volume 287, 123002, (2021). ISSN 0950-0618. http://dx.doi.org/10.1016/j.conbuildmat.2021.123002
12. Qiangsheng, D., You, Z., Cheng, L., Yanjun, Q., Allen, Z., Multiscale power spectrum analysis of 3D surface texture for prediction of asphalt pavement friction, Construction and Building Materials, Volume 293, 123506, (2021). ISSN 0950-0618. http://dx.doi.org/10.1016/j.conbuildmat.2021.123506
13. Yuchuan, D., Bohao, Q., Zihang, W., Difei, W., Chenglong, L., Promoting the pavement skid resistance estimation by extracting tire-contacted texture based on 3D surface data, Construction and Building Materials, Volume 307, 124729, (2021). ISSN 0950-0618. https://doi.org/10.1016/j.conbuildmat.2021.124729
14. Chen, J., Huang, X., Zheng, B., Zhao, R., Liu, X., Cao, Q., Zhu, S., Real-time identification system of asphalt pavement texture based on the close-range photogrammetry, Construction and Building Materials, Volume 226, 910-919, (2019). https://doi.org/10.1016/j.conbuildmat.2019.07.321
15. Wang, Q., Kim, M-K., Applications of 3D point cloud data in the construction industry: A fifteen-year review from 2004 to 2018, Advanced Engineering Informatics, Volume 39, pp. 306-319, (2019). https://doi.org/10.1016/j.aei.2019.02.007
16. Ullah, K., Lill, I., Witt, E., An Overview of BIM Adoption in the Construction Industry: Benefits and Barriers, Lill, I. and Witt, E. (Ed.) 10th Nordic Conference on Construction Economics and Organization (Emerald Reach Proceedings Series, Vol. 2), Emerald Publishing Limited, Bingley, pp. 297-303, (2019). https://doi.org/10.1108/S2516-285320190000002052.
17. Girelli, V.A., Tini, M.A., Dellapasqua, M., Bitelli, G., High resolution 3D acquisition and modelling in cultural heritage knowledge and restoration projects: The survey of the Fountain of Neptune in Bologna, ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 42 (2/W11), pp. 573-578, (2019). https://doi.org/10.5194/isprs-archives-XLII-2-W11-573-2019.
18. Barrile, V.; Fotia, A.; Leonardi, G.; Pucinotti, R., Geomatics and Soft Computing Techniques for Infrastructural Monitoring, Sustainability, 12, 1606, (2020). https://doi.org/10.3390/su12041606.
19. Laghi, V., Palermo, M., Gasparini, G., Girelli, V.A., Trombetti, T., On the influence of the geometrical irregularities in the mechanical response of Wire-and-Arc Additively Manufactured planar elements, Journal of Constructional Steel Research, Volume 178, (2021). https://doi.org/10.1016/j.jcsr.2020.106490.
20. Gentilini, C., Finelli, F., Girelli, V.A., Franzoni, E., Pull-out behaviour of twisted steel connectors employed in masonry: The influence of the substrate, Construction and Building Materials, Volume 274, (2021). https://doi.org/10.1016/j.conbuildmat.2020.122115.
21. Daniell, J. N., Traffic Incident Management In Hazardous Materials Spills In Incident Clearance, Federal Highway Administration, Office of Transportation Operation Washington, DC, (2009).