Archives of Environmental Protection
Vol. 50 no. 4 pp. 135–146

PL ISSN 2083-4772
DOI 10.24425/aep.2024.152903

Influence of road surface type on the magnetic susceptibility and elemental composition of road dust

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Keywords: chemical composition, magnetic susceptibility, source apportionment, road dust, concrete surface, asphalt surface

Abstract: The aim of the study was to determine the effect of the type of road surface (asphalt and concrete) and the presence of noise barriers (acoustic screens) on the magnetic susceptibility and chemical composition of road dust collected from national roads and motorways in central and southern Poland. Four roads with asphalt surfaces and four with concrete surfaces were selected for the study. Samples were taken at three control points: in the space between noise barriers, in the space without barriers and at road exits. Magnetic susceptibility measurements and elemental composition analysis (using an energy dispersive X-ray fluorescence spectrometer) were carried out. The results showed high variability with no clear differences between samples taken from asphalt and concrete roads. Magnetic susceptibility values were higher for road dust taken from asphalt pavements near noise barriers and motorway exits, while for open space samples the susceptibility values were about 1.3 times higher for dust from concrete pavements. A similar relationship was observed for the elemental composition. The results showed no clear differences between samples taken from asphalt and concrete roads. The location of the sampling point had a greater influence on the results: the surface of noise barriers, open spaces or motorway exits. Calculated enrichment factors indicated an extremely high enrichment of dust in elements such as Cr, Cu and Zn, a very high enrichment in Pb only for dust collected at motorway exits, and a significant and moderate enrichment in other elements.

Introduction

The growth of the global population is inextricably linked to urbanization, the development of transport, and the expansion of road infrastructure. In Poland, the motorization rate has increased rapidly in recent years, reaching approximately 650 vehicles per 1,000 inhabitants (GDDKiA 2020). This figure is significantly higher than the EU average of approximately 600 vehicles per 1,000 inhabitants. The environmental impact of vehicle operation is largely influenced by factors such as the type, technical condition, and age of the vehicle. One of the most significant contributors to environmental pollution is road dust - a mixture of particles deposited on the road. These particles originate from sources such as the abrasion of the road surface, car components (e.g. wheels, brakes, bodywork, etc.), and winter road maintenance activities. Road dust contains a number of compounds, some of which are potentially hazardous to human health (Khan and Strand 2018).

Assessing the impact of road dust emissions on air quality and human health reveals a troubling trend. In areas near busy roads, annual PM10 concentrations are estimated to be approximately 30% higher than in urban background areas (Baensch-Baltruschat et al. 2020, Starzomska and Strużewska 2024). Similarly, PM2.5 concentrations in these areas have increased by approximately 7%. These trends highlight the growing prominence of road dust pollution in urban areas across all European countries. This issue is particularly concerning due to the role of road dust emissions in deteriorating air quality and their adverse impact on respiratory and cardiovascular health. Traffic-related pollution has been linked to chronic obstructive pulmonary disease, asthma, allergies, infections, and carcinoma (Khan and Strand 2018, Rachwał et al. 2020, Rybak et al. 2023). To mitigate the adverse environmental effects of roads, measures such as noise barriers, also known as green buffers or sound walls, are frequently employed as a means of safeguarding against noise and dust dispersion.

The quality of road dust and aerosol pollutant emissions containing various elements and minerals is affected by a few factors. These include vehicle structure, traffic intensity, quality of communication, road surface type and construction,

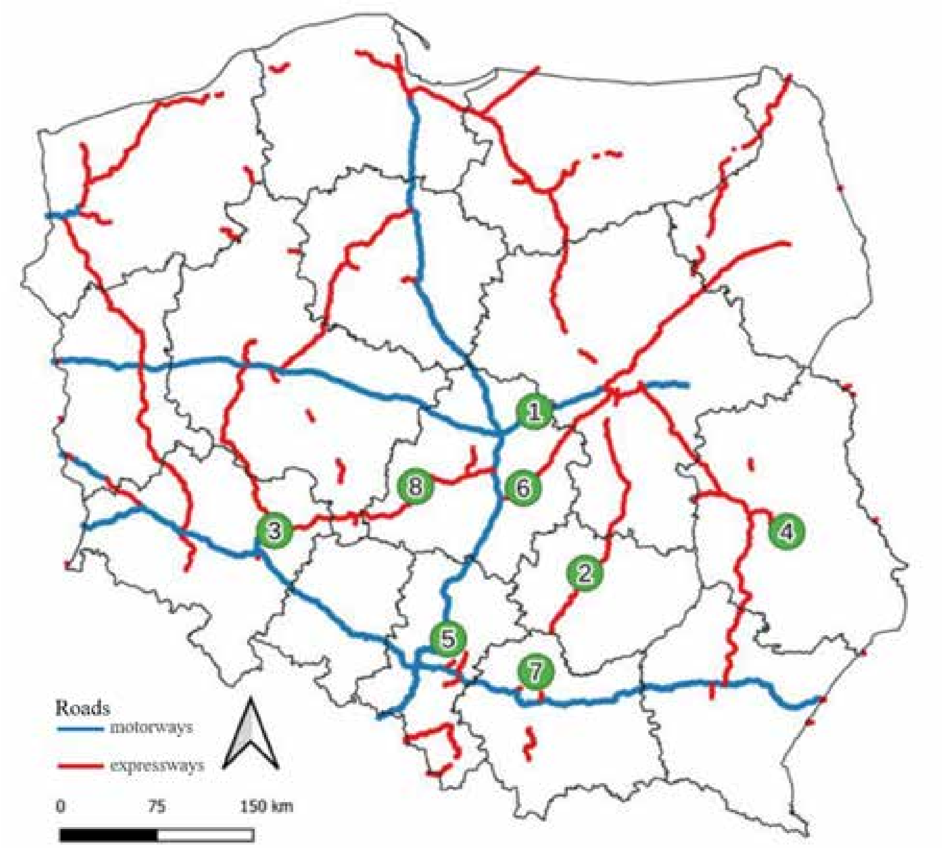

Figure 1. Location of measuring sites (1-4: roads with asphalt surface, 5-8: roads with concrete surface) (Rogula-Kozłowska et al. 2023)

as well as industrial pollution in the surrounding area (Łuczak and Kusza 2019). These emissions originate not only from vehicle emissions (exhaust emissions) but also, to a significant extent, from corrosion of car bodies and mechanical processes accompanying vehicle movement. These include the abrasion of tires, brake pads, and other moving car components, as well as the wear and tear of road surfaces (Bućko et al. 2010, Wawer et al. 2020). Furthermore, the term encompasses the processes like crushing, grinding, and dusting of organic and inorganic materials, including rocks, soils, ores and metals, which occur on or near the road.

Road dust is characterized by a highly complex chemical composition, consisting of a heterogeneous mixture of particles originating from both anthropogenic and geogenic sources (Adamiec et al. 2023, Abbasi et al. 2018). The primarily component of road dust is geogenic soil-derived minerals, including quartz and clay-forming minerals, which collectively account for over 60% of its total composition. Approximately 30% of dust consists of potentially toxic elements (PTEs), primarily originating from vehicular traffic emissions. A smaller fraction, approximately 2%, is composed of plant organic matter (Gunawardana et al. 2012). Road dust also contains secondary particles that have been resuspended in the atmosphere and subsequently deposited as fine solids on road surfaces (Vlasov, 2022). Vehicular emissions further contribute to the presence of technogenic magnetic particles (TMPs), which serve as primary carriers of heavy metals and other PTEs. TMPs are primarily magnetic iron (Fe) oxides and hydroxides, and their presence can be easily detected using magnetic susceptibility measurements (e.g. Hoffman et al. 1999, Bućko et al. 2010, Wawer et al. 2017). These particles are commonly found in soot and originate from corrosion processes as well as the abrasion of metal components, including brake linings, tires, and road surfaces (Marie et al. 2010, Wawer et al. 2020). Magnetic susceptibility, a long-established geophysical parameter, is used to qualify the concentration of magnetic minerals in a sample. Its value depends on the amount of magnetic material present (e.g. Petrovsky and Elwood 1999, Jordanova et al. 2014). Notably, positive correlations have been observed between magnetic susceptibility and heavy metal content in urban road dust (Xie et al. 2001, Bourliva et al. 2016). Fractionation studies separating magnetic and non-magnetic components of road dust have revealed that PTEs are significantly enriched in the magnetic fraction, whereas major elements such as calcium (Ca), aluminum (Al), sodium (Na), and potassium (K) are predominantly associated with the non-magnetic dust particles (Bourliva et al. 2016).

Although numerous scientific studies have been conducted on the magnetic and geochemical properties of road dust and its negative impact on the environment and human health, the diversity of road materials used in construction has not been sufficiently addressed.

Recently, however, the authors of this paper published research on the elemental composition of the finest dust fraction collected from roads with asphalt and concrete surfaces (Rogula-Kozłowska et al. 2023).

This study operates on the hypothesis that the type of road surface significantly impacts both magnetic susceptibility and the elemental composition of road dust. In addition, the location of the measurement point is considered a crucial factor, as it may vary between areas near noise barrier, open spaces, and road exits. The objective of this research, which is an extension of the study, is to determine the effect of road surface type (asphalt or concrete) and the presence of noise barriers on the magnetic susceptibility and chemical composition of road dust. Samples were collected from expressways and motorways in central and southern Poland to provide insights into these variables.

Materials and methods

The study included four roads with asphalt surfaces and four with concrete surfaces (Table 1), located in central and southern Poland (Figure 1). Samples were collected from three control points: between noise barriers (NB), in open spaces without barriers (OS), and at road exits (RE). The control points were spaced approximately 5 km apart, with sampling conducted on both the left and right sides of each selected road. For areas between noise barriers, sections were selected where barriers were present on both sides, with sampling performed approximately 2 m from the edge of the screen. In open spaces, locations free from terrain obstructions, such as trees or buildings, were selected. The road exit (RE) sampling points were situated in areas where the right lane leads to facilities such as service stations or car parks.

Two samples were taken from each side of the road to ensure accurate comparative results without the need to account for variables such as wind direction, wind strength, vehicle number, type, structure and average speed of the vehicles. In order to minimize the influence of de-icing agents and prevent moisture accumulation, sampling was conducted during the summer and autumn months. In total, 48 road dust samples were collected. The material was manually gathered from an area of at least 2 m^2 and stored in sterile 100 cm^3 plastic jars. Samples were then transported to the laboratory, where they were air-dried, sieved through a 2 mm mesh, and prepared for analysis. Magnetic susceptibility measurements were performed, followed by elemental composition analysis using an energy-dispersive X-ray fluorescence spectrometer. The elements analyzed included iron (Fe), chromium (Cr), copper (Cu), manganese (Mn), strontium (Sr), titanium (Ti), zirconium (Zr), lead (Pb), calcium (Ca), aluminum (Al), sodium (Na), and potassium (K).

The mass-specific magnetic susceptibility (χ, given in $m^3 kg^{-1}$) of the dried and weighted samples was calculated using the equation: $\chi = \kappa / q$, where q is the density of the material and κ represents the volume magnetic susceptibility values (dimensionless SI units). The κ values were determined using an MS2 Bartington laboratory magnetic susceptibility meter equipped with a dual-frequency MS2B sensor (0.47 kHz and 4.7 kHz) (Dearing 1994). Elemental composition analysis was conducted at the Centre for Engineering Studies of the National Academy of Applied Sciences in Chełm, using a Shimadzu EDX 7000 energy-dispersive X-ray fluorescence spectrometer. This instrument allows measurements in air, vacuum, or helium atmospheres. The X-ray source consists of a rhodium Rh anode tube, with the beam illuminating the sample from below. The device uses X-ray excitation to determine chemical composition. Instrument settings included a 10 mm collimator, an air atmosphere, and a total radiation exposure time of 60 s per sample. The results were normalized to 100% for semi-quantitative analysis.

Calculations of the enrichment factor (EF) and statistical data analysis were carried out using Microsoft Excel (Microsoft Office 365) and Statistica software (Statistica 13; TIBCO Software Inc). The data showed a normal distribution, enabling the calculation of Pearson's linear correlation coefficients. Additionally, Fisher's test was applied to determine whether the variances of two groups were equal. The correlation matrix was analyzed at a confidence level of $p < 0.05$. Principal Component Analysis (PCA) was used to classify cases and variables, aiming to reduce the dimensionality of the data while preserving key relationships between variables. The PCA results were used to create a principal factor graph, representing the factor structure derived from the variables.

Table 1. Roads selected for the research, mean daily annual volume of vehicular traffic (number of vehicles/day) and their magnetic susceptibility values (mean value of measurements of all control points)

Site number	Road number	Section of road	Surface	Daily traffic *	κ ($\times 10^{-5}$)	χ ($\times 10^{-5}$ $m^3 kg^{-1}$)
1	A2	Warszawa – Łódź	Asphalt	26962	594.83	399.90
2	S7	The bypass of Kielce	Asphalt	16919	28.08	17.97
3	S8	Wrocław – Sieradz	Asphalt	34832	525.61	398.55
4	S17	Lublin –Piaski	Asphalt	12376	395.61	275.10
5	A1	Częstochowa – Katowice	Concrete	31533	261.61	171.27
6	S8	Warszawa – Piotrków Trybunalski	Concrete	22089	502.83	348.28
7	S7	Kraków – Widoma	Concrete	15203	111.44	74.65
8	S8	Sieradz – Wrocław	Concrete	25290	535.17	369.05
Correlation coefficient between traffic intensity and magnetic susceptibility					0.50	0.52

* GDDKiA, 2020

To determine metal enrichment in road dusts and identify probable natural or anthropogenic sources, enrichment factors (EF) were calculated using the formula:

$$EF=(C_{el}/C_{ref})/(B_{el}/B_{ref}),$$

where: C_{el} represents the mass fraction of the element of interest determined in the study; C_{ref} represents the mass fraction of a reference element used for normalization; B_{el}, B_{ref} denote the concentrations of the element of interest and the reference element in the Earth's crust or background, respectively.

Aluminum was chosen as the reference element because its concentration in the sample is predominantly influenced by crustal sources (Reimann and de Caritat 2000).

Results and discussion

The results of magnetic susceptibility exhibit high variability, with no clear differences between samples taken from asphalt and concrete roads. The κ values range from 18.67 to 1097.17 $\times10^{-5}$ SI, while χ values range from 12.10 to 720.40 $\times10^{-8}$ m^3kg^{-1} (Tables 1 and 2), with mean values of 376.59 $\times10^{-5}$ SI and 262.55 $\times10^{-8}$ m^3kg^{-1}, respectively. The obtained mean value of magnetic susceptibility was lower than the reported values for road dusts in the cities of Burgas, Bulgaria (Jordanova et al. 2014) and Thessaloniki, Greece (Bourliva et al. 2016). Nevertheless, the observed values are considerably higher than those reported for road dust in Helsinki, Finland (Bućko et al. 2010) and Seoul, South Korea (Kim et al. 2007).

As demonstrated in Table 2, the mean and median values of κ and χ are elevated for asphalt road dust. The analysis of the results demonstrate that the type of control point has a more significant impact on the magnetic susceptibility values than road surface. The mean κ values increase in the following order: road exits (355.48 $\times10^{-5}$ SI) > noise barriers (371.22 $\times10^{-5}$ SI) > open space (403.06 $\times10^{-5}$ SI). However, the series differ in its median κ values: points at road exit exhibit the highest median value (376.83 $\times10^{-5}$ SI), while χ values remain almost identical for all types of control points. The highest mean magnetic susceptibility value is observed in road dust collected from concrete surfaces in open spaces, followed by dust from asphalt surfaces in open spaces and road exits. Lower κ and χ values were noted for concrete roads in the vicinity of noise barriers and road exits. Overall, the magnetic susceptibility measurements do not demonstrate a noticeable relationship between this parameter and road surface type, control point type, or traffic intensity. This conclusion is supported by a calculated correlation coefficient of approximately 0.5 (Table 1).

High values of magnetic susceptibility indicate a high content of magnetic iron minerals, predominantly magnetite and maghemite. This often results in high correlation coefficients with iron content, as reported by Jordanova et al. (2014). In the present study, strong but not statistically significant correlations were found between κ, χ and Fe (Table 3). However, it was observed that road dust from asphalt surfaces contains higher iron content than dust from concrete surfaces, aligning with the magnetic susceptibility values. The lack of a strong correlation may be attributed to the presence of diverse sources of iron, which are not always derived from high-temperature processes that form magnetic iron compounds.

A relationship comparable to that of magnetic susceptibility has been observed in the case of elemental composition. In this context, many elements exhibit a higher mass share in samples derived from asphalt surfaces compared to those from concrete surfaces (Figures 2–4). However, in several cases, the opposite trend is observed: higher mass shares are found in

Table 2. Basic statistics of the magnetic susceptibility values (A – asphalt surface; C - concrete surface)

	κ (×10^{-5})				χ (×10^{-5} m^3 kg^{-1})			
Group	**Mean**	**Median**	**Min.**	**Max.**	**Mean**	**Median**	**Min.**	**Max.**
All samples	376.59	365.67	18.67	1097.17	262.55	245.30	12.10	720.40
Asphalt	386.03	378.67	18.67	1097.17	272.88	264.65	12.10	720.40
Concrete	365.79	331.67	24.17	1064.67	250.75	227.80	16.30	702.30
noise barriers	371.22	367.33	22.67	1097.17	254.60	246.50	14.90	720.40
open space	403.06	362.50	18.67	1064.67	273.94	243.30	12.10	702.30
road exits	355.48	376.83	19.67	751.33	259.11	245.30	13.00	542.10
A noise barriers	436.90	424.25	22.67	1097.17	295.15	294.50	14.90	720.40
C noise barriers	296.17	331.67	24.17	508.17	208.26	223.20	16.30	356.60
A open space	344.44	329.17	18.67	668.50	242.79	236.15	12.10	450.20
C open space	470.05	365.67	31.50	1064.67	309.54	256.80	20.60	702.30
A road exits	376.77	378.67	19.67	751.33	280.70	280.25	13.00	542.10
C road exits	331.14	252.67	39.17	688.17	234.44	203.10	26.00	472.30

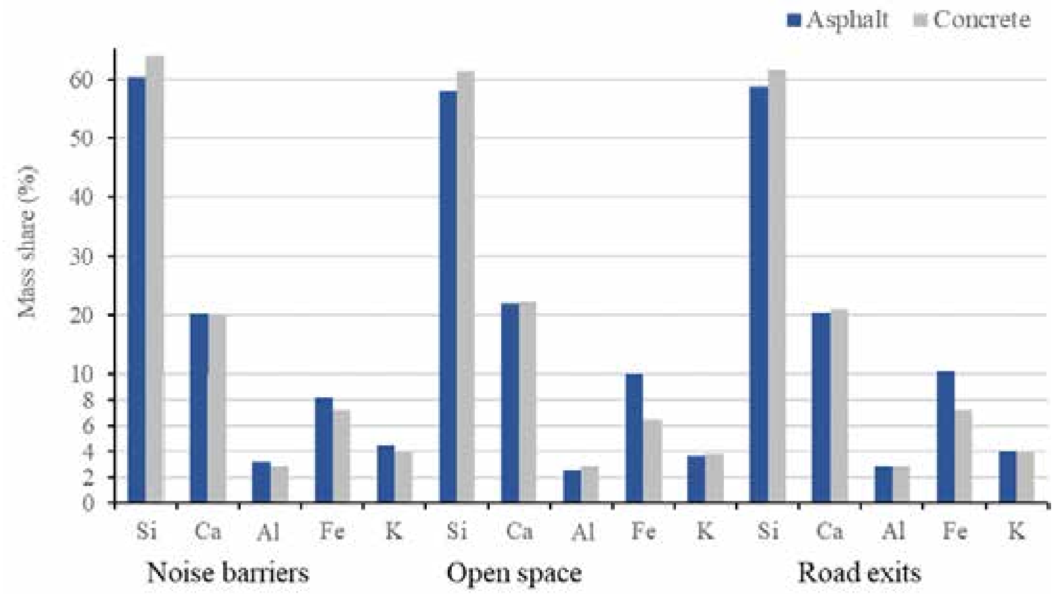

Figure 2. A proportion of the elements identified in road dust samples in quantities exceeding 1%: Si, Ca, Al, Fe, K and Ti

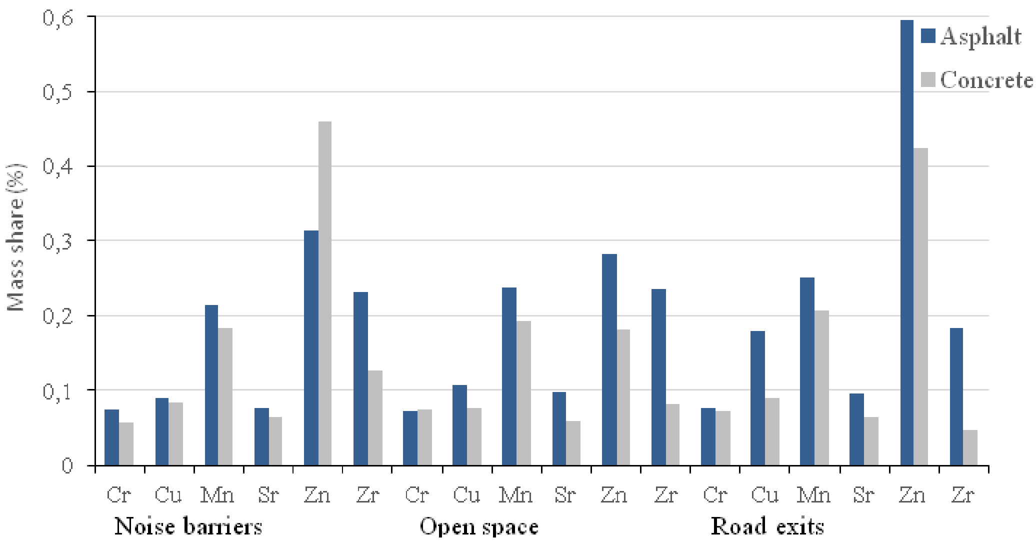

Figure 3. A proportion of the elements identified in road dust samples in quantities below 1%: Cr, Cu, Mn, Sr, Zn and Zr

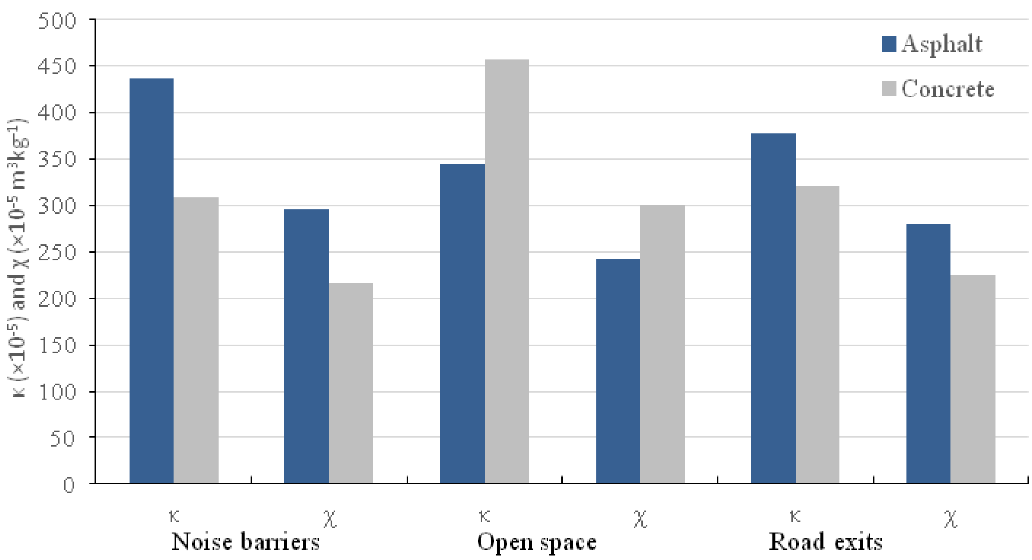

Figure 4. Magnetic susceptibility values (κ ($\times 10^{-5}$) and χ ($\times 10^{-5}$ m^3kg^{-1})) of road dust samples

Table 3. Correlation matrices between the tested variables for road dust from asphalt (A) and concrete (C) surfaces, divided into critical points: noise barrier, open space and road exit (correlation coefficients marked in red are significant with $p < 0.05$)

Noise barriers														
	A-Al	**A-Ca**	**A-Cr**	**A-Cu**	**A-Fe**	**A-K**	**A-Mn**	**A-Si**	**A-Sr**	**A-Ti**	**A-Zn**	**A-Zr**	**A-κ**	**A-χ**
A-Al	1.00													
A-Ca	-0.43	1.00												
A-Cr	-0.14	-0.62	1.00											
A-Cu	0.08	-0.93	0.79	1.00										
A-Fe	-0.02	-0.88	0.86	0.99	1.00									
A-K	0.99	-0.42	-0.22	0.06	-0.05	1.00								
A-Mn	0.22	-0.90	0.89	0.94	0.95	0.16	1.00							
A-Si	0.30	-0.85	0.24	0.78	0.69	0.36	0.59	1.00						
A-Sr	0.20	-0.95	0.55	0.95	0.89	0.22	0.81	0.94	1.00					
A-Ti	-0.42	-0.59	0.90	0.84	0.90	-0.46	0.79	0.40	0.67	1.00				
A-Zn	0.65	-0.93	0.30	0.75	0.65	0.67	0.70	0.90	0.87	0.27	1.00			
A-Zr	-0.69	0.33	-0.40	-0.15	-0.16	-0.59	-0.46	0.14	-0.01	0.03	-0.30	1.00		
A-κ	-0.37	-0.65	0.59	0.85	0.85	-0.35	0.64	0.73	0.84	0.85	0.46	0.39	1.00	
A-χ	-0.34	-0.67	0.57	0.85	0.85	-0.32	0.64	0.75	0.85	0.84	0.49	0.38	1.00	1.00
	C-Al	**C-Ca**	**C-Cr**	**C-Cu**	**C-Fe**	**C-K**	**C-Mn**	**C-Si**	**C-Sr**	**C-Ti**	**C-Zn**	**C-Zr**	**C-κ**	**C-χ**
C-Al	1.00	-0.40	-0.42	-0.76	-0.68	0.92	-0.85	0.65	-0.80	-0.42	-0.82	-0.87	-0.49	-0.57
C-Ca		1.00	-0.54	-0.25	-0.27	-0.63	-0.07	-0.95	-0.18	-0.63	-0.17	-0.11	-0.35	-0.30
C-Cr			1.00	0.90	0.95	-0.29	0.83	0.25	0.88	0.97	0.69	0.76	0.97	0.96
C-Cu				1.00	0.98	-0.59	0.98	-0.07	1.00	0.90	0.92	0.97	0.88	0.92
C-Fe					1.00	-0.56	0.96	-0.04	0.98	0.91	0.82	0.90	0.96	0.98
C-K						1.00	-0.73	0.85	-0.64	-0.20	-0.56	-0.66	-0.44	-0.51
C-Mn							1.00	-0.25	0.99	0.82	0.91	0.97	0.85	0.90
C-Si								1.00	-0.14	0.35	-0.11	-0.19	0.06	-0.01
C-Sr									1.00	0.88	0.92	0.97	0.88	0.92
C-Ti										1.00	0.78	0.80	0.89	0.89
C-Zn											1.00	0.98	0.63	0.70
C-Zr												1.00	0.74	0.80
C-κ													1.00	0.99
C-χ														1.00
Open space														
	A-Al	**A-Ca**	**A-Cr**	**A-Cu**	**A-Fe**	**A-K**	**A-Mn**	**A-Si**	**A-Sr**	**A-Ti**	**A-Zn**	**A-Zr**	**A-κ**	**A-χ**
A-Al	1.00													
A-Ca	0.33	1.00												
A-Cr	-0.24	-0.80	1.00											
A-Cu	-0.08	-0.97	0.80	1.00										
A-Fe	0.02	-0.93	0.81	0.99	1.00									
A-K	0.85	0.26	-0.49	-0.05	-0.01	1.00								
A-Mn	0.45	-0.68	0.66	0.85	0.90	0.32	1.00							
A-Si	-0.84	0.14	-0.33	-0.39	-0.49	-0.57	-0.82	1.00						
A-Sr	-0.49	-0.98	0.83	0.91	0.86	-0.43	0.56	-0.01	1.00					
A-Ti	0.34	-0.73	0.78	0.87	0.93	0.16	0.99	-0.77	0.64	1.00				
A-Zn	-0.09	-0.96	0.87	0.99	0.99	-0.13	0.85	-0.42	0.91	0.90	1.00			
A-Zr	-0.81	-0.48	0.68	0.29	0.25	-0.97	-0.09	0.42	0.62	0.08	0.37	1.00		
A-κ	0.05	-0.83	0.93	0.91	0.94	-0.16	0.89	-0.58	0.79	0.95	0.95	0.38	1.00	
A-χ	0.03	-0.82	0.95	0.89	0.92	-0.20	0.87	-0.57	0.79	0.94	0.94	0.42	1.00	1.00

	C-Al	C-Ca	C-Cr	C-Cu	C-Fe	C-K	C-Mn	C-Si	C-Sr	C-Ti	C-Zn	C-Zr	C-κ	C-χ
C-Al	1.00	-0.58	-0.56	-0.60	-0.60	0.96	-0.48	0.86	-0.46	0.06	-0.46	0.58	-0.44	-0.43
C-Ca		1.00	-0.32	-0.14	-0.19	-0.79	-0.21	-0.76	-0.45	-0.75	-0.28	-0.68	-0.47	-0.48
C-Cr			1.00	0.65	0.72	-0.29	0.55	-0.12	0.95	0.52	0.95	-0.19	0.97	0.97
C-Cu				1.00	1.00	-0.43	0.99	-0.53	0.81	0.74	0.37	0.28	0.76	0.73
C-Fe					1.00	-0.41	0.97	-0.48	0.86	0.76	0.46	0.25	0.82	0.80
C-K						1.00	-0.32	0.94	-0.19	0.29	-0.21	0.64	-0.16	-0.15
C-Mn							1.00	-0.47	0.75	0.80	0.25	0.42	0.69	0.66
C-Si								1.00	-0.12	0.16	0.04	0.37	-0.06	-0.04
C-Sr									1.00	0.75	0.81	0.11	1.00	0.99
C-Ti										1.00	0.29	0.74	0.72	0.70
C-Zn											1.00	-0.38	0.85	0.87
C-Zr												1.00	0.07	0.05
C-κ													1.00	1.00
C-χ														1.00
Road exits														
	A-Al	**A-Ca**	**A-Cr**	**A-Cu**	**A-Fe**	**A-K**	**A-Mn**	**A-Si**	**A-Sr**	**A-Ti**	**A-Zn**	**A-Zr**	**A-κ**	**A-χ**
A-Al	1.00													
A-Ca	-0.29	1.00												
A-Cr	0.22	-1.00	1.00											
A-Cu	-0.19	-0.89	0.92	1.00										
A-Fe	0.50	-0.97	0.95	0.76	1.00									
A-K	0.94	0.06	-0.12	-0.51	0.18	1.00								
A-Mn	0.51	-0.97	0.95	0.75	1.00	0.18	1.00							
A-Si	-0.83	0.78	-0.73	-0.40	-0.90	-0.59	-0.90	1.00						
A-Sr	-0.31	-0.82	0.85	0.99	0.66	-0.62	0.66	-0.27	1.00					
A-Ti	0.98	-0.47	0.41	0.01	0.66	0.86	0.66	-0.92	-0.12	1.00				
A-Zn	0.17	-0.99	1.00	0.94	0.94	-0.17	0.94	-0.70	0.88	0.36	1.00			
A-Zr	0.17	0.89	-0.92	-1.00	-0.77	0.50	-0.76	0.41	-0.99	-0.02	-0.94	1.00		
A-κ	-0.28	-0.84	0.87	1.00	0.69	-0.59	0.69	-0.31	1.00	-0.08	0.90	-0.99	1.00	
A-χ	0.14	-0.99	1.00	0.95	0.93	-0.20	0.93	-0.67	0.89	0.33	1.00	-0.95	0.91	1.00
	C-Al	**C-Ca**	**C-Cr**	**C-Cu**	**C-Fe**	**C-K**	**C-Mn**	**C-Si**	**C-Sr**	**C-Ti**	**C-Zn**	**C-Zr**	**C-κ**	**C-χ**
C-Al	1.00	-0.99	-0.86	-0.06	0.27	0.96	0.08	0.49	0.21	0.69	0.01	0.59	0.14	0.12
C-Ca		1.00	0.79	0.20	-0.14	-0.99	0.05	-0.60	-0.07	-0.59	0.13	-0.48	0.00	0.02
C-Cr			1.00	-0.45	-0.72	-0.69	-0.57	0.02	-0.67	-0.96	-0.51	-0.92	-0.62	-0.60
C-Cu				1.00	0.94	-0.34	0.99	-0.90	0.96	0.68	1.00	0.77	0.98	0.98
C-Fe					1.00	-0.01	0.98	-0.71	1.00	0.88	0.96	0.94	0.99	0.99
C-K						1.00	-0.20	0.71	-0.08	0.46	-0.28	0.34	-0.15	-0.16
C-Mn							1.00	-0.83	0.99	0.78	1.00	0.85	1.00	1.00
C-Si								1.00	-0.75	-0.29	-0.87	-0.41	-0.80	-0.81
C-Sr									1.00	0.85	0.98	0.91	1.00	1.00
C-Ti										1.00	0.73	0.99	0.81	0.80
C-Zn											1.00	0.81	0.99	0.99
C-Zr												1.00	0.88	0.87
C-κ													1.00	1.00
C-χ														1.00

dust from concrete surfaces for Si and Zn near noise barriers, K and Si in open spaces, Al, Ca, and Si at road exits.

Although high correlation coefficients between magnetic susceptibility and PTEs have been frequently observed in soils, industrial dusts, and bottom sediments (Kupka et al. 2021, Łuczak and Kusza 2019, Szuszkiewicz et al. 2016), the results of this study did not confirm such a relationship in the investigated road dusts. The Fisher test results were 1.188 and 1.242 for κ and χ, respectively. Since the critical table value for this test is 2.07, which exceeds the obtained results, the null hypothesis that the variances of both populations are equal cannot be rejected. This means that there are no significant differences between road dust from asphalt surfaces and concrete surfaces. (Iwanejko and Bajer 2012). Nevertheless, significant strong correlation coefficients (0.95–1.00) were identified in specific cases. For road dust from asphalt surfaces, Cr exhibited strong correlations across all locations, while Ti and Zn showed strong correlations in open spaces. For dust from concrete surfaces, Cr and Sr were strongly correlated across all locations, and Fe exhibited a strong correlation near noise barriers (Table 3).

The correlation matrix and principal component analysis revealed strong positive correlations (ranging from 0.95 to 1.00) between elements (Table 3, Figure 5). In asphalt road dust, the following pairs showed strong correlations: Fe-Cu, Al-K, Cu-Fe, Cu-Zn, Mn-Ti, and Cr-Zn. In concrete road dust, strong correlations were observed among Fe-Cr, Fe-Cu, Mn-Cu, Mn-Fe, Sr-Cu, Sr-Cr, Sr-Fe, Sr-Mn, Ti-Cr, Zr-Cu, Zr-Mn, Zr-Sr, Zr-Zn, and Zn-Cu.

Guda et al. (2024) identified moderate to strong correlations among Fe, Mn, Mg, Co, V, Cr, and Ni, attributing these to their lithogenic origin. In contrast, strong correlations between Cd, Pb, Mo, Zn, Sb, and Cu were linked to various human activities including industrial processes, automobile exhaust emissions, road surface aging, and solid waste accumulation. Additionally, strong negative correlations (from -1.00 to -0.96) were observed between specific elements, in asphalt road dust, including Ca-Cr, Cu-Zr, Ca-Cu, and Ca-Zn. The weak and/or negative correlations of Ca suggest a distinct origin, potentially from the fertilization of nearby fields or as a fundamental component of road surfaces (Guda et al. 2024).

The enrichment factors (EF) of the PTEs studied are presented in Table 4. EF demonstrates the relative increase or decrease in elemental content compared to the geochemical background and reference elements. According to Barbieri (2016), EF values are categorized into five contamination levels, which are highlighted in different colors in Table 4.

The dust collected from both asphalt and concrete surfaces exhibited extremely high enrichment in Cr, Cu and Zn, suggesting a predominantly anthropogenic origin for these elements. These elements are commonly present in exhaust gases but primarily enter road dust through road surface abrasion and the release of tire tread material (Harrison et al. 2021). The EF of Zn (ranging from 122 to 326) may result from the use of ZnO and Zn stearate, which are essential in the vulcanization process (Wagner et al. 2024). The enrichment of these elements is approximately twice as high for asphalt surfaces compared to concrete surfaces. Furthermore, the enrichment of Zr in dust from asphalt surfaces is markedly elevated, being three times higher than that observed in concrete surfaces. This, along with the enrichment of Cr, may indicate that these elements originate from tire abrasion (Wagner 2024).

Both surface types are characterized by similar EF values for K and Si, classified as significant enrichment. These elements likely originate from roadside soils. Furthermore, the EF of road dust in Pb was found exclusively in samples derived from asphalt surfaces. Potential sources of Pb include friction materials in vehicle braking systems (Harrison et al. 2021), as well as fertilizers and dyes.

Table 4. Enrichment factors (EF) of selected PTEs for all kinds of investigated sites (colors differ accordingly to contamination categories, Barbieri 2016)

EF*	Asphalt	Concrete	Noise barriers	Open space	Road exits
Cr	61	34	43	51	45
Cu	252	138	166	173	237
Fe	10	6	7	7	9
K	4	3	4	4	4
Mn	14	10	10	11	14
Pb	17	0	0	0	24
Si	6	5	5	6	5
Sr	9	5	6	7	8
Ti	15	10	11	12	13
Zn	293	184	254	122	326
Zr	26	8	20	16	12

* Colors suggest five contamination categories recognized on the basis of the EFs:
EF ≤ 2 Deficiency to minimal enrichment, 2 < EF ≤ 5 Moderate enrichment, 5 < EF ≤ 20 Significant enrichment,
20 < EF ≤ 40 Very high enrichment, EF > 40 Extremaly high enrichment *(Barbieri 2016)*

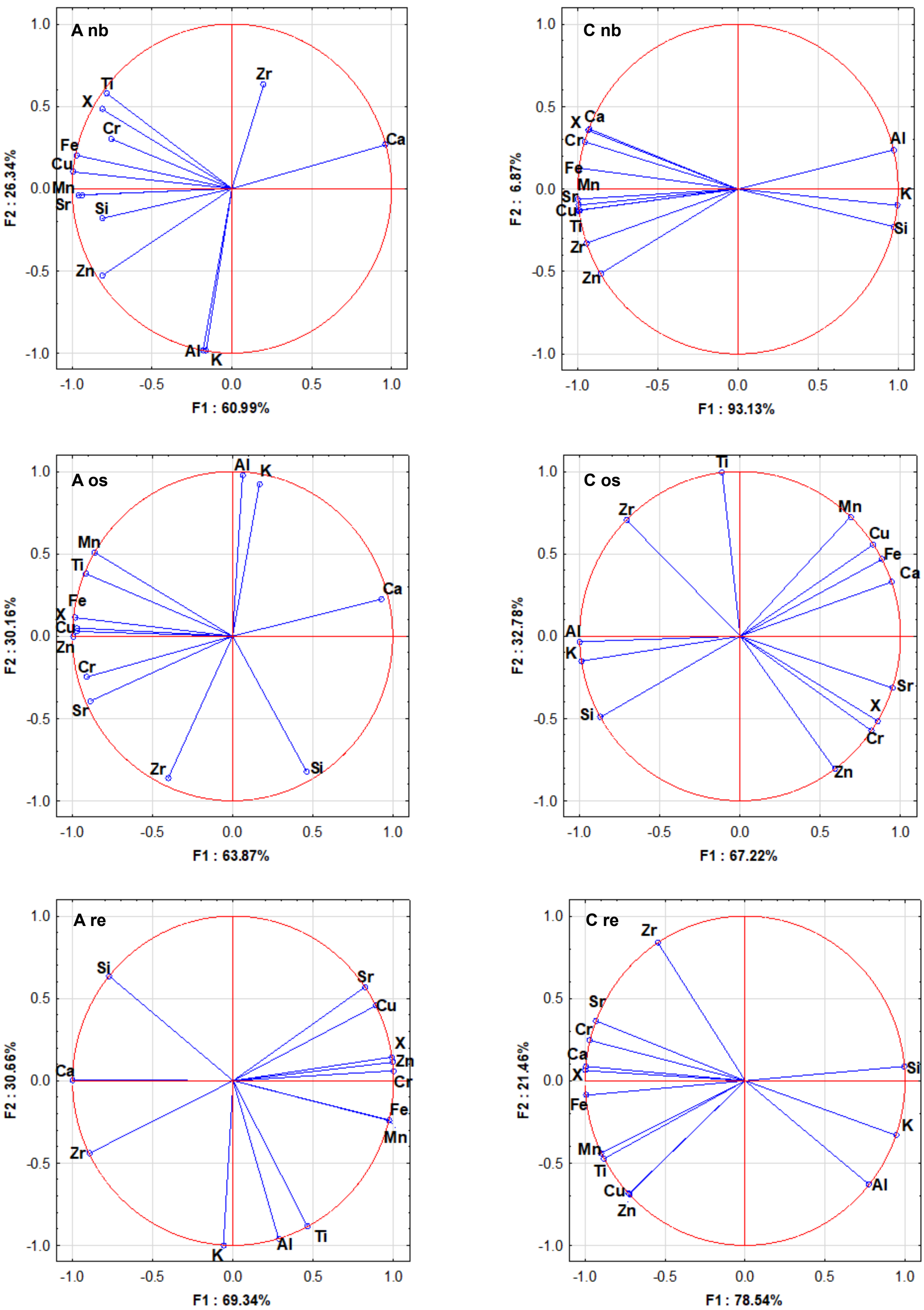

Figure 5. Biplots of the principal component analysis (F1 and F2 – factor 1 and factor 2) of the investigated elements in road dusts from asphalt surface (A - left charts) and concrete surface (C - right charts) with division into different types of control points (nb - noise barriers, os - open space and re - road exits); "X" in the graphs corresponds to a symbol χ and denotes magnetic susceptibility

Principal component analysis (PCA) was conducted with the results classified by surface type (asphalt vs. concrete) and control point type (noise barriers, open space, and road exit), resulting in six biplots (Figure 5). The factor analysis yielded some interesting distributions that can be interpreted in the context of source apportionment.

In each case, two principal components were identified, with factor 1 (F1) accounting for approximately 60% to 98% of the total variability. For asphalt and concrete road dust near noise barriers, the elements most strongly correlated with the first principal component were chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), and strontium (Sr). These elements likely originate from exhaust gases as well as road and tire wear (Rogula-Kozłowska et al. 2023). Additionally, they may derive from powder metallurgy products, coatings on steel surfaces, and corrosion of metal structures or stainless steel components in vehicles (Wang et al. 2019). In contrast, for samples collected in open spaces and road exits, the elements were highly dispersed, indicating a diverse range of origins.

In each combination of results, the second component (F2), accounting for approximately 7% to 32% of the total variability, primarily includes K and/or Si, which are strongly correlated with Al. Aluminum, used as the reference element for determining the enrichment factor, suggests that these components may originate from naturally occurring minerals. Potential sources of these elements include soils from arable fields, dust from construction sites, and gravel roads, with particles transported onto roads by wind or water flow.

It should be noted, however, that both asphalt and concrete contain mineral aggregates, sand, and gravel, the primary components of which are aluminum and silicon. The results of this analysis demonstrate a distinction between the dust collected from asphalt and concrete surfaces. The first factor (F1) is associated with aluminum (Al), silicon (Si) and potassium (K) for concrete surfaces, but only with aluminum (Al) and potassium (K) for asphalt surfaces. The presence of potassium (K) is considered an indicator of biomass combustion, as well as soil fertilization aimed at increasing crop yields (Abbasi et al. 2018).

Conclusions

The results demonstrated no discernible differences between the samples collected from asphalt and concrete road surfaces. The magnetic susceptibility of asphalt samples was only slightly higher than that of the concrete samples. The correlation matrix and principal component analysis results indicate no statistically significant differences between the asphalt and concrete surfaces. This suggests that magnetic susceptibility, as well as the average elemental composition of dust, is not significantly influenced by the type of road surface. It appears that the location of the sampling point has a greater influence on the results, with noise barriers, open spaces, and motorway exits being particularly influential.

The highest κ and χ values were observed in samples collected from open spaces, while the lowest were noted in samples taken near road exits. These values were likely influenced by soil particles transported from nearby fields, as well as from other sources such as construction and industrial plants. The calculated enrichment factors (relative to Al, a reference element commonly found in the Earth's crust) indicated extremely high enrichment of dust in elements such as Cr, Cu, and Zn. Pb showed very high enrichment only in dust collected at road exits, while Zr was notably enriched in dust from asphalt surfaces. Other elements were significantly enriched, except for K, which exhibited moderate enrichment.

Given that Cr, Cu, and Zn, elements primarily originating from non-exhaust particulate emission sources such as tire tread, brake wear, and road wear, were more enriched in dust from asphalt road surfaces, it can be inferred that asphalt may be slightly more susceptible to abrasion than the concrete. The number of vehicles on the roads also significantly affected the results, with a correlation coefficient of approximately 0.5.

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Wpływ rodzaju nawierzchni drogi na podatność magnetyczną i skład pierwiastkowy pyłu drogowego

Streszczenie. Celem badań było określenie wpływu rodzaju nawierzchni drogowej (asfaltowej i betonowej) oraz obecności ekranów akustycznych na podatność magnetyczną i skład chemiczny pyłu drogowego pobranego z dróg krajowych i autostrad w centralnej i południowej Polsce. Do badań wybrano cztery drogi o nawierzchni asfaltowej i cztery o nawierzchni betonowej. Próbki pobrano w trzech punktach kontrolnych: w przestrzeni między ekranami dźwiękochłonnymi, w przestrzeni bez ekranów oraz na zjazdach z drogi. Przeprowadzono pomiary podatności magnetycznej i analizę składu pierwiastkowego (z wykorzystaniem spektrometru fluorescencji rentgenowskiej z dyspersją energii). Wyniki badań wykazały dużą zmienność przy braku wyraźnych różnic między próbkami pobranymi z dróg asfaltowych i betonowych. Wartości podatności magnetycznej były wyższe dla pyłu drogowego pobranego z nawierzchni asfaltowych w pobliżu ekranów akustycznych i zjazdów z autostrad, natomiast w przypadku próbek z przestrzeni otwartej wartości podatności były około 1,3 razy wyższe dla pyłu z nawierzchni betonowych. Podobną zależność zaobserwowano w przypadku składu pierwiastkowego. Uzyskane wyniki nie wykazały wyraźnych różnic pomiędzy próbkami pobranymi z dróg asfaltowych i betonowych. Większy wpływ na wyniki miała lokalizacja miejsca poboru próbek: przestrzeń między ekranami akustycznymi, wolna przestrzeń lub zjazdy z autostrady. Obliczone współczynniki wzbogacenia wskazały na ekstremalnie wysokie wzbogacenie pyłu w takie pierwiastki jak Cr, Cu i Zn, bardzo wysokie wzbogacenie w Pb tylko dla pyłu pobranego na zjazdach z autostrady oraz znaczące i umiarkowane wzbogacenie w pozostałe pierwiastki.