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Impact of Street Sweeping and Washing on the PM10 and PM2.5 Concentrations in Cracow (Poland)

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1. Introduction

The growing public interest in the air quality in large cities and urban agglomerations has also been recently observed in Poland. According to the European Environment Agency (EEA) report on air quality in Poland (2010-2015), the percentage of the urban population exposed to concentrations exceeding the EU standards for the particulate matter PM10 was 80-88%. Poland is also listed among the countries leading both in PM10 and PM2.5 emissions. The average concentration of PM2.5 in Poland is 22.8 μg/m^3 (EEA report 206, 2015, 2016, 2017), and such a high-level results from the burning of solid fuels (mainly coal) in households (Choi et al. 2015, Sówka et al. 2018). Another important source of particulate and gaseous contaminants in urban areas is emissions from transport and industry (Bokwa 2008, Amato et al. 2009, 2009b, 2010, Chirizzi et al. 2017). It is estimated that air pollution in the EU is associated with transport in 12% for PM10, and 15% for PM2.5, and related to industry in: 28 and 24% respectively (Badyda 2009, Gliniak et al. 2015, EEA 2016, 2017).

The research also shows that PM concentrations in urban dust are related not only to sources of emitted flue gases, but also to particulate matter transfer from soils, abrasion of the road surface, construction works, and incineration (Amato et al. 2010, 2010b, Harrison et al. 2001, Lenschow et al. 2001, Bagieński 2015, Chirizzi et al. 2017, Jancsek-Turócziet et al. 2013). Studies have shown that the share of the road transport (emissions from engines and abrasion of tires, claddings, and road surfaces) in shaping the average concentrations of air pollutants in street canyons is also higher than for different type of sites, reaching 27% for PM 10, and 24% for PM 2.5 (Harrison et al. 2008, Kim and Guldman 2011, Bogacki et al. 2012).

One of the ways to reduce PM concentrations in the air is to prevent it from being deposited at the edge of roadways. Sweeping and/or washing of the road surface prevents dust from re-entering the air. In the literature, there is not much research on the impact of street sweeping on air quality (Amato et al. 2009, AIRUSE LIFE 11 2013). However, it has been already established that after sweeping the air dust contains more particles with smaller diameters (Katamaneni et al. 1996, AIRUSE LIFE 11 2013). Measurements performed during the spring season in Stockholm have shown that sweepers can also increase the PM10 levels by raising the dust deposited on the road along the curbs (Kuhns et al. 2003, Norman and Johanson 2006, AIRUSE LIFE 11 2013). In studies conducted in Madrid (Karanasiou et al., 2011), it was observed that daily levels of PM10 on unwashed streets during dry days were 215% higher than those during the day after night cleaning of the streets . Research carried out in urban areas (Karanasiou et al. 2012) showed that the resuspension of road dust should be considered an important source of elevated PM levels. The results showed that traffic intensity is the most important factor affecting the level of hourly PM concentrations, and it has been observed that there is a lower impact of the weather as well as for the frequency of street compaction. The combination of street sweeping and washing (rinsing with water) is one of the methods proposed to limit the share of road traffic in PM concentrations in the environment. Positive examples of street sweeping combined with washing (rinsing with water) caused a drop of PM10 in the air, up to 7-30% of average daily concentrations in Spain, Germany, Sweden, and Taiwan (Vaze and Chiew 2002 Chang et al. 2005, AIRUSE LIFE 11, 2013).

Cracow is the second largest city in Poland, with a population of approx. 800,000, and it is considered one of the EU cities with the highest level of air pollution (155 days with PM10 over the limit in 2014) (EEA 2017, Report GIOS 2014). The average annual concentration of PM10 in Cracow for the period of 2010-2014 was 69.34 $\mu g/m^3$, with 188 days exceeding the daily limit of 50 $\mu g/m^3$ (EU Air Quality Directive 2008) in 2016 (WIOS report 2015, 2016). Elevated concentrations of PM10 are observed regularly from November until March. This situation is caused by the unfavorable location of the city which is in a river valley (Vistula River), and the concentration of local emission sources. The dense housing development and the high traffic volume combined with the limited ventilation of the area further increases concentrations of dust particles in the air. The main sources of air pollution in Cracow are industry, coal-fired heating (central heating plant, and stoves in private houses), and transport(Bokwa 2008, Gliniak et al. 2015). The most significant types of industry in Cracow are ferrous metallurgy, the organic and non-organic chemical industry, rubber industry, mechanical, electric, electronic, and the energy industry. Due to the prevailing influx of air to the city from the west, significant amounts of pollution are also transmitted from the Upper Silesian areas (the main center of coal mining and metallurgy in

Poland). These unfavorable conditions cause that the air pollution is largely retained and accumulated in the area of the city(Bokwa, 2008, Gliniak et al., 2015). The impact of intensive sweeping and subsequent washing of streets in Cracow was investigated in 2015-2016. The field investigations were carried in three locations in the vicinity of air quality monitoring stations. The article also takes into account the impact of air quality on road traffic during the World Youth Days in 2016.

2. Methods

2.1. Sampling area description

This study was focused on the impact of street cleaning on improvement of the air quality performed in Cracow (southern Poland). The experiment was conducted between April 2015 and September 2016 in six series of measurements (Table 1). For technological reasons, the experiments were carried out in periods when the air temperature at night was above 0°C. During the experiments, the wet sweeping and washing streets with water, due to the safety of road users, made it impossible to carry out the experiments in the winter months, when the PM air pollution is the highest. The advantage of the summer period is that the impact of pollution from other sources than public transport is small. The study was conducted in three locations: Avenue of the Three Bards (Krasiński Ave. and Mickiewicz Ave.); Lieut. Halszki Street (from the intersection with F. Bujak Street to the intersection with W. Witosa Street); and at the intersection of Bulwarowa Street and Solidarity Avenue (Fig. 1). Sampling site selection was determined by the localization of the continuous air monitoring stations (Fig. 2). The air quality in the Cracow area is monitored by the Regional Inspectorate for Environmental Protection, and the monitoring network includes three stations: i) at the one of the busiest streets in the Cracow center (the Avenue of Three Bards – site C; ii) at the industrial area (Bulwarowa Street – site I); and iii) at the residential area (Lieut. Halszki Street – site R). Experiments were conducted by the Cracow Municipal Cleaning Company (MPO), together with the Cracow University of Technology (CUT), and the Regional Inspectorate of Environment Protection (WIOŚ).

Site C (the Avenue of Three Bards, Fig. 2a) is characterized by pre-war urban development of a "canyon" nature with residential buildings (2-5 stories), and the service and administrative facilities located on the ground floor. The traffic intensity on this avenue is about 4000 vehicles per hour (~100 thousand per day). According to the WIOŚ data from the local air monitoring station, the number of days with PM10 higher than 50 $\mu g/m^3$ was 260 in 2015, and 165 in 2016 (report WIOŚ 2015, 2016).

Series	Date
I	15.04. 2015-18.04.2015
II	19.05.2015-20.05.2015
III	15.09.2015-18.09.2015
IV	4.04.2016-7.04.2016
V	24.08.2016-27.08.2016
VI	13.09.2016-16.09.2016

Table 1. Experiment Series

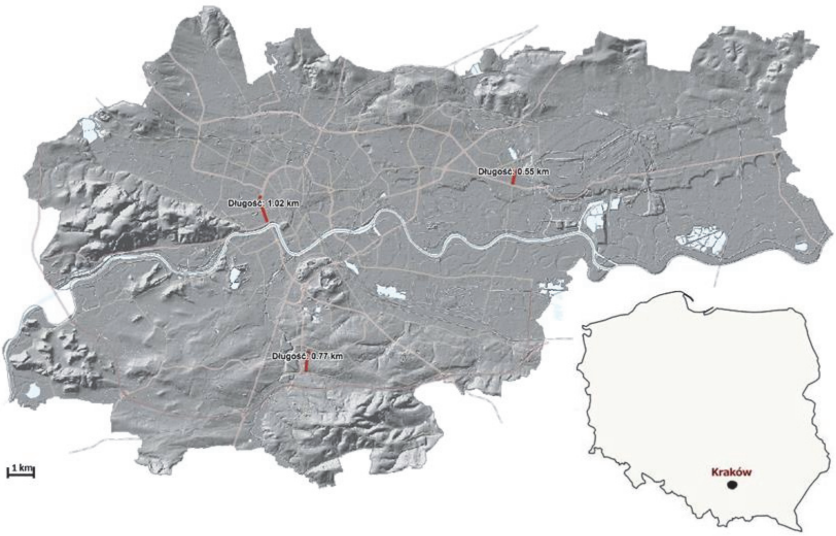

Fig. 1. Localization of the experimental locations in Cracow

Site I (Bulwarowa Street, Fig. 2b) is localized in the industrial/residential district of Nowa Huta, with one of the ArcelorMittal Poland's units, as the main industrial facility in the area. The streets included in the experiment are characterized by a traffic intensity less than 1000 per hour (~ 24 thousand per day), dispersed with residential buildings, and gardens. Access roads to residential development are combined with walking and bicycle paths. Bulwarowa Street is also surrounded from both sides by wide green belts, where the monitoring station is localized as well. The other part of the sampling area consists of the section of the Avenue of John Paul II, which is a two-lane route divided in the middle by tram lines. According to the WIOŚ data from the air monitoring station on Bulwarowa Street, the number of days in which the level of PM10 was higher than 50 μg/m^3 was 120 in 2015, and 74 in 2016 (report WIOŚ 2015, 2016).

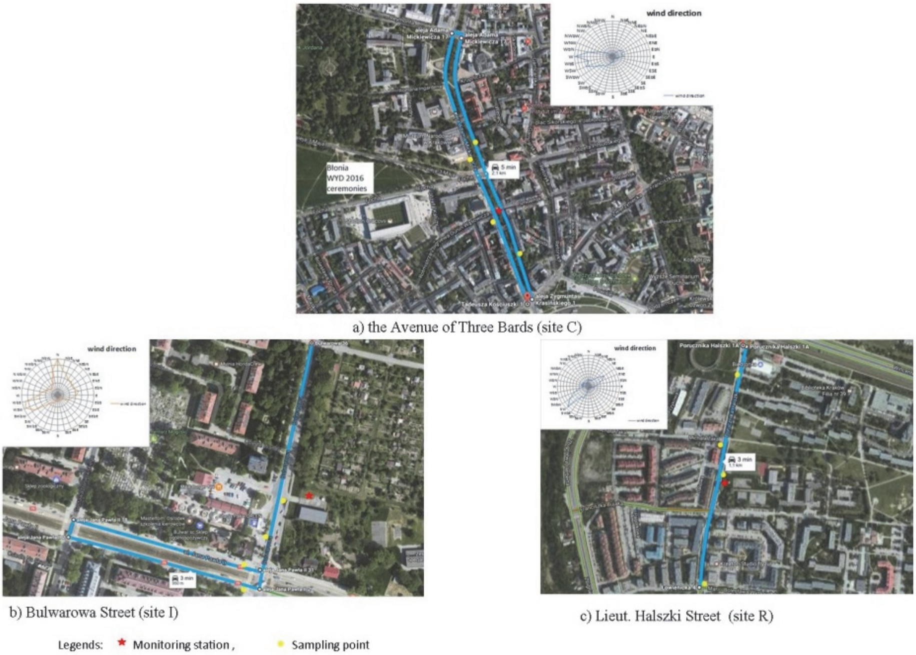

Fig. 2. The route of passing sweepers and washing cars during the experiment in: a) site C, b) site I, c) site R

Site R (Lieut. Halszki Street, Fig. 2c) is located in the Kurdwanów Housing Estate, which is part of the Podgórze District (southern part of Cracow). This housing estate consists mainly of high-rise residential buildings, which is a cause why the streets are mostly access routes to housing buildings and apartments. This estate is considered, and is one of the biggest "bedrooms" in Cracow, and it is inhabited by about 20 thousand residents. Lieut. Halszki Street is a small single-lane street, with a traffic intensity of 2000 per hour (~ 36 thousand per day). According to the WIOŚ data from the local air monitoring station, the number of days in with a level of PM10 higher than 50 μg/m^3 was 99 in 2015, and 78 in 2016 (report WIOŚ 2015, 2016).

2.2. Sampling pattern

In the first experiment (series I) sampling was only performed at site C (center transportation area). During this experiment the vehicle traffic was limited to only one lane. Every day (from 10 pm), the sidewalks along the road were washed, and both sides of the street were also swept. A moment later, three tankers escorted by police were moving across the width of the street. Washing was repeated every hour, until 4-5 am the next day. After weighing of the sweepers, samples of swept material for chemical analysis were collected. Water samples were collected at four points from the road surface during the first and last street washings. This procedure was repeated for another three days. Between experiments, these streets were swept and washed in accordance with the schedule of the MPO. During the experiments the MPO sweepers were used, which meet the highest ecological standards of EURO 6 exhaust gas. All the equipment was PM10 certified. Sweepers were working in the wet system with water recirculation, which means that water during the sweeping process was used repeatedly. Vehicles were also equipped with a third brush, which allowed sweeping on two different levels. Street washing trucks were equipped with a tank with water, and a sprinkler in the front of the vehicle which was used for street washing (Generowicz et al. 2017).

In the series II-VI sampling was conducted in all three locations (sites C, I, and R). Based on the experience gathered during the first series, the experimental methodology was modified. In these further series, the experiments were started on Tuesdays and ended Friday morning. During the first street washing, street traffic was carried out normally, other than in the first series. During all series the following procedure was implemented: wet sweeping and washing of the streets began at 10 pm with streets washed by the water tankers. This procedure was performed in a few cycles, until 5 am. In all series, sweeping samples after weighing were collected for chemical analysis. Water samples were also collected at four points from the road surface during the first and last washes. The whole procedure was repeated for another three days. During the experiments, the amount of street sweeps was measured and the amount of water and fuel used monitored.

In order to show how traffic impacts air quality in the city during the summer months, the article presents results of PM10 and PM2.5 measurements during the World Youth Days (WYD) in Cracow, in July 2016. In this period, traffic in Cracow was largely restricted, and a major part of the regular city residents left the city. However, the impressive number of visitors (2.5 million) was present in Cracow during the celebrations, with 800,000 people attending the main ceremonies at Błonia Park (recreational area in the direct vicinity of the Three Bards Avenue). During this time the main part of the avenue (Krasiński Ave.) was closed to car traffic, and the MPO was sweeping and washing the streets in a continuous system.

2.3. Laboratory analyses

After sample collection, the samples of sweepings were analyzed among the others for: total (solid) dry weight; mineral dry weight; and organic dry weight. Analyses were performed in the laboratory of the WIOŚ. Dry weight, mineral dry weight, and organic dry weight was determined in according to method PN-EN 12880:2004. In the laboratory of the CUT the size of sweepings, and the size of suspended particles in the wastewater from the streets were also measured.

2.4. Weather and air quality data

Information about weather conditions were downloaded from the WIOŚ and the Faculty of Physics and Applied Computer Sciences of the AGH University of Science and Technology official websites. The data on ambient air quality used in this paper was obtained from the WIOŚ. To control PM10 and PM2.5 concentrations the automatic stations were used. In these automatic measurements the following methods were used: UV fluorescence: beta attenuation: oscillating microbalance; and optical method for PM10 and PM2.5 Met One Instruments, Inc. (Grants Pass, OR, USA, model BAM-1020); and an optical method using orthogonal light scattering to count individual particles with a semiconductor laser as a light source for PM10, PM2.5 GRIMM Aerosol Technik GmbH & Co (Ainring, Germany, Grimm M 180) (Bokwa 2008, Choi et al., 2015).

3. Results and discussion

In series I at site C perfect traffic conditions for the first wash of the streets were provided on the first day of the experiment, since one direction of the vehicle traffic had been completely stopped. During the following days of the experiments, only one side of road was used normally due to the traffic jams being formed. During the first day a clear increase of the dust concentration was observed, although sweepers with the PM10 certificate were used for sweeping (Fig. 3). A similar phenomenon had been noticed in previous studies conducted in Stockholm(Norman and Johanson, 2006). The noticeable increase of the level of dust suspended in the air was caused not only by the resuspension of material previously deposited on the road and sidewalks of the roadway, but also by traffic jams forming at site C. The start time of the experiment, 10 pm, was chosen due to the decrease of traffic. The traffic flow between 10 and 11 pm was more than 2,000 vehicles per hour, while during the rush hours is usually above 6,000 (Gliniak et al., 2015).

On the second day of the experiment, 2/3 (2 lanes out of 3) of one side of the roadway was excluded from traffic, and the resulting blockage was smaller. The increase in PM10 and PM2.5 in the first washing phase was noticeably smaller (Fig. 3). After the end of the series, the highest decreases in PM10 and PM2.5 concentrations were recorded in the 48 hours after the experiment. Comparing the daily concentration of three days after the first cleaning cycle, a decrease of about 25.4% for PM10, and 20.3% for PM2.5 was observed.

Concentrations of PM10 and PM 2.5 during the days when no experiments were carried out, showed an increase of dustiness during the night time, regardless of the day of the week, and season. The analysis of the traffic impact on Krasińskiego Ave., and the particulate matter concentrations carried out by Gliniak et al. (2015) showed no significant dependence, while confirming a strong relationship between PM10 and PM2.5 particulate matter in the air. The tests also showed an increase in the air dustiness at night regardless of the day of week and season. Similar trends were found in the measurements of dust concentration in other WIOŚ measuring stations located in the Kurdwanów and the Nowa Huta districts (Gliniak et al., 2015).

Relatively low concentrations of PM10 and PM2.5 were observed after the experiment despite wind speed lower than before it.. To combine these observations with the current meteorological conditions the average wind conditions during the experiment were also depicted in Fig. 3. The decreasing wind speed during evening/night hours also contributed to the observed PM concentration pattern. A characteristic feature is the predominance of latitudinal directions (east-west) determined by the location of the Cracow agglomeration. At site C, which is located in a street canyon, the impact of these meteorological conditions is somehow limited (Weber et al., 2013, Oleniacz et al., 2016) . At this location, the intensity of vehicle traffic and local air turbulence mainly shape the air quality in a significant way. Based on the available research results (Kozielska et al., 2009, Bogacki et al., 2012), it is possible to assume that in this area (site C) the share of secondary dust (PM2.5) lifted from the road surface by road transport is about 20-25%. Additionally, here is a bigger summer share of road transport in the shape of PM2.5 which exceeds 40%, then the overall share of dust discharged from the road exceeds 30% of the total concentration. Such a high impact of transport on PM results is the fact that in the winter period dust emissions from the heating of houses and the energy industry is increased(Bogacki et al., 2015).

The second series of research was shortened to one day due to weather conditions, i.e. heavy rains. The experiment was discontinued, but the impact of the rain (natural intensive street cleaning during the rain, dust was not only removed from the road surface but also from the air) was taken into consideration during data analyses. During series II, a decrease of PM10 concentration was observed (comparing three days before to three days after) for site C 14.3%, site I 28.7%, and site R 19.9% (Table 3), reduction PM2.5 sites C 25.0%, sites I 22.3%, sites R 12.1% (Table 3).

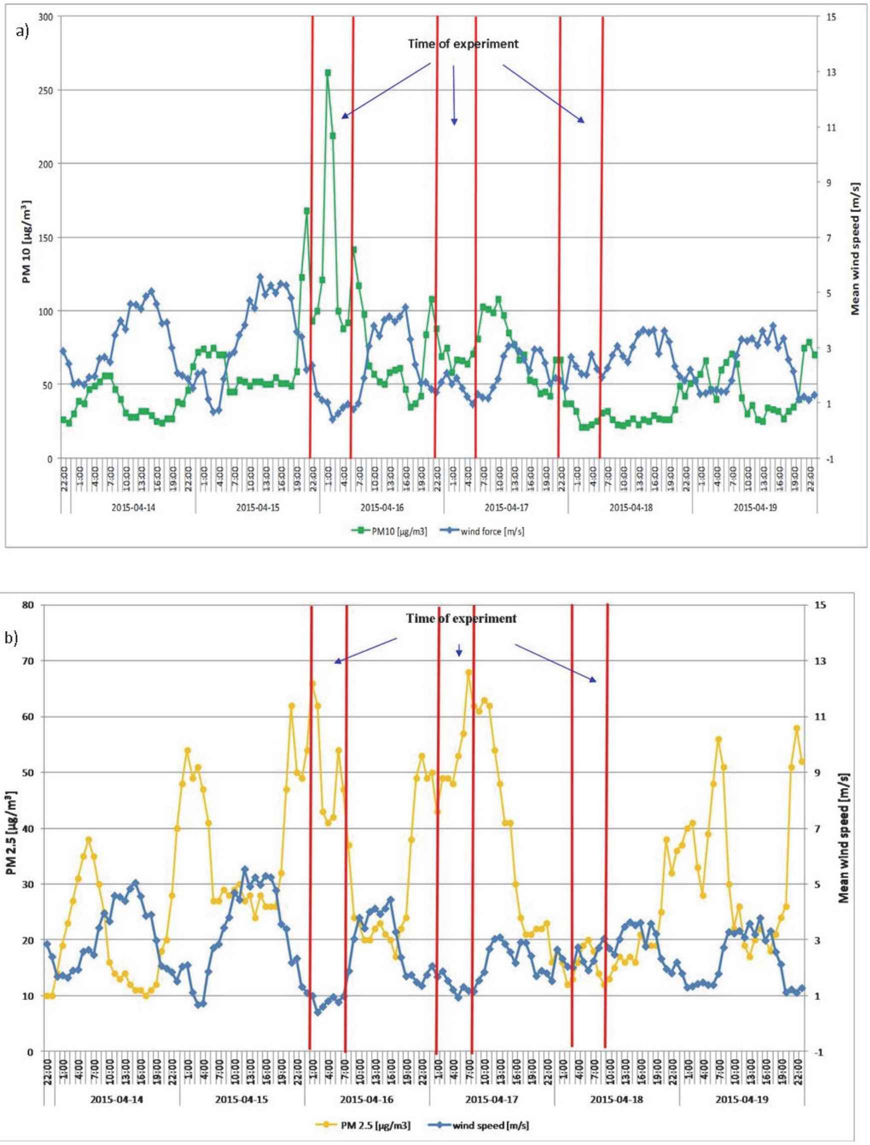

Fig. 3. Concentration PM10, PM2.5 and hour average wind speed during first series

Table 2. Results of chemical composition of water brushes from street washing and cleaning series IV

Site	C			I			R		
Date	2016-04-04	2016-04-05	2016-04-06	2016-04-04	2016-04-05	2016-04-06	2016-04-04	2016-04-05	2016-04-06
Air daily									
PM 10	86.0	106.0	82.0	74.0	90.0	70.0	62.0.0	76.0	57.0
PM 2.5	45.0	51.0	50.0	49.0	56.0	51.0	36	45.0	34.0
Sweeps									
Mass [kg]	860.0	540.0	380.0	1280	440.0	320.0	340.0	180.0	140.0
Total dry weight [g/kgs.s]	779.0	812.0	818.0	663,0	810.0	821.0	836.0	814.0	804.0
Mineral dry weight [g/kgs.s.]	974.0	990	989	91.2	980.0	983.-	984.0	989.0	991.0
Organic dry weight [g/kgs.s.]	26.0	10.0	11.00	88.00	20.00	17.00	16.00	11.00	9.00
Wastewater (Average four sample):									
First wash street									
Total suspended solid [g/dm^3]	13.02	11.86	3.62	6.000	6.860	6.14	18.80	7.890	2.920
Mineral suspended solid [g/dm^3]	12.486	11.726	3.156	5.766	6.684	5.2	15.42	7.102	1.962
Organic suspended solid [g/dm^3]	0.534	0.134	0.464	0.234	0.176	0.94	3.378	0.788	0.958
Last wash street									
Total suspended solid [g/dm^3]	3.4	2.16	0.692	1.98	1.496	2.05	1.830	0.856	0.378
Mineral suspended solid [g/dm^3]	2.946	2.068	0.506	1.782	1.356	1.668	1.650	0.742	0.226
Organic suspended solid [g/dm^3]	0.454	0.092	0.186	0.198	0.140	0.382	0.180	0.114	0.152

Table 3. PM 10 average concentration decreases after washing of streets [%]

Serie	C		R		I	
	daily	hourly	daily	hourly	daily	hourly
I	25.5	30.2	-	-	-	-
II	14.3	37.6	19.9	30.1	28.7	52.6
III	10.5	12.0	2.1	6.4	31.3	12.0
IV	16.7	4.5	5.8	4.1	17.4	24.5
V	25.3	13.8	4.5	1.0	19.2	10.5
VI	11.5	18.1	7.0	20.4	10.0	30.3
average	**17.3**	**19.4**	**7.8**	**12.4**	**21.3**	**26.0**
WYD	14.0	17.3	20.2	2.5	20.4	-5.2

Tables 3 and 4 present the results of PM10 and PM2.5 reduction efficiency calculated from hourly and daily hourly data from the WIOŚ monitoring station. The hourly averages were counted for the day from the end of the tests, i.e. from 5 am to 4 am, and the daily averages provided by the monitoring stations were counted from 0:00 am. Therefore, the daily average does not include the period in which the most effective cleaning of streets is observed. i.e. in the first 24 hours. The higher level of reduction was observed if hourly concentrations of particulate matter were analyzed than for daily concentrations (Table 3, 4) except for series II for site I. For sites R and I, the difference between the average daily and of daily concentrations is about 10% and up to 37% in site R. The average reduction of the PM10 hourly concentration for all series was respectively; for site C 19.4%, for site I 26%, and for site R 12.4%. In the case of reduction, PM2.5 was 21.2% for site C, respectively; 16.6% for site I, and 20.2% for site R.

Table 4. PM2.5 average concentration decreases after washing of streets [%]

Date	C		R		I	
	daily	hourly	daily	hourly	daily	hourly
I	20.3	55.6	-	-	-	
II	21.2	22.1	22.3	31.6	12.1	41.5
III	7.3	5.4	5.5	8.8	37.2	7.2
IV	3.1	2.1	6.7	7.0	15.4	21.1
V	27.4	21.8	24.4	23.6	12.0	3.0
VI	12.2	20.5	33.5	30.0	3.3	10.3
average	**15.4**	**21.2**	**18.5**	**20.2**	**19.2**	**16.6**
WYD	33.3	28.5	31.4	20.8	20.8	1.8

In all the series, a decrease in PM10 and PM 2.5 concentration was observed in the first few days after the end of the experiment, and then the level of air pollution increased. The time and size of the effects of combined mechanical sweeping and intensive street washing was influenced above all, by meteorological conditions and traffic. The shorter effect of decreasing the concentration of solid particles in sites I and R may be related to other factors than meteorological conditions such as, emissions from the ArcelorMittal steelworks, and combined heat and power plants or incinerators (site I). The improvement of air quality was observed for three to four days after such intensive cleaning of the road surface. The increase in particulate matter concentration during the street cleaning process (Fig. 3) is related to raising dust by sweeping vehicles and by creating traffic jams by slower vehicles (especially in site C). Strong winds disperse local air pollutants, but strong winds can also increase PM levels under certain meteorological conditions as a result of resuspension of soil and road dust, especially on warm and dry condition days. (Kukkonen et al., 2005, Kassomenos et al., 2012, Kassomenos et al., 2014). At site C, due to the canyon infrastructure development and the direction of the wind during the experiments, no significant influence of other sources of pollution was noticed than those resulting from road traffic and was related to secondary emissions of dust. In the case of this location, this effect in the summer months was observed in earlier studies (Kozielska et al., 2009, Bogacki et al., 2015, Bogacki et al., 2016). In the case of other locations, a greater impact of factors resulting from meteorological conditions was observed (Fig. 4). Cracow is struggling with poor air quality, especially during periods of calm winds from the south and west.

At the same time, stronger winds from northern directions contribute to periodic dilution of air pollution and improvement of ventilation in the city. Air masses originating from the south are mostly polluted with suspended dust, which can be explained by the inflow of fine particles from areas located further away from Cracow (Szulecka et al., 2017). In the case of site R, the concentration level of PM10 and PM2.5 depends on the quality of air flowing into Cracow, and also industrial sources (in this case mainly EDF Polska and the ARE Power Plant in Skawina), the impact is related in particular to the wind blowing from the east, and to a lesser extent from the south-east (Oleniacz et al 2016, Bajdur et al., 2016). Increased concentration of particulate matter (site I) is observed with the wind blowing from the east and north-east, and is related to the location of industrial plants (ArcelorMittal Poland SA Branch in Cracow, and other plants located in this sector). With the arrival of winds blowing from the west and north-west, the impact on the quality of air in this place also has road transport from nearby busy streets (Oleniacz et al., 2016).

Fig. 4. PM10 and PM2.5 concentration and hour average wind direction during series VI

One of the reasons for the stronger reduction of PM2.5 in relation to PM10 for the R area may be that the roadway on Halszki Street is located on a hillside. During intensive washing, the dust that remains is washed down with water from the street washing. This is due to the particle size distribution of the suspension in water. Based on the analysis of the particle size of the slurry in street washing water, the mean particle diameter of less than 2.5 μm was found to be 30%. On the basis of the obtained results, it can be concluded that the combination of sweeping washing followed by intensive street washing significantly increases the efficiency in removing dust particles with smaller diameters. Systematic removal of residual dust from the road contributes to the improvement of air quality.

Figure 4 present the effect of sweeping and intensive street cleaning on air quality on the example of series VI. They show the concentration of suspended dust depending on the wind direction for three days before, during, and three days after the experiment. It can be seen that during the sweeping and washing process the concentration of PM10 and PM2.5 increased, which is due to the increase of dustiness in the night hours as well as the excitation of dust during the sweeping process; in the afternoon the dustiness level decreases

The average daily concentration was lower after the first day of the experiment in relation to the concentration before the experiment: 61 μg/m^{3}for site C, 50 μg/m^3 for site I, and 44 μg/m^3 for site R; for PM 2.5, a similar phenomenon was observed of approximately 41 μg/m^3 for site I 25 μg/m^3 and 26 μg/m^3 for site R. At the end of the experiment, the concentration of PM10 was observed and decreased in all places, the average hourly concentration in over 60 (μg/m^3) after street cleaning was below the daily limit for PM10 (50 μg/m^3), and only at site C the concentration of PM2.5 was higher than 25 μg/m^3.

To compare the effect of cleaning street surfaces on air quality, the mean values of hourly concentrations of PM10 and PM2.5 were compared in the study area during the experiment, three days before and three days after. The results of dust concentrations in the air were made available by the air quality monitoring station of WIOŚ, Cracow. Figures 5 present the mean values of three-day concentrations, and the values of these concentrations can be reduced by 25.48% to 10.53%. In the case of PM10 particulate matter, their concentration can be reduced to the daily limit (50 μg/m^3) and sometimes even to the permissible annual average (40 μg/m^3).

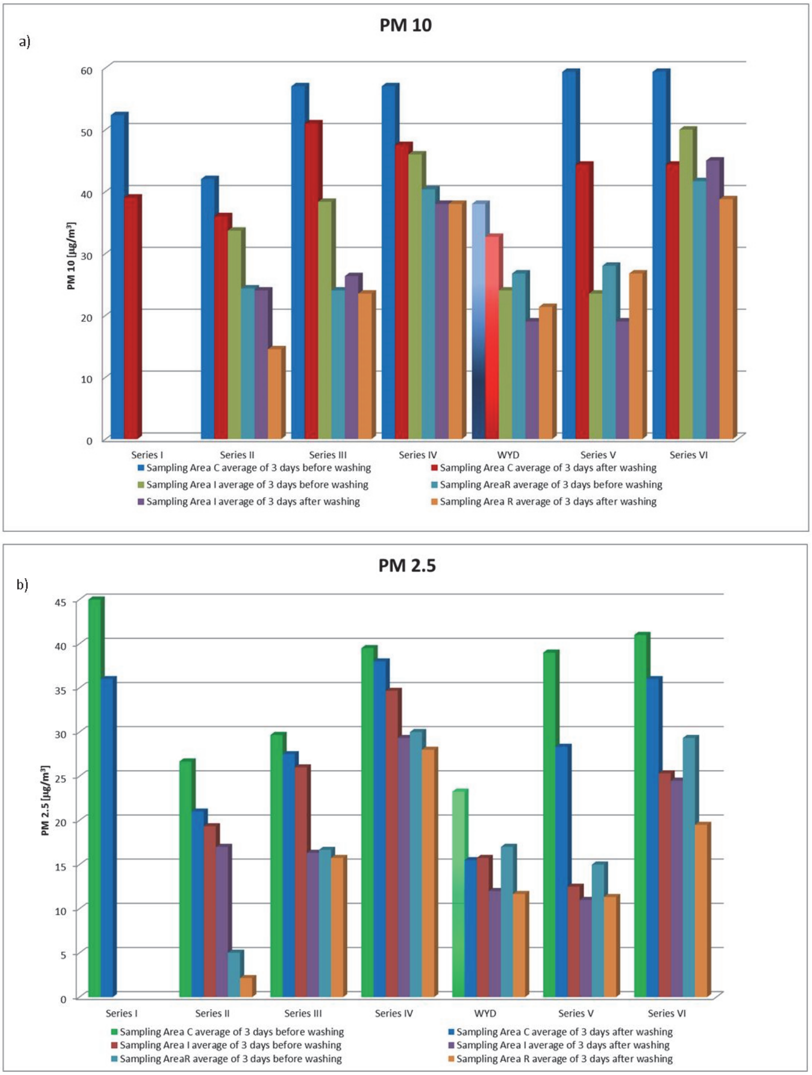

Fig. 5. Mean daily PM10 and PM 2.5 concentration in the air before and after the day experiment

The increase in dust concentration, which was observed after the WYD at the monitoring station located in the industrial area, is caused by the commissioning of the blast furnace at The Steelworks of ArcelorMittal after a few weeks break (Fig. 6). The metallurgical plant is located in the east facing the monitoring station. During the research, it was possible to observe a correlation between the concentrations of individual suspended dust fractions. During the launch of the blast furnace (http://krakow.pl), it was noticed the greater increase in the concentration of PM10 than PM 2.5.

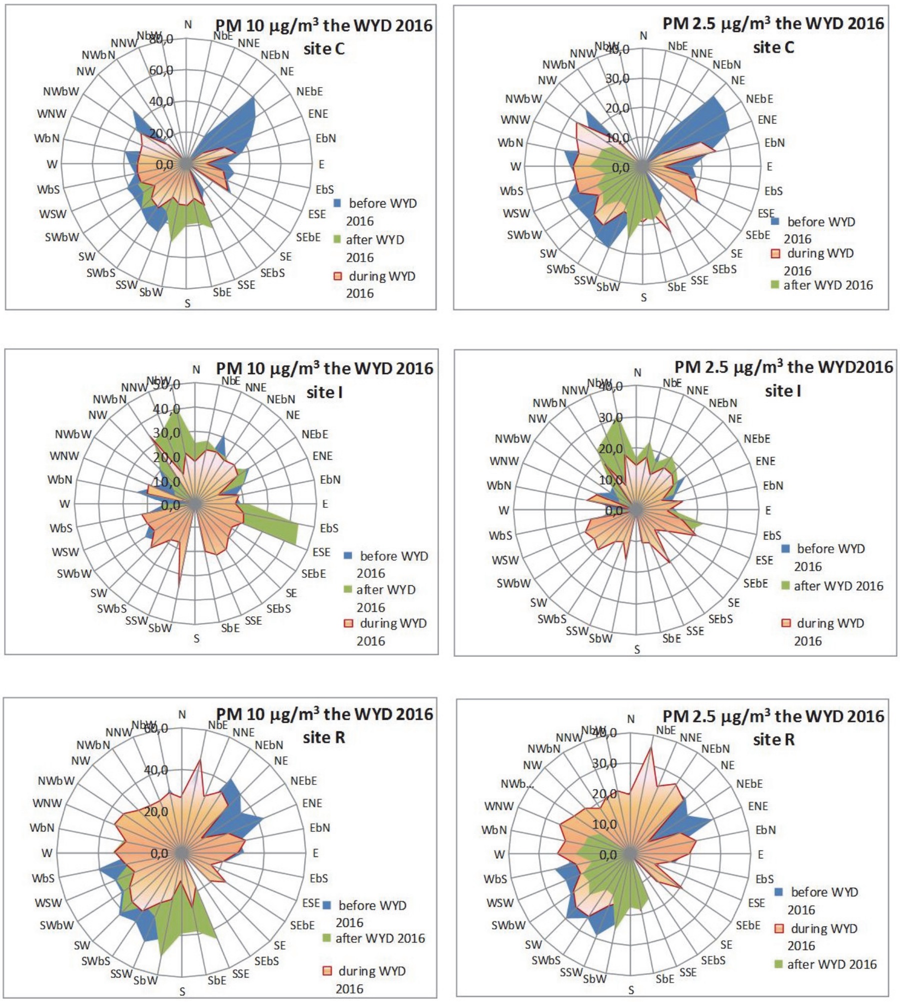

Fig. 6. Observed PM10, PM2.5 and average hour wind speed during WYD 2016

4. Conclusions

Cracow is one of the cities with the most polluted air in Europe, resulting from the combination of being in an unfavorable location (in a valley), as well as coal combustion as the typical heating method for Central and Eastern European cities. In the spring and summer seasons, the biggest impact on quality of air is car traffic, especially in the area of one of the main roads connecting the North and South of Poland, running through the city center (i.e. Three Bards Avenue). This study assessed the impact of street cleaning to reduce the amount of road dust by analyzing PM10, and PM2.5 concentrations after sweeping and street washing. After the experiments, average reductions in PM10 and PM2.5 concentrations were observed, which lasted up to three days from 17.3% for PM10 and from 15.4% for PM2.5.

The level of suspended dust in the air at sites I (industrial area), and R (residential area) was lower than at site C (transportation area) in the spring and summer seasons, and it did not exceed the daily limit (50 μg/ m^3). The effect of sweeping and washing of roads in sites R and I do not make such a big difference, as in site C. The reason is that the quality of air in these locations depends more on other factors than road traffic. The cleaning and intensive street cleaning activities carried out have contributed to the improvement of air quality in the test sites. The greatest impact of this action can be seen at sampling area C in the summer; where the main source of pollution in this place is traffic. Cracow is a city heavily burdened with significant emissions to atmospheric air, both by the location and the number of cars passing through, and industry. The limitation of these pollutants must take place on many levels, and cleaning and washing the streets acts only as a removal due to the consequences of pollution. The obtained results show very clearly the improvement of the state of the environment in terms of reduction of waste, improvement of the quality of urban infrastructure (pavements, and streets), and improvement of the quality of atmospheric air.

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Abstract

Road traffic is one of the most important factors triggering an increase of suspended dust air pollution in urban areas, especially during the summer. This phenomenon is caused not only by emissions from vehicle combustion engines, but mainly by the formation of dust during road use (tire abrasion, and resuspension of accumulated dust). Sweeping and street washing are the main methods used to remove dust deposited on road surfaces. This article presents the effectiveness of the PM10 and PM2.5 reduction as a result of sweeping, and then intensive street washing in one of the most polluted cities in Europe (Cracow, Poland). The study was carried out in three locations: i) on one of the city's busiest streets; ii) the industrial zone; and iii) at a residential area. The combination of intensive sweeping and roadway cleaning led to the reduction of the suspended dust concentration by 14-20.4% PM10 and 20.8%-33.3% for PM2.5. The greatest impact of this activity was observed in the area where the vehicle traffic was the main source of air pollution. In other places, the obtained effect was reduced by meteorological conditions or emissions from industry.

Keywords:
street cleaning, street sweeping, street washing, PM10, PM2.5

Wpływ zamiatania i mycia ulic na stężenie PM10 i PM2,5 w Krakowie

Streszczenie

Ruch drogowy jest jednym z najważniejszych czynników, który powoduje wzrost zanieczyszczenia powietrza zawieszonym pyłem na obszarach miejskich, zwłaszcza w okresie letnim. Zjawisko to jest spowodowane nie tylko przez emisje z silników spalinowych pojazdów, ale głównie przez tworzenie się pyłu w czasie użytkowania drogi (ścieranie opon i ponowne zawieszanie nagromadzonego pyłu). Zamiatanie i mycie ulic to główne metody usuwania kurzu leżącego na nawierzchniach dróg. W artykule przedstawiono skuteczność redukcji PM10 i PM2,5 w wyniku zamiatania, a następnie intensywnego mycia ulic w jednym z najbardziej zanieczyszczonych miast w Europie (Kraków, Polska). Badanie przeprowadzono w trzech lokalizacjach: i) na jednej z najbardziej ruchliwych ulic w mieście; ii) strefie przemysłowej; oraz iii) w dzielnicy mieszkalnej. Połączenie intensywnego zamiatania i mycia jezdni doprowadziło do zmniejszenia stężenia pyłu zawieszonego o 14-20,4% PM10 i 20,8-33,3% w przypadku PM2,5. Największy wpływ tej aktywności zaobserwowano na obszarze, gdzie ruch pojazdów był głównym źródłem zanieczyszczenia powietrza. W innych miejscach uzyskany efekt został zmniejszony przez warunki meteorologiczne lub emisje z zakładów przemysłowych.

Słowa kluczowe:
sprzątanie ulic, zamiatanie ulic , mycie ulic, PM10, PM2,5