Quantifying Emissions of PM₁₀ Generated by the Implosion of Concrete Grain Silos

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ABSTRACT

This study quantified the effect of imploding old concrete grain silos in Aqaba, Jordan, on the eastern side of the Gulf of Aqaba, an arid region, on air quality by measuring the PM₁₀ concentrations before and after the implosion at four monitoring locations. The implosion of the silos forms part of a comprehensive plan to relocate and upgrade the Port of Aqaba, which is situated on the coast of the Red Sea, with the goal of freeing space for development and improving the infrastructure in the heart of the city. The demolition, which occurred at 11:00 a.m. (local time) on 13 January 2019, generated a massive cloud of dust that was transported to nearby areas. To characterize these emissions, descriptive statistics, graphical methods, inverse distance weighting interpolation, decision trees constructed with recursive partitioning, the Gaussian dispersion model, the modified box model, and regression analysis were applied. The PM₁₀ concentrations were in compliance with the Jordanian 24-h standard of 120 µg m⁻³ prior to the implosion but substantially increased (although still varied by distance from the demolition site) at all four stations afterward, with the maximum values (259–587 µg m⁻³) exceeding the pre-implosion ones by as much as 26 times. However, these high concentrations were short-lived, and the majority of the stations returned to background levels within 30–33 hours. According to our calculations on the implosion, the PM₁₀ emission rate was $17 \pm 2 \text{ mg m}^{-2} \text{ s}^{-1}$, which is equivalent to $215 \pm 22 \text{ kg silo}^{-1}$, and the air mixing height was $613 \pm 72 \text{ m}$, or approximately eight times the height of the silos.

Keywords: PM₁₀; Demolition; Implosion; Emission rate; Air pollution; Aqaba.

INTRODUCTION

It is commonly known that air pollution by particulate matter (PM) has chronic and acute health impacts, including cough, wheezing, asthma attacks, bronchitis, skin and eye irritation, high blood pressure, heart attack, strokes and increased mortality rate (Eggleston *et al.*, 1999; Rand *et al.*, 2000; Castro *et al.*, 2001; Peters *et al.*, 2001; Samoli *et al.*, 2008). Sources of dust in urban areas are various, including construction and building demolition resulting in the release of a huge quantity of fugitive dust leading to severe deterioration of air quality that affects the quality of life of local people and their businesses (Muleski *et al.*, 2005; Joseph *et al.*, 2009; Font *et al.*, 2014; Azarmi *et al.*, 2015). Rabito *et al.* (2007) argued that demolition of old structures having lead-based paint are potential sources of environmental lead exposure.

Building demolition is carried out either by implosion or mechanical means that involve excavators or wrecking balls.

Mechanical means have longer impact on air quality at the demolition site and its surroundings (Dorevitch *et al.*, 2006) as compared to implosion which seems to have a short-lived but severe impact. Beck *et al.* (2003) studied air quality immediately after the implosion of a 22-story building within a four-block radius in east Baltimore and reported a fugitive dust increase by up to 3,000 times the amount before the implosion. Similarly, the implosion of a hospital in Calgary, Alberta, Canada, caused a massive increase in total suspended particulates (TSPs) in areas surrounding the implosion site (Stefani *et al.*, 2005).

Although there is a wealth of studies that have tackled air pollution from diverse sources such as road vehicles (Kumar *et al.*, 2014; Goel and Kumar, 2015), road works (Fuller and Green, 2004; Tian *et al.*, 2007), non-vehicular activities (Saliba *et al.*, 2010; Kumar and Morawska, 2014), and industrial works (Rodríguez *et al.*, 2004; Toledo *et al.*, 2008; Diapouli *et al.*, 2013; Kumar *et al.*, 2014), there is a lack of studies that address PM emanating from demolition sites. Consequently, the focus of this paper is related to (1) quantifying particulate matter with aerodynamic diameter less than or equal to 10 µm (PM₁₀) emissions during the implosion of concrete grain silos located at the old seaport in Aqaba off the Gulf of

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Aqaba that took place on 13 January 2019 and (2) estimating particle mass emission rate of PM₁₀ produced by the collapse of imploded silos.

DATA AND METHODS

Study Site and PM₁₀ Monitoring Stations and Data

The study site (Fig. 1) has 75 grain silos arranged in five parallel rows occupying a rectangular area of 8,246 m² (133 m × 62 m) on the eastern coast of the Gulf of Aqaba in Aqaba. It is located between longitudes 34°57'E and 35°02'E and latitudes 29°21'N and 29°33'N. The silos were constructed in 1975 and made of reinforced concrete. Diameter and height of each silo are 9 m and 75 m, respectively. The silos were demolished by implosion, which took place at 11:00 a.m. (local time) on 13 January 2019, by deploying 1,000 kg of explosives. Jordanian Department of Civil Defense (firefighting) placed several firefighting tankers and a jet to spray water at the collapsing silos in order to reduce dust emission. A square block surrounding the implosion site was fenced off and guarded by police and city officials on the morning of the implosion. Public access was restricted preceding the implosion as well as for two hours following the event.

To differentiate implosion-generated PM₁₀ from background values, four MP101M analyzers (ENVEA, Poissy, France), which use the standard beta gauge measurement method, were installed at four monitoring stations (Fig. 1). The monitoring stations were also equipped with combined wind speed and direction anemometers DNA021-022 (LSI SpA, Milano, Italy). The first station is City Station located in downtown Aqaba about 3,830 m north of the silos. The other

three stations are Mobile Station, South Station, and New Port Station. They are located south of the silos along the Gulf of Aqaba about 3,059 m, 12,080 m, and 16,005 m away, respectively. Monitoring continued for 72 hours starting at 9:15 a.m. (local time) on 12 January 2019 and ending at 9:00 a.m. (local time) on 15 January 2019.

Descriptive Statistical Analysis and Spatial Visualization

Measures of descriptive statistics (represented by mean, minimum, and maximum) in addition to graphical methods (represented by time-series scatter plots) were produced for the PM₁₀ time-series data before and after imploding for the four stations (Freedman *et al.*, 2007).

For quick visualization of the spatial and temporal variability of PM₁₀ time-series data at the four stations before and after the imploding, inverse distance weighting (IDW) interpolation technique was applied (Borga and Vizzaccaro, 1997).

Recursive Partitioning Analysis

Decision trees were constructed from the PM₁₀ time-series data for the four stations by applying recursive partitioning (Zhang and Singer, 2010). The aim is to partition the time series into homogeneous meaningful clusters (nodes). These clusters should describe the expected behavior of PM₁₀ in the study area pre-implosion, post-implosion, in addition to decaying after the dispersal of the impact resulting from implosion. Decision trees consist of root nodes, internal nodes, and terminal nodes. Root nodes contain the entire observations from which the trees are grown.

In the present study, decision tree size (i.e., number of cut-off points) was determined interactively by first growing the

Fig. 1. Location map of the study site.

tree to a large enough size one split at a time and then pruning so that subgroups that cannot increase significantly the explanation power of the tree (measured by the coefficient of determination (R^2)) were eliminated (Izenman, 2008).

PM₁₀ Emission Rate

PM₁₀ emission rate from imploding of the silos were calculated by employing the Gaussian plume dispersion formula:

$$C = \frac{Q}{2\pi u \sigma_z \sigma_y} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left\{ \exp\left(-\frac{(z-h_{eff})^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+h_{eff})^2}{2\sigma_z^2}\right) \right\} \quad (1)$$

where C is steady state concentration at point (x, y, z) ($\mu\text{g m}^{-3}$), Q is emission rate ($\mu\text{g s}^{-1}$), u is wind speed at stack height (m s^{-1}), σ_y and σ_z are dispersion coefficient functions, and h_{eff} is elevation of emission point (m).

When calculating ground-level PM₁₀ concentration directly below the centerline of a dust plume that emanates from a ground-level source, y , z , and h_{eff} were all assumed to be zero. In this case Eq. (1) becomes:

$$C = \frac{Q}{\pi u \sigma_z \sigma_y} \quad (2)$$

Solving Eq. (2) for Q yields:

$$Q = \pi u \sigma_z \sigma_y C \quad (3)$$

PM₁₀ emission rate could also be calculated by applying the modified box model (Fig. 2) that has been developed and used by previous studies (Jamriska and Morawska, 2001; Font et al., 2014; Azarmi et al., 2016):

Fig. 2. Schematic diagram of the box model showing all dimensions: L and W refer to length and width of the box, respectively, H refers to air mixing height, and $\bar{u}$ refers to wind velocity (adapted from Jamriska and Morawska, 2001; Font et al., 2014; Azarmi et al., 2016).

$$\text{PM}_{10} = B + \frac{Wq}{uH} \quad (4)$$

where q is PM₁₀ emission rate from unit area ($Q/8,246 \text{ m}^{-2}$) (in $\mu\text{g m}^{-2} \text{ s}^{-1}$), u is wind speed, W is the box width parallel to wind velocity $\bar{u}$, H is mixing height (box height), and B is average background concentration. Mixing height (how high the dust spewing by the implosion can reach during the implosion) depends on atmospheric stability. It plays important role in dust dilution and dispersion. Therefore, it can be calculated by solving Eq. (4) for H , which yields the following expressions:

$$H = \frac{qW}{u(\text{PM}_{10} - B)} \quad (5)$$

$$H = \frac{qW}{u\Delta\text{PM}_{10}} \quad (6)$$

where ΔPM_{10} is the difference between average PM₁₀ concentration during the spread of the dust plume resulting from the implosion and the average PM₁₀ before the implosion (background concentration). It had to be calculated at the sides of the hypothetical box that surrounds the collapsing silos. This was achieved by developing a logarithmic decay profile for ΔPM_{10} in order to back-calculate PM₁₀ concentrations at the box faces about 31 m away from the silos' center (Azarmi et al., 2016):

$$\Delta\text{PM}_{10} = a \cdot \ln(d) + b \quad (7)$$

$$H = \frac{qW}{u(a \cdot \ln(d) + b)} \quad (8)$$

where d is the distance from the implosion site, a and b are regression coefficients.

RESULTS AND DISCUSSIONS

Table 1 and Fig. 3 show some basic descriptive statistics and scatter plots for the PM₁₀ time-series data recorded at the four monitoring stations. It can be observed that before implosion, all PM₁₀ values (background) were in compliance with the Jordanian 24-h standard of $120 \mu\text{g m}^{-3}$ but have increased substantially after the implosion and exceeded background values by several times. The lowest pre-implosion values of PM₁₀ were recorded at South Station where PM₁₀ varied from $23 \mu\text{g m}^{-3}$ to $85 \mu\text{g m}^{-3}$ with mean of $51 \mu\text{g m}^{-3}$, whereas the highest pre-implosion PM₁₀ values were recorded at Mobile Station where PM₁₀ varied from $58 \mu\text{g m}^{-3}$ to $119 \mu\text{g m}^{-3}$ with a mean of $82 \mu\text{g m}^{-3}$. However, the lowest post-implosion PM₁₀ values were recorded at New Port Station, which is the farthest station from the silos, where PM₁₀ varied from $34 \mu\text{g m}^{-3}$ to $259 \mu\text{g m}^{-3}$ with a mean of $193 \mu\text{g m}^{-3}$. The highest post-implosion PM₁₀ values were recorded at Mobile Station, which is the closest station to the

Table 1. Basic descriptive statistics for PM₁₀ data for the four stations.

Monitoring Station	Mean ($\mu\text{g m}^{-3}$)	Minimum ($\mu\text{g m}^{-3}$)	Maximum ($\mu\text{g m}^{-3}$)
City Station (before imploding)	79.65	25.57	116.72
City Station (after imploding)	255.25	57.51	442.14
Mobile Station (before imploding)	81.99	58.00	119.00
Mobile Station (after imploding)	291.75	101.00	587.00
South Station (before imploding)	51.38	23.00	85.00
South Station (after imploding)	179.75	60.00	355.00
New Port Station (after imploding)	193.22	34.00	259.00

Fig. 3. Scatter plots for the PM₁₀ ($\mu\text{g m}^{-3}$) time-series data for the four stations showing the Jordanian standard (horizontal dashed line) and the time of implosion (vertical solid line).

silos, where PM₁₀ varied from 101 $\mu\text{g m}^{-3}$ to 587 $\mu\text{g m}^{-3}$ with a mean of 292 $\mu\text{g m}^{-3}$. These observations indicate that post-implosion PM₁₀ values were up to 26 times higher than the background values. This is higher than those obtained by other studies (Dorevitch *et al.*, 2006; Azarmi *et al.*, 2016) who reported up to 11-fold-higher PM₁₀ values during demolition than background levels, but less than the 3,000-fold-higher post-implosion PM₁₀, which is reported by Beck *et al.* (2003). It is worth mentioning that Beck *et al.* (2003) measurements were carried out at only four blocks away from the implosion site which is much closer than our monitoring locations which were located between 3.1 km and 16 km away from the imploded silos. Furthermore, mitigation measures (represented by spraying water at the collapsing silos) that have been implemented during implosion in our case have likely reduced dust emissions; otherwise post-implosion PM₁₀ values would have been more than 26 times higher than pre-implosion PM₁₀. Windrows of wind speed and direction recorded at the four stations indicate that wind speed was relatively low (0–7.5 m s^{-1}) during the monitoring period with continuous shift of wind direction. This would have enhanced the chance to transport dust evenly to surrounding areas. Nevertheless, values of PM₁₀ recorded in the present study before and after the implosion show that the amount of dust emitted from the implosion site was massive, but it decayed rapidly as it dispersed away from the site.

Two major peaks of PM₁₀ values (Fig. 3) can be noticed after the imploding in all monitoring stations. For City

Station, which lies to the north of the silos, these two peaks appeared about 6 hours (PM₁₀ of $\sim 433 \mu\text{g m}^{-3}$) and 21 hours (PM₁₀ of $\sim 442 \mu\text{g m}^{-3}$) after the implosion. For Mobile Station, South Station, and New Port Station, the first peaks existed about 4 hours (PM₁₀ of $\sim 587 \mu\text{g m}^{-3}$), 6 hours (PM₁₀ of $\sim 346 \mu\text{g m}^{-3}$), and 8 hours (PM₁₀ of $\sim 259 \mu\text{g m}^{-3}$), respectively, after implosion while the second peaks existed at about 21 hours (PM₁₀ of $\sim 439 \mu\text{g m}^{-3}$), 23 hours (PM₁₀ of $\sim 355 \mu\text{g m}^{-3}$), and 25 hours (PM₁₀ of $\sim 253 \mu\text{g m}^{-3}$), respectively, after implosion. Hence, for monitoring stations that lie to the south of the silos, it can be concluded that the times at which these two major peaks are noticed increase as the distance between the monitoring station and silos increases, while their magnitudes decrease as the distance between the monitoring station and silos increases. A third minor peak of PM₁₀ values can be detected after the implosion in New Port Station (33 hours after implosion with PM₁₀ of $\sim 204 \mu\text{g m}^{-3}$) and City Station (33 hours after implosion with PM₁₀ of $\sim 281 \mu\text{g m}^{-3}$). This third minor peak of PM₁₀ values can hardly be detected at Mobile Station (29 hours after implosion with PM₁₀ of $\sim 331 \mu\text{g m}^{-3}$) and South Station (30 hours after implosion with PM₁₀ of $\sim 212 \mu\text{g m}^{-3}$).

Fig. 4 shows snapshots of the spatial and temporal distribution of PM₁₀ values before and after implosion at 10 distinct times resulting from applying IDW. This figure supports our previous stated observation. That is, before implosion all areas at different times had PM₁₀ values below the Jordanian standard. After implosion, areas with PM₁₀

Fig. 4. The results of applying inverse distance weighting (IDW) on the PM_{10} time-series data for the four stations before and after implosion. Areas with PM_{10} values greater than the Jordanian standard are also shown.

values above the standard by several times appeared first in locations centered on Mobile Station, then gradually covered the whole study area, and then air returned to its background values as it was before implosion. The last traces of PM_{10} values above the standard after implosion were seen around New Port Station.

The results of applying recursive partitioning on PM_{10} time-series data for the four monitoring stations are shown in Table 2 and Figs. 5–6. Regarding all monitoring stations, the decision trees explained about 80% of the variability in PM_{10} data (Table 2). For City Station, Mobile Station, and South Station, the analysis partitioned the data into three distinct homogeneous clusters with two cut-off points, while for New Port Station, four distinct homogeneous clusters were constructed with three cut-off points (Figs. 5–6). The first cut-off point for City Station is located 1 hour and 45 minutes after the implosion. For Mobile Station, South Station, and New Port Station, the first cut-off points are located at 1 hour and 15 minutes, 2 hours and 45 minutes, and 4 hours and 45 minutes after the implosion, respectively. The last cut-off point for City Station is located 34 hours and 30 minutes after the implosion. For Mobile Station, South Station, and New Port Station, the last cut-off points are located at 32 hours and 15 minutes, 32 hours and 45 minutes, and 37 hours and 45 minutes after the implosion, respectively. Hence, it is obvious that the times at which the first and last cut-off points are located are directly proportional to the distances between the monitoring stations and silos. That is, the longer the distance between the monitoring station and

the silos, the longer the time at which the cut-off point is observed.

Furthermore, the predicted means of PM_{10} , which were calculated for the clusters, obtained for City Station and Mobile Station are almost similar. They increased from $81 \mu\text{g m}^{-3}$ to $305 \mu\text{g m}^{-3}$, and then decreased to $141 \mu\text{g m}^{-3}$ for City Station, and increased from $84 \mu\text{g m}^{-3}$ to $366 \mu\text{g m}^{-3}$, and then decreased to $143 \mu\text{g m}^{-3}$ for Mobile Station. The distances between these two stations and the silos are very similar; however, City Station is located to the north of the silos while Mobile Station is in the south. For South Station, the predicted means of PM_{10} , which were associated with the clusters, increased from $55 \mu\text{g m}^{-3}$ to $218 \mu\text{g m}^{-3}$ and then decreased to $113 \mu\text{g m}^{-3}$. For New Port Station, the predicted means of PM_{10} associated with the clusters increased from $168 \mu\text{g m}^{-3}$ to $227 \mu\text{g m}^{-3}$, and then decreased to $185 \mu\text{g m}^{-3}$, and finally went down to $117 \mu\text{g m}^{-3}$. Again, it is clear that (excluding New Port Station) the magnitudes of the predicted means of PM_{10} data associated with different clusters, which were obtained for the monitoring stations, are inversely proportional to the distances between the monitoring stations and silos. This means that the longer the distance between the monitoring station and the silos is, the smaller the magnitude of the predicted mean of PM_{10} is.

For City Station, Mobile Station, and South Station, the first and last cut-off points can be regarded as representing the times at which these monitoring stations started and ended recording the impact of imploding on PM_{10} values, respectively. Similarly, the first clusters and the associated

Table 2. Predictive powers of the decision trees constructed from applying recursive partitioning technique on the PM₁₀ time-series data for the four stations and the associated decision rules.

Monitoring Station	R ²	Decision Rule	
City Station	0.801	If (Time < 12:45, 13 Jan.)	Then (PM ₁₀ = 80.67 µg m ⁻³)
		If (12:45, 13 Jan. ≤ time < 21:30, 14 Jan.)	Then (PM ₁₀ = 304.75 µg m ⁻³)
		If (Time ≥ 21:30, 14 Jan.)	Then (PM ₁₀ = 141.05 µg m ⁻³)
Mobile Station	0.799	If (Time < 12:15, 13 Jan.)	Then (PM ₁₀ = 84.03 µg m ⁻³)
		If (12:15, 13 Jan. ≤ time < 19:15, 14 Jan.)	Then (PM ₁₀ = 365.52 µg m ⁻³)
		If (Time ≥ 19:15, 14 Jan.)	Then (PM ₁₀ = 143.20 µg m ⁻³)
South Station	0.796	If (Time < 13:45, 13 Jan.)	Then (PM ₁₀ = 54.68 µg m ⁻³)
		If (13:45, 13 Jan. ≤ time < 19:45, 14 Jan.)	Then (PM ₁₀ = 218.49 µg m ⁻³)
		If (Time ≥ 19:45, 14 Jan.)	Then (PM ₁₀ = 112.81 µg m ⁻³)
New Port Station	0.809	If (Time < 15:45, 13 Jan.)	Then (PM ₁₀ = 168.00 µg m ⁻³)
		If (15:45, 13 Jan. ≤ time < 14:45, 14 Jan.)	Then (PM ₁₀ = 227.28 µg m ⁻³)
		If (14:45, 14 Jan. ≤ time < 00:45, 15 Jan.)	Then (PM ₁₀ = 185.00 µg m ⁻³)
		If (Time ≥ 00:45, 15 Jan.)	Then (PM ₁₀ = 117.38 µg m ⁻³)

Fig. 5. Scatter plots for the R² values resulting from interactively growing the decision trees constructed from applying recursive partitioning technique on the PM₁₀ time-series data for the four stations to large enough sizes one split at a time and then pruning. **Fig. 6.** Plots for the decision rules constructed from applying recursive partitioning technique on the PM₁₀ time-series data for the four stations showing the Jordanian standard (horizontal dashed line) and the time of implosion (vertical solid line).

predicted means of PM₁₀, the second clusters and the associated predicted means of PM₁₀, and the third clusters and the associated predicted means of PM₁₀ can be regarded as representing the background for PM₁₀ before the implosion, the change in values of PM₁₀ resulting from the implosion, and the change in values of PM₁₀ after the dispersal of the impact resulting from the implosion, respectively.

Emission rate of PM₁₀ (Q) was estimated by applying Eq. (3). It was found to be $140 \pm 14 \text{ g s}^{-1}$ (Table 3). Therefore, emission rate of PM₁₀ per unit area per second (q) was attained by dividing this value by 8,246 (the total area occupied by the silos), which yields $17 \pm 2 \text{ mg m}^{-2} \text{ s}^{-1}$. This value is about 500-fold greater than that observed by Azarmi *et al.* (2016) who reported emission rates of about $0.035 \text{ mg m}^{-2} \text{ s}^{-1}$ for PM₁₀ from a building demolition that took place in south England using an excavator. This finding clearly demonstrates that implosion releases a massive amount of dust that severely deteriorates air quality at the surroundings of the implosion site. Weather, soil type, and absence of green areas in Aqaba whose climate is hot and dry have likely sustained dust re-entrainment, which is contrasted to south England, whose wet climate that supports a lush and green landscape, lowers dust generation considerably.

Total mass of fugitive dust emanating from the demolished silos in 32 hours (the average time that took PM₁₀ to decrease to background value as determined from recursive partitioning) is about $16 \pm 2 \text{ t}$. PM₁₀ emission rate expressed in kilograms per silo was calculated by dividing the total mass of generated PM₁₀ by 75 (number of silos), which yields $215 \pm 22 \text{ kg silo}^{-1}$. Air mixing height (H) was calculated by substituting the value of PM₁₀ emission rate per unit area (q) along with the values of a and b from Fig. 7, which are $-73.1 \text{ } \mu\text{g m}^{-3}$ and $824 \text{ } \mu\text{g m}^{-3}$, respectively in Eq. (7), and found to be $613 \pm 72 \text{ m}$, which is about eight times the original silos' height. The calculation of H is important for determining the turbulent domain in which dispersion takes place. In addition, it could be used as a scaling factor to describe the vertical profiles of the atmospheric boundary layer variables (Beyrich *et al.*, 1998).

SUMMARY AND CONCLUSION

The Aqaba Special Economic Zone Authority has been implementing a comprehensive plan to relocate and upgrade the Port of Aqaba, which is situated on the coast of the Red Sea, with the goal of freeing space for development and improving the infrastructure in the heart of the city. The new site is set approximately 20 km south of the current location, near the border of Jordan and Saudi Arabia. The project involves massive amounts of construction and demolition, which will potentially elevate the airborne particulate matter concentrations in the vicinities of the work areas. Most of

Fig. 7. Logarithmic decay profile of PM₁₀ at the implosion site.

the old facilities, which contain asbestos, have been dismantled by selective excavation in order to suppress fugitive dust. However, the asbestos-free grain silos that were built south of Aqaba next to the Gulf of Aqaba in the 1970s have been demolished by implosion. The demolition, which occurred at 11:00 a.m. (local time) on 13 January 2019, generated a massive cloud of dust that was transported to nearby areas. The PM₁₀ levels were measured at four monitoring stations surrounding the demolition site before and after the implosion.

The monitoring period can be divided into three phases, namely, the stage preceding the implosion, the implosion and its aftermath, and the return to pre-implosion conditions. The PM₁₀ concentrations during the first phase were below the Jordanian 24-h limit of $120 \text{ } \mu\text{g m}^{-3}$ and represent the areal background levels. The second phase commenced with the implosion and lasted 30–33 hours, depending on the location of the station. During this stage, the concentrations increased substantially, resulting in maximum values ($259\text{--}587 \text{ } \mu\text{g m}^{-3}$) that exceeded the minimum background values ($23\text{--}58 \text{ } \mu\text{g m}^{-3}$) by up to 26 times. Mitigation measures (spraying the imploding silos with water) in addition to favorable meteorological conditions (low wind speed and continual wind shifts) likely reduced the emission of dust and enhanced the evenness of the dispersion to surrounding areas; otherwise, the post-implosion values would have been even higher. Hence, mitigation and timing (with respect to meteorological conditions, specifically, the wind speed and direction) are critical factors in minimizing the adverse effects of such projects. During the third phase, the PM₁₀ emitted by the implosion dispersed, and the concentrations returned to their background values. The results indicate that the concentrations associated with an implosion decay logarithmically with distance; in this case, the PM₁₀ emission rate was $17 \pm 2 \text{ mg m}^{-2} \text{ s}^{-1}$, which is equivalent to $215 \pm 22 \text{ kg silo}^{-1}$, and the air mixing height was $613 \pm 72 \text{ m}$, or approximately eight times the height of the silos.

After World War II, the need for large-scale reconstruction in dense urban areas led to the emergence of the demolition

Table 3. PM₁₀ emission rate. Values of σ_y , σ_z are calculated by following Martin (1976) method, assuming slightly unstable air (Class C).

Monitoring Station	D (m)	σ_y (m)	σ_z (m)	Q (g s ⁻¹)	Q_{avg} (g s ⁻¹)	Q_{STDV} (g s ⁻¹)
City Station	3.8	343	206	150	140	14
Mobile Station	3.1	286	171	130		

industry, which, employing controlled implosion among other methods, grew and matured throughout the world during the latter half of the twentieth century (Blanchard, 2002). The current study, however, is unique, as no demolition projects using implosion have been previously investigated in Jordan. Furthermore, the lack of regulations in this sector demonstrates a significant gap in the regulatory system of the nation, which must be filled by establishing well-defined and scientifically based rules. Mitigation measures, as mentioned previously, can reduce the risks to surrounding communities and the environment.

Finally, future studies should extend the third phase of the monitoring period in consideration of the relatively long dispersal time of PM₁₀. Additional time-series data will enable us to examine the time lapse of the decrease in concentration and determine exactly when the background value is reached, which is the most important question in terms of health.

ACKNOWLEDGEMENT

Immense gratitude is due to Aqaba Special Economic Zone Authority for permitting the authors to use meteorological and air quality data in preparing this paper.

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Received for review, February 17, 2020

Revised, May 15, 2020

Accepted, May 21, 2020