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PM_{10} Concentration Emitted from Blasting and Crushing Processes of Limestone Mines in Saraburi Province, Thailand

Kanokrat Makkwao, Tassanee Prueksasit

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***Abstract*—**This study aimed to investigate PM_{10} emitted from different limestone mines in Saraburi province, Thailand. The blasting and crushing were the main processes selected for PM_{10} sampling. PM_{10} was collected in two mines including, a limestone mine for cement manufacturing (mine A) and a limestone mine for construction (mine B). The IMPACT samplers were used to collect PM_{10}. At blasting, the points aligning with the upwind and downwind direction were assigned for the sampling. The ranges of PM_{10} concentrations at mine A and B were 0.267-5.592 and 0.130-0.325 mg/m³, respectively, and the concentration at blasting from mine A was significantly higher than mine B ($p < 0.05$). During crushing at mine A, the PM_{10} concentration with the range of 1.153-3.716 and 0.085-1.724 mg/m³ at crusher and piles in respectively were observed whereas the PM_{10} concentration measured at four sampling points in mine B, including secondary crusher, tertiary crusher, screening point, and piles, were ranged 1.032-16.529, 10.957-74.057, 0.655-4.956, and 0.169-1.699 mg/m³, respectively. The emission of PM_{10} concentration at the crushing units was different in the ranges depending on types of machine, its operation, dust collection and control system, and environmental conditions.

***Keywords*—**Blasting, crushing, limestone mines, PM_{10} concentration.

I. INTRODUCTION

In Thailand, high-quality limestone resources can be found widely and can make the highest income for primary industries [1]. Furthermore, Thailand also has a high limestone demand for cement manufacturing and construction to support the infrastructure to upgrade communication with other countries and enhance international trade. Certainly, the production of limestone in the future is going to expand for supporting high consumption. Saraburi province is the area that has the highest quantity and high quality of limestone in Thailand [2]. Also, Saraburi has a lot of limestone mines, crushing plants as well as cement factories densely. There are more than seventy limestone mines, especially in Chalermprakiet and Praputthabath district. Nevertheless, the critical environmental problem at this site is air pollution; in particular, particulate matter (PM) contributed from limestone mining. PM-generating by mining processes might disperse to the vicinity and affect people living around. Local people believe that mining is a primary emission source of PM in this area, and they often have complaints to local authorities. Therefore, the major industries in Saraburi, limestone mines, should be estimated completely about the PM_{10} distribution and concentration in the processes. The major limestone industries in Saraburi are limestone for cement manufacturing and limestone for construction. The main processes to produce limestone composed of blasting and crushing would be selected to estimate PM_{10} emission in this study.

There was a previous study that assessed the dust dispersion from the crushing of hard rock aggregates. They compared the coarse particles, PM_{10} collected from the different types of crushers. They found that the tertiary crusher produced PM_{10} more than the secondary crusher two times [3]. Types of crushers can grind the aggregated rock into various sizes so it can influence the PM_{10} emission. For example, the higher levels of crusher can produce more PM due to the smaller sizes of production. Similarly, the study about airborne dust in the Italian basalt quarry presented PM_{10} concentration at the secondary crusher was higher than at the primary [4]. Therefore, the result can be interpreted as the crusher breaking into smaller size contributed more PM_{10} than the coarse size product. Besides, in the study about fugitive dust at gravel processing sites in Taiwan, three size-ranges of PM were collected, including total suspended particles (TSP) as the largest and followed by PM_{10} and $PM_{2.5}$, respectively, at the unpaved road, bare ground, crushing process and piles. The crushing process emitted PM including TSP, PM_{10}, and $PM_{2.5}$ more than those released from the piles which generated the lowest concentration [5]. Furthermore, PM concentration from the stone crushing industry was measured at source, near the crushing process, around the crushing units, and ambient PM around the process. The study confirmed the significant respirable particle size in mining sites was PM_{10} in the crushing process. Also, the meteorological data could affect the PM_{10} concentration at the source. The results showed average PM_{10} concentration at the downwind (0.11-1.2 mg/m³) was higher than the upwind (0.090-0.156 mg/m³) [6]. Therefore, this study was assigned to measure the PM_{10} concentration emitted from blasting and crushing, the main process of a limestone mine, and compared with the different limestone industries represented by mine A and mine B in Saraburi province. The study results would be beneficial to identify the main emission activities in limestone mining and the emission control for PM_{10} would be properly

Kanokrat Makkwao is a master's student of International Program in Hazardous Substance and Environmental Management (IP-HSM) Graduated School, Chulalongkorn University, Bangkok 10330, Thailand (e-mail: Kanokrat.9266@gmail.com).

Tassanee Prueksasit is an Assistant Professor at Department of Environmental Science, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand (e-mail: Tassanee.c@chula.ac.th).

recommended.

II. Materials and Method

A. Study Area

Two mines located in Praputthabath subdistrict, Saraburi province where there are a lot of limestone mining and crushing plants were selected for this study as shown in Fig. 1. These selected mines are the open-pit mines locating at 200-300 meters from mean sea levels (MSL).

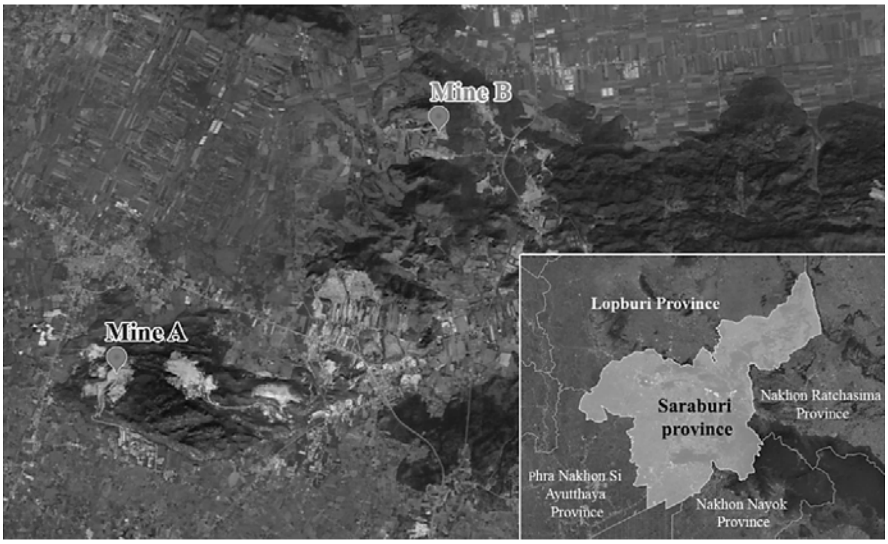

Fig. 1 The location of the study area

The first mine (mine A) is a limestone mine for cement manufacturing which has different processes from another limestone mine for construction (mine B). A boundary area of mine A is larger than mine B so that the amount of limestone production is also higher. The distance between these two mines is 12 km approximately. Also, the surrounding areas in a one-kilometer radius are agricultural and residential.

Blasting and crushing of each mine were assigned as the main sections for PM_{10} sampling. At the blasting zone, time, and location of PM_{10} sampling had to follow the mining plan and possibly be located in a different location. The sampling points at the crushing zone of two mines were selected corresponding to their production lines which are totally different. Mine A has only one simple step to grind only 80 mm in size range using a rotary crusher and transferred to the crushed limestone stockpiles by a conveyor belt (Fig. 2) whereas mine B has a more complicated process that produces more than one size. There are three crushing steps which consist of primary (a jaw crusher), secondary (a gyratory crusher), and tertiary crusher (an impact crusher). After that, a vibrating screen is used to sieve crushed limestone for size segregation at the screening station and transferred to the stockpiles (Fig. 3).

B. PM_{10} Sampling

The sampling points at the blasting zone were set accordingly to the wind direction and in the safe zone. Before sampling, the current wind direction was measured by the wireless weather station (Devis, Vantage PRO2). Then, IMPACT samplers (SKC, Cat. No. 225-390) containing PTFE filter with diameter 46.2 mm for the PM_{10} sampling as well as portable real-time PM_{10} monitors, Aeroqual series 500, were set at upwind for one point and at downwind for three points before blasting time 30-60 minutes approximately as illustrated in Fig. 2. After blasting, all samplers were operated for 15-30 minutes approximately depending on the weather condition and mining operation.

For the crushing process, four sampling points (St.1-4) at mine A were selected for installing the sampler, as shown Fig. 3. Crushers are located inside the large-enclosed building. Two samplers were set inside the building that the crushing was operating, and the others were placed near the plies which one was in an open area and another one had a roof covering. The PM_{10} sampling had been done for two hours. The crushing process at mine B is different from mine A; the sampling was taken place at four points (St.1-4) regarding the production lines of different size limestone products for construction as shown in Fig. 4. There was different PM emission control including water spraying for secondary crushing, using a bag filter for tertiary crushing, and both techniques are applied for the screening process while no dust collector at piles. The crushing and screening are operated in the enclosed building while piles are in an open area. All samplers were calibrated with a calibrator, TSI Model 4140, every time before and after sampling.

C. Calculation of PM_{10} Concentration

PM_{10} concentration was calculated by (1) and (2):

$$\mathrm{PM_{10}\ concentration\ (\mu g/m^3)} = \frac{W_{\mathrm{post}}\,(\mu g) - W_{\mathrm{pre}}\,(\mu g)}{V_{\mathrm{air}}\,(m^3)} \quad (1)$$

$$V_{air}\,(m^3) = \text{Air flow rate}\left(\frac{m^3}{min}\right) \times \text{Time range (min)} \quad (2)$$

where Wpost = A filter's weight after sampling (μg); Wpre = A filter's weight before sampling (μg); Vair = Total air sampling volume (m^3).

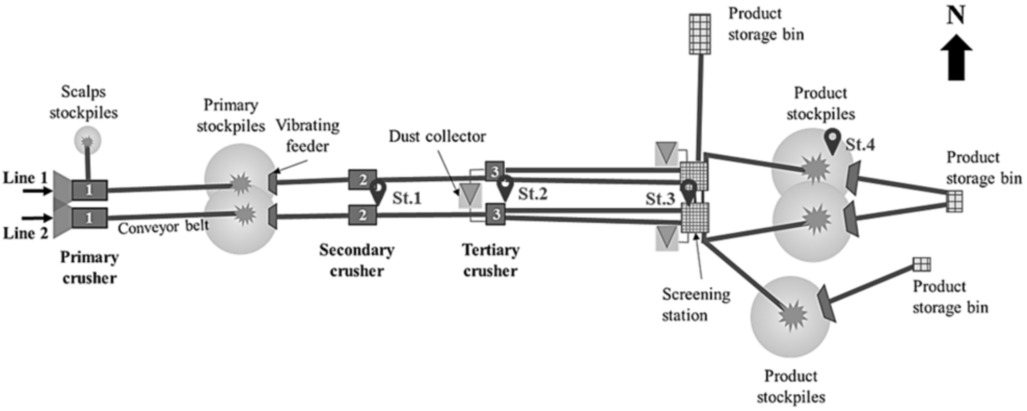

Fig. 2 The schematic crushing process at mine A

D. Quality Control

All filters were kept in a desiccator for at least three days before weighing. The filters were weighed by a microbalance, the Metter Toledo: METLER UMX 2 with 0.0001 mg readability which was placed in a conditioned room, closed and clean room with 24 ± 1 ºC, to avoid contamination and other surrounding disturbances. To control the quality of filter weighing, two standard pendulums, 100 and 200 mg, were weighed before starting and after finish weighing to recheck the daily reliability of the gravimetric analysis. Moreover, each filter had to be weighed three times and calculated in an average mass. The standard deviation of three times weighing derived from all samples was less than 0.0021.

E. Data Analysis

The maximum PM_{10} concentration found during the blasting each day at mine A and mine B were selected for statistical analysis. Nevertheless, the maximum concentration selected for the analysis should not have a disturbance from baseline activities such as the resuspension of soil dust from vehicles traveling surrounding the sampling stations, and the selected value should relate to wind direction and location reasonably. The PM_{10} concentration from crushing was grouped depending on the operation units.

The IBM SPSS Statistics 22 program was used for statistical analysis. Descriptive statistics, e.g. mean, median, range, standard deviation, were generally described in the data set. Non-parametric statistics with non-normal distribution used Mann-Whitney U test for comparison analysis between PM_{10} from blasting at mine A and mine B, and between the PM_{10} from all crushing units of two mines whereas the Kruskal-Wallis test was used for three dataset comparison analysis of the PM_{10} concentration from four stations in crushing units of mine B. Also, the difference of PM_{10} concentration from piles in mine A and mine B was analyzed by Mann-Whitney.

III. RESULTS AND DISCUSSION

A. PM_{10} Concentration at the Blasting Area of Limestone Mines

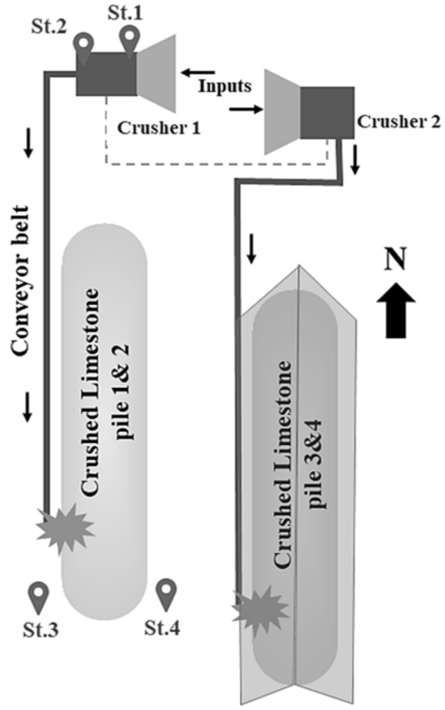

Fig. 3 The schematic crushing process at mine B on the operation units

The daily PM_{10} concentrations from the blasting of two mines were found 0.267-5.592 mg/m³ at mine A and 0.130-0.326 mg/m³ at mine B as depicted in Fig. 5. The result shows that the concentrations varied in a wide range. The median ± standard deviation of PM_{10} concentration of mine A, 0.930 ± 2.105 mg/m³, was higher than mine B, 0.241 ± 0.062 mg/m³. According to PM_{10} concentration from mine A, high

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concentrations were observed for days 1, 3, 5, and 6. From the observation during the sampling on day 1, there was another blasting closely to the selected blast, as well as the wind blew to the sampling point at the upwind direction that could increase PM_{10} concentration whereas the distinguished affecting factor on day 3 was from weak wind speed which obstructed PM_{10} dispersion. Also, the distance between the sampling point and the blasting zone could influence the PM_{10} concentration on days 5 and 6 which the samples were collected from the nearest distance. Moreover, in the blasting area, it can be noticed that there were some baseline activities emitting PM_{10}, for example, limestone loading by trucks. According to the data from real-time measurement, the PM_{10} levels in day 2 and day 4 of mine A might be slightly affected by vehicular transportation and machine processing. Considerably, low PM_{10} concentration in day 5 of mine A was influenced by the strong wind before raining resulting in PM_{10} dispersed rapidly during a short sampling period.

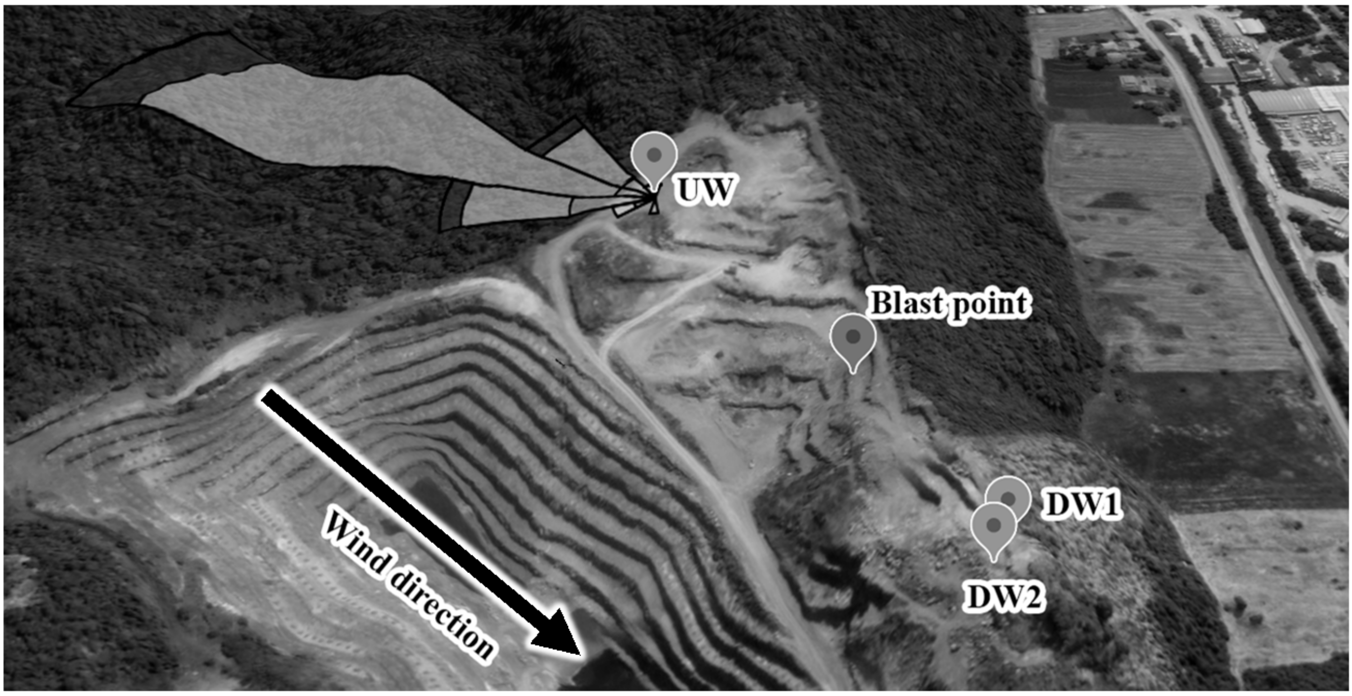

Fig. 4 Sampling points of the blasting zone

In the case of mine B, the PM_{10} concentration of all sampling days was not varied as much as at mine A. The highest PM_{10} concentration was found on day 10 as 0.326 mg/m^3. This highest value might influence by the weather with low wind speed and high humidity as 75-77% which caused low ventilation and PM_{10} could not disperse well. Likewise, a similar concentration (0.317 mg/m^3) was observed on day 5 even the humidity was lower than day 10. It might be affected by the sampling location which was not far from the hillock and forest so that PM_{10} dispersion might be obstructed as well as the highest % calm wind was observed. Consequently, a high amount of PM_{10} could be monitored. In addition, the amount of limestone production from blasting could be a considerable effect on the PM_{10} emission. At mine A, a production rate of 35,000 tons per blast caused to drill a blast hole approximately two times larger than that of mine B which produced only 374.4 tons, so that significant higher emission of PM_{10} at mine A than mine B could be observed ($p < 0.05$). Similarly, [7] measured PM_{10} concentration from the blasting of two large opencast coal mines in India that resulted in different emissions depending on the scale of production as in coal blasts only. At the Dudhichua sites, the coal production per day was approximately 174,500 tons per day, PM_{10} emitted more than that at the Bharatpur sites, which produced coal as 30,192 tons per day. As well as types of the blast could affect the PM_{10} emission as in the Dudhichua sites where the overburden blast emitted PM_{10} in the range and the average of 0.329-2.730 mg/m^3 and 1.195 mg/m^3, respectively, that more than the coal blasts, 0.262-4.532 mg/m^3 and average as 2.2 mg/m^3.

B. PM_{10} Concentration at the Crushing Zone of Limestone Mines

The daily PM_{10} concentration at the crushing process of mine A was presented corresponding to different three crushing units as shown in Fig. 6. In the crushing process at mine A, the median ± SD and the range of PM_{10} concentration from the crusher was 2.013.30 ± 0.791 mg/m^3 and 1.153-3.716 mg/m^3, respectively. A high variation of PM_{10} concentration was found at either opened air or roof covered piles with the range of 0.085-1.724 mg/m^3 and the median ± SD of was 0.311 ± 0.502 mg/m^3. Besides, PM_{10} emitted from crusher and piles was different significantly ($p < 0.05$).

Noticeably, PM_{10} concentration at the opened air piles rose remarkably on day 4 because there had a reclaimer, a machine

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for shaping the stockpile, operating at piles as well as the height between stacker and pile was higher than other days whereas the elevated levels observed on day 5 and day 6 at the roof-covered piles resulted from cleaning the ground by the workers nearby the sampling point that could induce dust resuspension. The high variation of PM_{10} emission from the crusher and piles was much dependent on different operating conditions and activities in the sampling area. The ventilation at limestone piles located in the opened or roof-covered areas is better than at the crusher unit locating inside an enclosed building so that the significant lower PM_{10} was measurable. Moreover, the meteorological condition such as wind speed, humidity can affect the contribution of PM_{10} as well.

For the crushing process of mine B, PM_{10} concentrations measured at four sampling points, including secondary crusher, tertiary crusher, screening unit, and piles, were illustrated in Fig. 7. There was a difference in the ranges, e.g. 1.032-16.529, 10.958-74.057, 0.655-4.956, and 0.169-1.699 mg/m³, respectively. Considering the median ± S.D. of PM_{10} concentration, the highest level was found at the tertiary crusher (24.581 ± 20.658 mg/m³) and followed by those at secondary crusher (6.143 ± 4.638 mg/m³), screening unit (3.476 ± 1.835 mg/m³), and piles (0.293 ± 0.611 mg/m³). Also, the PM_{10} concentration in crushing compared between four sampling points was significantly different (p-value < 0.05). Similarly, [3] observed PM_{10} at a tertiary crusher (3.400 mg/m³) which was double of secondary crusher (1.700 mg/m³). Conversely, the lowest concentration (0.210 mg/m³) was observed at piles by [5].

The results demonstrated that a tertiary crusher emitted the highest PM_{10} because this type of crusher ground limestone into the smallest sizes and the type of machine as an impact crusher can generate a high quantity of dust. In addition, dust collection and control systems might help reduce the PM_{10} contribution. As for mine B, the water spraying was applied for the secondary crusher to have a lot of dust agglomerated on the limestone, while a bag filter was suitable to collect a lot of dust at the tertiary crusher. And at the screening unit, both bag filter and water spraying were assigned to collect dust, and to reduce the dust at the limestone transferring points and clean the crushed limestone following the concrete specification, respectively. These operations at the screening station could result in low PM_{10} concentration and also low concentration at piles. Generally, the US.EPA [8] indicated that three main factors are influencing the PM emission from the crushing process, i.e. 1) the material properties (e.g. type of materials, the surface moisture content), 2) the equipment in processing and operation (e.g. the type of crushers) and 3) environmental factors (e.g. topography and weather condition). Moreover, the size of the final product also affected the dust generation in crushing [9].

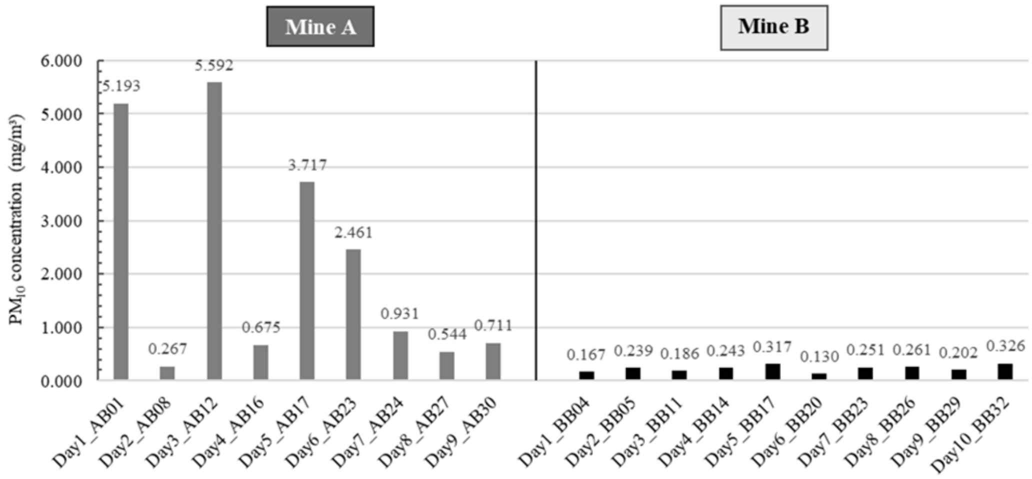

Fig.5 PM_{10} concentration from the blasting of mine A and mine B

Interestingly, PM_{10} concentrations measured at the piles of mine A and mine B were not different and in the same range even though the sizes of final products from both mines were different. The limestone produced for cement manufacturing was bigger than that for construction as in the 80 mm. Normally, the production of smaller limestone in various sizes for construction (e.g. mine B) would contribute to the high amount of PM_{10}, but low concentration as thesame as the production of large size of limestone for cement manufacturing could be measured which might be due to implementation of dust collection and control systems during the crushing process line of mine B such as water spraying and bag filter at the screening unit before transferring to piles. These control systems helped to wash and clean the limestone so that low PM_{10} emitted at storage piles.

Comparison of the PM_{10} concentration monitored in crushing in this study with other mines is summarized in Table I. PM_{10} concentration at mine B of this study was higher than the others obviously since the PM_{10} was collected at the source located inside the enclosed building covering the crusher whereas other studies monitored PM_{10} closely or a bit far distance with sources that could be affected by wind speed and wind direction. So, PM_{10} could disperse well, and then the concentration was lower.

Among other studies that measured PM_{10} in the same condition while the distancing was different, PM_{10} sampling in the crushing sites with the dust control systems such as water spraying regarding [10] represented lower PM_{10} concentration, 0.576 ± 0.089 mg/m^3, than the sites with no control systems as in Multiverse quarry, 14.09 ± 2.01 mg/m^3, reported by [11]. For distance from the source, [5] measured PM_{10} at 10 m downwind and [3] collected at 40 m downwind but the PM_{10} concentration could be different as resulting the PM_{10} concentration of 0.360 and 0.165 mg/m^3, respectively so that the distance between source and sampler could affect the PM_{10} concentration. Similarly, PM_{10} at piles, [12] found that the concentration could decrease when the distance increase as the PM_{10} at 30 m. and 120 m. were found at 0.094 and 0.046 mg/m^3, respectively. Comparing with this study, PM_{10} measured at the source representing the nearest distance, there was significant higher levels than those of other studies as 0.311 mg/m^3 in mine A and 0.293 mg/m^3 in mine B.

Interestingly, the number of crushers could affect the PM_{10} concentration. For example, the PM_{10} from the crushing site covering 50 crushers by [6] and 72 crushers by [13] resulted differently as 0.11 and 1.01 mg/m^3, respectively.

From the overall factors affecting PM_{10} concentration, the measures for dust control systems were recommended by [6] and [13]. The crushing sites should be cleaned and wetted regularly and the dump should have the equipment for dust containment and suppression system. In addition, the wind-breaking wall should be constructed to prevent the windblown dust and for sustainable dust control, the boundary of the crushing sites should have a green belt to block dust dispersion. Similarly, [12] also represented that the dust control system could affect the average emission. Especially, apart from water spraying or bag filter, [11] recommended that decreasing the height of dropping the crushed stone at stacker in the piles would help PM_{10} contribution reduction.

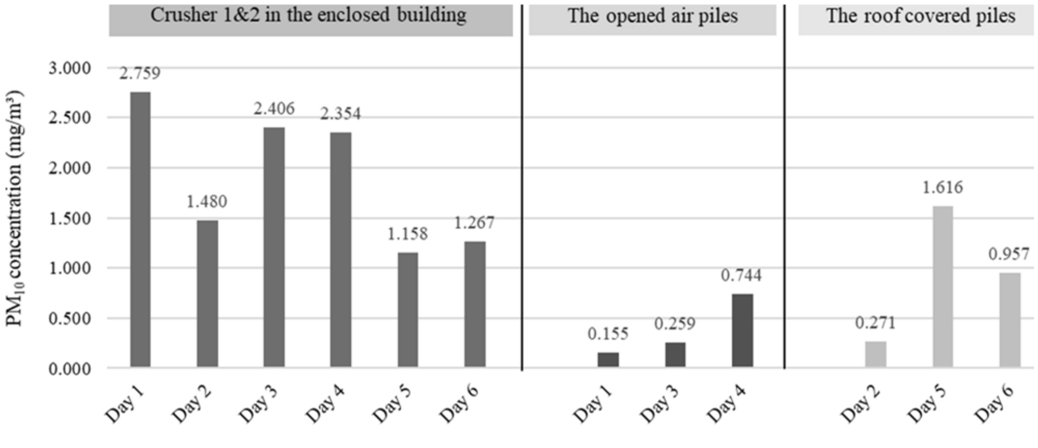

Fig. 6 Comparison of PM_{10} emitted from crusher and piles of mine A

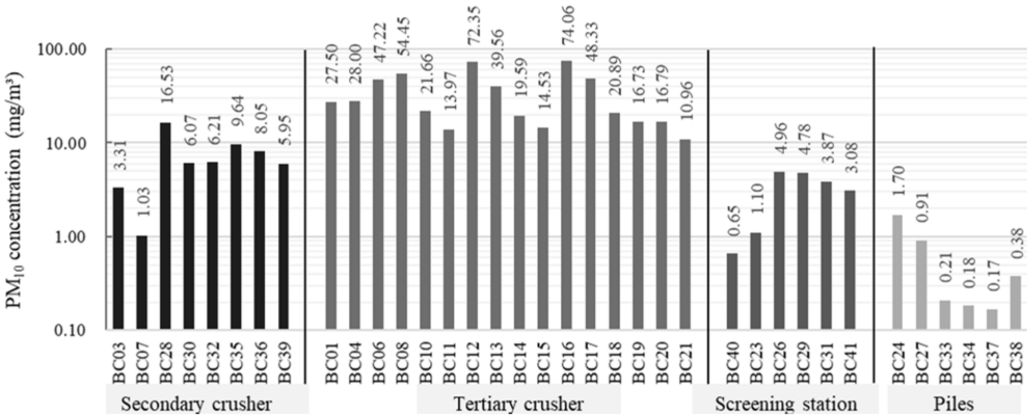

Fig. 7 PM_{10} concentration at four crushing units of mine B

IV. CONCLUSION

The emission of PM_{10} in the study sites revealed that the blasting of mine A generated more PM_{10} than mine B significantly ($p < 0.05$) which corresponded to the amount of limestone production. Moreover, the difference of PM_{10} concentration in each day was affected by environmental conditions, i.e., wind direction, wind speed, the other blasts nearby, and distance from the blasting. For the crushing process, a tertiary crusher generated the highest quantity of PM_{10} and followed by a secondary crusher, screening unit, and piles, respectively. The emission of PM_{10} from the crushing process might be influenced by material properties, equipment in processing and operation, environmental factors, and the requirement of the final product. Also, the sizes of the final limestone product at the piles might not be a strongly influenced factor of high PM_{10} distribution as with or without the dust collection and control systems.

TABLE I
COMPARISON OF PM_{10} CONCENTRATION FOUND IN THE CRUSHING PROCESSES OF DIFFERENT MINES

Reference	Type of mine	Sites	Crushing units (mg/m³)				Piles (mg/m³)	Dust control systems	Note
			Primary crusher	Secondary crusher	Tertiary crusher	Screening units			
This study	Limestone	Mine A, limestone for cement manufacturing in Saraburi, Thailand	1.153– 3.716 (Range) 2.013 ± 0.791 (Median ± S.D.)	-	-	-	0.085 – 1.724 (Range) 0.311 ± 0.502 (Median ± S.D.)	None	Not considering the weather condition and the distance due to the collected PM_{10} for source profiles
		Mine B, limestone for construction in Saraburi, Thailand	-	1.032 –16.529 (Range) 6.143 ± 4.638 (Median ± S.D.)	10.958 -74.057 (Range) 24.581 ± 20.658 (Median ± S.D.)	0.655– 4.956 (Range) 3.476 ± 1.835 (Median ± S.D.)	0.169 – 1.699 (Range) 0.293 ± 0.611 (Median ± S.D.)	Bag filter at tertiary crusher and screening units and water spraying at secondary crusher and screening units	
Degan et al. [4]	Basalt	An opencast Dark-Grey Basalt quarry, nearby Rome.	4.223 ± 0.824 (Average ± SD)	4.940 ± 0.610 (Average ± SD)	-	-	-	Unidentified	
Richardson [12]	Coal	Two coal mining areas in Queensland and New South Wales	-	-	-	-	0.094 (Average)	Unidentified	at 30 m.
							0.071 (Average)		at 60 m.
							0.046 (Average)		at 120 m.
Chang [10]	Limestone	The quarry area inside the Hsin-Ta Cement Company, northeast of Taiwan.	0.576 ± 0.089 (Average ± SD)				-	Water spraying	at 50 m. upwind and downwind in summer
Chang et al. [5]	Gravel	Four gravel extraction sites in Taiwan	0.360 ± 0.070 (Average ± SD)				0.330 ± 0.1 (Average ± SD)	Unidentified	PM_{10} from the crusher at 10 m. upwind and downwind
Sairanen et al. [3]	Limestone, gneiss, amphibolite	At aggregate quarries in southern Finland.	0.165 (Average)				-	Unidentified	at 40 m. downwind
Oguntoke et al. [11]	quartzite gneiss complex	Chinese quarry	11.01 ± 1.27				-	Unidentified	These values were PM_{10} collected within the five selected quarry sites in Abeokuta metropolis, Nigeria.
		Green palm quarry	7.97 ± 0.63				-		
		Kasagrand quarry	9.54 ± 0.77				-		
		Veritas quarry	11.91 ± 1.82				-		
		Multiverse quarry	14.09 ± 2.01				-		
Jayabalou et al. [6]	Quartz, feldspar, Pyroxene, Biotite and free silica	The southwest of Chennai city, India covering 50 crushers	Downwind 0.110 – 1.200 Upwind 0.090 – 0.156				-	None	PM_{10} collected at source
Sivacoumar et al. [13]	Stone	In the southwest of Chennai city, India covering 72 crushers	1.010 (Average)				-	None	

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