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Job Tasks as Determinants of Thoracic Aerosol Exposure in the Cement Production Industry

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Abstract

Background: The aims of this study were to identify important determinants and investigate the variance components of thoracic aerosol exposure for the workers in the production departments of European cement plants.

Methods: Personal thoracic aerosol measurements and questionnaire information (Notø *et al.*, 2015) were the basis for this study. Determinants categorized in three levels were selected to describe the exposure relationships separately for the job types production, cleaning, maintenance, foreman, administration, laboratory, and other jobs by linear mixed models. The influence of plant and job determinants on variance components were explored separately and also combined in full models (plant&job) against models with no determinants (null). The best mixed models (best) describing the exposure for each job type were selected by the lowest Akaike information criterion (AIC; Akaike, 1974) after running all possible combination of the determinants.

Results: Tasks that significantly increased the thoracic aerosol exposure above the mean level for production workers were: packing and shipping, raw meal, cement and filter cleaning, and de-clogging of the cyclones. For maintenance workers, time spent with welding and dismantling before repair work increased the exposure while time with electrical maintenance and oiling decreased the exposure. Administration work decreased the exposure among foremen. A subjective tidiness factor scored by the research team explained up to a 3-fold (cleaners) variation in thoracic aerosol levels. Within-worker (WW) variance contained a major part of the total variance (35–58%) for all job types. Job determinants had little influence on the WW variance (0–4% reduction), some influence on the between-plant (BP) variance (from 5% to 39% reduction for production, maintenance, and other jobs respectively but an 79% increase for foremen) and a substantial influence on the between-worker within-plant variance (30–96% for production, foremen, and other workers). Plant determinants had little influence on the WW variance (0–2% reduction), some influence on the between-worker variance (0–1% reduction and 8% increase), and considerable influence on the BP variance (36–58% reduction) compared to the null models.

Conclusion: Some job tasks contribute to low levels of thoracic aerosol exposure and others to higher exposure among cement plant workers. Thus, job task may predict exposure in this industry. Dust control measures in the packing and shipping departments and in the areas of raw meal and cement handling could contribute substantially to reduce the exposure levels. Rotation between low and higher exposed tasks may contribute to equalize the exposure levels between high and low exposed workers as a temporary solution before more permanent dust reduction measures is implemented. A tidy plant may reduce the overall exposure for almost all workers no matter of job type.

Keywords: AIC; Akaike information criterion; cement factory; dust; longitudinal; mixed models; stepwise mixed model; within- and between-worker variance

Introduction

Cross-shift studies have been performed in the cement industry indicating that there might be some possible health risks concerning lung function among their workers (Fell *et al*., 2017) and with the implementation of REACH The European Cement Association (CEMBUREAU) decided to investigate this. The present study is part of this initiative to improve knowledge and we were appointed to organize a longitudinal study of exposure and lung function in 2006 with planned sampling start in 2007 and follow-ups in 2009 and 2011. Calculations of power indicated that a follow-up of 2000 persons were needed to detect a putative small loss in lung function due to exposure during this period. We decided to measure the thoracic aerosol fraction as the best suited particle size fraction for comparison with lung function (CEN 1993).

In a previous paper, plant-specific characteristics together with job types were analyzed as predictors of exposure among cement production workers (Notø *et al*., 2015) and in the present paper we will explore information on tasks as determinants of exposure.

Numerous determinants can be recorded and evaluated on plant, department, job type, and individual level in cement plants. Identifying influential determinants is a crucial part of the exposure characterization. Relevant determinants of exposure may differ according to the purpose, regarding epidemiological studies versus exposure control (Burstyn *et al*., 1999). In the early 1990's Rappaport and Kromhout published comprehensive evaluations of within- and between-worker components of variance in occupational exposure studies (Rappaport 1991a, 1991b, 1993, 1995; Kromhout *et al*., 1993) and since then many studies have used mixed models to estimate and predict workers exposure (Burdorf 2005; Symanski *et al*., 2006).

This is the first study to our knowledge identifying determinants of thoracic aerosol exposure and analyzing variance components based on mixed models in the cement production industry. In this paper, we focus on job tasks that influence the exposure for the main job groups. We also studied the influence of these determinants on the between-plant (BP) (plant), between-worker-within-plant and within-worker (WW) variance components.

Materials and Methods

A total of 6111 personal thoracic aerosol measurements of 2534 workers in 22 cement production plants situated in seven European countries and Turkey were available from the previous study. The data collection took place between 2007 and 2012. Repeated measurements are included in the data with 28, 17, and 14% of the persons having 2, 3, or >3 repeated measurements, respectively (Notø *et al*., 2015).

Questionnaires

A questionnaire (Supplementary Material A1, available at *Annals of Occupational Hygiene* online) was developed to collect information about the workers' job types and tasks and was mainly filled out by personnel employed at each plant (hygienists, health, and safety workers). A few measurements from 2009 were also conducted by the investigators themselves. These were also used in the paper (Notø *et al*., 2016). In agreement with the national coordinators and employees from some of plants, we selected determinants suspecting to influence the exposure but still keeping the questionnaire as short and simple as possible. We decided to group the workers into seven job types: production, cleaning, maintenance, foreman administration, laboratory, and other. The workers indicated one or more job types performed at the day of sampling.

More detailed information about time spent on different tasks within the jobs was recorded in the questionnaire (questions 8 in Supplementary Material A1, available at *Annals of Occupational Hygiene* online).

Time spent on a specific task was recorded in six categories, from <15 min to a full shift. Job situations regarded by the research team as being high-exposed, especially cleaning tasks, were recorded by a second set of questions (questions 9 in Supplementary Material A1, available at *Annals of Occupational Hygiene* online) where workers reported hours and minutes spent on each task.

Data analysis

Measurements from workers that checked for more than one job type (the category several jobs from Notø *et al.*, 2015) or those that indicated time absent from work during the shift were excluded from the original data set and a total of 4765 measurements from 2373 persons were now available for the exposure modeling (Table 2).

For the job types production, cleaning, maintenance, administration, and laboratory, we had predefined the tasks that were typical for each group. When workers spent less than half a shift (<210 min) on these tasks, measurements were also excluded from the analysis. The work of foreman and workers with other jobs could change from shift to shift depending on situations in the production process or temporary lack of personnel in the other job types. All determinants from the main questionnaire and the significant plant determinants from the technical questionnaire (Notø *et al.*, 2015) were therefore included in the analysis of the job categories foreman and other. The determinants included in exposure models for each job type are listed in Table 1. The job types have been described in more detail previously (Notø *et al.*, 2015).

The exposure data were log-normal distributed and were $\log_{10}$ transformed before statistical analysis. Different categorizations of the determinants were explored and an example representing the production job type can be found in Supplementary Table B1 (available at *Annals of Occupational Hygiene* online). The alternative with three categories was selected for simplicity. The categories were no time spent, between zero and 210 min (up to half a shift), and 210 or more minutes (more than half a shift) spent during the work shift. If the number of measurements in one or both of the two categories for spent time (less and longer than half a shift) was <5, these measurements were combined into one category. If this combined category still had <5 measurements, the determinant was not explored. As women contributed with only 1.5% of the measurements the effect of gender was not explored.

Correlations between the determinants belonging to each job type were evaluated by Spearman correlation coefficients (r_S). If pairs of determinants had r_S values >0.8 both determinants were tested in separate mixed models. The determinant from the model with the highest Akaike information criterion (AIC) was excluded from the model.

Modeling was performed separately for all seven job types to study the contribution of the determinants to the WW, between-worker within-plant (BW), BP, and total variance. All models were specified with plant and worker as independent nested random intercepts estimated by maximum likelihood. Analysis of variance type tests of the significance of each determinant in the models were calculated by the contrast command in STATA.

Mixed models with no fixed effects (null model), and models including all plant determinants (plant), with all job determinants (job) and with both plant and job determinants (plant&job) as fixed effects were tested. The number and type of job determinants varied with the job type while the plant determinants were the same for all job types. The questionnaire included only one job determinant for laboratory workers. In order to select models containing only the most important determinants, we chose for each job type the model with the lowest AIC value (hereafter referred to as "best model"). This model selection procedure compared all possible alternative mixed models ($2^{\text{number of determinants}}$) and was developed and implemented in the statistical program R (Supplementary Material A2, available at *Annals of Occupational Hygiene* online).

The data were analyzed using STATA 14.2 (StataCorp LP, College Station, TX, USA) and *R* version 3.2.5, (The *R* Foundation for Statistical Computing, Vienna. Austria).

Results

The applied restriction of measurements (see footnote to Table 2) resulted in small changes of the arithmetic mean (AM) exposure and geometric standard deviations (GSD) for most job types, except for cleaners where AM exposure increased by 0.8 mg m^{-3} and GSD decreased from 4.0 to 3.2 on the restriction of samples, compared to AM (GSD) among all the available samples from the original data set.

The null, plant, job, and plant&job models obtained for all job types are shown in the online Supplementary Tables B5a–B5g (available at *Annals of Occupational Hygiene* online).

Production work

The correlations between job determinants belonging to this job type were low with r_S between −0.29 and 0.23.

Table 1. Determinants used in mixed model analysis of thoracic aerosol exposure in job types of cement production workers.

Determinants	Job types						
	Production	Maintenance	Foreman	Other	Cleaning	Administration	Laboratory
Job determinants							
Question 8							
Control room	XF		XF	XF			
Packing and shipping	XF		XF	XF			
Laboratory			X	XF			XF
Electrical maintenance		XF	XF	XF			
Mechanincal maintenance		XF	XF	XF			
Storage	XF		XF	XF			
Safety			X	XF		X	
Oiling		XF					
Administration			XF	XF		XF	
Other production			XF	XF			
Question 9							
Cleaning in production areas							
Raw meal	XF		XF	XF	XF		
Clinker	XF		X	XF	XF		
Cement	XF		X	XF	XF		
Filters	XF				XF		
Lepol grates	XF				XF		
By-pass filters	XF				XF		
De-clogging of cyclones	XF		X	XF			
Dismantling before relining		XF					
Dismantling before repair		XF	X	XF			
Handling of fuel	XF		X	XF			
Welding		XF	X	XF			
Other repair work	XF	XF					
Plant determinants							
Number of employees	XF	XF	XF	XF		XF	XF
Maximum cement production capacity, 10^6 ton year^{-1}	XF	XF	XF	XF		XF	XF
Maximum cement production/ employee, 10^3 ton year^{-1}	XF	XF	XF	XF		XF	XF
Tidiness	XF	XF	XF	XF		XF	XF

F = determinants included in the full models of the job types. X = determinants included in the time spent variable. The job determinants are from question 8 and 9 in the main questionnaire and the plant determinants from the technical questionnaire that was published in 2015 (Notø *et al.*, 2015).

Variance components

The best model is shown in Table 3 and the other models in Supplementary Table B5a (available at *Annals of Occupational Hygiene* online). In the null model, the BP variance, the BW variance, and the WW variance accounted for 20%, 27%, and 53%, respectively, of the total variance. The effect has been calculated by using effect size = $10^{(\beta 1-1)}$ * 100 and compared to the corresponding reference value of the covariate (100).

Introducing plant determinants to the null model decreased the BP by 55% while the BW and the WW were unchanged. Job determinants explained 30% of the BW while the BP and also the WW showed small reductions (4–5%). When all plant and job determinants were in the model BP was reduced by 61% compared to the null model while the BW and WW were reduced by 30% and 4%, respectively. The best model explained 21% of the total variance in the null model and the variance components were close to the plant&job model.

Table 2. Thoracic aerosol exposure (mg m^{-3}) and estimated variance component by job type after selection of valid measurements for the present analysis.

Job type	Empirical data								Mixed model estimates			
	N_O	N	K	AM	GM	Median	SD	GSD	BP	BW	WW	Total
Production	2357	2124	1084	2.9	1.0	0.95	8.2	3.9	0.067	0.091	0.178	0.336
Maintenance	1725	1346	693	2.4	0.82	0.68	7.0	3.7	0.079	0.058	0.192	0.329
Foreman	148	142	98	0.60	0.27	0.30	1.3	3.3	0.040	0.030	0.019	0.089
Cleaning	217	95	63	3.4	1.8	2.1	5.0	3.2	0.077	0.027	0.149	0.253
Administration	226	157	103	0.16	0.077	0.089	0.42	3.2	0.041	0.063	0.135	0.238
Laboratory	481	417	209	0.94	0.41	0.40	3.0	3.1	0.088	0.062	0.089	0.239
Other	555	484	310	0.81	0.30	0.29	1.6	4.0	0.109	0.131	0.135	0.375
Total	5709	4765	2373	2.2	0.70	0.67	6.8	4.2	0.088	0.120	0.176	0.384

AM = arithmetic mean; BP = between-plant variance; BW = between-worker variance; GM = geometric mean; GSD = geometric standard deviation; *K* = number of persons contributing to *N*; N_O = Number of measurements from the original data set; *N* = number of measurements included in analysis (a single job type is checked, no absence from work, and 210 or more minutes altogether for work on the job related tasks; SD = standard deviation; Total = total variance are estimated from mixed models on $\log_{10}$ transformed data of *N* measurements; WW = within-worker variance.

Effects of determinants

Work in the control room and handling of fuel was associated with lower exposure. For those spending <210 min with these tasks, the thoracic aerosol exposure was 24% and 16% lower, respectively, compared to work without these tasks. For those working more than half a shift in the control room or with handling of fuel, the exposures decreased with 54% and 52%, respectively. Packing and shipping was associated with increased exposure (12% and 33%) when working less than and more than half a shift, respectively.

The other tasks showed more complicated associations. Less than half a shift work with the tasks cleaning in raw meal, cement, and filter areas, and de-clogging of the cyclones increased the exposure by 52, 83, 104, and 36%, respectively. Those that spent more than half a shift with these tasks also had increased exposure by 11, 37, 31, and 27%, respectively, but less than the previous category. Plant determinants showed significant contributions to the models for production workers. If the production workers were employed in plants that had been subjectively assessed as less clean their exposure were 80% higher than for those employed in plants regarded as cleaner. Production workers from plants with a medium-size workforce (144–204 workers) were less exposed (21%) than those from plants with fewer employees. Production workers from plants with >212 workers had 43% higher exposure than those from plants with <138 workers.

Example of the estimation of the thoracic aerosol exposure for a production worker

Exposure of production workers can be estimated from the regression equation of the best model of the production job type shown in Table 2:

$\log_{10}$Thoracic aerosol$_{\text{Production worker}}$ = −0.17 − 0.12 * (Control room 1–209 min) − 0.34 * (Control room ≥ 210 min + 0.048 * (Packing &shipping 1–209 min) + 0.13 * (Packing &shipping ≥ 210 min) + 0.18 * (Cleaning in raw meal areas 1–209 min) + 0.046 * (Cleaning in raw meal areas ≥ 210 min) + 0.26 * (Cleaning in cement areas 1–209 min) + 0.14*(Cleaning in cement areas ≥ 210 min) + 0.31 * (Cleaning of filters 1–209 min) + 0.12 * (Cleaning of filters ≥ 210 min) + 0.13 * (De-clogging of cyclones 1–209 min) + 0.10 * (De-clogging of cyclones ≥ 210 min) − 0.08 * (Handling of fuel 1–209 min) − 0.32 * (Handling of fuel ≥ 210 min) − 0.010 * (Number employed 144–204) + 0.16 * (Number employed 212–483) + 0.26 * (Tidiness Less Clean).

Example 1: A production worker working less than half a day with packing or shipping, and less than half a day with cleaning of filters and employed at a plant with a large work force and assessed as clean will have an estimated exposure of:

$\log_{10}$ Thoracic aerosol$_{\text{Example1}}$ = −0.17 + 0.048 * (Packing &shipping 1–209 min) + 0.31 * (Cleaning of filters 1–209 min) + 0.16 * (Number employed 212–483) = −0.17 + 0.048 + 0.31 + 0.16 = 0.348.

The GM exposure estimate is the antilog of $\log_{10}$ Thoracic aerosol$_{\text{Example1}}$ = $10^{0.348}$ = 2.2 mg m^{-3}.

Example 2: Another production worker from a plant of the same size category and tidiness who has been working less than half a shift in the control room, and less than half a shift with handling of fuel will have an estimated exposure of:

$\log_{10}$Thoracic aerosol$_{\text{Example2}}$ = −0.17 − 0.12 * (Control room ≥ 210 min) − 0.08 * (Handling of fuel

Table 3. Production workers.

Production				Best mixed model			
Job tasks	*N*	*K*	AM	*β*	SE	*P* value	*P* contrast
Intercept	2124	1084	2.9	-0.17	0.072	0.02	
Control room							0.000
0	1488	815	3.0				
1–209	293	210	4.0	-0.12	0.036	0.001	
≥210	343	230	1.8	-0.34	0.035	0.000	
Packing and shipping							0.003
0	1763	912	3.1				
1–209	20	19	2.2	0.048	0.11	0.7	
≥210	341	204	1.9	0.13	0.037	0.001	
Cleaning of areas							
Raw meal							0.000
0	1806	990	2.6				
1–209	218	151	5.0	0.18	0.039	0.000	
≥210	100	82	4.7	0.046	0.052	0.4	
Cement							0.000
0	1836	992	2.8				
1–209	159	133	4.1	0.26	0.041	0.000	
≥210	129	94	3.3	0.14	0.049	0.005	
Filter							0.002
0	2072	1066	2.9				
1–209	26	24	6.6	0.31	0.094	0.001	
≥210	26	25	4.1	0.12	0.10	0.2	
De-clogging of cyclones							0.030
0	2006	1057	2.8				
1–209	83	68	6.8	0.13	0.056	0.02	
≥210	35	33	3.7	0.10	0.08	0.2	
Handling of fuel							0.05
0	2061	1066	3.0				
1–09	47	42	1.5	-0.077	0.073	0.3	
≥210	16	10	0.76	-0.32	0.14	0.02	
Number employed							0.04
69–138	616	255	3.0				
144–204	577	334	1.4	-0.10	0.10	0.31	
212–483	931	495	3.8	0.16	0.10	0.13	
Tidiness							0.003
Clean	1222	600	2.2				
Less clean	902	484	3.9	0.26	0.085	0.008	
Variance components				Variance	SE	% of null	
Between plant (BP)				0.030	0.010	44	
Between-worker within-plant (BW)				0.065	0.0079	72	
Within-worker (WW)				0.171	0.0072	96	
Total				0.266		79	

Best mixed model of work tasks as determinants of thoracic aerosol exposure. AM = unadjusted arithmetic mean in mg m^{-3}; ANOVA = analysis of variance; *β* = regression coefficient for change in thoracic aerosol exposure in mg m^{-3}; *K* = number of persons; *N* = number of measurements; *P* value = significance level compared to the reference level; *P* contrast = ANOVA-test of main effect of the determinant; SE = standard error.

1–209 min) + 0.16 * (Number employed 212–483) = –0.21.

The estimated GM exposure for this worker is: $10^{-0.21}$ = 0.62 mg m^{-3}.

Maintenance

The job determinants electrical and mechanical maintenance were correlated (r_S –0.77), and also the plant determinants number of employees and maximum cement production (r_S 0.91). The other correlation coefficients for determinants in the plant&job model varied between –0.29 and 0.26. The correlation coefficients between determinants in the best model varied between –0.28 and 0.09. The best model is shown in Table 4 and the other models in Supplementary Table B5c (available at *Annals of Occupational Hygiene* online). The determinants of dismantling before repair work and tidiness are included in the best model because of lower AIC although *P* contrast values did not reach statistical significance (*P* = 0.059 and 0.088).

Variance components

In the null model, the BP, BW, and WW accounted for 24%, 18%, and 58%, respectively, of the total variance. Introducing the plant determinants to the null model reduced the BP with 36% while the BW and WW were unchanged. Adding the job determinants to the null model lead to 20% reduction of the BP and almost unchanged BW and WW (–1% change and no change, respectively). Inclusion of both plant and job determinants in the plant&job model reduced the BP with 58%, the BW with 20%, and the WW was almost unchanged (1% reduction). The best model had 22% lower BP compared to the null model, and 20% lower BW and only 1% lower WW which were identical to the Job and

Table 4. Maintenance workers.

Maintenance				Best mixed model			
Job tasks	***N***	***K***	**AM**	**β**	**SE**	***P* value**	***P* contrast**
Intercept	1346	693	2.4	–0.12	0.074	0.11	
Electrical maintenance							0.000
0	865	459	2.8				
1–209	31	30	2.2	–0.068	0.092	0.46	
≥210	450	244	1.5	–0.18	0.034	0.00	
Oiling							0.000
0	1280	671	2.4				
1–209	10	10	0.9	–0.28	0.15	0.070	
≥210	56	37	1.2	–0.26	0.072	0.000	
Dismantling before repair							0.059
0	1238	665	2.4				
1–209	71	62	1.8	0.11	0.061	0.067	
≥210	37	34	3.3	0.14	0.082	0.095	
Welding							0.024
0	1112	631	2.1				
1–209	131	107	4.6	0.13	0.047	0.007	
≥210	103	71	2.1	0.024	0.055	0.66	
Tidiness							0.088
Clean	728	387	0.52				
Less clean	618	306	1.0	0.20	0.12	0.10	
Variance components				Variance	SE	% of null	
Between plant (BP)				0.062	0.020	78	
Between-worker within-plant (BW)				0.047	0.010	80	
Within-worker (WW)				0.190	0.010	99	
Total				0.30		91	

Best mixed model of work tasks as determinants of thoracic aerosol exposure. AM = unadjusted arithmetic mean in mg m^{-3}; ANOVA = analysis of variance; *β* = regression coefficient for change in thoracic aerosol exposure in mg m^{-3}; *K* = number of persons; *N* = number of measurements; *P* value = significance level compared to the reference level; *P* contrast = ANOVA-test of main effect of the determinant; SE = standard error.

plant&job models. The total variance for the best model was reduced by 9% compared to the null model.

Effects of determinants

Working with electrical maintenance or oiling indicated lower exposure compared to not doing these tasks. The exposure was reduced with 14% when working less than half a shift with electrical maintenance and with 34% when this task lasted more than half a shift. If a worker had been working with oiling no matter of the duration he had 47% exposure reduction compared to those not oiling. Working with dismantling before repair work increased the exposure levels with 29% or 37% depending on if time spent was less or longer than half a shift. Welding for less than half a shift increased the exposure by 34% but for longer duration only by 6% compared to not welding.

The exposure of maintenance workers increased by 57% if the plant was categorized as 'less clean'.

Foremen

The Spearman correlation coefficients for the job determinants were weakly correlated (r_S −0.24 to 0.37). The plant determinants correlated between r_S −0.22 and 0.76. Determinants in the best model had correlation coefficients between −0.38 and 0.37. The best model is shown in Table 5 and the other models in Supplementary Table B5d (available at *Annals of Occupational Hygiene* online).

Variance components

In the null model, the BP, the BW, and WW were 23%, 42%, and 35%, respectively, of the total variance. Adding the plant determinants eliminated the BP, increased the BW by 8% and kept the WW almost constant (reduced by 1%). Introducing all job determinants to the null model increased the BP by 80% and reduced the BW with 74% and the WW was unchanged. The plant&job model with all plant and job determinants reduced the variances by 59, 68, and 2%, respectively, for BP, BW, and WW. The best model for the foremen reduced the BP by 62%, the BW by 46%, and the WW by 9% compared to the null model. The total variance of this model was 37% lower than the null model.

Effects of determinants

Job determinants that increased the exposure in the foreman group were packing and shipping (86%), and cleaning in raw meal areas (68%).

Less than half a shift in the control room indicated 18% increase in exposure but more than half a shift reduced the exposure by 56%. The more time spent with administrative work the less exposure (17% and 58% reduction, respectively). Plants that were in the highest cement production category per year had 115% higher exposure, and if the plant was assessed as less clean the exposure of foremen increased by 152%.

Other

The correlation coefficients of the determinants varied between r_S −0.30 and 0.75 where the highest value was between Number of employees and Maximum cement production per year. Determinants in the best model had correlations of r_S from −0.37 to 0.37.

Variance components

In the null model, the BP accounted for 29%, the BW 35%, and the WW for 36% of the total variance. Introducing the plant determinants decreased the BP with 58% and the BW and the WW were practically unchanged. Adding the job determinants to the null model reduced the BP by 39% and the BW by 96% while the WW variance only had a 4% reduction. Compared to the null model the plant&job model had 81% reduced BP, 54% reduced BW, and 4% reduced WW while the values for the best model were 78%, 54%, and 1%, respectively. The best model (Table 6) had 78, 54, and 1% lower BP, BW, and WW, respectively, and the total variance was 42% lower than in the null model.

Effects of determinants for other work

The exposure increased with increasing time spent with the job determinants: packing and shipping (69% and 68%, respectively, for working less than half a shift and longer than half a shift,), cleaning in clinker areas (32% and 222%), cleaning in cement areas (44% and 206%), welding (224% for longer than half a shift), and by increasing number of employees in the plant (47% and 206%). De-clogging of cyclones increased the exposure by 231% for those working longer than half a shift with this task. We had no data on less than half a shift of de-clogging. For the tasks control room (20% and −45%), storage (153% and −31%), other production work (33% and −30%), the effect was mixed with higher exposure levels for the medium time spent with the tasks, but lower levels when working more than half a shift with these tasks compared to no time spent. Working with safety tasks more than half a shift reduced the exposure by 77%.

Table 5. Foremen.

Forman				Best mixed model			
Job tasks	*N*	*K*	AM	*β*	SE	*P* value	*P* contrast
Intercept	142	98	0.60	−0.64	0.11	0.000	
Control room							0.000
0	65	50	0.69				
1–209	31	23	0.95	0.072	0.10	0.5	
≥210	46	36	0.23	−0.36	0.091	0.000	
Packing and shipping							0.03
0	126	87	0.60				
≥1[a]	16	12	0.61	0.27	0.12	0.03	
Administration							0.02
0	117	80	0.63				
1–209	8	6	0.61	−0.079	0.17	0.6	
≥210	17	14	0.37	−0.38	0.14	0.006	
Cleaning of area							
Raw meal							0.1
0	136	96	0.55				
≥1[a]	6	6	4.1	0.23	0.15	0.1	
Maximum cement production, (10^6 ton year^{-1})							0.06
0.43–1.1	73	41	0.35				
1.2–1.8	48	39	0.62	−0.027	0.14	0.8	
1.9–4.0	21	18	1.4	0.33	0.15	0.03	
Tidiness							0.002
Clean	97	65	0.41				
Less clean	45	33	1.0	0.40	0.13	0.002	
Variance components				Variance	SE	% of null	
Between plant (BP)				0.024	0.025	38	
Between-worker within-plant (BW)				0.062	0.022	54	
Within-worker (WW)				0.086	0.017	90	
Total				0.172		63	

Best mixed model of work tasks as determinants of thoracic aerosol exposure. AM = unadjusted arithmetic mean in mg m^{-3}; ANOVA = analysis of variance; *β* = regression coefficient for change in thoracic aerosol exposure in mg m^{-3}; *K* = number of persons; *N* = number of measurements; *P* value = significance level compared to the reference level; *P* contrast = ANOVA-test of main effect of the determinant; SE = standard error.
[a]Combined categories of 1–209 and ≥210 min.

The results for the job types cleaning, administration, and laboratory are shown in the online Supplementary Tables B2–B4 (available at *Annals of Occupational Hygiene* online).

Discussion

Tasks associated with increased exposure

The following tasks were associated with increased exposure: packing and shipping among production workers, foremen and workers with other jobs, cleaning in cement areas and de-clogging of cyclones among workers in production and with other jobs, and cleaning in clinker areas among workers with other jobs. Dismantling before repair work was close to significantly associated with exposure among maintenance workers. Welding caused increased exposure among maintenance workers working less than half a shift but for other jobs this was observed when working longer than half a shift. Among production workers performing cleaning in the raw meal area and cleaning filters, the exposure was higher when working shorter than half a shift than for longer periods.

Plants assessed as less clean had significantly higher exposure for production and foremen indicating that tidiness was an effective preventive measure.

Tasks associated with low exposure

Not surprisingly increasing time spent with administrative work resulted in decreased exposure, reaching significance for foremen, administration, and other work.

Table 6. Workers with other jobs.

Other work				Best mixed model			
Job tasks	*N*	*K*	AM	β	SE	*P* value	*P* contrast
Intercept	484	310	0.81	−0.62	0.097	0.000	
Control room							0.0006
0	389	245	0.88				
1–209	16	16	1.1	0.078	0.12	0.5	
≥210	79	67	0.40	−0.26	0.073	0.001	
Packing and shipping							0.008
0	390	253	0.54				
1–209	8	7	1.3	0.23	0.17	0.2	
≥210	86	62	2.0	0.23	0.078	0.004	
Storage							0.006
0	385	273	0.89				
1–209	6	6	1.9	0.40	0.19	0.04	
≥210	93	42	0.40	−0.16	0.07	0.03	
Safety							0.0001
0	473	305	0.82				
1–209	0						
≥210	11	7	0.15	−0.64	0.16	0.000	
Other production							0.03
0	374	250	0.93				
1–209	15	15	0.51	0.12	0.12	0.3	
≥210	95	65	0.37	−0.16	0.07	0.03	
Administration							0.0001
0	435	285	0.84				
1–209	17	15	0.38	−0.20	0.12	0.1	
≥210	32	28	0.56	−0.39	0.10	0.000	
Cleaning of areas							
Clinker							0.03
0	471	299	0.79				
1–209	7	7	0.95	0.12	0.18	0.5	
≥210	6	6	2.2	0.51	0.20	0.01	
Cement							0.008
0	452	297	0.64				
1–209	22	20	2.1	0.16	0.11	0.1	
≥210	10	8	5.5	0.49	0.17	0.004	
De-clogging of cyclones							0.003
0	476	304	0.81				
≥1[a]	8	7	0.84	0.52	0.18	0.004	
Welding							0.004
0	478	307	0.78				
≥1[a]	6	6	2.6	0.51	0.18	0.01	
Number employed							0.0001
69–138	111	66	0.25				
144–204	228	154	0.66	0.17	0.12	0.2	
212–483	145	90	1.5	0.49	0.12	0.001	

Table 6. *Continued*

Variance components	Variance	SE	% of null
Between plant (BP)	0.023	0.015	22
Between-worker within-plant (BW)	0.060	0.017	46
Within-worker (WW)	0.134	0.015	99
Total	0.218		58

Best mixed model of work tasks as determinants of thoracic aerosol exposure. AM = unadjusted arithmetic mean in mg m^{-3}; ANOVA = analysis of variance; β = regression coefficient for change in thoracic aerosol exposure in mg m^{-3}; K = number of persons; N = number of measurements; P value = significance level compared to the reference level; P contrast = ANOVA-test of main effect of the determinant; SE = standard error.
[a]Combined categories 1–209 and ≥210 min.

Work in control rooms among production workers, foremen and workers with other jobs also decreased the exposure. Handling fuel among production workers, electrical maintenance and oiling among maintenance workers, and safety work and other production work among workers with other jobs reduced their exposure when working longer than half a shift. The most complex association was observed for storage work among workers with other jobs, where working less than half a shift was strongly associated with high exposure while longer work indicated low exposure.

Direct comparison of the effect of similar determinants across job types is complicated because intercept values differ between the job types. For example, the effect of packing and shipping seems smaller for production workers than for foremen and workers with other job types, but the estimated exposure when working for more than half a shift with this task is higher for production workers than the other two groups due to a higher background level for production workers.

Pros and cons

The present study consist of measurements of the thoracic aerosol fraction (the most relevant particle fraction for considering bronchial effects) but almost all other studies have measured either "total" dust, respirable, or inhalable aerosol. Comparison with other studies is therefore difficult but the relationships between the different particle size fractions have been published (Notø *et al*., 2016) within the CEMBUREAU project.

The size of the present study made it possible to perform a detailed determinant analysis in different job groups. Strict selection criteria were applied in order to remove less reliable measurements and to obtain more accurate models. In total, we had numerous data in all job types but foreman and cleaning. Detailed and systematic information about the time spent on the selected job tasks was available but the lack of information on other relevant tasks contributing to the explanation of exposure levels is a limitation. The amount of details about working conditions, degree of automation, ventilation, etc. which may differ across plants, was also limited, as also indicated by the variability between plants and the effects of plant determinants. The models explained 9–42% of the total variance which is in the same range of what others have published. Mikkelsen *et al.* (2002) found by passive inhalable sampling that 31% of the total variance was explained by the model for woodworking personnel but only 10% for those handling and assembling wood. Meijster *et al.* (2007) found that the total explained variability were 29% and 37%, respectively, for inhalable flour dust among flour millers and production workers. Basinas *et al.* (2013) reported explained total variability of 35% for inhalable dust measured among pig farmers.

A further weakness of the present study is that the sampling was performed by different teams. The impact of this, which could have introduced bias has been discussed previously (Notø *et al*., 2015) but the use of plant as random intercept may adjust partly for such bias. A study of this size would not have been feasible without contribution from national sampling teams.

A problem with our choice of stratifying the data by job type is that comparing the same task among different job types is not straight forward.

If a task is performed less than a day other tasks will fill the working shift, which may influence the regression coefficient showing more complicated relationships. It is therefore difficult to evaluate if a task done over longer time is differently exposed than when done for shorter periods. This could be expected for jobs like cleaning. Short-term cleaning may be due to production problems, while long-term cleaning can be a part of normal maintenance.

De-clogging of the cyclones caused significant increased exposure for production workers spending less than half a shift with that task. Workers performing de-clogging (and other workers) normally wear respiratory protective equipment during parts of their work. Our measurements are obtained outside of these and are therefore not representative for the inhaled dose.

Modelling

The WWs variance contributed most to the total variance of the null models (35–58%). We looked further into the influence of the job and plant determinants on the variance components to explore if the presented models can be generalized to all plants.

The job determinants had only minor influence (0–4% reduction) on the WW for the different job types but they reduced the BW from 30% to 96% for production, foreman, and other workers. The small effect on WW indicated that workers within a job group performed a specific set of tasks that differed between workers. The fairly large explained BW shows that the recorded tasks were good indicators of exposure. The job determinants reduced the BP by 5, 20, and 39%, respectively, for production, maintenance, and other jobs but increased it for foremen (79%). This indicates that there are differences in organization of the work across plants. This effect was small for production workers indicating that this model is valid for all plants.

Plant determinants reduced BP by 36% to 58% indicating that they explain a large part of the plant differences. However, except for tidiness, these determinants are related to production and workforce size and only indirectly indicate why exposure levels differ. The plant determinants had small effects on the BW and WW. Thus, the plant determinants were good and quite specific predictors explaining the variation of the exposure levels between plants.

Comparison with other studies from cement plants

To our knowledge only 4 studies (Mwaiselage *et al.*, 2005; Peters *et al.*, 2009; Zeleke *et al.*, 2011; Kakooei *et al.*, 2012) have discussed the variability of 'total' dust or inhalable aerosol exposure among workers in cement production plants. Three of the studies explored job type as determinants of exposure. The fourth (Peters *et al.*, 2009) contained 25 inhalable samples measured on 14 persons which is too small to provide reliable estimates of variance components.

Mwaiselage *et al.* included 120 personal 'total' dust samples from 80 randomly selected workers from eight job types (cranes, packing, crusher, cement mill, kiln, raw mill, maintenance, and administration) with AM from 0.59 to 55 mg m^{-3}. They used mixed model regression of log-normal transformed data with occupational group and worker as random effects and they showed that BW was larger than the WW for four out of the eight job groups. This is opposite to our study where all WW were larger than BW but with plant as grouping variable.

Zeleke *et al.* collected 262 personal 'total dust' samples among 105 randomly chosen production workers (GM = 432 mg m^{-3}) and cleaners (GM = 8.2 mg m^{-3}) from two plants in Ethiopia. They used worker as random effect and reported higher WW than BW for both production workers and cleaners. Kakooei *et al.* included 129 total dust measurements from seven job types (crusher, raw mill, kiln, cement mill, packing, maintenance, and administration with AMs from 0.04 to 39 mg m^{-3}) but did not report variance components from mixed models. These studies are not directly comparable to our study because of use of different particle size fractions and models.

Suggested actions to reduce exposure

A simple and logical advice for this industry is to keep the plants tidy by removing settled dust by regular vacuum cleaning using vacuum cleaners and ventilated trucks. Repair of broken filters and leakages should be performed as soon as possible. Avoid spreading of fine ground raw materials, fuels, and clinker by construction of wind shields and storage silos were possible. Humidify raw materials and plant areas in the dry season. In the laboratories use, ventilation systems in areas where samples are sieved, milled, or subjected to other dusty procedures.

It seems likely that a reduction of the thoracic aerosol exposure is possible for all job types except administration if the plants are kept tidy and clean. However, for the cleaner's exposure, the use of cleaning equipment producing no or low dust is important.

Rotation of tasks during the shift based on dust exposure models by combining low- and high-exposed tasks might reduce the exposure for high exposed but increase it for the low exposed. This solution should only be used as a temporary solution before more permanent measures are applied. Respiratory protective equipment was frequently used in high-exposure situations (Notø *et al.*, 2015); however, clear exposure-response associations for lung function decline were observed among workers included in this study in spite of respirator use (Nordby *et al.*, 2016). Therefore respiratory protection should be intensified until technical solutions have improved the dust levels.

Conclusion

The prospective design, the size, and quality of this study is unique for the cement production industry. The large amount of samples collected each second year (three times) in many plants in different countries and with fairly high quality will give less biased results than what is found in smaller studies. We used mixed models to estimate exposure for different combinations of job tasks and allowing the variance of persons and plants to vary.

The results can visualize areas or job tasks that can influence the workers exposure and indicate areas where technical or other improvements are needed. Thus, determinant analysis can enable future planning of actions to improve dust control and exposure reduction. For risk assessment of thoracic aerosol exposure in cement production plants a detailed exposure–response analysis of lung function decline has been published on basis of these measurements (Nordby *et al*., 2016). Our results are based on thoracic aerosol concentrations and cannot directly be compared with threshold limit values for example for 'total' dust but a relationship between 'total' dust and thoracic aerosol showing a median ratio of 2.4 has previously been published from this project (Notø *et al*., 2016).

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

Declaration

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