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DISTRIBUTION PROFILES OF THE AIR'S ALKALINE FINE PARTICLES DURING DRY SHOTCRETE IN ROAD TUNNEL CONSTRUCTION

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A B S T R A C T

Shotcrete is now becoming a common area support for ground control in underground construction and tunnels as a stand-alone, or in combination with other support systems such as bolts and screens. Fine dust generated from shotcrete however, involves various risks to the workers' health and safety. Although dust generation is an inseparable part of shotcrete, long-time exposure and inhalation of dust can lead to serious damaging health effects especially when working in tunnels and mining jobs. This study investigates the distribution of alkaline fine particles in the air, while shotcreting in the underground construction. A series of tests were conducted at different distances from the shotcrete operator (nozzleman) and tunnel openings and in different heights from the surface, in order to measure the pH value of the air in three consecutive days, right after the shotcrete process. Using the data obtained from the tests, a mathematical model is developed to predict the pH value distribution profile while dry shotcrete and up to three days after that.

INTRODUCTION

The construction of underground chambers, passageways, shafts, and tunnels are inseparable parts of the infrastructure engineering projects. Shotcrete plays an important role in today's underground constructions and tunneling, by being used for protecting the working team and machinery and ensuring the stability of the underground site. Shotcrete describes the spraying of concrete or mortar that may be accomplished through either a dry- or wet-mix process (Wang *et al*. 2015, Beckett and Ciancio 2016). In the dry process, the dry cementitious mixture is blown through a hose to the nozzle, where the water is injected immediately prior to application (Roberts *et al*. 2003, Armengaud *et al*. 2017). Because complete mixing of the water and dry ingredients is not possible in the nozzle, mixing is completed as the material impinges on the receiving surface, through manipulation of the nozzle. This requires highly skilled nozzlemen and operating tram, in particular in the case of thick or heavily reinforced sections. Use of the wet mix is increasing in the underground construction because it produces less dust (Fernandez *et al*. 2012). However, studies show that the wet mix may produce more harmful dust than the dry mix (Ono and Franzén 1996). Conventionally, shotcrete is manually operated by the nozzleman and a team of operators, who are subjected to hazards such as, concentrations of noise, dust, rebound, causticity, poor visibility, and the chemicals floating in the air. Although Non-alkaline accelerators show a low pH-value content of sodium or potassium(Salvador *et al*. 2016), in many cases there are tunnel sites, where shotcrete cement is not available and therefore ordinary (Portland-) cement in combination with non-alkaline accelerator has to be used (Draganović and Lagerblad 2016). Moreover, shotcrete cement cannot be used in the wet-mix process, due to their flash setting, that result in high pH-value and high content of sodium or potassium floating in the air. Repeated exposure to cement dust will lead to irritation to eye, nose, throat and upper respiratory system. When skin is directly exposed to cement, further irritation can occur and skin cracking can result from chemical burns. Rinse eyes or skin with water and soap if it comes into contact with cement

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The amount of pH-value is a critical factor in the chemistry of concrete. “The amount of pH-value is a critical factor in the chemistry of concrete." "It can directly affect the reinforced concrete cover size, i.e. the cost of material (Sharafi *et al.* 2014a, 2012a, 2012b). Portland cement is the binding component in concrete and has a pH approaching 11, which is very alkaline. According to the World Health Organization (WHO), health effects are most pronounced in pH extremes; not to mention the harmful effects on the environment. Being exposed to the environment with an elevated pH above 10 can cause skin, eye and mucous membrane irritation, in addition to a variety of negative long-term after-effects.

There are regulations, guidelines, or standards regarding dust concentration (Ono and Franzén 1996), and in many countries, specifications are applied to dust control in tunnel construction, including threshold limits for mineral dust and particles. Yet, there is no specification regarding the pH limits or control methods, despite its crucial potential effect on the human and environment health and safety. Measuring the shotcrete induced pH of the air in underground construction and a model that illustrates the distribution of pH value in the air can facilitate decision making in order to tackle this problem. This study proposes a model for measuring pH-value distribution in the underground construction in order, and attempts to pave the way for the future pH limit control and guidelines.

Background of the study

There are some methods for measuring pH, which fall roughly into the following four categories: indicator methods, metal-electrode methods, glass-electrode methods and semiconductor sensor (pH imaging) methods. More information on these methods can be found in a study by Yuqing *et al*. (2005).There are also some methods being proposed for measuring the pH of the indoor air. Sano (1999) used a specific test by a "pH Test Paper" in Japan, to evaluate the acidity of indoor air. Using this method, changing the color of the pH test paper shows the "alkalinity" of the indoor air. Also, some advanced methods for air alkali particles have been introduced by inventors and researchers. Poutilina (1991) published employed a new photometric technique of measuring caustic alkali content in the working zone air, which was sensitive to the presence of carbonic acid gas. With regard to the shotcrete in tunnel construction, before the catastrophic tunnel collapse at Heathrow in October 1994, there were limited studies on Health Safety Environment (HSE) in the shotcrete-lined tunneling (Oliver, 1995). One of those studies carried out by Bates (1974) in a road tunnel construction site. The main goal of that study was the measurement of the amount of Alkali particles around the shotcrete operator. According to the test results, there is 4.4 to 94 milligram per cubic meter (average of 16 milligrams per cubic meter) of particles smaller than 5 microns near the operator. Also, between 10 to 84 milligrams/m3 (average of 14 milligrams/m3) of particles are in the distance ranging from 20 to 170 meter from the operator. Since 5% to 15% of these particles comprised silica, it was revealed that the current amount of silica in this area is more than the existing HSE standard limitations. During another experiment, which was carried while shotcreting in a tunnel in the US, by installing red litmus sheets at various distances from the operator and other workers, even within their mouth mask, some interesting results were found. After 20 minutes, not only the sheets in the distance of 3 meters at the open area, but also the ones in mouth masks turned into blue color, and the corresponding pH value was calculated as 11 which is absolutely a burning threshold (Nemati 2006). In a similar study in Norway by Bakke *et al*. (2001), personal exposures to dust and gases were measured among 189 underground construction workers who were divided into seven occupational groups performing similar tasks and working conditions: drill and blast crew; shaft-drilling crew; tunnel-boring machine crew; shotcreting operators; support workers; concrete workers and electricians. Outdoor tunnel workers were included as a low-exposed reference group. The highest geometric mean exposures to total dust (6-7 mg/m3) and respirable dust (2-3 mg/m3) were found for the shotcreters, shaft drillers, and tunnel-boring machine workers. Shaft drillers and tunnel-boring machine workers also had the highest GM exposures to respirable SiO_2 (0.3-0.4 mg/m3), which exceeded the Norwegian standard limitation of 0.1 mg/m3.

In another research study by Praml *et al*. (1998), several simultaneously applied measuring systems were used in a mine tunnel construction site during the shotcrete process. According to the results, the fine-dust amounts were 11.6 mg/m3 for nozzle-man and 4.2 mg/m3 for mixer operator. The peak loads were up to five times the mean concentration values. In addition, under unfavorable conditions such as sites with a partially badly ventilated headway, in spite of good general ventilation, higher concentrations may consequently occur (Praml *et al*. 1995).

Zhou *et al*. (2016) conducted some numerical simulations on gunite dust of migration law and mass concentration during dry and wet spraying. The results show that the wet spraying materials' rebound jet has much more influences on the air's radial offset compared with that of dry spraying. Moreover, the dust particle size of wet spraying is large, so it has even diffusion and high settling velocity. The wet spraying dust concentration in the whole roadway is much smaller than that during dry spraying. The best operating area should be more than 16 m behind the wet spray gun. In order to decrease the dust concentration in the process of shotcrete and avoid the shortcomings i.e. wet spraying machine and mixer work as two separate bodies and their applications and movements are not convenient, the integral wet spraying machine with the functions of stirring, spraying and moving are designed according to the hydraulic driving principle. Compared with dry shotcrete, after applying the integral wet spraying machine, the mass concentration of whole and respirable dust and the rebound ratio of concrete materials in the working areas sharply decrease.

In recent years, using robotic systems in shotcrete construction has addressed some HSE concerns (Ford *et al*. 2010). The invention of low alkali cements was another achievement research in this area. Low alkali cements are new types of cements that have been developed for the long term stability of the steel barrier systems whose performance could be negatively affected by highly alkaline conditions. This cement is less popular in underground construction compared to the ordinary Portland cement, and still carries high risks with regard to the environmental safety and human health. In addition, the reduced strength of low alkaline concrete is a significant problem in shotcreting (Nakayama *et al*. 2010). It also requires using new methods and portable test equipment to measure shotcrete strength on-site in the first six hours after application (Clark *et al*. 2010).

Increasing the bond between shotcrete and rock is an indirect way to reduce the alkali dust during shotcrete operation. To study the bond performance in a tunnel, experiments on wet-sprayed shotcrete specimens under different hot and humid curing conditions with a relative humidity of 95% were performed by Cui *et al*. (2016) to examine the influence of thermal damage. The results show that the bond strength at 35°C is higher compared with that at usual curing conditions at 20°C, but decreases when the temperature rises. Some experimental investigations on reducing the dust density and the rebound rate of shotcrete were conducted in China (Ceng *et al*. 2014), in order to improve the strength by using magnetized water in the mining worksite. The research also shows that the magnetized water can enhance the strength of shotcrete by 10% and reduce the dust density by 50% in comparison with the ordinary shotcrete. The rebound rate of shotcrete mixed with magnetized water is certainly improved compared with that of ordinary water shotcrete and obviously improved.

The Experimental Program

To evaluate and monitor the environmental and human safety related concerns of pH- value in shotcreting in the underground construction, a set of tests were conducted in a great tunneling project in Iran. The testing site was the Ahram-Farashb and great tunnel construction site in Boushehr, which was the greatest road tunnel in that area, at the time of the test. The length of this tunnel is 2056 meter, whose location is shown in Figure 1.

Due to geographical situation of this tunnel, highest safety standards were applied during the construction. The tunnel's excavation radius was six meter, which performed by New Austrian Tunneling Method (NATM) with the application of temporary meshing sheet covers and dry shotcrete. The NATM integrates the principles of the behavior of rock masses under load and monitoring the performance of underground construction in order to provide stabilization and support to the tunnel itself.

Tests were carried out in three days in approximate depths of 100, 175 and 250 meters from the tunnel outlet. The excavation process was a two-way convergence excavation. At the time of testing the two sides of the tunnel had not converged yet. Therefore, a single-way ventilation system was being used at the time. The measurements were carried out along the tunnel length in every 10 meters up to 100 meters from the operator to the tunnel outlet. In every measurement section, 3 series of air suspension alkalinity tests were conducted in 1, 2 and 3 meters from ground level. It should be noted that during the tests, the normal ventilation system of the tunnel was turned off to have consistency in data collection. The type V Portland cement was being used in the concrete mixture for shotcrete, which fulfilled the ASTM requirements of ASTM C150(2002). The shotcrete mixture design compromised 400 kg/m3 of sulfate resistance cement with the experimentally evaluated 28-day strength of 330 kg/cm2.The physical characteristics and chemical compositions of the Portland cement are summarized in Table 1. The sand used in these experiments was standard sand employed in strength tests of cement, which complied with the requirements of the ASTM C33 (1994).

TEST RESULTS AND DISCUSSION

The results of the data (measured pH-values) collected from the site in three days, at the depths of 100, 175and 250meters from the tunnel entrance, and heights of 1, 2 and 3 meters from ground level, along the tunnel length in every 10 meters (up to 100) meters from the operator to the tunnel outlet are shown in Table 1.

Figure 1 The location of the testing site

The pH longitudinal profiles in three different heights, shown in Figure 2, demonstrate rather similar sensitivity to distance.

Table 1 pH values measured in different heights, distances, and times

Situation of nozzleman from tunnel entrance (m)	**Distance from the nozzleman (m)**	**pH measurements in different level from the ground on different days**								
		1st Day			***2nd Day***			***3rd Day***		
		Level 1 (m)	***Level 2(m)***	***Level 3 (m)***	***Level 1 (m)***	***Level 2(m)***	***Level 3 (m)***	***Level 1 (m)***	***Level 2 (m)***	***Level 3 (m)***
	10	11.4	11.1	11.5	11.2	11.1	12	11.3	11.2	12.2
	20	11.1	11.1	11	11.1	11.1	11.6	11.4	11.4	11.8
	30	10.6	10.3	10.5	10.6	11	11.1	10.8	11.6	11.6
	40	10.3	9.8	10.5	10.5	10.2	10.5	10.6	10.4	10.5
100	50	10.3	9.8	10.4	11	11.2	10.6	11.6	11.6	11
	60	10.3	8.8	10.3	10.5	9.2	10	10.6	9.5	10.4
	70	9.2	8.8	9.3	9.9	9.2	9.2	10	9.5	9
	80	9	8.1	8.6	9.1	8.4	8.5	9.6	8.6	8.6
	90	8.7	8	8.1	9	8.2	8.8	9.7	8.6	8.8
	100	7.7	7	7.2	8.2	7.5	8.1	8.6	7.8	8
	10	12.6	11.2	11.6	11.5	11.1	11.6	11.6	11.2	11.6
	20	11.4	11.5	11.2	11.3	11.3	11.2	11.2	11.3	11.2
	30	10.7	10.6	11	10.7	10.4	11	10.6	10.4	10.6
	40	10.2	9.4	11.1	10.5	9.8	10.9	10.9	9.9	10.3
175	50	10.5	9.6	11.2	10.6	9.9	10.2	10.4	9.9	10
	60	10.5	9	10.2	10.4	9.4	10.1	10.6	9.1	10.9
	70	9.4	8.6	9.2	9.7	8.7	9.5	9.4	8.9	9.5
	80	9.4	8.4	8.4	9.1	8.1	8.7	9.2	8.4	8.7
	90	8.8	8.6	8	9	8.1	8.2	8.8	8.5	8.1
	100	7.9	7.2	7.4	8	7.2	7.4	8	7.6	7.4
	10	12.5	11.6	11.8	11.7	11.3	11.4	11	11.2	11.2
	20	11.8	11.4	11.4	11.4	11.3	11.4	11.4	11.3	11
	30	10.8	10.7	11.6	11.65	10.6	10.6	10.2	10.5	10.6
	40	10.6	8.5	11.4	10.7	9.4	11	10.7	10	11.3
250	50	10.4	9.7	10.9	10.8	9.5	10.6	10.6	9.9	10.5
	60	10.7	9.4	11	10.5	9	10.1	10.2	8.5	10.6
	70	9.5	8.8	9.3	9.6	8.9	8.5	8.5	9.1	8.5
	80	9.6	8.5	8.7	9.3	8.5	8.6	9.1	8	8.4
	90	9	8.7	8.5	8.7	8.4	8.4	11.3	8.2	8.5
	100	8.1	7.4	8	8.1	7.5	7.4	7.5	7.4	7.5

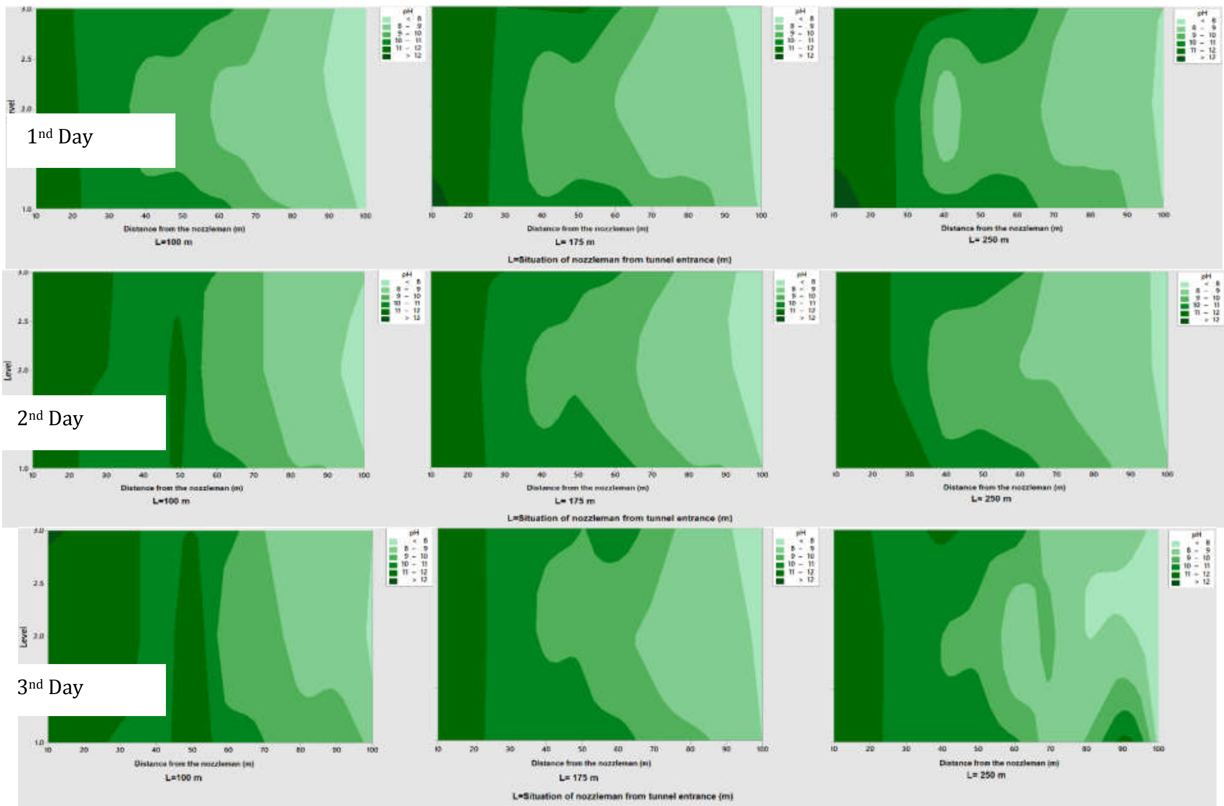

Figure2 pH longitudinal profiles in different height versus distance from tunnel opening

Near the shotcrete operation, the pH at the surface of the concrete tunnel was very high; therefore, higher pH value was measured in the first few meters from the operator. After that, pH values started to decrease and converged to 7 in distance.

Comparing the pH values measured at different heights demonstrates a difference between the trends in the first 100 meters, where pH value for2 and 3-meters height from the ground surface showed much higher decreasing rate than that of1-meter height. Therefore, the amount of pH near the ground has much higher value rather than heights. Moreover, a higher decreasing rate of pH at the first day resulted in lower pH later. This could be explained by accelerated dissipation rate of pH at the surface of concrete during the early concrete spraying due to the effect of natural ventilation. This apparently led to lower pH content at the surface of concrete which corresponded to lower risk for operators. It could be concluded that pH measurements are sensitive to the time too.

The sensitivity of pH values to the distance from tunnel entrance is shown in Figure 3. For measurements with the same age under the same ambient condition, the distance from the tunnel opening made a significant difference for pH measurements. The decreasing rate for measurements in 100, 175, and 250 meters were almost uniform. As more distance from the tunnel entrance, the more pH values measured. The pH values at 250 meters from the entrance are the highest. Although some of the trends showed minor variation in this trend.

function is used. In probability theory and statistics, the Weibull distribution is a continuous probability distribution (Sharafi *et al*. 2014b, 2015, Kaveh & Sharafi 2007, 2011).The results of many research studies show that the Weibull distributions provide good probability models for describing "length of life" and other endurance data (Rinne 2008).

The relation between the values of pH value, measured in distance from the nozzleman is governed by the probabilistic relationship that is affected by time as well. The (pH) is the mean value of measurements for each spot is shown as Eq.(1).

$$\overline{pH} = \int_1^\infty p(x)dx \qquad (1)$$

where the p(x) is the probability density function that is appropriate for pH data. This is, typically, a log-normal, Gumbel, or Weibull distribution, which is described below in Eq. (2).

$$p(x) = \gamma\lambda(\gamma x)^{\gamma-1} \exp -(\lambda x)^\gamma \qquad (2)$$

in which the γ *and* λ are shape and scale parameters, respectively. The cumulative probability distribution function P(x), which corresponds to the Weibull probability density function and fits through the data points relating $\overline{pH}$ and distance from nozzleman, is shown in Eq. (3).

$$P(x) = 1 - exp[-(\lambda x)^\gamma] \qquad (3)$$

Figure 3 pH variation in different distances from the tunnel opening

A Mathematical Model

In order to better understand the character of the pH value distribution in underground construction, based on the experiment results, a modified Weibull distribution

When γ = 1, the Weibull reduces to the exponential model, with α=1/λ. Depending on the value of the shape parameter γ, the Weibull model can empirically fit a wide range of data histogram shapes to appropriate mathematical equations. A modified Weibull distribution function is shown in Eq. (4) was used to generate regression curves for the pH measurements.

$$\varepsilon_r = \tau \left\{ 1 - e^{-\left[\frac{\beta}{t}\right]^{\alpha}} \right\} \quad (4)$$

In Eq. (4), t is the elapsed time in hours; τ is the amplifying parameter; β is the scaling parameter; and α is the shift parameter. The fitted regression parameters for all other sections are presented in Table2. The fitted regression curves for the first day in the height of 1 meter and 100 meters from tunnel opening is shown in Figure 4.

Table 2 β in regression parameters

Distance from the tunnel opening (m)	β in regression parameters (%)								
	1st Day			*2nd Day*			*3rd Day*		
	1 (m)	*2 (m)*	*3 (m)*	*1 (m)*	*2 (m)*	*3 (m)*	*1 (m)*	*2 (m)*	*3 (m)*
100 m	7.73	9.01	9.38	8.04	9.02	8.18	7.34	8.85	8.88
175 m	7.99	8.61	9.88	7.54	8.85	9.14	7.90	7.84	9.88
250 m	7.30	9.06	9.26	8.20	8.27	9.28	5.27	8.83	9.23

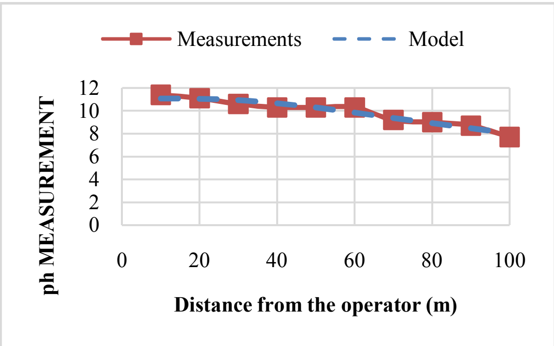

Figure 4 Regression curve (1st Day- Height of 1 m – 100 m from tunnel opening)

As shown in Table 2, a direct relationship was found between dispersing pH and regression parameters β. The Low intendancy in decreasing pH is generally associated with a lower β, which represents a lower decreasing rate of pH measurements and higher potential danger for operators. Therefore, the usability of using β measurements to qualify alkalinity of a tunnel is validated. Figure 4 demonstrates that by aging, the value of function converges to 7 in extreme time, as it anticipated. More test results could further understand the relationship between pH rate and β. Yet, the presented values indicate good potential for using β to extend the evaluation of the current situation in tunnels. Based on the regression parameters shown in Table 2, it is found that the regression parameter β which represents the decreasing rate for 1-meter height is lower than that of for other heights elevations. This could indicate that by going up from the ground surface, the chance of high alkalinity increases. Regression parameter β related to decreasing rate of the pH measurements for the test sections shows promises for predicting the endangerment of working in high alkaline situations.

CONCLUSION

To help employers protect the safety and health of underground construction workers, the occupational safety and health guidelines and documents required data collected from the actual construction sites. One of the major risks for underground construction workers, under difficult or limited access and egress, is the potential for exposure to air contaminants such as the exposure to alkaline cement dust. In this study, the data collected from a series of tests in a tunnel construction site in Iran, were used to develop a mathematical model for the prediction of the pH value distribution profile while shotcreting and up to three days after that.

The summary of the results indicated that the pH measurements in three different heights showed very similar sensitivity to distance. Near the shotcrete operation, the pH at the surface of the concrete tunnel is very high. Comparing the pH values measured for different height indicates that the amount of pH value near the ground is the highest. In addition, the higher decreasing rate of pH value at the first day the lower pH value measured later. This could be explained by accelerated dissipation rate of pH at the surface of concrete during the early concrete spraying. In addition, the pH value is very sensitive to the distance from the tunnel entrance. Further distance from the tunnel entrance results in higher pH values.

With regard to the mathematical model, a direct relationship was found between dispersing pH and regression parameters of beta. The low intendancy in decreasing pH is generally associated with a lower beta which represents a lower decreasing rate of pH value and higher potential risk for operating team.

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