EFFECT OF ENVIRONMENTAL TEMPERATURE AND HUMIDITY ON DUST EMISSION FROM CERAMIC RAW MATERIALS

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1. SUMMARY

The diffuse emissions of particulate matter generated during the management and handling of dusty materials in ceramic and related industries contribute significantly to the global emissions of particulate matter (PM) into the atmosphere. Furthermore, in addition to the problems associated with these emissions, such processes also include problems of PM exposure in the workplace.

Thus, the most recent legislation on industrial emissions establishes the application of Best Available Techniques (hereinafter BATs) to minimise the environmental impact associated with this type of emission. On the other hand, legislation on occupational health emphasises the need to limit the risks inherent in PM exposure, mainly by inhalation, of personnel in the workplace.

A very important parameter in controlling and minimizing PM emissions and/or exposure is the dustiness of particulate materials. Dustiness is defined as the tendency of materials to generate dust on handling.

In this sense, standard EN 15051 proposes two methods for determining this parameter: the rotating drum method and the continuous drop method. In these devices, three fundamental stages may be distinguished: generation of dust, transfer of arising dust to the sampling area and collection of the dust generated in the filtering systems.

In this study, a modular system has been developed that consists of an air conditioning module, a dust generation module (rotating drum tester) and a module for characterizing the generated dust. The system enables simulation of different environmental conditions (temperature and humidity) and continuous characterization of the arising dust. The results obtained were used to identify the optimal conditions for managing dusty materials.

2. INTRODUCTION

Industrial activities in which dusty materials are handled give rise to two problems: 1) generation of diffuse emissions of particulate matter (hereinafter PM) [1-2] and 2) occupational exposure to PM [3].

In this sense, a very important parameter to be assessed in controlling and minimizing risks associated with PM emissions and exposure generated in handling particulate materials, is the dustiness of the materials, i.e. their tendency to produce dust when handled [4].

2.1. DUSTINESS

The dustiness of a particulate material may be determined using various devices. In this sense, given that a material's dustiness depends on the equipment used, Standard UNE EN 15051:2014 [4] provides two methods: the rotating drum method and the continuous drop method.

In this study, the rotating drum method has been used. The dustiness tester consists of a drum that rotates with a known volume of bulk material. The dust generated in the drum is transferred by a horizontal current of air to the sampling area.

The test results allow the inhalable (w_I), thoracic (w_T) and respirable (w_R) dust mass fractions to be determined. In addition, the results enable the materials to be classified into different categories according to their corresponding dustiness, in accordance with the criteria established in the above standard (Table 1)

Classification	Method	Dust mass fraction (mg/kg)		
		w_I	w_T	w_R
Rotary drum	Very low	<300	<80	<10
	Low	300 to 650	80 to 300	10 to 60
	Moderate	>650 to 3000	>300 to 1000	>60 to 210
	High	>3000	>1000	>210

Table 1. *Classification of dust emission in accordance with UNE EN 15051:2014 [4]*

2.2. INFLUENCE OF ENVIRONMENTAL CONDITIONS ON DUST EMISSION

By analogy with liquids, the dustiness of particulate materials may be considered a parameter equivalent to that of volatility for liquids. But while the ability of a liquid with a given chemical composition to emit gases or vapours depends basically on its temperature, pressure and the liquid-gas interface area, dustiness is not an intrinsic characteristic of a chemical composition. Rather, it depends on the test used, the material's physical characteristics (particle and/or granule size distribution, moisture content, specific surface area, shape, flowability, true density and bed density, etc.) [5-7] and on the environmental conditions [7].

With regard to the effect of environmental conditions, several authors have observed that the relationship between relative humidity and dustiness is complex. Thus, in some materials, dustiness decreases with increased relative humidity, whereas in other materials, dustiness peaks at high relative humidity [7].

Temperature and relative humidity condition the moisture equilibrium of a material. In general, increased moisture content raises inter-particle attraction forces and, therefore, increases cohesion while decreasing dust generation. Indeed, many studies have shown that adding water to a wide variety of particulate materials reduces their dustiness [5-7]. In addition, there are numerous industrial examples in which water is used as a dust suppressant: water sprayed on the surface of stockpiles of material (in ports, quarries, mines, etc.), wet processing of materials and/or use of suspensions and wet materials in the ceramics industry [8]. Water may therefore be considered the most common dust suppressant at industrial level due to its low cost, availability and chemical compatibility.

However, review of specific studies on the effect of moisture content shows that small increases in moisture content can sometimes lead to greater dustiness, whereas significant increases almost always entail a decrease. On the other hand, several studies show that the effect of moisture content may increase or decrease dustiness depending on the material [5-9].

The effect of moisture content may therefore be deemed complex and may vary among materials, depending on the water content adsorbed internally or superficially [6], which in turn depends on the material's surface properties and hygroscopicity [8].

3. OBJECTIVES

The objectives of this study were as follows:

- To develop a modular system for evaluating the influence of environmental conditions (temperature and relative humidity) on the dustiness of hygroscopic particulate materials, as well as on the characteristics of the dust generated.
- To establish optimal environmental conditions for handling dusty materials in the ceramics and related industries.

4. MATERIALS AND EXPERIMENTAL TECHNIQUES USED

4.1. SAMPLES

A hygroscopic material was selected to evaluate the effect of environmental temperature and relative humidity on dustiness. The test material was a white-firing clay. The specific surface of the sample was 29m^2/g, determined by nitrogen adsorption with a Micromeritics TriStar 3000 analyser, in accordance with ISO 9277:1995. The average particle size of the selected clay was 4 µm, determined by wet laser diffraction using a MasterSizer 2000 particle size analyser, in accordance with ISO 13320-1:2009.

4.2. METHODOLOGY

The methodology used involved two lines of work: 1) development of a modular system for evaluating the influence of environmental temperature and relative humidity on dustiness while simultaneously and continuously characterizing the dust generated and 2) evaluation of the optimal conditions for handling dusty materials.

4.2.1 DUST EMISSION

Testing was carried out using the rotating drum method.

The test apparatus consisted of a 300-mm diameter stainless steel rotating drum that rotated at 4 min^{-1}, equipped with eight longitudinal vanes that lifted and dropped a known volume of bulk test material (dust generation section), and a three-piece system for collecting samples of dust (output section) through which the emitted dust cloud was drawn by a vacuum pump at a flow rate of 38l·min $^{-1}$ during the test. The stainless-steel vanes, 230 mm long and 25 mm wide, were fixed longitudinally to the inner walls of the drum and were directed radially inwards, towards the centre of the drum.

The dust sampling system (Figure 1) consisted of two sections of size-selective foam in series followed by a final filter. To separate the two sections of foam from the final filter and prevent contamination between these sections, polytetrafluoroethylene (PFTE) spacer rings, 80 mm in diameter and 2 mm thick, were used. The dust entering the conical duct and the sample collection system provided an estimate of the inhalable fraction. To select the thoracic and respirable fractions, size selectors were used in the form of cylindrical plugs made of porous metallic foam, having 800 pores per metre and 3200 pores per metre, respectively. The foam and the final filter were weighed before and after testing in order to obtain estimates of the three fractions as a function of emitted dust particle size.

In addition, at the drum entrance there was a 150-mm diameter fibreglass filter to protect it from dust contamination while disseminating air flow inside the drum. The air flow through the testing apparatus was controlled by an online mass flow meter, which also measured the sampled air volume.

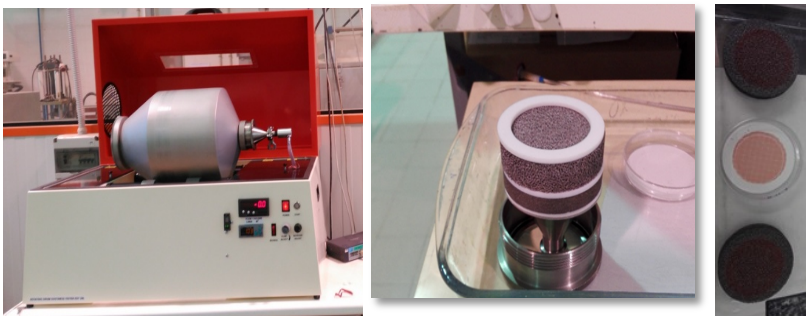


Figure 1. *Device for determining dustiness and 3-piece sampling system before and after testing*

4.2.2 MODULAR SYSTEM

To evaluate the effect of environmental temperature and relative humidity on dustiness of the samples, the samples were conditioned for 24 hours before testing. For this, a climate chamber (Heraeus Votsch) was used. This chamber enables operation in a temperature range of 10-90ºC and relative humidity of 10-98%.

On the other hand, to maintain the conditions of the material during the dustiness test, a system was assembled (PVC conduit and adapter, Figure 2) that enabled the drum to be fed with air from the climate chamber (air at set temperature and relative humidity conditions).

With regard to characterization of the generated dust, a Grimm (Mini-Las 11-R) instrument has been used. The device enables continuous recording of the inhalable, thoracic and respirable PM concentrations, as well as size distribution of the generated dust. The operating range for this instrument was as follows: temperature: 4ºC - 40ºC and maximum relative humidity: 95%.

Modification of the rotating drum was required by incorporation of a system of bearings as well as installation of an aerosol inlet that enabled representative sampling of the generated aerosol. Additionally, prior to sample monitoring, a dilution system (1:10) was installed to ensure that the maximum concentration for the device was not exceeded. (Figure 2).

Figure 2. *Drum adapted to enable connection of the conditioning module (left) and drum adapted to enable connection of the characterization module (right).*

A modular system consisting of an air conditioning module, a dust generation module (rotating drum) and a module for characterizing the generated dust was thus developed

5. RESULTS AND INTERPRETATION

5.1. EFFECT OF ENVIRONMENTAL CONDITIONS ON DUST EMISSION

Figure 3 shows the water adsorption isotherm of the sample. The isotherm was gravimetrically determined using a DVS Aquadyne Quantachrome instrument. Table 2 shows the results obtained, including the conditioning parameters of the material and air (relative humidity and temperature), material moisture content and inhalable, thoracic and respirable dust fractions. Finally, the PM concentrations recorded during testing are shown. Note that the conditioning parameters were selected based on the operating range of the climate chamber and of the Mini-Las instrument, as well as on the dew point temperature to avoid possible condensation in the ducts.

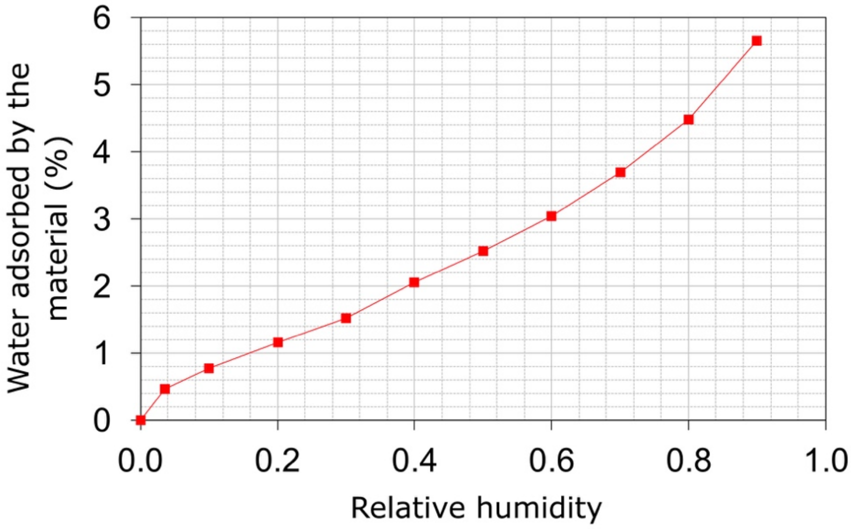


Figure 3. *Water adsorption isotherm of clay (obtained at 20ºC)*

Conditions		Solids moisture content (%)	[a] Dust mass fraction (mg/kg)			[a] Maximum concentration recorded (μg/m^3)		
T (ºC)	HR (%)		W_I	W_T	W_R	C_I	C_T	C_R
20	45	2.52	1,136	375	82	220,000	200,000	85,000
20	65	3.25	943	305	73	135,000	120,000	550,000
20	70	3.51	746	270	55	110,000	100,000	3,500
20	75	3.63	351	143	32	55,000	50,000	15,000
20	80	4.51	628	202	43	272,680	87,710	18,670
20	84	5.20	382	169	16	45,500	40,000	15,000
20	85	5.61	366	135	35	70,000	65,000	25,000
20	88	5.79	236	57	16	65,000	55,000	15,000
30	45	2.41	1,224	418	97	200,000	180,000	80,000
30	65	3.22	944	326	78	155,000	145,000	60,000
30	85	5.26	367	141	32	45,000	40,000	15,000

[a] *I, T, R: Inhalable, thoracic and respirable, respectively.*

Table 2. *Results obtained*

Figure 4 shows the variation of the concentration and mass fraction of inhalable dust with the absolute moisture content of the material. It may be noted that the use of a dilution system may entail a loss of particles and may therefore underestimate the concentration.

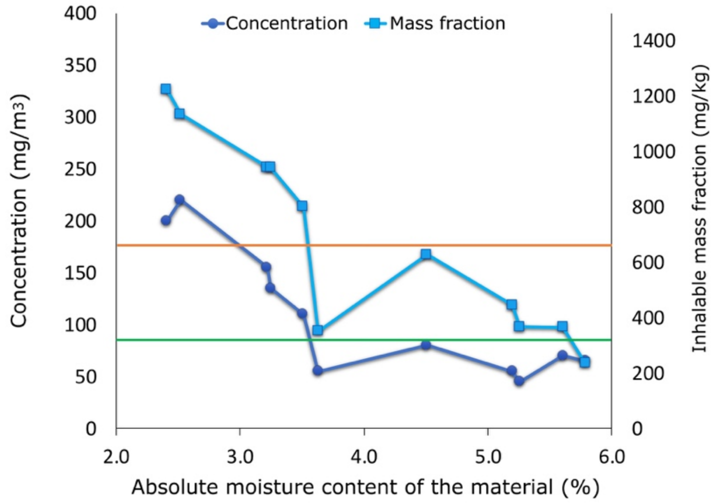


Figure 4. *Concentration and mass fraction of inhalable dust*
(-Dustiness limit Very low-Low, - Dustiness limit Low-moderate)

The results obtained (Figure 4) indicate that the relationship between moisture content and dustiness is complex. The presence of a maximum and a minimum value relative to intermediate moisture contents, possibly associated with the formation of different monomolecular layers of water on the surface of the clay particles may be highlighted. Thus, previous studies have shown that, during the clay hydration process, water can act as a binder or as a lubricant, depending on the predominant mechanism [9].

However, despite the highly complex relationship between relative humidity and dustiness, a relationship could be established between relative humidity and the classification of the samples as a function of their dustiness in accordance with Standard EN 15051:2014 (Table 3).

Dustiness classification	Relative humidity
Very low	>85
Low	75-85
Moderate	45-75

Table 3.*Relationship between relative humidity and dust emission*

On the other hand, relative humidity not only affects the amount of dust generated but also dust particle size distribution. This effect was evaluated using the characterization module. By way of example, Figure 5 shows the comparison of the particle size distribution recorded by the sampling system during testing under the following conditions expressed as pairs of temperature-relative humidity values: 20ºC-45%, 20ºC-85% and 30ºC-45%. In the temperature and relative humidity ranges evaluated, temperature was not observed to affect particle size distribution, whereas increased relative humidity resulted in displacement of the dust particle size distribution larger sizes, probably because the water acted as a binder.

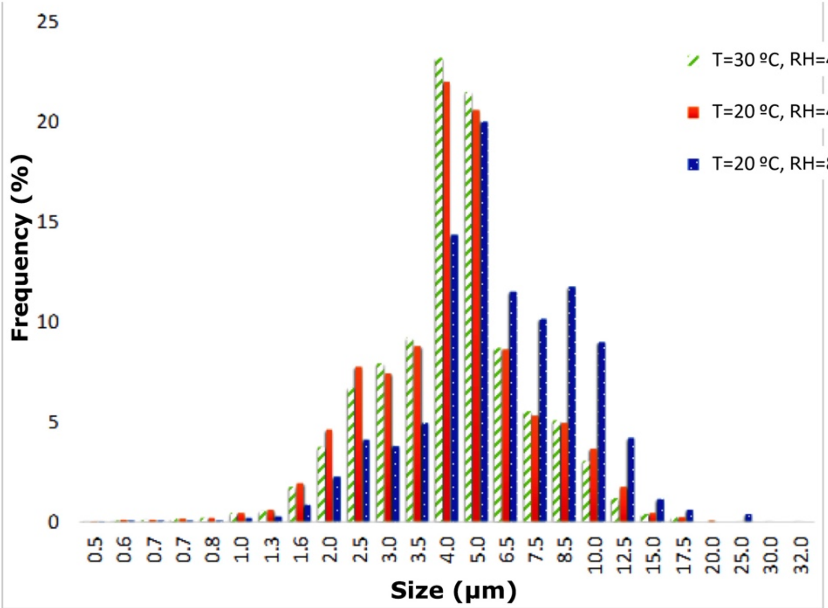


Figure 5. *Comparison of particle size distribution of the dust generated during testing under different temperature and relative humidity conditions*

5.2. EVALUATION OF OPTIMAL CONDITIONS FOR MANAGING DUSTY MATERIALS

Based on historical data from the air quality network stations at Onda and Grao de Castellón (stations representative of the inland and coastal ceramic region, respectively), the daily evolution of temperature and relative humidity during the different seasons of the year was evaluated. By way of example, Table 4 shows the data obtained for typical summer and winter days.

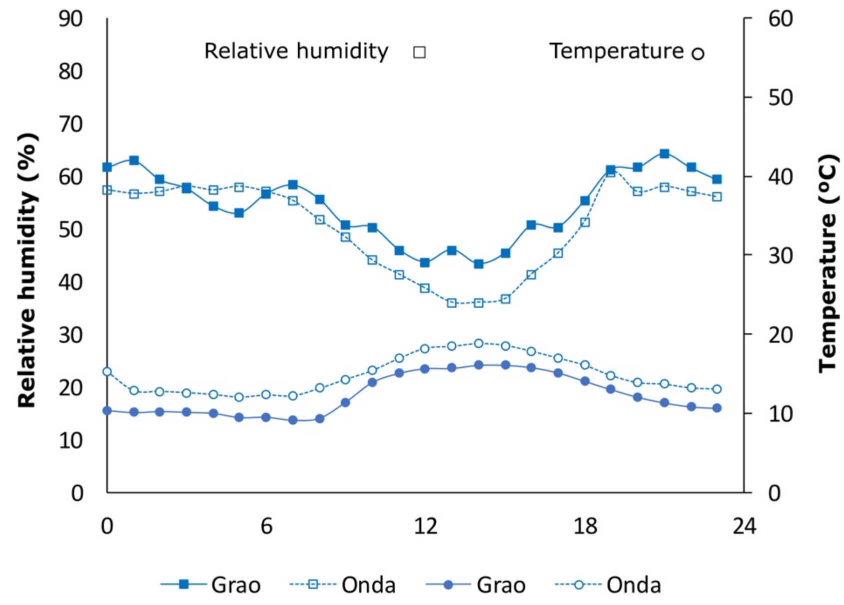
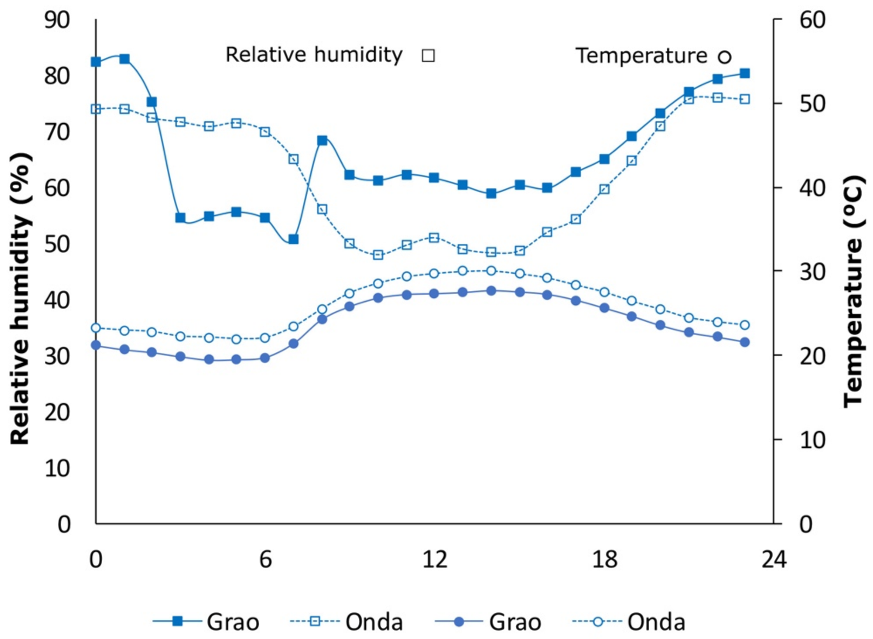
Season	Hourly evolution of temperature and relative humidity
Winter	
Summer	

Table 4. *Daily evolution of temperature and relative humidity at the Onda and Grao de Castellón air quality stations (historical data 2016).*

Based on the evaluation of the effect of temperature and relative humidity on dustiness (Table 3) and considering the daily evolution of these parameters (Table 4), a series of practical recommendations may be drawn up for handling the samples under study. Specifically, (Table 5) indicates the periods in which environmental conditions were associated with low or very low dustiness (√) and those that gave rise to moderate dustiness (X).

Season	00:00-06:00	06:00-12:00	12:00-18:00	18:00-00:00
Winter	X	X	X	X
Spring	√	X	X	√
Summer	[a]√	X	X	√
Autumn	[b]√	X	X	[b]√

[a] At the Grao the recommended period was from 00:00 to 03:00. From 03:00 on, relative humidity dropped significantly.
[b] At the Grao, the recommended period was only from 19:00 to 20:00. The rest of the day relative humidity was very low.

Table 5. *Identification of optimal conditions for the handling of pulverulent materials*

Table 5 shows that the environmental conditions associated with low dustiness only took place naturally at night. Additionally, in summer, according to the results, no period of time was suitable for handling dusty materials.

For this reason, a possible practical recommendation would be to handle the dustiest materials during night shifts. However, considering the results as well as the prevailing climate conditions in the ceramic region, wetting the material appears almost indispensable (during most of the day), either by spraying water or by humidifying the air, if the material is stored indoors.

In both cases, based on the results obtained, it is considered essential to control the absolute moisture content of the material, since it has been shown that, if the degree of wetting is inadequate, implementation of this measure may even lead to increased generation of PM emissions.

By way of example, in the case studied it would be necessary to reach relative humidity levels above 75-80% (Table 3) for the material to attain an absolute moisture content above 4.5-5% (Figure 3), associated with low dustiness (Figure 4).

However, given the complex relationship observed between moisture content and dustiness, the optimal moisture content range must be evaluated for each material.

Therefore, if wetting the material and/or humidifying the air enabled the material to reach an optimal moisture content, this could entail a significant reduction in dustiness and, therefore, could presumably be used as an effective preventive measure to reduce PM emissions and/or exposure.

6. CONCLUSIONS

- The modular system developed enables evaluation of the effect of environmental conditions on dustiness, as well as obtaining continuous information on the characteristics of generated dust.
- Modification of environmental conditions showed that the relationship between a material's moisture content and the dustiness of hygroscopic materials is highly complex, a maximum relative to intermediate moisture contents being observed.
- The results obtained by using a modular system enabled proposal of specific low- or no-cost measures to reduce PM emissions and exposure, resulting from the handling of the materials under study. It may be noted, however, that this study focuses on the effect of temperature and relative humidity and, therefore, meteorological variables such as wind direction and speed, which may significantly affect PM emissions and exposure during outdoor storage or handling, were not considered. In addition, the effect on dustiness was contingent upon the material being in equilibrium with the environment.
- The time range in which optimal environmental conditions occurred (in relation to dust generation) in the Castellón ceramic district was very limited. For this reason, it is deemed necessary to implement measures that enable wetting the material by means of spray systems or air humidification. In the case of air humidification, especially if working at relative humidity levels above 70%, it is recommended to evaluate the level of hygrothermal comfort at the workstations involved, as the recommended values are usually 30-70%.
- For both wetting and humidification, it is necessary to ensure that the system used allows the material to reach an optimal moisture content, because otherwise implementation of these measures might even increase PM emissions as a result of the presence of relative maximum values for dustiness at intermediate moisture contents.
- Given the complexity of the relationship between moisture content and dustiness, the results obtained cannot be directly extrapolated to other materials. However, the use of the methodology developed (modular system) together with a thorough evaluation of the meteorological conditions of the installation should enable establishment of optimal conditions for the reduction of PM emissions and exposure associated with the handling of other clays or even of materials of a different nature.

7. ACKNOWLEDGMENTS

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