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Assessment of RBD Palm Oil-in-Water Emulsion to Reduce Dust Exposure and Crystalline Silica in Abrasive Blasting

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Abrasive blasting, oil-in-water emulsion, dust exposure, palm oil, occupational safety and health

Abstract

Abrasive blasting widely used as surface preparation in industrial applications but poses significant occupational health risks due to airborne dust, particularly crystalline silica. This study investigates the effectiveness of Refined, Bleached, and Deodorized (RBD) palm oil-in-water emulsions in reducing inhalable and respirable dust concentrations during abrasive blasting. Using garnet abrasive media (30-60 mesh size) and varying emulsion ratios (95:5, 96:4, 97:3, 98:2, 99:1 and 100:0–water:oil ratio), dust exposure was measured via NIOSH methods; NMAM 0500 for inhalable dust and NMAM 0600 for respirable dust and analyzed using X-Ray Diffraction (XRD). Results show that the 95:5 emulsion ratio achieved up to 86% reduction in inhalable dust and 75% in respirable dust compared to dry blasting. XRD analysis confirmed a significant decrease in crystalline silica content. These findings suggest that RBD palm oil emulsions offer a safer, eco-friendly alternative for industrial blasting operations.

1. Introduction

Abrasive blasting is a fundamental surface treatment process across diverse industries, including maritime, aerospace, civil engineering, and manufacturing. This method, which involves accelerating an abrasive medium to a high velocity to impact a work piece [1], is critical for tasks such as surface preparation for coating, rust and scale removal, and achieving desired surface textures. While various techniques exist, the most common approach employs compressed air to propel the abrasive stream [2], often executed in open environments like shipyards and construction sites, or in enclosed blasting chambers [3].

The selection of an appropriate abrasive medium is critical to the blasting process, with media chosen based on the desired surface finish, required aggressiveness, and material properties [4]. While early blasting practices relied predominantly on silica sand [5], the industry has evolved to employ a diverse range of media classified into four main categories: mineral, metallic, synthetic, and agricultural [6]. Each category offers a distinct set of characteristics. For instance, synthetic media like aluminium oxide and silicon carbide are valued for their extreme hardness and aggressive cutting properties, making them ideal for etching and profiling [7]. Conversely, agricultural media such as corn cob or walnut shells are a softer, organic alternative used for delicate cleaning and stripping where surface preservation is paramount [6]. Metallic media like steel shot are used for polishing, while mineral abrasives such as garnet [8] are widely used for preparing surfaces for coating [9].

Despite its industrial utility, conventional dry abrasive blasting is associated with significant and well-documented occupational and environmental hazards [10], [11]. The process generates a substantial amount of airborne particulate matter from the fragmentation of abrasive media, the removal of surface contaminants, and the workpiece itself [12], [13]. This particulate matter (PM), a complex mixture of carbonaceous particles, metals, and organic compounds, is classified by size into coarse (PM10), fine (PM2.5), and ultrafine (PM0.1) particles [14], [15]. Of particular concern is the pervasive use of abrasives containing crystalline silica (SiO_2), the inhalation of which poses a severe health risk [16]-[20].

The inhalation of fine particles is associated with a range of adverse health outcomes, including diminished lung capacity, increased mortality, and exacerbated respiratory conditions such as asthma [21]-[23]. Chronic exposure to respirable crystalline silica particles, which can penetrate deep into the small airways and alveoli [24]-[26], can lead to silicosis, a debilitating and incurable fibrotic lung disease [27]-[29], as well as an increased risk of chronic obstructive pulmonary disease (COPD) and lung cancer [30]-[33]. In addition to respiratory ailments, dust exposure is linked to various health issues, including dermatitis and other skin disorders [34]-[38], as well as systemic effects on the cardiovascular system [39], [40]. Furthermore, the dust can carry heavy metals and paint particles, which can enter surrounding ecosystems through runoff, presenting a distinct environmental threat [5], [14], [21]. Consequently, stringent regulatory bodies, such as the Occupational Safety and Health Administration (OSHA) or Department of Occupational Safety and Health (DOSH), have established strict exposure limits to mitigate these risks [12].

In response to these challenges, wet abrasive blasting has emerged as a primary dust-suppression alternative. This method effectively combines abrasive media with a high-pressure water jet, which binds dust particles, increasing their mass and preventing them from becoming airborne [41], [42]. While this technique significantly reduces ambient dust pollution and improves operator visibility, it introduces new operational drawbacks [43]. These include the potential for flash rusting on steel surfaces [44], which compromises the integrity of the prepared substrate, and the generation of a contaminated slurry that requires specialized and often costly collection and disposal procedures [45], [46]. These limitations highlight a persistent need for a more efficient and sustainable dust mitigation strategy that can overcome the shortcomings of both dry and water-based methods.

This study proposes a novel dust mitigation paradigm through the application of a refined, bleached, and deodorised (RBD) palm oil-in-water emulsion. Crude palm oil generally contains higher acid values and free fatty acids compared with refined palm oil and normally occur in the form of semi solid at the temperature below than 38-degree Celcius [3], while the refining process improves the chemical stability and quality of the oil for various applications. Leveraging the unique physiochemical properties of palm oil [30], which is a readily available, non-toxic, and biodegradable resource in Malaysia, this approach is hypothesised to provide superior dust encapsulation and suppression capabilities. As shown in Fig. 1, an emulsion is a viscous, homogeneous product typically formed by combining two immiscible liquids, such as oil and water, with the help of a third ingredient that acts as a mixing agent [45]. The oil phase of the emulsion is expected to more efficiently wet and bind hydrophobic and hydrophilic dust particles alike, increasing their settling velocity and significantly reducing airborne concentrations. The viscous nature of the oil-in-water emulsion, also with high-shear mixing, will produces smaller and more stable droplets compared with water sprays [44]. This strategy not only addresses the critical health hazards of respirable dust but also circumvents the issues of flash rusting and costly slurry management associated with traditional wet blasting. The main objective of this research is to quantitatively assess the efficacy of the RBD palm oil-in-water emulsion in reducing both total and respirable crystalline silica dust exposure compared to conventional dry and water-based blasting methods.

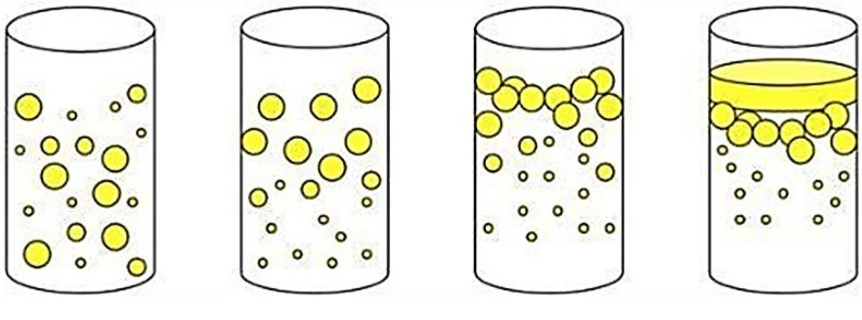

Fig. 1 *Emulsification process*

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2. Material and Methodology

This study employed a systematic experimental approach to evaluate the efficacy of RBD palm oil-in-water emulsion in mitigating dust and crystalline silica exposure during abrasive blasting. The methodology was structured into several distinct phases: the preparation of the emulsion, the execution of the abrasive blasting trials under controlled conditions, and the subsequent analysis of collected airborne dust samples. The procedures were designed to ensure a robust and replicable assessment of dust suppression performance across three distinct blasting conditions.

2.1 Production of RBD Palm Oil-in-Water Emulsion

The RBD palm oil-in-water emulsions were prepared using specific volume-to-volume ratios as detailed in Table 1, with the goal of creating a stable dispersion for each concentration. The process involved combining the RBD palm oil with a suitable non-ionic emulsifying agent. The water phase was then added incrementally under continuous high-shear mixing, with the mixture processed using a homogeniser to achieve a uniform droplet size distribution. This process was carried out under vacuum pressure (0 bar) at a constant stirrer speed of 45,000 rpm for a duration of 10 minutes. The resulting emulsions were collected for use in the abrasive blasting trials.

Table 1 *Volume-to-volume ratio RBD palm oil-in-water emulsion*

Specification	Description
Ratio (water:RBD palm oil, v/v)	95:5
	96:4
	97:3
	98:2
	99:1
Pressure	0 bar
Stirrer speed	45,000 rpm
Duration of process	10 minutes

2.2 Abrasive Blasting Process

Experimental abrasive blasting trials were conducted in a controlled environment to minimise external variables. A standard dry abrasive blasting system was used, consisting of a piston air compressor, a blast machine with a pressure pot (model TBP-100), and a hand-held nozzle. The blasting abrasive used for all trials was garnet with a specified particle size distribution (30-60 mesh) and certified crystalline silica content. The workpiece material was a standard steel plate coated with a rust-inhibiting primer, simulating a typical industrial application. All trials were performed at a constant compressed air pressure (7-10 bar), a consistent standoff distance from the workpiece (6 cm), and a fixed nozzle angle (45-60 degree). Three distinct blasting conditions were tested:

1. Dry blasting (control): Abrasive was propelled with compressed air alone.
2. Wet blasting: The abrasive was fed through a separate nozzle and injected alongside a concurrent stream of plain tap water at the point of impact.
3. Emulsion blasting: The abrasive was fed through a separate nozzle and injected alongside a concurrent stream of the prepared RBD palm oil-in-water emulsion at the surface.

Each condition was repeat 8 times to ensure the reliability of the collected data. Fig. 2 illustrates the setup for abrasive blasting.

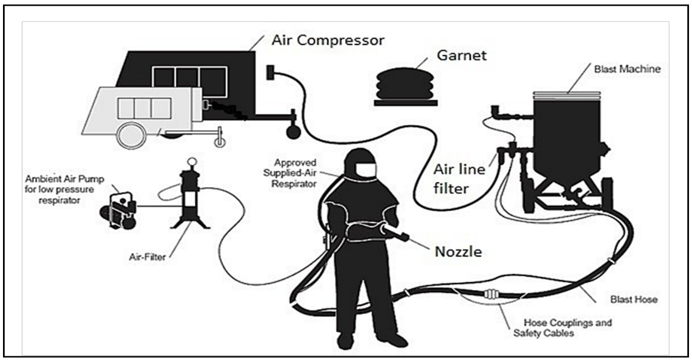

Fig. 2 *Setup for abrasive blasting*

2.3 Dust Exposure Monitoring and Sample Collection

Airborne dust exposure was monitored through a series of personnel sampling procedures to measure both respirable and inhalable fractions, which is necessary for accurately calculating and evaluating the exposure of the abrasive blaster. The specific methods used for dust concentration measurement were NIOSH Method NMA 0500 for inhalable dust and NIOSH Method NMAM 0600 for respirable dust. The sampling setup consisted of high-volume personal air sampling pumps attached with a cassette and tubing. The equipment used included a GilAir Plus personal sampling pump, a filter holder and cassette, a PVC filter medium, and a connecting tube. For respirable dust collection, additional equipment such as a 10 mm nylon cyclone, Higgins-Dewell (HD) cyclone, or aluminium cyclone was used. The airflow rate for the inhalable dust pump was set at a fixed rate of 2.0 L/min, while the respirable dust pump operated at 1.7 L/min. Sampling volumes were maintained within 7-133 L for inhalable dust and 20-400 L for respirable dust.

Personnel sampling was conducted by locating the sampling head within the abrasive blaster's breathing zone, defined as a hemisphere with a 0.3 m radius centred on a midpoint of a line joining the ears [51]. This ensured that the collected samples were representative of the air inhaled by the operator. The duration of sampling for each trial was based on workplace conditions, with a full-period (8-hour) consecutive sample taken when possible. The start and end times for each sampling period were meticulously recorded on a sampling sheet for subsequent volume calculations, with the final unit of measurement being.

2.4 Filter Media and Cassette Blanks

For gravimetric analysis, 37 mm closed-face filter cassettes with polyvinyl chloride (PVC) filters were used to collect total inhalable dust, while 10 mm nylon cyclones with 25 mm PVC filters were used to collect the respirable fraction. To account for any background contamination or handling effects, a minimum of two identical cassette blanks were included with each batch of samples. These blanks were handled in the same manner as the active samples but were not connected to a pump.

The filter medium is a crucial component of the sampling cassette, as it is responsible for screening and capturing airborne particulates. Various filter materials exist, including glass fibre, plastic fibre, cellulose, and membranes made of silver or plastic, each possessing distinct characteristics (Table 2). Their selection is based on the type of particulate being monitored (Table 3). For this study, polyvinyl chloride (PVC) filters were specifically chosen for their cost-effectiveness and proven suitability for collecting silica dust.

Table 2 *The characteristics of the filter*

Specification	Description
Glass fibre	Moderately robust and low moisture pick-up
Plastic fibre	Moderately robust and low moisture pick-up
Organic membrane	Brittle, very low moisture pick-up
Silver membrane	Tough, flexible
Cellulose	Considerable tensile strength, rapid uptake of moisture

Table 3 *Recommended filter to be used for various types of particulates*

Specification	Description
Silica	0.8 µm or 5 µm PVC or MCE membrane
Wood dust	5 µm PVC
Welding fumes	Glass fibre or 0.8 µm cellulose estermembrane
Asbestos fibre	0.45 to 1.2 µm cellulose ester membrane
Elements	0.8 µm cellulose ester membrane
Lead	0.8 µm cellulose ester membrane

For gravimetric analysis, mm closed-face filter cassettes with PVC filters were used to collect total inhalable dust, while 10 mm nylon cyclones with 25 mm PVC filters were used to collect the respirable fraction. To account for any background contamination or handling effects, a minimum of two identical cassette blanks were included with each batch of samples. These blanks were handled in the same manner as the active samples but were not connected to a pump.

The cassette blanks, comprising two or three parts of the filter housing, keep the filter in place during sampling. The number of blanks included in a sample set varies depending on the chosen method. Their primary purpose is to account for any potential pollutants introduced during the handling and transportation of samples. A field blank is a set of sample media that undergoes the identical conditions as the sampled media but is not attached to a sampling pump. Field blanks are essential for determining the background signal contributed by the collection media and the environment. A minimum of two field blanks were included in each sample set, regardless of the total number of samples, with the acceptable number being 10% of the total samples. These blanks were handled in the same manner as the active samples but were not connected to a pump.

2.5 Sample Analysis and Crystalline Silica Quantification

After each trial, the filter cassettes were carefully sealed and transported to a laboratory for gravimetric and compositional analysis. For gravimetric analysis, each filter was conditioned in a humidity-controlled environment for 24 hours before being weighed using a microbalance with a precision of 0.001 mg. The total mass of dust collected was determined by subtracting the pre-weight of the filter from its post-weight.

For XRD composition testing, the crystalline silica content of the respirable dust samples was determined using XRD, a highly flexible method that provides both chemical phase and elemental analysis [45]. This technique is also valuable for stress measurements and texture analysis. However, it is important to note that XRD can only be used on samples that are crystalline. The analysis was performed according to a validated standard method, specifically the NIOSH Method NMAM 7500, which is designed for crystalline silica analysis by XRD [46], [47]. The dust from the filters was prepared on silver membrane filters, and the mass of crystalline silica on each filter was quantified by comparing the integrated peak intensities from the dust sample to those of prepared standards. Fig. 3 shows how the XRD machine works.

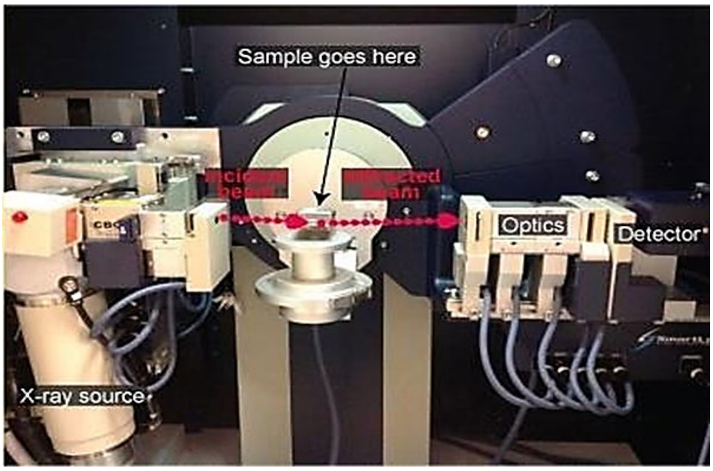

Fig. 2 *XRD machine*

2.6 Data Analysis and Results Calculation

The final results were calculated based on the collected data to determine the concentration of both total and respirable crystalline silica dust. According to NIOSH methods, the total amount of dust to which a worker is exposed is determined by the following non-specific method, which accounts for background contamination from the blank samples:

$$C = \frac{(W_2 - W_1) - (B_2 - B_1)}{V} \times 10^3 mg/m^3 \quad (1)$$

where:

- C: Concentration of the sample in mg/m3
- W1: Weight of the capsule before sampling (mg)
- W2: Weight of the capsule after sampling (mg)
- B1: Weight of the blank capsule before sampling (mg)
- B2: Weight of the blank capsule after sampling (mg)
- V: Volume of air sampled in litres (V = flow rate × sampling duration)

The results from the three blasting conditions (dry, wet, and emulsion) were then compared using appropriate statistical methods, such as a one-way ANOVA, to determine if there were statistically significant differences in dust and crystalline silica suppression.

3. Results and Discussion

This section presents the findings from the Dust Exposure Monitoring, which involved the collection, measurement, and analysis of both total inhalable and respirable dust. To ensure statistical robustness, the study employed both personnel and area monitoring methodologies, collecting eight samples for each tested condition: dry abrasive blasting and RBD palm oil-in-water emulsion abrasive blasting. The Time-Weighted Average (TWA) was calculated over an 8-hour period using standard exposure calculation methods as outlined by NIOSH.

The collected data from the abrasive blasting trials were analysed to compare dust exposure levels against established regulatory limits. Figs. 4 to 7 present comparative data for inhalable and respirable dust from both dry and emulsion blasting, contrasted with the Permissible Exposure Limit (PEL) and the Maximum Exposure Limit (MEL). A significant reduction in dust exposure was observed when the RBD palm oil-in-water emulsion was employed. The inhalable dust values for dry abrasive blasting were substantially higher than those for the emulsion-based methods, with the initial dry abrasive blasting sample recording a TWA of 631.9304 mg/m^3, the highest value among all conditions. Similarly, an analysis of the respirable dust data (Fig. 4) indicated a considerably higher TWA value for dry abrasive blasting compared to the emulsion-based blasting. The dry abrasive blasting condition (100:0 ratio) had the second-highest TWA value, exceeded only by the dry abrasive blasting TWA. The emulsion with the 95:5 ratio demonstrated a TWA value nearest to the PEL. The second sample from the 95:5 ratio emulsion recorded the lowest TWA value of 19.5659 mg/m^3, indicating superior dust suppression performance.

Fig. 5 illustrates the inhalable dust concentrations for both dry abrasive blasting and RBD palm oil-in-water emulsion blasting with MEL, enabling a clear visual comparison of exposure levels. Each data point represents the Time-Weighted Average (TWA) value for a specific sample and emulsion ratio. Among all conditions, dry blasting recorded the highest mean inhalable dust level at 1476.42 mg/m^3, significantly exceeding those observed with emulsions. The average concentrations decreased progressively with higher oil content: 505.60 mg/m^3 for the 99:1 ratio, 391.93 mg/m^3 for 98:2, 343.75 mg/m^3 for 97:3, 301.58 mg/m^3 for 96:4, and the lowest value of 200.55 mg/m^3 for the 95:5 ratios. The distribution of points highlights a clear downward trend in inhalable dust exposure with increasing oil proportion, though overall values still remain above established occupational safety thresholds.

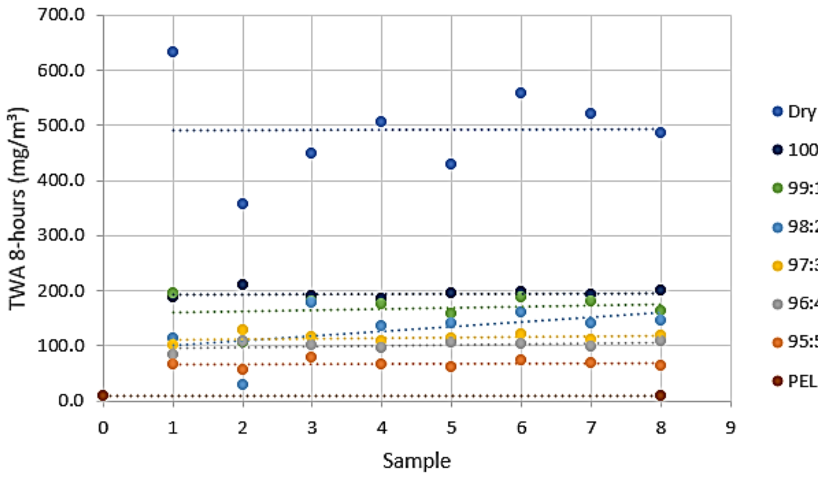

Fig. 4 *Comparison PEL for inhalable dust between RBD palm oil-in-water emulsion*

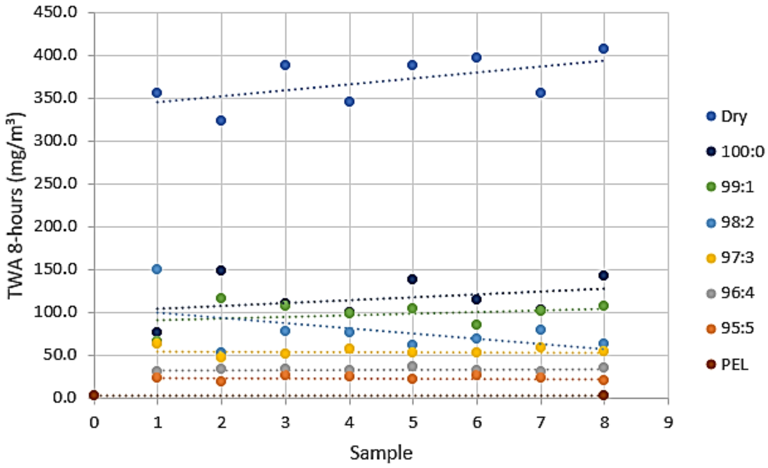

Fig. 5 *Comparison PEL for respirable dust between RBD palm oil-in-water emulsion*

Fig. 6 shows the respirable graph for dry abrasive blasting and RBD palm oil-in-water emulsion abrasive blasting with MEL. The lowest value mean was 550.8942 mg/m^3 at an emulsion ratio of 95:5. The average values were 2347.1334 mg/m^3 at a ratio of 99:1, 1887.2289 mg/m^3 at a ratio of 98:2, 1296.0904 mg/m^3 at a ratio of 97:3, and 798.1866 mg/m^3 at a ratio of 96:4. The trend graph indicates that an increased RBD palm oil concentration in the oil-in-water emulsion correlates with a reduced dust content during blasting operations.

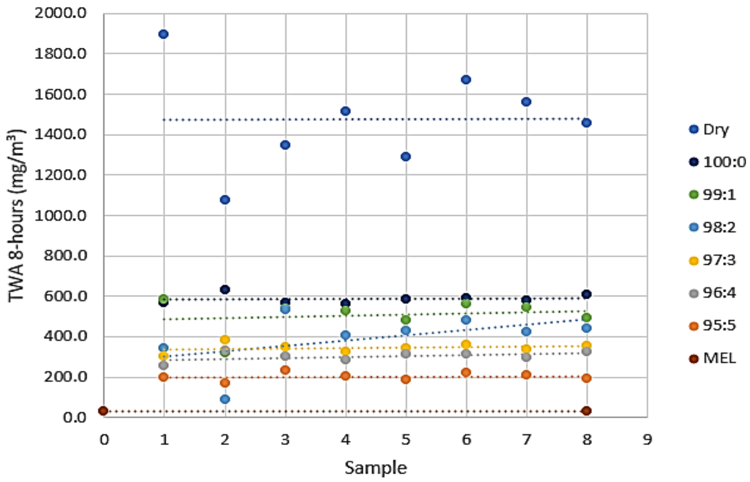

Fig. 6 *Comparison MEL for inhalable dust between RBD palm oil-in-water emulsion*

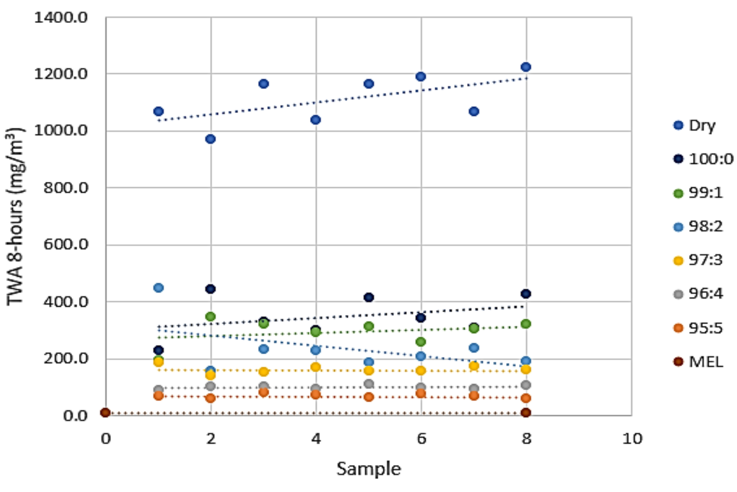

Fig. 7 *Comparison MEL for respirable dust between RBD palm oil-in-water emulsion*

Furthermore, environmental dust monitoring, also known as area monitoring, confirmed these findings. Fig. 8 and Fig. 9 illustrate the data for inhalable and respirable dust, respectively, where the dry abrasive blasting process yielded the highest TWA 8-hour value for inhalable dust, at 107.96 mg/m^3, and for respirable dust, at 99.1285 mg/m^3. A clear trend of decreasing TWA 8-hour values was observed with increasing RBD palm oil ratios in the emulsion. The lowest values were recorded for the 95:5 oil-to-water ratio (11.2290 mg/m^3 for inhalable dust and 17.480 mg/m^3 for respirable dust).

The use of garnet as an abrasive media, which is primarily composed of silicon dioxide (SiO_2), means that the dust produced is heavily influenced by this material's composition. XRD was employed to determine the chemical composition of the dust samples and to compare analytical results with the manufacturer's Safety Data Sheet (SDS) and relevant regulations. XRD scans were performed on samples from both the dry abrasive blasting and RBD palm oil-in-water emulsion processes across all tested ratios (95:5, 96:4, 97:3, 98:2, 99:1). Variations in the percentages of tridymite, cristobalite, and quartz revealed significant changes in the crystalline structure of the dust. To enhance the accuracy of the results, XRD analysis was conducted at five different angles. This multi-angle approach provides more detailed information about the samples, improving phase identification and quantification and effectively differentiating among various crystalline polymorphs such as quartz, cristobalite, and tridymite. This comprehensive analysis of the structural properties, phase composition, and potential health effects of crystalline silica dust is essential for evaluating health risks and ensuring compliance with regulatory standards.

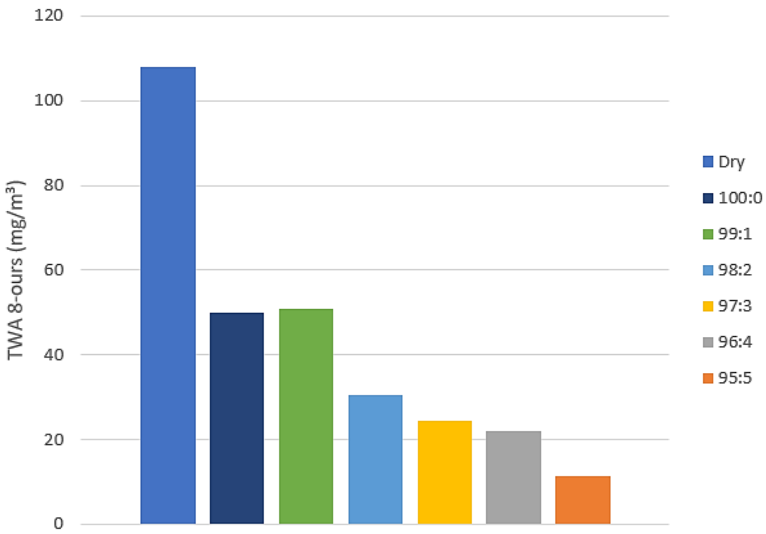

Fig. 8 *Comparison area monitoring for inhalable dust between RBD palm oil-in-water emulsion*

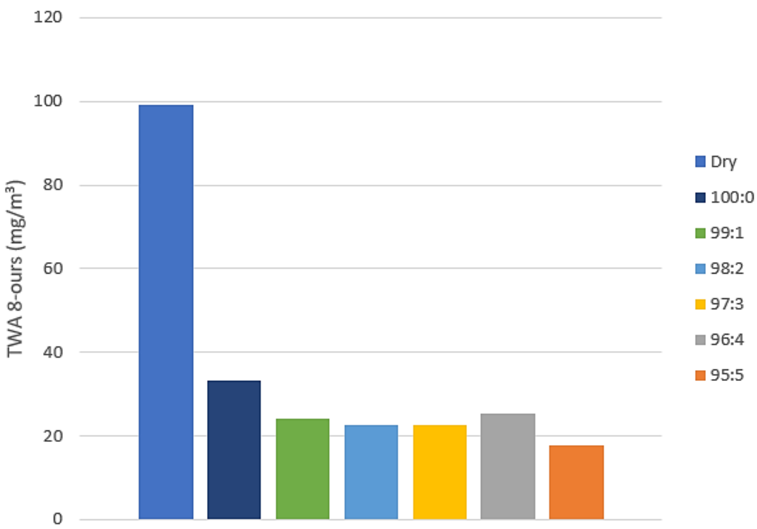

Fig. 9 *Comparison area monitoring for respirable dust between RBD palm oil-in-water emulsion*

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The XRD analysis was instrumental in identifying and quantifying the amount of silica in the dust samples. Fig. 10 presents the percentage of crystalline silica found in samples from both the dry and emulsion blasting processes. Although crystalline dust itself may not be a direct carcinogen, the type and shape of the crystalline particles can be highly hazardous, with effects on human health similar to those of crystalline silica. Chronic inhalation of crystalline silica dust is known to cause pulmonary inflammation and the development of fibrosis, as documented in both animal studies and observations on exposed humans. Most research indicates that inhaling respirable crystalline silica (RCS) can lead to serious health conditions, including silicosis, lung cancer, autoimmune disorders, kidney disease, and an increased risk of tuberculosis.

The experimental results demonstrate significant improvements in dust suppression and occupational health risk reduction when using RBD palm oil-in-water emulsions in abrasive blasting compared to conventional dry blasting methods. Area and personal dust monitoring, conducted using NIOSH methods 0500 and 0600, consistently revealed substantial reductions in inhalable and respirable dust concentrations with increasing proportions of RBD palm oil. The 95:5 water-to-oil ratio proved optimal, yielding the lowest dust levels—approximately 86% reduction in inhalable dust and 75% in respirable dust—effectively bringing exposures within Malaysian USECHH regulatory limits. This finding extends earlier work by Intan et al. [48], who reported a 30% reduction using biodegradable oil emulsions, suggesting that the optimized formulation and specific use of RBD palm oil enhanced dust suppression efficiency due to its stability, local abundance, and environmental compatibility.

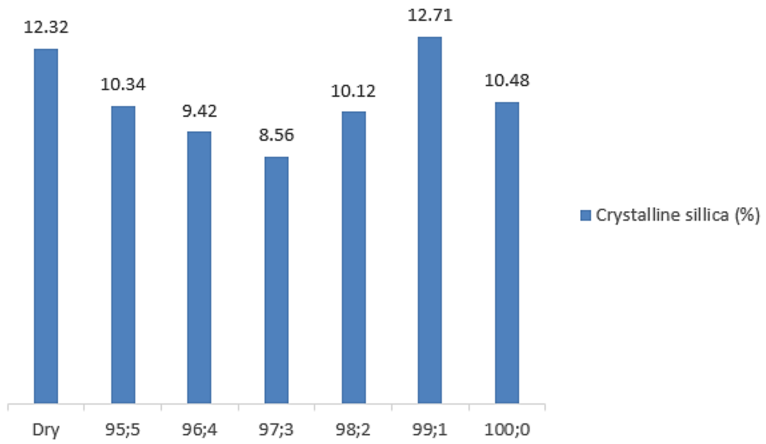

Fig. 10 *Percentage of crystalline silica for dry and RBD palm oil-in-water emulsion*

A critical occupational concern in abrasive blasting is exposure to crystalline silica, the principal cause of silicosis and other respiratory diseases. XRD analysis confirmed that RBD palm oil-in-water emulsions not only reduced overall dust emissions but also significantly lowered respirable crystalline silica concentrations. Compared to dry blasting, which produced intense quartz, tridymite, and cristobalite peaks, the oil-in-water emulsion did not show a consistent reduction in quartz or tridymite concentrations, with results fluctuating for all emulsions ratio. While conventional wet blasting effectively suppresses dust, it does not reliably decrease crystalline silica content and can lead to flash rusting. Nevertheless, RBD palm oil emulsions offer a greener alternative, providing simultaneous dust control and potential mitigation of crystalline silica exposure. This study demonstrated that an oil-to-water ratio of 95:5 resulted in the greatest observed enhancement in dust suppression. Literature indicates the higher oil content in an oil-to-water ratio results in minimal further dust suppression while potentially causing operational issues. These observations align with the findings of Han et al. [49] and Ashwini et al. [50], who also reported that higher oil contents offered minimal benefits while introducing environmental concerns when chemical corrosion inhibitors were employed. The present study, however, demonstrates that RBD palm oil avoids such drawbacks, maintaining ecological safety without compromising performance.

Collectively, these results confirm that RBD palm oil-in-water emulsions not only suppress inhalable and respirable dust but also reduce the crystalline silica content of airborne particulates. By empirically identifying 95:5 as the optimal ratio, this study advances prior research and provides practical evidence that sustainable, biodegradable, and non-toxic palm oil emulsions represent a viable alternative to conventional abrasive blasting methods. Beyond dust control, their ecological advantages further strengthen their potential for safer, more environmentally responsible industrial practices.

4. Conclusions and Future Recommendation

The experimental results of this study clearly demonstrate significant improvements in dust suppression and occupational health risk reduction when using RBD palm oil-in-water emulsions in abrasive blasting, compared to conventional dry blasting methods. The total dust concentration measured by area monitoring showed a clear and consistent decline with increasing proportions of RBD palm oil in the emulsions. The 95:5 water-to-oil ratio proved to be the most effective formulation, yielding the lowest inhalable and respirable dust values and reducing dust concentrations by approximately 80-86% and 75%, respectively, compared to dry blasting. Furthermore, XRD analysis showed markedly lower intensities of quartz, tridymite, and cristobalite peaks in dust samples collected during RBD emulsion blasting versus dry blasting. This result not only indicates less overall dust emission but also a compositional shift in the particulate matter towards less harmful forms. Unlike typical wet blasting, which can cause flash rusting, RBD palm oil-in-water emulsions offer a greener, more effective alternative for dust control. The substantial reductions in dust and crystalline silica exposure achieved suggest that RBD palm oil-in-water emulsions with the optimised ratio can effectively reduce occupational health risks, bringing airborne dust concentrations within regulatory limits and enhancing worker safety. Additionally, the biodegradable and non-toxic nature of RBD palm oil offers ecological advantages over synthetic oils and chemical suppressants, reducing environmental impacts associated with conventional abrasive blasting processes.

For future research, it is recommended to test other abrasive media such as aluminium oxide, silicon carbide or steel shot to evaluate the generalizability of the findings beyond garnet. Additionally, exploring a broader range of water-to-oil ratios and different emulsifying agents may help identify formulations that further improve dust suppression performance. Furthermore, conducting field-scale trials is essential to assess the effectiveness and practicality of the RBD palm oil-in-water emulsion under diverse environmental and industrial conditions, thereby validating its suitability for real-world applications. It also recommended that future studies examine the effect of residual oil films on the steel substrate and their potential impact on the adhesion performance of subsequent coating layers.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Authors' contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Hanis Zakaria, Muhammad Ikhwanuddin K. Samsudin, Muhammad Firdaus Abdul Rahman, Mohd Azham Azmi*; ***data collection:*** *Hanis Zakaria, Muhammad Ikhwanuddin K. Samsudin, Suhaimi Hassan*; ***analysis and interpretation of results:*** *Hanis Zakaria, Muhammad Ikhwanuddin K. Samsudin, Muhammad Firdaus Abdul Rahman, Noorul Azreen Azis*; ***draft manuscript preparation:*** *Hanis Zakaria. All authors reviewed the results and approved the final version of the manuscript.*

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