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<http://dx.doi.org/10.1002/pts.2294>

PUBLISHER

© Wiley

VERSION

AM (Accepted Manuscript)

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Torres, Carmen, and Nikolaos Balodimos. 2019. "Effective and Eco-friendly Lubrication Protocol Using Nanodiamonds in a Dry Regime for Conveyor Systems in the Beverage Industry". figshare.
<https://hdl.handle.net/2134/24298>.

Effective and eco-friendly lubrication protocol using nanodiamonds in a dry regime for conveyor systems in the beverage industry

Abstract

Conveyor belts play an important role in the production process. Their efficiency and lifespan are strongly influenced by the use of appropriate lubrication systems, cleaning procedures and operator handling. Overuse of chemicals and detergents can result in belt degradation and corrosion. Excessive friction between the packages and the load bearing surface of the conveyors (e.g. belts or chains) can wear the packaging, delay start-ups and increase product waste. A suitably lubricated conveyor system increases longevity and promotes operational reliability. However this has traditionally been achieved by using large amounts of water and harsh detergents. The solution proposed in this study comprises the formulation of a nanodiamond particle-loaded food-grade lubricating oil, a nanolubricant, for use on packaging transport and conveyor systems. Deployed in a 'dry' regime, the nanolubricant is hydrophobic, its viscosity is suitable to be sprayed and a long shelf-life ensures stable dispersions. Tribological performance on HDPE conveyor belts transporting aseptic carton packs was studied. When using the nanolubricant, wearing on the packages was reduced 60% compared to no-lubricating conditions and 17% lower than current commercial solutions used for benchmarking purposes. The preparation of the nanolubricant using sonication technology presents efficiencies and carbon footprint reductions derived from lower energy consumption in the production process. This nanolubricant is an environmentally friendly solution for the maintenance of machinery for packaging and transporting and a novel mechanism to curb product returns due to aesthetic and structural damages on the packaging.

Keywords - beverage conveyor system, lubrication, machinery maintenance, nanodiamond, environmental, food and drink

1. Introduction

Cans, aseptic carton packs (e.g. Tetra Pak[®] and SIG Combibloc packages), plastic and glass bottles and jars are often processed on mechanized conveyor systems which are lubricated to reduce friction between the packaging and the load bearing surface of the conveyor. Filling, capping, labelling, sealing, packing and discharge stations on beverage processing lines, helical conveyor tracks (i.e. lifting between levels) and buffering tracks that regulate flow of packages are areas in the factory where in occasions these containers remain unintentionally stationary for long periods of time due to start/stop occurrences in preceding or subsequent stations.

Belts and chains move linearly underneath these packages potentially producing damages (e.g. scaring, scratches, scuffing, peeling off) to the packages which result in production loss and waste. Milk, sauces and soft drinks cartons, fizzy drinks cans and alcohol and spirits bottles compete in the very crowded market of fast moving consumer goods and any defect on the packaging or label is perceived as detrimental to the brand [1]. In order to avoid undesirable flaws caused by the transport in the filling/packaging lines, lubrication solutions are applied.

2. State of the technology: Lubrication systems in the packaging industry

Both solid and liquid lubrication approaches are currently in practice in the food processing, beverage, brewing and distilling industries and have been classified in Table 2. The former include the so-called 'running dry', i.e. low friction coated and/or polymeric materials for the conveyor surfaces [2], and solid particles (e.g. graphite, PTFE and metal dichalcogenides [3] (i.e. MX_2 , where M is, for instance, molybdenum (Mo) or tungsten (W) and X is sulphur (S) or selenium (Se)) scattered or sprayed onto the surfaces subject to friction [4]. The main drawbacks of the 'running-dry' group are the large coefficients of friction, despite the low-friction surfaces compared to lubricated surfaces, which consequently increases energy consumption and carbon footprint, and the presence of the slip-stick phenomenon. These diminish operational reliability in the process line with packages dropping out of the line and the corresponding down time. They are also specific to container-conveyor material pairs rendering them less flexible in their use within the industrial setting. On the other hand, the solid particles require frequent reapplication of the powders to the conveyors. As they tend to stick to the containers, they have to be cleaned regularly. The coating is suitable for heavy load mechanical applications but not considered safe for food contact applications.

The liquid lubricants commonly used on the conveyor systems can be classified into two main groups: 'wet' and 'dry'¹, with an intermediate subgroup known as 'semi-dry' or 'half-wet'. The difference between these groups resides in the quantity and application rate of liquid sprayed, pumped or spread onto the lubricated surfaces. Good lubricity to reduce coefficient of friction and wear, low viscosity which allows easy application (via spraying or pumping), and compatibility with the beverage packaging material are the most sought after specifications in the liquid lubricating system. Compatibility is important because it is not desired that the package suffers damage or cracking in transit or in storage, or solid precipitates form when content and lubricant come into contact in the event of spillage.

(i) Wet regime lubricants: water only or water-soap mixes which contain fatty acids and alpha-olephin sulfonates (of dilution ratios 100-500 parts of water to 1 part of

¹ Industry practice refers to 'dry' regimes and this should not be confused with the 'running dry' condition described above

concentrated lubricant) are typically sprinkled or sprayed onto the conveyor surfaces [5] in a continuous fashion or at least 50% of the operating time (ratio 2:1, not applied:applied). The main drawbacks in using these lubricants are the large amounts of water used, their germ promoting character, and when containing soap, their uncontrolled foaming which derives onto package flow control problems, poor biodegradability (as they contain solvents, EDTA– a metal stabiliser – or other chelating agents to compensate for the hard cations present in water (Ca^{2+} and Mg^{2+}) and avoid their precipitation), pH and temperature-dependant performance [6, 7]. Antimicrobial agents (e.g. amines) added to prevent slime formation has been found to be deactivated by the presence of the fatty acids. The presence of surfactants as thinning ingredients to reduce soap viscosity has been seen to produce further precipitates which results in lubricity reduction [8]. The excess of water makes necessary the use of drip pans and overflow trays to contain spillages which carries the added inconvenience of factory floor safety. Although typically ‘wet’ lubrication is of aqueous nature, oils and greases may also fall within this category if the amounts used for lubrication are such that the surfaces are wetted thoroughly creating elasto-hydrodynamic and full film lubrication systems. Their use is becoming less common in conveyor systems in the beverage and packaging industry given their residues and smearing on containers and labels.

(ii) Dry regime lubricants: aqueous or non-aqueous fluids, oils, oil mixtures and oil-particle emulsions and dispersions typically applied intermittently through dispensing or spraying nozzles without dilution. The dispensing rate can further divide the dry lubricants into ‘semi-dry’ (or ‘half-wet’), when the rate is larger than 2:1 and less than 32:1, or ‘dry’ regime when the application ratio is larger than 32:1 (not applied:applied time)[9]. The ‘dry’ lubricants, because they are more concentrated (typically <50% of dispersant [10]) and because water use is minimal, compensate the drawbacks presented by the ‘wet’ regimes. This application has become very popular in recent years. However, most of the lubricants applied in the ‘dry’ regime still suffer from being specific to each application. For example, silicone-based [10] and fluorine-containing lubricants [11] are good performers with PET bottles (i.e. containers made of ethylene terephthalate homopolymers, copolymers and mixtures) but less effective on glass and metal containers, particularly on a metal surface [10]. Silicone with fatty amines dispersed in a ‘semi-dry’ regime are recommended for glass on stainless-steel [9]. Lubricants that contain amines, alcohols, potassium hydroxide, ammonium salts or mixtures are incompatible with PET containers causing them to crack in transit or storage [12-14]. Polytetrafluoroethylene (PTFE) particles of the micro scale are mixed with mineral oils to be used as lubricants in cartons conveying belts. Applied by brushes and nozzles, PTFE adheres very strongly to the chains and this soiling curb the performance profile of the lubricant gradually [15]. In addition, PTFE has also been shown to produce stress-cracking in PET bottles [11].

2.1 Nanoparticle-containing lubricants

In the most recent years the nanoparticle-containing suspensions have surged as promising lubricants. Although the majority of examples are oil-based, there are also examples of water-based lubricants [16]. The nanometre scale of the particles improves solubility into the oils, compared to the micro scales [17]. The lubrication mechanism promoted by nanoparticles is a physical effect [36]. The nanoparticles act as spacers and produce ball [37] and sliding effects [38] via mechanical entrapment of the particles between the rubbing surfaces (e.g. through exfoliation and third body transfers [39]).

Nanodiamond is a nanoparticle already reported for its lubrication properties which shows a promising future as a lubricant component for the food technology. Its carbon chemistry biodegradability, non-toxicity [44], bearing-like shape promoting rolling as lubrication mechanism [45], solubility in both mineral oil and others ([31, 46] and feasible production into de-agglomerated [47, 48] and stable dispersions [49] (via the detonation method [50-53]) makes it a suitable candidate for formulations designed for the use in the mechanical services in the food factory and for the occasional contact with food materials and containers (namely H1 USDA approved).

In the present study we focused on the development of a new lubrication solution which surmounts the disadvantages of the current lubrication approaches with the following specifications: (1) liquid lubrication in the 'dry' regime, therefore the use of lubricant is minimal but effective, stirring away from the many disadvantages of the 'wet' lubrication regimes **and offering an eco-friendly alternative**; (2) nanoparticles were used as lubricating agents, given the environmental advantages derived from its chemistry; and (3) the production process of the nanolubricant was energy- and cost-efficient, when compared to traditional methods. The following sections of this paper introduce the formulation of the nanodiamond particle-loaded food grade oil, the nanolubricant, its characterisation and testing. Its tribological performance on aseptic carton packs travelling on a HDPE conveyor belt is reported. Carton packs were selected as being largely present in conveyor lines around the world. A commercial lubricant was used as a benchmark. Industrial scale container transport equipment and typical working conditions were chosen to simulate a realistic factory setting. The last section is dedicated to the novel production methodology devised for the nanolubricant, along with its ageing and stability studies before conclusions are drawn.

3. Experimental

3.1 Materials

The nanodiamond particles used in this study were purchased from Adámas Nanotechnologies (USA). The nanoparticles were synthesised by the detonation method [52] and then aggregated to a range of 10-30nm (noted in this study as slurry '30') and <5nm (noted as slurry '5'). The nanodiamonds were supplied as a

slurry containing also additives (molybdenum di(2-ethylhexyl) phosphoridithioate [54] and a fluorinated stabiliser [55] in proportions proprietary to the company. A commercial oil (Kristol M24, a white mineral oil (Petrochem Carless Ltd, United Kingdom) was used as the base oils without further treatment. Nanolubricant samples were prepared by dispersing 0.01%wt ratio of nanodiamonds in the base oil. This concentration was informed by previous studies [54].

3.2 Materials Characterisation

The nanoparticle population in the slurry was characterized using a Nanosight LM-10 instrument (Malvern Instruments Ltd, UK) and its stability (i.e. zeta-potential and conductivity) measured using a Zetasizer Nano ZS (Malvern, UK). The zeta-potential is a measure of the surface charge and a large (absolute) value indicates high surface charge, strong particle repulsion and high stability of the nanoparticles in the solution. The zeta-potential resulted in -116mV with a conductivity of 4.12 μ S/cm and electrophoretic mobility of -6.83e-3 μ m.cm/Vs, values that confirmed full stability of the dispersions. The properties of the oil are listed in Table 1. The rheological characteristics of the nanolubricants were measured using a Brookfield Rheometer DV-II+ Pro with a RV-1 spindle at a spindle speed of 60rpm. The dynamic viscosity (in cP) of the nanolubricants could be fitted to linear relationships against the temperature (in °C) of the form $y=48.317-0.415.x$. The measurements within the range [20-100°C] yielded a linear relationship between the dynamic viscosity and the temperature. The size of the nanoparticles did not affect these coefficients. This viscosity value was within the range of ISO VG32 (typical industrial application oil) and appropriate for the lubricant to be applied by spraying in a dry lubrication regime maintaining in this way a high degree of system cleanliness in application below and above the conveyor line.

3.3 Study of the tribological performance on the conveyor belts

3.3.1 Methodology

A high density polyethylene (HDPE) industrial-sized conveyor was used for testing friction and wearing (or scuffing) on the bottom of aseptic cartons typically found in the packaging and filling food industries (mass 1.088kg, contact area onto belt 72.60mm x 70.60mm). The belt travelled at a speed of 20m/min and the tests were run for 60min (Figure 1). This timeframe corresponds to a long term residence time typically observed in industrial settings with abrupt flows which originates the larger incidence of package damage and customer complaint. K-type thermocouples were fitted to the carton/conveyor interface for monitoring purposes. A set of tests was run without any lubrication (labelled as 'blank'). When lubricants were present, these were sprayed onto the conveyor belts in 'dry-regime' conditions (i.e. >32:1) on top of the chain (comprising 50%vol of the amount) and on the wear strips (comprising 25%vol each) for a total amount of 8ml consumed during 60min. The lubricants tested were nanolubricants comprising the dispersion of nanodiamonds in the

mineral oil: 30nm ('Min30') and 5nm ('Min5'). Commercial lubricant RM2000T was also tested for benchmarking purposes. RM2000T is a PTFE-based food grade lubricant with a suspension in mineral oil of particles in the micro scale which has been in the market since 1999 and it is broadly used in bottling and Tetra-PakTM filling lines. As a comparison, the tribological properties of the base oil without carrying the nanodiamonds or additives, in their pure form, were also evaluated (labelled 'Min').

The friction force was measured by means of the sliding force of the conveyor when the packages were under motion-restricted mode. A digital force gauge (Mecmesin Ltd, UK) collected sliding forces at a 10Hz sampling rate as shown in Figure 1. This allowed the calculation of the coefficient of friction (COF) using equation (1), with force F being the load (N) registered by the force gauge, ' i ' the number of packs, g the gravitational constant (m/s^2) and mass m the average value (kg) of the packs used in each run.

$$COF = \frac{F}{i \cdot g \cdot m} \quad (1)$$

The wear scar surfaces on the bottom of the packages were inspected by high resolution scanning (2400dpi) on and EPSON Perfection Scanner 1640SU (Figure 2) and the results analysed with ImageJ (W. Rasband, 1997, National Institutes of Health, USA), a java-based open-source software for image processing and analysis. Statistical analysis: COF tests were obtained from 5 different experiments. Wear tests were conducted on 6 specimens per test. Both are expressed as means $\pm$ standard deviation (SD). Differences amongst the groups were analysed by the t-test for paired samples for means and hypothesised a normal distribution. A p-value of ≤ 0.05 was considered to indicate statistically significant differences.

3.3.2 Results

The coefficient of friction (COF) for each of the packages as a function of time for each of the lubricating fluids including the 'blank' is plotted in Figure 3. Temperature was monitored throughout the tests with no significant changes (data not shown). The results of the measurements for the COF and the wear scar area are summarised in Figure 4 and Table 3. Results from the t-test that hypothesised a paired relationship between the COF and the wear scar results yielded a Pearson coefficient of 0.935 and a p-value 0.05, which confirms the correlation within the limits for a confident statistical significance. As it can be seen in Figure 3, maximum COF values (0.269-0.221) were reached when there was no lubricating fluid present (i.e., in 'blank' conditions). In the presence of lubrication, COF values were reduced generally for all the lubricating fluids, as per Table 3.

3.3.3 Discussion

Aseptic cartons (Figure 3) presented an increasing COF value with time for all the lubricants which is typical when the boundary layer is the dominant regime of lubrications (i.e. the lubricating fluid film thickness is small and asperities from rubbing surfaces come into contact and wear is high). It remained stable throughout the duration of the friction test in all cases. In the 'running-dry', non-lubricant conditions ('blank') there was an initial drop in the COF (0-15min) and this is attributed to a 'waxification' (i.e. third body transfer – plastic film particles- from the package onto the transporting belt and or the lubricant) of the conveyor, since there was material removed from the cartons (Figure 2). In the presence of mineral oil and 30nm-loaded mineral oil the COF reached a plateau at approx. 10mins (Mineral) and 15mins (Min30) indicating a stable boundary layer regime of lubrication, although the COFs for the nanodiamond-loaded oil is 19% smaller compared to the base oil. This observation reinforces the hypothesis of the 'ball-bearing' effect produced by the nanoparticles that ease the travel of the packages over the conveyor, in that way protecting from solid-to-solid abrasion (Figure 5a). This plateau was not reached with the RM2000T or the 5nm-loaded mineral oil which presented an ascending trend for the COF throughout the length of the test. This indicates that in the presence of these two lubricating fluids, there was no self-organisation of the particles which did not agglomerate further to create a local ball-bearing effect on the lubricating regime. The micro-scale particles present in RM2000T were too large to maintain a stable self-organisation that contributed to forming an effective lubricating layer (Figure 5b). The comparison between 5nm and 30nm suggests that the former are too little particles which do not form agglomerates large enough to create a boundary layer (Figure 5c). An episode of rupture in the sliding layer can be observed in the experimental results and it is indicated with a blue arrow in Figure 3.

The results obtained from the mineral oil used as a lubricant present a lower COF value with respect to the 'blank' conditions. However, the wear scar area is the largest of all cases, including when no lubricating fluid was present. The bottoms of the cartons were seen to soak in the oil through the torn outer plastic layer into the deeper layers, affecting the aesthetics of the packaging. The red arrow in Figure 3 shows an event of sudden increase for the COF which is suspected to have provoked the further tearing on the bottom of the package. Therefore, it can be concluded that beyond a value of $\text{COF} > 0.121$, the packaging gets damaged substantially. The COF values for the other lubricating fluids were below this level and therefore the oil soaking phenomenon was not present.

3.4 Study on the stability of the dispersion comparing production methods

3.4.1 Methodology

Two methods were devised to prepare the nanolubricants (i.e. the nanodiamonds-loaded lubricating oil): (i) mixing: the particles were mixed into the oil and stirred continuously for 5min at 65°C; (ii) sonication: the particles suspended in an equal quantity of oil were subjected to an ultrasonic sonication regime of 170µm peak to peak for a duration in the range of 5 to 15s or until the suspension was transparent. Temperature was controlled so it would not exceed 65°C. The slurry chosen for this work was the <30nm particle size. Nanodiamond dispersions were prepared by both the mixing and the ultrasonic sonication methods. The power consumption in each operation was measured with a domestic energy monitor (Eco-eye real-time electricity monitor, UK). The dispersions were aged (i.e. fluid stored stationary) for an excess of 17 weeks (120days). The stability of the suspensions prepared (particle size population distribution on fresh and aged dispersions) was monitored both visually and also using the Malvern Nanosight LM-10 instrument to capture 5x60s videos at 30fps per sample.

3.4.2 Results

Visual monitoring on the samples confirmed clear and transparent nanolubricants during the aging process without sedimentation of nanodiamond aggregates. To confirm the absence of agglomerated nanoparticles, particle size measurement and analysis were carried out on recently prepared samples (labelled as 'fresh') and on stored samples (120+days, labelled 'aged'). The results are presented in Figure 6. Power consumption values in the sonication process were 3% of those in the mixing process for an equal amount of oil treated.

3.4.3 Discussion

From a shelf-life viewpoint aging did not seem to have a significant impact and all suspensions remained stable and deagglomerated (agglomerates size <30nm) after 120+ days. With regards to both production methods, the sonication showed to create dispersions of a smaller mean agglomerate size when compared to the mixing. The dispersion of the aged sonicated samples presented more variation and a wider particle size distribution bell compared to the mixing. However, the efficacy of the sonication method versus the mixing is demonstrated because of the advantage of a short and cold process versus the traditional slow mixing. The savings in power consumption were largely derived from the fact that the oil was not heated in the sonication process. The heating operation was typically an order of magnitude larger than the mixing alone.

4. Conclusions

Safeguarding the integrity of packages when these are travelling long distances on belts or when they suffer unexpected stops in filling/packing stations is crucial to prevent product returns and loss of consumer confidence. Appropriate lubrication of

the food-processing conveyance system is important as well as considering environmental factors in the operation and maintenance of the transport machinery. In this study the formulation, testing and shelf-life characterisation of a nanolubricant prepared with nanodiamonds dispersed in commercial mineral oil was studied. Its 'dry' regime application and non-aqueous nature presents advantages when compared with traditional wet, water-based, bacterial-growth prone approaches to lubrication. Tribological performance of the nanolubricant has been assessed on a factory-sized set-up using commonly used aseptic carton packs as the packages travelling on the conveyor system. Friction and wear tests under load conditions were conducted. The nanolubricants present a good behaviour with respect to non-lubricated conditions and other commercial lubricants currently used in the food and drink industry. It is suggested that the nano-sized particles promote an effective 'ball-bearing' effect between the surfaces in contact (e.g. the surface between the chain and the package). The nanolubricant prevents from reaching large values of coefficient of friction and therefore extensive wearing. The main advantage in the use of the nanolubricant is to avoid the tearing of the package walls and prevent the 'soaking in' of the lubricant onto the deeper layers of the carton packs. This phenomenon is particularly poignant if the content is of a high pressure vapour nature (e.g. alcohol) since this event can precipitate structural damage of the package due to extensive wicking and soaking of the package multi-layered walls. The predominant regime of lubrication was boundary film and the solid-solid friction mechanisms observed were plastic deformation and adhesion bond/third body transfer. Further environmental benefits arise from the novel preparation protocol for the dispersions. The sonication method (fast and with no need of heat treatment) delivered stable suspensions in the shelf-life studies.

This work has shown how to produce stable and long shelf-life suspensions of nanodiamonds in a food-grade lubricating oil for the direct application onto typical conveyor systems in a packaging factory. The results from this study are useful to packaging industry managers and operators because they show the advantages of using a nanolubricant deployed in a 'dry' regime fashion, an environmentally friendly solution with no water wasted and no harmful soapy and solvent effluents onto the industrial sewage system which also reduces stock costs. In addition to this, an additional recommendation is to explore the application of lubrication products that contain nanodiamonds due to their effective performance and biodegradability. Future work will address the tribological studies of this newly formulated nanolubricant on other conveyor systems and packages such as cans, plastic and glass bottles to assess full compatibility amongst all constituents of the conveying system.

Acknowledgements

The authors are grateful to Innovate UK for their grant KTP9434 which has supported this work. Mr Charles Brunton and his team at Specialist Lubricants Ltd have been instrumental in carrying out the tests conducted on the conveyor belts.

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Tables:

Table 1: Rheological properties of the base oil

Mineral oil	
Commercial name	Kristol M24
Kinematic viscosity (mm²/s) 40°C	36.0
Pour point (°C)	-6
Flash point (°C)	180
Specific gravity (at 15°C)	0.859
pH	6.5
Colour /Odour	Colourless / Odourless

Table 2: Industrial lubrication regimes

Method	Type	Application regime	Agent	Dispersant or carrier and dispersion ratio (carrier:agent)
Solid	'running dry'	None, it relies on friction properties of materials in contact	none	none
	Solid particles	Requires frequent reapplication	Macrosized solid particles	None
Liquid	Wet	Continuous or at least 50% of the time, i.e. <2:1	Soap compounds	Water (typically) largely diluted [100-500]:1
	Semi-dry (or half wet)	32:1>x>2:1	Micro or nanosized particles	Water or oil, heavily concentrated (≤2:1)
	Dry	>32:1	Micro or nanosized particles	Water or oil , heavily concentrated or no dilution (≤2:1)

Table 3: Coefficient of friction and wear scar area values for the aseptic carton packages when using the lubricating fluids on the conveyors

	COF(SD) (Δ%)	Wear, cm ² (SD) (Δ%)
Blank	0.231(0.003) (-)	0.55(0.08) (-)
RM2000T	0.113(0.003)	0.31(0.11)

	(-51%)	(-43%)
Min	0.149(0.003)	0.72(0.13)
	(-36%)	(31%)
Min30	0.121(0.002)	0.22(0.08)
	(-48%)	(-60%)
Min5	0.114(0.003)	0.26(0.05)
	(-51%)	(-52%)

*note: Coefficient of friction (COF) and Wear Scar area are averaged values with a standard deviation (std). $\Delta\%$ is the percentage of reduction (negative scalar) or increment (positive scalar) with respect to the blank tests with no lubricating fluid

Figures:

Figure 1: Experimental set up for the conveyor belt

Figure 2: Representative scars and scuffing on packages used on the conveyors

Figure 3: COF values for cartons on the conveyor system. The blue arrow represents an episode of rupture in the sliding layer and the red arrow the indication of further tearing.

Figure 4: COF and Wear Scar area summary per lubricant type for the aseptic carton packs. Table 3 presents details in full

Figure 5: Schematic of nanoparticle size affecting the 'ball bearing' lubrication effect

Figure 6: Results from particle analysis. Samples prepared with mineral base oil, a) Fresh by mixing, b) Fresh by sonication, c) Aged by mixing, d) Aged by sonication