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Oil and Gas Well Brines for Dust Control on Unpaved Roads – Part 1: Ineffectiveness

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Abstract

Natural gas and oil drilling have expanded rapidly in the U.S in recent years. The volume of various associated waste products has been increasing. One such waste product is the typically saline water produced from the wells along with the hydrocarbons. A variety of methods are currently being employed to dispose of this oil and gas well brine (OGB). One such practice is spreading OGB on unpaved roads for dust control and road stabilization. This investigation focused on the likely effectiveness and anticipatable risks of spreading OGB on unpaved roads. Despite decades of regulated use of OGB for dust control, there appears to be a complete lack of data indicating the practice is effective. Analysis of regulations, related literature, and original data indicated spreading OGB on unpaved roads is ineffective and likely counterproductive for dust control and road stabilization as reported here in Part 1, and presents numerous potential and immediate environmental, health and economic risks as reported in Part 2 (publication pending).

Keywords: Oilfield brine, produced water, dust suppression, dust control, road stabilization, unpaved roads, oil and gas wastewater disposal

Introduction

1. Oil and gas well brine and its disposal

It is not common knowledge that oil and gas wells typically produce substantially more water than oil or gas, usually less water earlier, and increasingly more later in the production life of a well (Conselman, 1967; Veil et al., 2004; Morris, 2004). That water must be separated from the hydrocarbon product stream before the product is transported.

Produced water typically has a high salt content, mostly sodium chloride, and is consequently also referred to as oil and gas well brine (OGB).

Once separated, the OGB is a waste. Conventional gas wells produce somewhat less wastewater than conventional oil wells. Horizontal wells typically produce more wastewater per unit of production than vertical wells, and wells stimulated with hydraulic fracturing typically produce more than their conventional counterparts. It has been reported that before 2000, nearly no U.S. oil wells were hydraulically fractured, but 51% of oil produced in the U.S. in 2015 came from hydraulically fractured wells (USEIA, 2016). Consequently, oil and gas well wastewater production will likely increase along with the management challenge it presents.

Numerous practices have been used to manage oil and gas well wastewater (Veil et al., 2004). Among such practices are deep-well injection, evaporation, and various treatment methods followed by recycling for use in oil and gas wells and other industrial processes. One of these, due to the typically elevated salt content, is to apply OGB to paved roads as a winter deicer and to unpaved roads as a summertime dust-control and stabilization agent. Though less important than some other methods of disposal with respect to total amount of wastewater involved, application on roadways is common and locally important in some areas, including at least the states of Michigan, New York, Ohio and Pennsylvania.

2. Studies on the application of OGB to roads

Michigan appears to have the oldest developed documentation of the history and regulation of the spreading of OGB on roads. A thorough report prepared in 1984 by J.E. Herrold of the Michigan Department of Natural Resources (DNR) is among the most informative single documents available on the history, theory, and the limited data on the use of OGB on roads, though it does not address brine impacts on road stability.

Herrold (1984) concluded application of OGB to unpaved roads seems to date back to early development of the oil and gas industry in Michigan. Similarly, the Pennsylvania Department of Environmental Protection (PaDEP) Environmental Quality Board (2016) stated, “Throughout the history of conventional oil and gas development, brine has been beneficially used in dust suppression and road stabilization activities on dirt roads….” Historical data from Michigan show that there was an industrial market for OGB until the early 1950s. When that industrial demand ended, road spreading of OGB increased substantially in Michigan. Due to its high salinity, OGB was applied as a deicer on paved roads and for dust control on unpaved roads, substituted for commercial brine or related dry products.

2.1. Risk to water quality recognized

Despite those practical uses, realistically, road application of OGB was primarily an oil-well waste-disposal practice. In the 1970s, concerns arose in Michigan that widespread abusive spreading of OGB on land, including roads, was occurring and could impact water quality. The Michigan DNR developed rules, issued in 1981, to regulate use of OGB on roads. Herrold (1984) discussed those rules, similar to rules adopted in other states, and how their effectiveness depends on compliance and enforcement, neither of which had been achieved by 1984. Non-compliance and a lack of enforcement, usually due to lack of resources to support enforcement, are still common problems that can result in exploitation of roadways as OGB disposal grounds.

The PaDEP (1996) investigated the potential for water contamination from OGB applications for dust control at seven locations from 1992 to 1995. Based on the findings and recommendations of that investigation, PaDEP lowered its maximum allowable application rate. That PaDEP report contained a brief literature review, which included most of the literature reviewed by the present author. However, the PaDEP review of the literature was neither critical nor thorough, and the report recommended application rates based solely on the subjective opinions of OGB users.

2.2. Limited evidence supporting effectiveness

Herrold (1984) found very limited data on the effectiveness of OGB as a dust-control agent for unpaved roads. Now, over 30 years later, there is still surprisingly little. Herrold (1984) cited a report by Moore and Welch (1977) at the College of Engineering at the University of Arkansas on their brief investigation. Moore and Welch (1977) applied an industrial-waste brine with a composition similar to OGB and concluded the brine did provide dust control for a period of about 30 days when applied at a rate of 0.3 gallons per square yard.

Interestingly, neither the Moore and Welch (1977) application rate of 0.3 gallons per square yard (gal/sq yd) nor schedule (monthly) appeared as part of the Michigan rules for OGB applications to roads for dust control, but are the OGB road-spreading application rate and schedule adopted in several states, including as recently as 2013 by the North Dakota Department of Environmental Quality. It appears that many current guidelines for road spreading of OGB for dust control are based on the single Moore and Welch (1977) study done 40 years ago, which suggests an ongoing need to critically examine that study.

2.3. Moore and Welch: Experimental design and data analysis

The Arkansas State Highway and Transportation Department commissioned the Moore and Welch (1977) study. The report was not found as a peer-reviewed article, raising the possibility that the methods and conclusions were not subjected to external scientific or engineering scrutiny. A closer examination of Moore and Welch (1977) reveals a series of shortcomings, especially with regard to the conclusions drawn.

The field investigation of dust control involved 5 sequential sections of unpaved road, each about 1,000 feet long. For experimental design purposes, each road section may be regarded as the equivalent of an experimental field plot. There were 4 treated plots and one untreated control plot. Plots 1 and 2 ran north-south, 4 and 5 ran more northwest-southeast, and 3 was curved and sloped between the 1-2 and 4-5 sections. The brine application rates (treatments) were not randomized among the plots, running effectively sequentially from low in plots 1 and 2, somewhat higher in 3, highest in 4 and none in 5, the control plot (see table below).

Plot (road section)	Brine application rate (gal/sq yard)
1	0.19
2	0.19
3	0.21
4	0.31
5	0

Over approximately 5,000 running feet of test road, variations could have occurred, and in some cases definitely did occur, in local soil type, slope, distribution of rainfall and direction of wind, aspect and insolation, and potentially other factors that could affect dust release. The experimental design provided no means of accounting for such variations. That such variations did have an effect is suggested by the authors' report of lack of significant difference (t-test 95% confidence level) between the mean dust data for plot 3 (0.21 gal/sq yd) and the no-brine control plot (5), while finding significant differences between the control plot (5) and both the low (plots 1, 2) and high (plot 4) brine levels. The authors speculated that the slope of plot 3 might have caused more rapid washing of brine from plot 3, resulting in earlier loss of dust control, but closer examination of the dust data shows that plot 3 always had the highest dust level among the brined plots. That is, the data indicate there were inherent differences in potential dustiness among the plots.

Given that it is reasonable to expect variations in potential for dust release over 5,000 feet of roadway, and that the data suggest such differences did occur, it follows that responses to wind, weather and solar exposure would differ among the plots on a daily basis. Further, it would be reasonable to expect the variability of the data (e.g., standard deviation) would increase as dust levels increase, i.e., dustier plots would have higher variability, with or without brine treatment. It would, therefore, be more appropriate to compare treatment effects on each sample date instead of mean behavior over the 15 sample dates.

The present author performed such an analysis by examining whether the 95% (t-test) confidence intervals for each of the 4 brined plots (1-4) and the no-brine control plot (5) overlapped on each of the 15 reported sample dates, a total of 60 treatment-vs.-control by-date comparisons. That analysis showed that the confidence intervals overlapped, i.e., there was no significant difference between the treated and untreated road sections for 35 of the 60 by-date differences. Of the 25 by-date differences suggesting a significant effect due to brining, 13 occurred following a rain event, when dust levels for all plots were, or would have been expected to be, low.

Further, of the 25 by-day differences suggesting a significant dust-reducing effect due to brine, 7 occurred for plot 2 (the lowest brine application rate) but only 6 for plot 4 (the highest brine application rate). The only sampling date away from rain events on which all 4 treated plots had significantly lower dust levels than the control plot was the first sampling date, 2 days after the brine application.

It is the present author's opinion that the dust palliation data collected in the Moore and Welch (1977) study, in fact, showed that application of an industrial waste brine similar to OGBs provided little or no dust control, and that the contrary conclusion by Moore and Welch was due to a failure to adequately consider the complexity of factors inherent in their experimental design. This suggests that 40 years of OGB use for dust control has been based on a study the data from which actually indicated the practice provided measurable dust control for not more than three days.

2.4. Moses: more questions than answers

Herrold (1984) also cited a comparative investigation of dust control reported by P.J. Moses (1982) of the Dow Chemical Company. Referring to the Moses study, Herrold (1984) stated that the "…study…found that LIQUIDOW may provide three times better dust suppression than will a typical oil field brine." LIQUIDOW is a liquid calcium chloride product sold by Dow Chemical Company as a dust-control product. In his report, Herrold (1984) pointed out that the maximum calcium content of Michigan oilfield brine (75 g/L) is about 3 times lower than that of LIQUIDOW (195 g/L). The average calcium content of Michigan oilfield brine (28 g/L) is about 7 times lower than that of LIQUIDOW, but also contains 50 g/L sodium.

The present author has been unable to locate a copy of the Moses (1982) study. Consequently, a detailed examination of its methods, data and conclusions could not be developed for this review. The following are among questions of concern for any such studies, which for now must remain unanswered for the Moses (1982) study:

- Where were the test roads, and what were the road characteristics?
- What was the composition (mineralogy, particle size distribution, etc.) of the road material?
- What were weather conditions during the investigation?
- How were dust levels measured?

  - What were the application methods and rates?
  - Was there one application, or multiple?
  - Did application of the brine reduce dust emissions by 1/3 compared to LIQUIDOW at the next dust event, or did it provide similar dust reduction, but for only 1/3 the time that LIQUIDOW reduced dust?

2.5. Russell and Caruso data: Even high-volume applications exceeding most state guidelines show rapid decline in effectiveness

After consideration of Moore and Welch (1977) and what we know of Moses (1982), one is left with a practice that is without verified effectiveness. There was apparently another related investigation. In Cowherd and Kinsey (1986) their "Figure 5-5. TSP [Total suspended particulates] control efficiency decay for light-duty traffic on unpaved roads" plotted data generated by a test of oil-well brine for dust control reported by Russell and Caruso (1982). As of the time of submission of this report, the present author has been unable to locate a copy of the original Russell and Caruso (1982) study. Consequently, Cowherd and Kinsey's Figure 5-5 appears to be the only, albeit secondarily, documented data from an actual test of the use of oil well brine for dust control.

Cowherd and Kinsey (1986) gave a "C" quality rating to the Russell and Caruso (1982) results as data from "Tests that are based on an untested or new methodology or that lack a significant amount of background data." The Cowherd and Kinsey (1986) report focused on methods of designing and estimating effectiveness and costs of particulate emissions control efforts and offered no further interpretation of the Russell and Caruso (1982) oil-well brine dust control data. Nevertheless, it appears that the Russell and Caruso (1982) data as presented by Cowherd and Kinsey (1986) is the only actual measurement data on an actual use of oil well brine for dust control on an unpaved road (see also 2.6 below). Consequently, it is necessary to consider that data more thoroughly.

The dust measurement method, experimental design, weather conditions, and characteristics of the road (or roads) and the oil well brine used by Russell and Caruso (1982) were not documented beyond Cowherd and Kinsey (1986) data quality rating of "C.” Cowherd and Kinsey (1986) report that Russell and Caruso (1982) used an upwind/downwind approach to determine the dust levels for each experimental plot (treatment). Presumably, all treatments were run in a single experimental effort that lasted only 32 days. The average vehicle characteristics for traffic on the road were a total of 4 wheels and gross weight of 6000 pounds. Oil-well brine was initially applied at a very heavy rate of 3.8 gallons per square yard, with a heavy follow-up application of 0.6 gallons per square yard 22 days later.

It is notable that an application rate of 3.8 gal/sq yd is equivalent to a standing layer of brine 0.68 inches deep on the road surface. Assuming a void space volume of 10% in the presumably compacted road material, such an application rate would saturate the road surface soil to a depth of 6.8 inches—an unworkably high moisture content. Alternatively, since a graded and compacted road surface would result in runoff of most of such a heavy brine application, the test road may have been loosened and prepared for a single 3.8 gal/sq yd application and compacted subsequently. However, even if the road material were loosened to an effective pore space of 30%, 3.8 gal/sq yd would still result in saturated conditions to a depth of over 2 inches, which would drain to an unworkably high moisture content to a considerably greater depth. Hence, application to a prepared, graded but un-compacted road surface would likely require the road to be out of service for at least a few days. Consequently, it appears reasonable to assume that the initial brine application was accomplished as a series of lighter applications until the target application rate was reached. Since the follow-up application was 0.6 gal/square yard, it also would appear reasonable to assume that was an application rate that did not result in excessive runoff.

In light of the preceding, the present consideration of the results of Russell and Caruso (1982) assumes an initial application applied in 5 increments of about 0.6 gal/sq yd, because if that were not the case, then the Russell and Caruso (1982) data cannot be considered representative of any reasonable practice. Presumably the entire application could have been completed in 3-5 days. This assumption leaves unclear whether days after initial application were counted from the day of the first or the last incremental application.

Apparently, day 8 after the heavy brine application was the first dust-control sample date. The 3.8 gal/sq yd oil-well brine application resulted in a 91% reduction in dust emissions on days 8 and 18. However, on day 19, the dust control effectiveness dropped slightly to 90%. While this minor decline could have been within measurement method variability, it appears likely that it was associated with an actual decline in effectiveness for three reasons:

1. The other two dust control products being tested also began to decline in effectiveness on or soon after day 18.
2. Use of a relatively heavy (0.6 gal/sq yd) follow-up application of brine on day 22 would appear unreasonable if a decline in effectiveness had not become observationally apparent between days 18 and 21.
3. The follow-up application increased dust control to 94% on day 26; however, effectiveness dropped to 83% by the final sample date only six days later (sample day 32).

So, apparently the only available data on an actual use of oil-well brine for dust control (see 2.6 below) indicated that an application of 3.8 gallons of brine per square yard had a dust-control effectiveness that began to decline after

18 days, and that an additional application of 0.6 gal/square yard extended the time to decline of dust control by only a few days, with a steep decline in effectiveness apparent by day 32, despite an exceptionally heavy total brine-application rate of effectively 4.4 gallons per square yard per month. Such rates exceed by far the state guideline once-per-month, 0.3 to 0.5 gal/sq yd rate that purportedly poses an acceptable environmental risk.

2.6. Data on OGB for dust control: a 45-year hiatus

A reasonable literature search by the author found no publications or mentions of studies involving actual measurements of dust control effectiveness of OGB after 1982, with a single exception by Graber et al. (2017), too recent to have influenced state guidelines. Citations in documents of relevant authorities from various states suggest that the only documented basis for the acceptance of the use of OGB for dust control was, and remains, the Moore and Welch (1977) study, the conclusions of which on further examination appear to be unsupported by their data (see 2.3 above). The 1982 findings of Russell and Caruso (1982) indicating that effective dust control using OGB requires high-risk application rates do not appear to have been cited, except by Cowherd and Kinsey (1986).

It appears the only scientific or engineering work on the dust control effectiveness of OGB since the 1980s is that of Graber et al. (2017), who concluded that the OGB was not effective as a dust control agent. So, within the relevant historical context, the consistency of the maximum brine application guidelines across states and time would seem to require that the findings of Russell and Caruso (1982) have been ignored; imply that current OGB application guidelines are based on a single, one-month study done 40 years ago on bromide plant waste brine, not OGB; and indicate that when applied as directed by state guidelines, OGB is not effective for dust control.

3. Studies on commercial dust-control products: requirements for effectiveness

Given the foregoing, one must either conclude that OGB applied at anywhere near the state-advocated maximum rates will not provide effective dust control, or seek additional information to further consider the potential dust control effectiveness of OGB. Additional useful information on the likely effectiveness of OGB for dust control can be extracted from investigations of the effectiveness of commercial dust-control chloride products.

E.N Johnson and R.C. Olson (2009) reported on a 2006-2008 study of the effectiveness of commercial magnesium and calcium chlorides and organic-polymer-plus-binder products, and concluded that the chlorides were effective for dust control and road stabilization. The data suggested the chlorides caused increased moisture retention in road material, which improved mechanical stability and reduced dust release and need for maintenance (re-grading of road surface). The authors pointed out the importance of fine road-soil particles (passing 0.075 mm sieve). Among the particle-size fractions unpaved road materials contain, the small-particle-size fraction interacts most strongly with moisture, increasing in strength as moisture levels increase (up to a limiting moisture level beyond which strength of the soil-fines fraction, or “binder,” decreases).

Johnson and Olson (2009) reported findings with respect to application methods, rates, and schedules. Though their findings were for commercial products that are much more concentrated (typically 32-38% calcium chloride) than OGB (average 11-12% sodium chloride and 4-5% calcium chloride), the results provide a useful reference for consideration of reasonable expectations of OGB in similar use. Johnson and Olson (2009) found application rates of 0.18 to 0.55 gallons per square yard were effective for up to 200 days. Numerous others reported or cited similar results from their own or others’ investigations (Sanders and Addo, 1993; Bolander and Yamada, 1999; Gebhart, 1999; Scott et al., 2004; Monlux and Mitchell, 2006; Jones et al., 2013; McHattie, 2015; Vermont Local Roads Program).

3.1. Incorporation improves performance

All those authors and agencies recommended or applied calcium and/or magnesium chlorides for dust control by mixing with the road materials during or following road-surface preparation. Recommended road-surface preparation included scarifying to loosen and break up surface materials to a minimum depth of 2 inches and to reduce maximum individual aggregates to <2 inches in diameter, application of dust control product and thorough mixing to assure a consistent blend of particle sizes over the entire road surface, and subsequent crowning and compaction of the road surface. Establishment of effective roadway drainage was regarded as essential to an effective road-preparation effort. Effective drainage requires construction of ditches and ancillary drainage ways along the roadside to assure water drains freely and uniformly from the road surface and road base.

None of the authors or agencies recommended surface application of chlorides for dust control and stabilization without incorporation into road material. Only one agency, the Wisconsin Transportation Information Center (1997)(WTIC), recommended road-surface preparation and surface application of dust control product if followed by sufficient watering to dissolve and infiltrate the chloride into the road material, but cautioned that incorporating the product during preparation would be necessary on roads where difficulties are encountered getting uniform dissolution and infiltration of the chloride.

There were varying degrees of admonition against surface spreading without incorporation. Two concerns were most commonly cited. First, all three chlorides (Na, Ca, Mg) used for dust control, whether in commercial products or OGB, are readily soluble salts. Consequently, when on the surface of a roadway, the next occurrence of rain in sufficient amount will dissolve these chlorides and carry them off the road, reducing their stabilizing effects. Second, such runoff water and its dissolved salts will move into the associated ditches and other drainage pathways, where they can impact ground or surface waters, soils and plants.

The more permeable a road surface, the more efficiently water runoff will deplete surface-applied chlorides, and the greater the potential for contamination of soils and surface waters. Among the objectives of compaction during road construction is establishing a surface that is minimally permeable.

On roads where chlorides are applied and incorporated into the surface material, compaction reduces permeability, reducing water infiltration, which reduces leaching of incorporated chlorides. It follows that application of brines to a finished, well-constructed road surface will not be as effective as incorporation before compaction.

In contrast, spreading OGBs on poorly maintained or unstable road surfaces has destructive implications. On unstable roads, traffic can increase degradation of the surface, especially during periods of high moisture. Moisture interacts with and occurs predominantly in the pockets of fines and void spaces among coarser particles within the road soil. When moisture levels rise too high, the bulk strength of bound (aggregated) fines in the road soil decreases. The road can become noticeably softer, even muddy. Even when such obviously "soft" conditions are not readily observable, minor softening of aggregates of fine particles can result in traffic-load-induced movement of coarser particles "pumping" soil fines toward the surface.

As fines are pumped from below they accumulate nearer, or on, the road surface. Due to the cumulatively increasing fines content of the developing surface layer, water-retention capacity increases and permeability decreases. Without sufficient coarser material, the fines-enriched surface layer cannot resist mechanical forces of traffic loads, increasing dust during dry weather, and softening and muddiness during wet weather. Fines on the road surface are then more subject to loss by wind erosion (dust), water erosion, and removal due to throw by, or attachment to, passing vehicles. When dust is released, the texture (particle-size distribution) of the surface road soil becomes coarser. As those fines are lost, the more permeable, coarser underlying layer becomes more exposed. Loose surface material, a.k.a. "float," accumulates on the road surface. Such float material is now texturally distinct from, and no longer hydraulically contiguous with the underlying more stable road surface, and even within itself is texturally heterogeneous. Water infiltration into the still-intact road surface increases, more fines are pumped to the surface, and the degradation of the road becomes a self-promoting process.

Any solution applied to a road surface will be preferentially absorbed by finer compared to coarser materials. Consequently, any fine road-float material will absorb and retain applied brine, becoming obviously wet, often muddy, in the process. If any of the chloride solution does get through to the underlying intact road surface, that more stable material is now both texturally and hydraulically distinct from the loose surface material. At such textural hydraulic boundaries, bonding between texturally distinct soil volumes is weak. When the wetted soil materials dry out, the body of float material will undergo dimensional changes at a rate different from the underlying intact road soil. The float body will peel away from the more stable intact road surface, a phenomenon known as "biscuiting." The float "biscuit" will destabilize to dust more quickly than and separately from the underlying, more stable material.

Loss of fines has still another destructive impact. As fines are lost as dust or sediment, loose, coarser particles will accumulate in the float material on the surface. Traffic action on those coarse particles will increase breakdown of coarse particles into fines, as well as abrasion of the underlying stable road surface. That is, once stability of the road surface has diminished to the point dust release is substantial, the constituents of any chloride solution applied to a worn, impermeable road surface will become part of the road dust, and will likely increase the amount of dust emitted and will consequently destabilize the road.

Consequently, spray application of chlorides to the surface of roads in poor condition is not only a wasted effort, but can be expected to exacerbate the already poor condition (Jones et al., 2013). Further, Na-rich brines can be expected to have more negative effects than calcium or magnesium (see section 7. below). Because application of brines is not reasonable or practical on poor-condition roads that are wet, most such applications occur when dust emissions are occurring or imminent, i.e., when conditions are, or soon will be, dry enough to promote dust release, and assure the brine application will enhance rather than reduce dust emissions.

3.2. Dust control vs. road stabilization

Some authors and agencies recommend incorporation of chlorides into road material as a road-stabilization practice, others as a dust control practice. Other authors and agencies also point out that dust control and the related road construction and maintenance objective of stabilization are functionally inseparable (e.g., Gesford and Anderson, 2007). A road that is producing dust is necessarily losing road material. A road that is losing material is unstable.

It is interesting to note that instead of regarding road stabilization as an objective, Gesford and Anderson (2007) define road stabilization as a practice that includes application of chlorides during road construction at rates already discussed, a practice they more accurately named "full depth reclamation." This distinction is important in that it eliminates the confusion implicit in recurring statements by various state authorities regarding use of OGB for "dust control and road stabilization," as though road stabilization were a passive sideeffect of dust control. This suggests an important, and erroneous, misunderstanding of the dependency of the two objectives.

Dust control is a necessary consequence of road stabilization, but road stabilization is not necessarily a consequence of dust control. For example, a surface application of water will provide short-term dust control, but will not stabilize the road. Ambiguous usages undoubtedly are in part the source of the apparently widespread misconception that "road stabilization" is a concomitant effect of "dust control".

4. State guidelines lack supporting data

As an example, consider the following from the North Dakota "Guidelines for the Use of Oilfield Salt Brines for Dust and Ice Control" (2013):

> When used in the manner outlined in this guidance, the North Dakota Department of Health (NDDoH) considers oilfield-produced saltwater (brine) to be an effective substitute for commercial dust and ice control products.
>
> …
>
> 4. Brine spreading guidelines
>
> …
>
> d) Recommended rates for dust control: The initial application of brine shall be spread at a rate of approximately one-half… gallon per square yard, after the road or parking lot has been freshly graded. …Subsequent applications shall not exceed an application rate of one-third (1/3) gallon per square yard per month, unless weather or traffic conditions require more frequent applications to suppress the dust or stabilize the road bed. Application rates for race tracks and mining haul roads shall not exceed one (1) gallon per square yard.

In the three-page North Dakota Depart of Health Guidelines (2013) the word "dust" appears 18 times, 16 of which in the term "dust control." In contrast, there is only one occurrence of the word "stabilize" in "[brine] applications to…stabilize the road bed," (quoted above). Functionally, it appears that the NDDoH distinguishes dust control from road stabilization, but it is not clear from the ND Guidelines (2013), or any similar, related or predecessor document, why occasional applications of small amounts of mixed chlorides, mostly sodium, in OGBs to the road surface can be reasonably expected to have any stabilizing effect on the underlying road bed.

In fact, sodium loading of the cation exchange sites on many soil clays, which comprise much of the fines in many unpaved road surface materials, including the road bed, will result in dispersion of the clay particles (see section 7. below). Under conditions that occur frequently on many unpaved roads, sodium dispersion of the clays will have a number of destructive effects. When the road is dry, dispersion of the clays will destabilize the road surface, leading to increased dust, and, when wet, will increase softening, muddiness and slipperiness. If the sodium reaches and disperses the clays in the road bed, the resulting destabilization will increase potholing and other structural problems in the affected road.

Further, section 4.b) of the ND guidelines requires that brine be applied “in a way that minimizes impact to the environment” only in amounts “necessary to control dust…” and “controlled to minimize the impact of brine infiltrating to ground water or running off the road surface into” surface waters. Then, as in other states, the ND Guidelines (2013) specify that amount of brine is 1/3 gallon per square yard per month, but then relinquishes the need to control brine application to minimize impact by stating, “unless weather or traffic conditions require more frequent applications,” and adds a final exception regarding racetracks and mine haul roads. Those who would apply brine in compliance with the ND Guidelines (2013) need to be able to evaluate several conditions, which can be considered as sets of questions implied by the guidelines [implications of some of which will be addressed in Part 2, publication pending].

1. When is a dust problem sufficient to warrant an OGB application? How does one evaluate the severity of a dust problem? When is another OGB application for dust control appropriate under the guidelines?
2. When is a “road bed” in need of stabilization? How can one know if OGB will work to stabilize a particular “road bed”? How can one determine if OGB has improved road stability?
3. How can one assess when impacts to the environment are no longer being minimized? Which impacts? How much impact to waters is acceptable or unacceptable?
4. What about other environmental impacts besides water quality? What about dust impacts on plant, animal, and human health? Nuisance impacts? Are those impacts reduced or increased by use of OGB for dust control or road stabilization?

The ND Guidelines (2013) provide no guidance as to how one should operate to assure compliance. One could interpret Sections 4.b) and d) as license to apply amounts considerably beyond the prescribed rates if weather or traffic or dust conditions or road stability are judged to be beyond some never-specified range implied by the guidelines. The vagueness of the ND Guidelines (2013) leaves the impression that the effectiveness of OGB for dust control or road stabilization, and its environmental impacts, were more likely presumed than determined. The guidelines used by several other states are functionally identical to those of ND.

In 1998, the Pennsylvania Department of Environmental Protection, Bureau of Oil and Gas Management issued guidance titled, “Approval of Brine Roadspreading Plans.” The ND guidelines (2013) are effectively identical to the PA guidelines (1998). In Ohio, OGB spreading has been controlled by regulations since the 1980s. Ohio did provide a more thorough guidance document (Kell et al., 2004), but its application rate, 3000 gallons per 12-foot-wide road mile, guidance is applicable to control of both ice and dust. Ohio imposed no minimum time intervals other than sufficiently separated in time to prevent environmental impacts. New York guidelines are similar to those of Ohio. Prior to 1998, Pennsylvania allowed a 1 gal/sq yd application rate, but based on a PaDEP (1996) study, concluded there was potential for degradation of surface and ground waters, and lowered the recommended rates for dust control/road stabilization to the currently common rate of ½ gal/sq yd initial application plus supplemental applications of 1/3 gal/sq yd per month (recall Moore and Welch, 1977). Notably, no state authorities have spoken to air quality impacts of application of OGB for dust control.

The lack of cited supporting data sources, facile citation of equivocal or contraindicating data sources, lack of specific enforceable rules and monitoring or enforcement standards among the reviewed guidelines of various states suggest an overall lack of supporting evidence for the practice. Instead, the guidelines provide a vague endorsement of OGB spreading for “dust control and road stabilization.” Although the guidelines stipulate or recommend application rates, all provide the same escape clause, which functionally makes the local responsible party the sole authority over how much brine can be applied.

The guidelines suggest application of brine for dust control and road stabilization is a legacy waste-disposal practice of convenience, instead of a road maintenance practice of verified efficacy. There has been no functional revision or documented additional data supporting the effectiveness of brine use on roads since the early 1980s, and the only recent investigation concluded the practice is not effective (Graber et al., 2017). Flannery and Lannan (1988) in an industry response to U.S. Environmental Protection Agency (EPA) findings of environmental impacts, cited Moody and Associates (1984) who concluded, “since oil and gas well fluids are not substantially different in composition from commercial salt, similar concerns are apparent. However, with proper management techniques… to minimize environmental impact, these fluids can be used effectively for dust and ice control.” The Moody “conclusion” appears to be more of a proposition based on a facile assembly of presumptions rather than a conscientious analysis of facts.

Contrary to the Moody and Associates (1984) conclusion, OGBs have substantially lower (salts) concentrations than commercial dust-control salt products, so much so the presumption of effectiveness must be regarded as baseless (see section 8 below). Further, though OGBs do give rise to the same concerns as commercial chloride products, OGBs give rise to numerous other concerns as well. The Moody conclusion supporting OGB as functionally equivalent to commercial salt/brine products for dust control or road stabilization must be regarded as either deceptive or misguided reasoning.

The Pennsylvania Environmental Quality Board (2013)(EQB) published a proposed new regulation titled "Environmental Protection Performance Standards at Oil and Gas Well Sites." The proposed regulation contained sections on disposal of OGB, including use on roads. In accord with state law, the Pennsylvania Independent Regulatory Review Commission (2014)(IRRC) reviewed and commented on the proposed regulations. The IRRC stated, "… we remain concerned that the final-form regulation fulfill EQB's obligation to protect the quality and sustainability of the Commonwealth's natural resources." Later in their report the IRRC wrote:

> "EQB has indicated that data is not the basis for this regulation. If data is not the basis for this regulation, how did EQB determine that the many standards being imposed are adequate? … Since the regulation is not based on data, we ask EQB to explain how it determined that the numerous standards being proposed are appropriate… ."

Further indication of the lack of data supporting the use of OGB for dust control and road stabilization is the wording of a 2014 letter from the PaDEP approving a brine spreading plan submitted by Farmington Township, Warren County, Pennsylvania. The brine application rates and other presumed environmental protection measures are as described in the foregoing discussion of guidelines of various states. Near the end of the letter the following text occurs:

> "The approval of these pollution prevention measures is not an approval of the activity itself. The Department of Environmental Protection neither approves nor denies the activity of spreading brine fluids for dust control, but reviews the activity due to its potential for water pollution."

This PaDEP disclaimer of the effectiveness of spreading of OGB for dust control seems to confirm the validity of the comments of the Pennsylvania IRRC, as well as the broader impression that there is no data that supports the effectiveness of OGB for dust control. This seems to have been further supported by a recent conclusion by PADEP that its previous approvals of applications of OGB to roads did not comply with state waste management law and that it must cease granting approvals for the practice (Pennsylvania Environmental Hearing Board, 2018).

There appears to be no literature that directly addresses effectiveness of use of OGB for dust except the data of Russell and Caruso (1982) and Graber et al. (2013). The conclusion from the Russell and Caruso (1982) data is that an OGB application of at least 7 times higher than permitted by various state guidelines can reduce dust, but effectiveness begins to decline in 20 days, and such a heavy application rate effectively guarantees environmental impacts. Graber et al. (2013) concluded an exceptionally high-calcium OGB applied at the state guideline rate was not effective. There appears to be no data from any source that comes close to suggesting OGB, or any similar brine, could have the effectiveness several state agencies presume in their use guidelines, which, given that the risk of pollution increases as the amount of applied OGB increases, raises several questions. Why are plan submitters effectively granted functional discretionary authority for how much OGB should be applied? Why is water pollution the only pollution of concern? Can dust from OGB-treated roads carry contaminants from the brine to surfaces, including skin and lungs, leaves, clothing, etc.? Could such OGB-treated-road dust impose additional health risks to those who are exposed? Some of these questions can be preliminarily answered with reasonable confidence by consulting relevant science and engineering literature. [Some of these questions are considered in Part 2, publication pending.]

5. Data on actual use of commercial products and OGB for dust control

As previously discussed, there is considerable literature on the effectiveness of calcium, magnesium and sodium chlorides for road stabilization and dust control. In 2013 the U.S. Department of Transportation Federal Highway Administration released two related reports, “Unpaved Roads Chemical Treatments-State of the Practice Survey” (Kociolek, 2013) and “Unpaved Road Dust Management-A Successful Practitioner’s Handbook” (Jones et al., 2013). These two reports summarize current actual and best practices.

Neither OGB nor sodium chloride was mentioned in the Handbook (Jones et al., 2013); however, sodium chloride was included in “Appendix E. Basics about Road Dust Suppressant Categories.” The Survey (Kociolek, 2013) did not mention OGB, but 15 respondents indicated they used “other brine” and all “other brine” was applied by spraying directly onto the road surface. Out of 198 respondents, 3 explicitly commented that they used OGB. When asked, “If your agency/organization manages unpaved roads but does not use any form of chemical treatment, please state why,” one of the 3 responded that his organization used gas-well brine for dust control. Presumably the respondent did not perceive gas-well brine as a “chemical treatment” or “other brine”. When asked for positive comments to the survey question, “For your agency/organization’s most commonly used treatment, how would you rate your satisfaction with performance?” another respondent commented, “Lower chloride content in oil field brine," apparently regarding lower chloride content desirable even though chloride content is the basis for any dust-control or road-stabilizing effects of OGBs, if there were any. To the same question, the third OGB-using respondent commented, "Oil-well brine controls the dust and doesn't cost us anything."

Among the general results of the Survey (Kociolek, 2013), 80% of respondents stated they had been using chemical treatments for their unpaved roads for at least 6 years, while 25% reported not using any chemical treatments. Of those that used treatments, >50% used $MgCl_2$ or $CaCl_2$ or both; 98% of those who used chemical treatments did so primarily for dust control, regulatory compliance, health or public opinion concerns; and 52% to reduce road-maintenance (surface-grading) needs. Among respondents using treatments, >90% applied treatments by spraying directly on the road surface, ~40% also mixed treatments into the wearing course, ~10% into deeper portions of the road structure. While 95% reported satisfaction, only ≤25% used objective methods to evaluate effectiveness of treatments. With regard to best management practices, 80% considered chemical treatments an unpaved road best management practice, while 60% believed their own program represented a best management practice. More than 80% agreed more research and comprehensive guideline documentation are needed. According to the general responses to the Survey (Kociolek, 2013), cost is a primary concern, effectiveness is evaluated subjectively, and application is often by spraying directly on road surface.

The three comments from three OGB-using respondents and the general results of the full Survey (Kociolek, 2013) provide some insight into who uses OGB and how. OGB users obtain brine at no or minimal cost and apply only by spraying directly onto the road surface. Most state approved OGB application rates are similar, but state OGB spreading plans typically have numerous exceptions that allow application at unspecified higher rates. Given that actual application rates are unknown, this report presumes that OGB users follow state guidelines, typically an initial application at 1/2 gal/sq yd with follow-up applications of 1/3 gal/sq yd at monthly intervals.

OGBs are lower in chlorides than commercial chemical treatments. The most commonly used commercial chemical treatment products are (typically 30%) $MgCl_2$ and (typically 38%) $CaCl_2$ solutions. OGBs from western Pennsylvania average 0.8%$MgCl_2$, 5.0% $CaCl_2$ and 11.4% NaCl (Dresel and Rose, 2010). Concentrations of chlorides in OGBs vary with source, but western Pennsylvania brines are reasonably representative of OGBs generally.

The Handbook (Jones et al., 2013) and other reports state that water is the oldest, fastest, and most readily available dust suppressant. In Appendix E of the Handbook (Jones et al., 2013), which is the source of the following information, water is the first listed dust suppressant. The surface tension of water between moistened road particles holds them together, preventing separation and suspension as dust particles. Water is typically readily available. Use of water as a dust suppressant is, however, expensive because the effect lasts only until the water evaporates, usually <1 to 12 hours. The longer-lived effectiveness of any brine is due to the deliquescent quality of chloride salts the brine contains. Deliquescent salts attract and retain moisture from the atmosphere, resulting in moisture-binding of fines in the road surface.

The Handbook (Jones et al., 2013) Appendix E allows comparison of water with other dust suppressants, including NaCl, the most relevant to consideration of OGBs. Magnesium chloride ($MgCl_2$) is deliquescent when relative humidity (RH) is above 29%. It generally requires an initial application at 1/2 gal/sq yd and a follow-up at 1/4 gal/sq yd about 2 months later. The characteristics of calcium chloride ($CaCl_2$) are very similar, though $CaCl_2$ becomes effective at a lower RH, 20%-29%, depending on temperature. NaCl is hygroscopic, but not deliquescent until RH≥79%. NaCl also does not increase surface tension as much as $MgCl_2$ or $CaCl_2$, that is, does not strengthen the road surface as much even at RH>79%. However, because it is only deliquescent at higher humidities, under sufficiently dry conditions NaCl can dry to form crystals that may function to bind road soil particles together. NaCl must be applied at higher rates, which, according to the Pennsylvania Department of Transportation (2009), are 1 to 2 lb/sq yd per inch of compacted soil depth, compared to ½ lb/sq yd per inch for $CaCl_2$. Notably, the Handbook (Jones et al., 2013) Appendix E states that when used at concentrations below 20%, $CaCl_2$ and $MgCl_2$ solutions suppress dust about as well as water, and that NaCl tends “not to hold up as well” when applied directly to the road surface.

6. Commercial products and OGBs: expectable effectiveness

6.1. Concentration deficiencies

The information in the Handbook (Jones et al., 2013) Appendix E enables comparisons of expectable dust suppression effectiveness of OGBs and commercial chloride products. OGBs are mixtures of Mg, Ca, and Na chlorides. Mg and Ca chlorides have similar dust-suppressant properties, hence, the sum of their concentrations should approximate their effective dust suppressing concentration. Two to four times as much NaCl is needed to provide the same stabilization as $MgCl_2$ or $CaCl_2$ (Pennsylvania Department of Transportation, 2009).

The average total concentration of Mg and Ca chlorides in western Pennsylvania oil well brine is 5.8%, for convenience herein rounded to 6% (Dresel and Rose, 2010). NaCl is 11.4%, for convenience herein, rounded to 12%. The Handbook (Jones et al., 2013) Appendix E indicates $CaCl_2$ brines with concentrations <20% will be no more effective than water. It follows that there would be no reason to expect an average OGB with a $MgCl_2+CaCl_2$ concentration < 6% to be more effective than water. There is, however, more dust suppression potential in the NaCl in OGB. Assuming a generous 2:1

equivalence, 12% NaCl in OGB would be equivalent to another 6% $CaCl_2$ and raise the total $CaCl_2$ equivalent concentration in an average OGB to 12%, still just over half the minimum concentration necessary to be more effective than water. That is, the chlorides concentrations in OGB do not justify an expectation that OGB will provide more effective dust suppression than an equal volume of water. This result is compatible with the no-effect data of Moore and Welch (1977), the results of Russell and Caruso (1982), which showed dust suppression but only at several times the state maximum application rates, and Graber et al. (2013), who concluded that even exceptionally high-Ca OGB is not effective at state-recommended application rates.

6.2. OGB not incorporated

The Handbook (Jones et al., 2013) states, “Spraying dust control treatments onto unprepared roads is a waste of time and money.” The Survey (Kociolek, 2013) indicated 90% of all users spray them on the road surface, but did not indicate how many prepare the road surface before spraying. Anecdotal reports and the author’s observations are that OGB is typically sprayed directly onto the road surface without prior grading or preparation. The Handbook (Jones et al., 2013) Appendix E indicates that surface-applied NaCl tends not to hold up as well as, presumably, mixed-in applications. Consequently, in actual use, the previous assumption of a 2:1 dust suppression equivalence of NaCl to $CaCl_2$ in OGB is likely to be overly optimistic. Hence, it is even less likely OGB will be an effective dust suppressant.

6.3. OGB use in road stabilization likely precluded by required application rates

As mentioned in the Handbook (Jones et al., 2013) Appendix E, typical treatment application rates assume adequate road preparation and incorporation into the wearing course. OGB tends to be applied to unprepared road surfaces with no effort to incorporate into the wearing course. This raises a question about whether OGB could be a practical substitute for commercial chloride products if it were applied during or following appropriate road preparation.

Using the recommended chlorides application rates (Pennsylvania Department of Transportation, 2009) and the average chlorides concentration of western PA OGB (Dresel and Rose, 2010), one can calculate that 1.65 gallons of OGB would be needed to provide a total of sodium, calcium and magnesium chlorides (assuming 2 lb NaCl has the dust suppression equivalence of 1 lb $CaCl_2$) equivalent to the recommended initial 38% $CaCl_2$ brine application rate of 0.5 gal per sq yd of treated road. A working compacted soil depth of 2 inches over an area of 1 sq yd contains 2592 cubic inches of soil. 1.65 gallons of brine contains 381 cubic inches of water. So, the application of 1.65 gal/sq yd OGB would increase the moisture content by 15%. For many soils, 15%

moisture is too wet for compaction. Many road soils under field conditions will contain moisture before the application of 1.65 gal/sq yd OGB, further increasing the moisture content following, and reducing the practical usability of, OGB in many common road situations. If the road were prepared, including compaction, before the OGB application, then substantial runoff or puddling would be expected if 1.65 gal/sq yd OGB were applied. Therefore, it appears substitution of OGB for commercial $CaCl_2$ or $MgCl_2$ solutions during recommended road preparation work would be impractical in many, perhaps most, cases.

6.4. OGB use as refresher brine not cost effective

Given substitution of OGB for commercial brine during an initial road stabilization/dust-suppression treatment appears impractical, could OGB potentially be used for follow-up applications to maintain an already effectively chloride treated road? It is not clear that replacing dissipated Ca or Mg chlorides in an already treated road using high-NaCl follow-up treatments would be as effective as Ca or Mg chloride follow-up. Further, a 2:1 NaCl: $CaCl_2$ dust suppression equivalence is likely be overly optimistic. Nevertheless, one can disregard these concerns to explore whether use of OGB might be reasonable in terms of foreseeable costs.

To begin, one might, despite no supporting data, accept that state guideline OGB follow-up applications of 1/3 gal/sq yd per month will be effective. For commercial calcium and magnesium chloride products the Handbook (Jones et al., 2013) Appendix E indicates only one follow-up application per season is typically needed. Assuming the dust suppression season is 6 months long, and no follow-up applications will be needed until 2 months after the initial commercial dust suppression treatment, then 3 or 4 months will remain in the season for monthly OGB applications. Repeating the previous calculation of OGB application rate equivalence for these conditions (see sections 5 and 6.3), one finds that 3 successive monthly applications of average OGB at 0.3 gal/sq yd would be total-chlorides equivalent to a single application of 38% $CaCl_2$ at 0.25 gal/sq yd.

At this point the cost effectiveness of three machine operations with presumably no-cost brine must be compared to a single machine operation with 38% $CaCl_2$. Prorating from the data in the Handbook (Jones et al., 2013) "Appendix C—County Road Budget Proposal," operations for a single application of brine or $CaCl_2$ solution per mile of 24-foot-wide road costs \$685. Over the same road mile, 0.25 gal/sq yd $CaCl_2$ product cost would be \$1,230 and OGB cost is assumed to be \$0. One application of $CaCl_2$ then would cost \$685+\$1,230=\$1,915 while 3 applications of brine would cost 3x\$685=\$2,055. So, costs do not favor use of brine for follow up treatments in lieu of commercial $CaCl_2$, even without considering likely additional maintenance (grading) cost savings from use of $CaCl_2$ or that the actual functional mass equivalence of $NaCl$:$CaCl_2$ may actually be >2:1.

7. Clay-cation interactions and effectiveness of OGB vs. commercial brine – implications for dust control and road stabilization

Certain useful properties of many soils depend on the type and amount of clay minerals present. Briefly, in many soils, the predominant clay minerals belong to a class known as layer alumino-silicates. A set of images with introductory information on the structure, properties and uses of clays has been assembled and posted by H.Z. Hassan (2016).

The three most common layer alumino-silicate clay minerals in soils are kaolins (a form that would be known to some as Fuller's earth), illites (more recognizable forms of which are mica and vermiculite), and smectites (or montmorillonites, a more well-known form of which is called bentonite). Most soil clays occur as colloidal-size particles. In soils kaolin and montmorillonite particles typically are a few micrometers in their longest dimension. Illites in soils can and do occur as larger particles, though usually <100   m in their longest dimension. All exist as layered crystalline particles, the thickness of which is typically 100 times smaller than the length or width. Because clay particles are sheets, they have high surface areas per unit weight.

All of these layer alumino-silicate clay minerals carry some net negative point charges in their crystalline structure, many of which occur on their outside surfaces. Kaolins, which have the least such negative charges, are relatively inert minerals with low cation exchange capacity (CEC). In contrast, smectites have many surface charge sites and consequently high CEC. Illites are intermediate in charge density and CEC. These clay minerals retain cations in proportions determined by the particular mineral and the relative concentrations of the cations in the water that the clay mineral contacts.

The cations held by a clay mineral affect the properties of that mineral, including its physical behavior at the scale of individual particles and bulk properties (Hassan, 2016; Sullivan and Graham, 1940; Warrence et al., 2018; Bell, 1992; Trask and Close, 1957). Clay minerals are considered desirable in unpaved road materials because they can function as binder, filling voids and providing flexible bonding at contact points among larger particles and aggregate, thereby reducing porosity and increasing strength of the road surface. The most favorable road soils contain 4-15% fines, most of which will often be clay minerals (US Department of Transportation, 2015).

Sodium is a particularly important cation with respect to clay-mineral behavior (Hassan, 2016; Sullivan and Graham, 1940; Warrence et al., 2018; Bell, 1992; Trask and Close, 1957). When sodium ions are held by a clay mineral two conditions develop. First, when a sodium ion is attached to a clay-surface charge site, both charges are neutralized and the capacity of the clay to form charge-based connections to other particles or ions at that charge site ends.

Second, when a sodium ion attaches to one of the charge sites, it brings much of its hydration shell of water molecules with it.[a] Consequently, clay particles bearing excessive sodium cannot approach each other due, in part, to the hydration water molecules retained in the remaining hydration shell of the sodium ions. This retention of inter-particulate water reduces the bulk strength of the clay, which can lead to liquefaction of clay soils, as in landslides, or, on a smaller scale, a consistency some refer to as “slickness” or “sliminess” of soils, including road soils.

Ca and Mg occur as divalent cations and interact with clay particles very differently than sodium. When a Ca ion attaches to a point-negative charge site on a clay crystal surface, one calcium positive charge is neutralized, but one remains and is exposed to the surroundings of the crystal. In many situations, or over time, the nearest charged entity in the clay particle surroundings is another clay particle. When the clay particles are in proximity, the remaining positive charge on the calcium ion can attach to a point-negative charge site on a nearby clay crystal. That is, calcium (and magnesium, or other multivalent cation) ions can effectively bond clay particles together, a structural condition called “cation bridging”, resulting in an associated increase in bulk strength.

This effect is exploited when working with colloidal suspensions of soil clay minerals in the laboratory, sometimes referred to as “chocolate milkshakes” due to their appearance. If there is need to collect the clays from that suspension, a small amount of $CaCl_2$ can be added, causing the dispersed clay particles to flocculate, settling out of suspension for collection. Flocculation is important in soil structure and strength, including in unpaved roads. Flocculation is reversible, the reverse process, known as dispersion, can be induced by addition of NaCl to a flocculated clay suspension.

It is also important at this point to consider the phenomenon known as “salting out.” In the previous example of a “chocolate milkshake” laboratory clay suspension, the clay in suspension was settled out by adding a small amount of $CaCl_2$. A similar effect will result from addition of a large amount of NaCl. When a large amount of NaCl, or other ionic salt, compared to the amount of clay, is added, the suspended clay particles are in effect pushed toward each other as the sodium ions attract water away from the clay particles. As the clay particles coalesce, or gel, within the high-salt suspension, the density of the coalescences of clay particles will eventually become high

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[a] All soluble cations carry a hydration shell. [http://www1.lsbu.ac.uk/water/ion_hydration.html] In solution, divalent calcium and magnesium ions have larger hydration shells than monovalent sodium ions, but when held by a clay particle as an exchangeable cation the hydration shell of monovalent sodium ions is particularly important with respect to clay behavior.

enough that they will settle out of suspension. This response of clay particles to high levels of soluble salts is, in fact, one of the objectives of chloride treatments of roads to control dust or stabilize structure. High concentrations of deliquescent salts attract water into the road material matrix while also causing clay particles to "salt out." That is, under high-salt conditions, the fine-particle aggregates in the road matrix are strengthened by the presence of a stabilizing amount of water due to the deliquescence of the salt and the "salting out" coalescence of clay particles.

In the case of treatment with $CaCl_2$, the clay-particle charge sites are saturated with calcium, causing the clay particles to be attracted and bonded to each other, resulting in flocculation. This flocculation can then be further enhanced by the addition of more $CaCl_2$, adding repulsive forces of salting-out to the attractive forces of flocculation. In the case of treatment with NaCl the clay particle charge sites are saturated with sodium, electrostatically neutralized, resulting in no attraction or bonding between clay particles, which then coalesce only when there is a sufficiently high concentration of sodium in the surrounding solution.

One importance of salting out of clays by NaCl compared to flocculation plus salting out by $CaCl_2$ lies in what happens in a typical seasonal sequence of dust control on unpaved roads. Assume that at the beginning of the season one of these salts is applied in an effective amount and appropriately incorporated into the road surface layer. Either salt can provide effective dust control until enough rain and associated leaching of the chloride agent have occurred.

If the chloride used was NaCl, the concentration of NaCl drops, "salting out" ceases, and sodium saturation of the clay particles takes effect and disperses the clay particles, weakening the road structure. If the chloride used was $CaCl_2$, then the effect of calcium saturation of the clay charge sites takes effect, the clay particles bond to each other, providing strength to the road material matrix. With respect to dust control on unpaved roads, the work of Graber et al. (2017) provides clear indication of the importance of the type of clay and flocculation/dispersion vs. salting out, which they assessed through sodium-adsorption ratio and electrical conductivity, respectively.

The stabilizing effects of "salting out" clays with high salt concentrations are greater than the stabilizing effects of calcium (or magnesium) flocculation of the clays. Nevertheless, it should also be recognized that the flocculating effects of calcium are effective along with "salting out" at high concentrations of $CaCl_2$, and continue after those high concentrations have been depleted. In contrast, "salting out" with NaCl must overcome the dispersing effect of sodium saturation of the clay charge sites, and that dispersing effect will remain after the high concentration of NaCl has been depleted. Hence, the better performance of $CaCl_2$ (and $MgCl_2$), compared to NaCl, as a dust control agent on unpaved roads, is due not only to its stronger deliquescence but also the effects of calcium on clay-aggregate formation and stability, which is, again, supported by the findings of Graber et al. (2017).

All cations in solution around a clay particle compete for the negative charge sites on the clay surface. Consequently, whether a clay is loaded with calcium or sodium depends primarily on which one is present in greater effective concentration in the surrounding solution. Soil scientists have long been concerned with this property because dispersed clay soils have poor soil structure, low porosity, low strength, and tend to be soft and sticky when wet, and hard and dusty when dry (Warrence et al., 2018). An index has been developed to assess whether a water is likely to cause soils to acquire too much sodium. That index is the sodium adsorption ratio, or SAR, which may be calculated as

$$SAR=\sqrt{2}\, C_{Na}/\sqrt{(C_{Ca}+C_{Mg})}$$

where C_{Na}, C_{Ca}, and C_{Mg} are the concentrations of Na^+, Ca^{2+} and Mg^{2+} in meq/L, respectively.[b]

Water with SAR values above 3 will result in eventual sodium displacement of calcium and magnesium; at values above 9, sodium will displace calcium and magnesium quickly. The high-Ca OGB used by Graber et al. (2017) had an unusually low OGB SAR of 7.5. The average western Pennsylvania OGB (Dresel and Rose, 2010) had a SAR of 85. The sodium in a single application of such high-SAR brines applied to a road surface will cause sodium to dominate the behavior of the clays in the road soil. Repeated applications will cause sodium to displace calcium and magnesium from the clays to continuously increasing depth, eventually reaching below the wearing course down into the road base (Occidental Chemical Corporation, 2006).

The effects that make NaCl effective as a dust control and stabilizing agent in the wearing course are not desirable in the subgrade, which needs to be mechanically stable, but permeable. Over time, water percolating through a NaCl-treated wearing course into the subgrade will cause sodium loading of the charge sites on the clays in the subgrade. If the dissolved sodium concentration is not high enough to "salt out" the clay particles, they will disperse, clay aggregates will fail, dispersed clays will migrate out of the road base in percolating water (Winston et al., 2016), and the road subgrade will be de-stabilized. When the dissolved sodium levels fall too low in the overlying wearing course of the road, clay dispersion will occur with increased dust under dry conditions and increased mud and slipperiness when wet. If the Na-dominated (sodic) condition continues, the road will eventually be destabilized throughout its depth.

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[b] Or, in a more traditional form, $SAR = (Na^+ meq/L) / \sqrt{(1/2\ (Ca^{2+} + Mg^{2+} meq/L))}$.

Use of multiple applications of OGB can be expected to generate such sodic conditions any time of year, because brine applications do not provide the spring-to-fall stabilization that a properly executed initial granular NaCl application could provide. That is, for reasons previously discussed, applications of OGB in accord with the recommendations of various states will provide little or no dust suppression, but, instead, because of the very high SAR of OGBs, load the road clays with sodium and destabilize the road.

Use of OGB can be reasonably expected to exacerbate dust problems for another reason. As previously mentioned, magnesium and calcium chlorides, the most used commercial chloride dust-suppression agents, work because they are strongly deliquescent. NaCl, in contrast, is much more weakly deliquescent. Sodium chloride, though it does absorb some moisture at RH≥79%, cannot absorb nearly as much water, or at as low RH, as calcium or magnesium chloride. Consequently, though it has some moisture-related dust-suppressing ability when humidity levels are high, its dust-control mechanism is distinctly different at more typical daytime humidity below 79%.

Sodium chloride controls dust at normal daytime humidity levels by salting out clay particles, as previously discussed, and by forming crystals that bind the road surface particles together. When granular sodium chloride is incorporated into the working course of a road, i.e., pressed into place during compaction of road surface materials with an appropriate moisture level for incorporation and compaction, it will remain present as crystals, or somewhat moistened crystals, at night or when humidity is higher, binding adjacent road particles together until it is eventually dissolved and leached or washed out. An effective application of sodium chloride during construction of a well-designed unpaved road can strengthen the roadway for several months (Pennsylvania Department of Transportation, 2009).

The same benefits, however, cannot be expected from most surface applications of sodium chloride that are not appropriately designed and incorporated into the road itself, i.e., a surface application of NaCl-rich OGB to an inadequately prepared road. Dust control applications to roads can be assumed to occur in the summer, during the day, when temperatures are higher and humidity is lower, and dust release is occurring or imminent. When a NaCl-rich solution is applied under these conditions, the water in the brine solution will be absorbed predominantly by surface fines and then evaporate relatively quickly. Any sodium chloride present, unlike calcium and magnesium chlorides, will crystallize. If crystallization occurs among inadequately compacted road surface fines, the growth of the crystals will exclude any surrounding particles, pushing those fines apart while forming small mechanically separate crystalline salt particles among them. That is, the very property that makes sodium chloride effective when incorporated into a compacted road working course also makes it damaging and dust-increasing when applied to an inadequately prepared road surface.

So, when applied to the road surface without effective incorporation, sodium chloride solutions will either soften road structure and contaminate surrounding waters in wet weather; or will exacerbate dustiness of the road, while becoming part of the actual dust leaving the roadway under dry conditions. Such entrainment of chlorides in dust from brine-treated roads was confirmed by field investigations of impacts on roadside trees as early as 1936 (Strong, 1944).

8. No supporting evidence for use of OGB for dust control

At this time there appears to be no actual measurement data that support the use of OGB as an effective dust-control agent. The very limited available data indicates that OGB cannot be effective unless applied at rates several times the maximum rates state authorities consider acceptable environmental risks. Further, examination of the more thorough literature on commercial chloride dust-control agents clearly indicates there is no reason to expect OGB to be an effective dust control agent. Due to the effects of sodium ions on behavior of soil clays, typical applications of sodium-rich OGB to unpaved roads can be reasonably expected to increase dustiness and weaken soil structure. Finally, a conservative cost comparison for dust control, based on OGB compared to a commercial $CaCl_2$ product, showed the use of brine is actually more expensive, without considering potential need for more road maintenance work if sodium-rich brine is used instead of calcium chloride, and without considering increased health and environmental risks.

A subsequent paper, Part 2, anticipated publication in October 2018, will address known or anticipatable environmental and health impacts of the practice of applying OGB for dust control on unpaved roads.

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