lubricants

Review

An Overview of Grease Water Resistance

Alan Gurt and Michael Khonsari *

Department of Mechanical and Industrial Engineering, Louisiana State University, Baton Rouge, LA 70803, USA; agurt2@lsu.edu

* Correspondence: khonsari@lsu.edu

Received: 9 June 2020; Accepted: 19 August 2020; Published: 21 August 2020

Abstract: Many grease-lubricated components operate in wet environments, making them susceptible to water contamination which degrades their performance, functionality, and useful life. Hence, selecting a grease with appropriate water-resistant properties can have a significant influence on the life of the machine. While industry standards attempt to evaluate a grease's water resistance, research indicates that a more thorough understanding of water resistance is needed to properly match a grease to an application. This paper provides an overview of the interaction of grease and water, covers existing water-resistance standards, discusses the results of available experiments aiming to describe the effects of water on grease, demonstrates the need for more meaningful standards, and suggests additional measures for characterizing a grease's water resistance.

Keywords: grease contamination; water resistance; water contamination

1. Introduction

Water is one of the most common contaminants that interferes with the operation of machinery as it becomes mixed into the lubricating grease due to incomplete sealing of bearings, storage containers, or other grease containment devices. Water contamination often significantly alters the rheological and chemical properties of grease and leads to accelerated failure of equipment through intensified corrosion, oxidation, leakage, and oil flow restriction [1,2]. Concentrations as low as 100 ppm can yield significant changes to lubrication performance – and therefore – the fatigue life of a bearing [3]. It is imperative to consider the presence of water for grease applications including steel mills [4–6], paper mills [7], mining operations [8], food production equipment, outdoor equipment, wheel bearings, and many others in order to prevent premature failure.

A particular industrial concern is grease lubrication of rolling-element bearings where free water is known to promote corrosion, exacerbate starvation, and cause bearing failure [9]. In selecting an appropriate grease, a user typically seeks a grease that prevents the formation of free water. Sometimes this means identifying a water-repellent grease that provides good sealing. For bearings operating at very low speeds, a large portion (over two thirds) of the volume can be filled with grease, which allows for good sealing and prevention of water ingress [10]. However, for bearings operating at higher speeds, overfilling the bearings leads to churning of the grease and overall poor lubrication. Such bearings must, therefore, rely on bearing shields/seals or other protection to limit the amount of water that can enter. For such situations, it may be preferable for grease to have the ability to absorb as much water as possible or to absorb water as easily as possible. Still in other cases, it may be desired for a grease's rheological properties to be affected as little as possible so as to maintain adequate performance. Providing information about all of these properties would allow a user to more thoughtfully select a grease for a given application.

Overall, the most pertinent characteristics of a water-resistant grease are water solubility, formation and adequacy of lubricant film thickness, non-reactivity with water, retention of consistency, proper adhesion to surfaces, and prevention of corrosion [9,11–14]. The properties among these directly addressed by current standards are static water resistance (DIN 51807 [15]), consistency maintenance (ASTM D7342 [16] and D8022 [17]), surface adhesion (ASTM D1264 [18] and D4049 [19]) and corrosion preventiveness (ASTM D1743 [20], D6138 [21], D5969 [22], D7038 [23], and D4048 [24]). However, these tests provide no information on how a grease's consistency changes due exclusively to water, on a grease's maximum water absorption potential, on a grease's ease with which it absorbs water, or on a contaminated grease's ability to provide a high-quality lubricating film. Therefore, researchers have developed tests to address these concerns among others.

At the present time, there are only a few standards available for the characterization of water resistance of greases. Further, there is a lack of standardized tests that a manufacturer can provide to the consumer and a paucity of meaningful information for the user to select an appropriate grease for operation in a wet environment. Indeed, reliable quantification of the water-resistance property of grease is needed to assist both the manufacturers and the users. Examination of relevant standardized tests, common grease recommendations, and results of testing by various independent researchers indicates that there is a lack of understanding of the nature of water resistance, leading to poorly justified recommendation and selection of grease for wet environments. This paper details the interaction of grease and water that leads to machinery failure in Section 2, covers water resistance standards and other useful tests in Section 3, discusses results of these tests in Section 4, provides suggestions for future work in Section 5, and provides conclusions in Section 6.

2. Details of Water Contamination

2.1. Interaction of Grease and Water

Unlike the case of oil and water—where a very small amount of water can be absorbed [3]—grease is capable of absorbing a considerable amount of water largely due to the polar nature of the thickener and additives [25]. More specifically, the degree to which a grease can absorb water depends strongly on the concentration and nature of the surface-active components [26]. Nevertheless, recent investigations reveal that the base oil can play a significant role in a grease's water-contaminated performance [27]. To avoid potentially damaging hydrolytic reactions, one may consider using a base oil with high hydrolytic stability such as polyalphaolefin [28].

The water contained within grease can exist in three phases: dissolved, emulsified, and free [14]. If water is either dissolved or emulsified into a grease, it can be considered absorbed. When water becomes dissolved within a grease, there is no visual change; however, when the saturation point is reached and water is emulsified, the appearance can change significantly (shown in Figure 1) [29]. In order to form an emulsion, agitation is necessary to get the water into small enough droplets to be dispersed within the grease [4]. Overall, emulsified and free water are the most damaging to bearings, since an emulsion can reduce film strength and free water can easily cause corrosive damage [28].

Figure 1. Calcium sulfonate grease contaminated with 0% (left), 1% (middle left), 10% (middle right), and 50% (right) water.

Grease is capable of forming stable emulsions which may not release the water even when heated to high temperatures and subjected to a dry atmosphere [14]. When exposed to air, the water concentration in the grease decreases exponentially with time but reaches a limiting value at which the outer layer is "dry" and prevents water from inner layers from escaping into the atmosphere. The dry outer layer of grease appears to have the same thickness regardless of the size of the slab of grease [14]. Clearly, more research on water transport activity is needed to adequately describe this phenomenon. However, a more recent investigation [27] has identified two distinct populations of water that tend to diffuse at different rates. Better understanding of the nature of these groups may answer important questions about the interaction of grease and water.

2.2. Water Contamination Leading to Machinery Failure

Understanding how water causes grease-lubricated components to fail can arm the users to more thoughtfully prevent this from occurring. Generally, water causes machinery to fail by simultaneously damaging the bearing surfaces and impacting the performance of the lubricant. To prevent damage to surfaces, they should be coated with a protective layer of lubricant, without which the surfaces will be subjected to corrosion [30]. This often takes place after water displaces the lubricant and directly interfaces with the surfaces [28]. This effect is minimized if the grease is capable of absorbing water, as it is the free water that leads to corrosion [11,30,31]. However, water also damages bearing surfaces through cavitation and hydrogen embrittlement as it penetrates into microcracks [32]. These effects accumulate over time and can dramatically decrease the fatigue life of a bearing.

Though damage to the bearings themselves often is a leading cause of failure, the impact water has on the lubricant must also be considered. Perhaps most importantly, water contamination acts as a catalyst to oxidation degradation of all components of grease [14], thereby degrading performance considerably. Water can also degrade additives—particularly antiwear and extreme-pressure additives [33]—through hydrolysis [28,34], forming acids capable of etching bearing surfaces. Water also causes structural changes to the thickener whose magnitude depends on the thickener type [30]. At low temperatures, free water can easily freeze into ice networks, disrupting oil flow [13] and leading to dramatically increased start-up torque [13,35]. An overall effect of water can be observed as decreasing effective viscosity, decreasing film thickness, and lowering load-bearing capacity [28].

To prevent damage, a grease must be thoughtfully selected to counteract the weaknesses of a particular device. One must consider the amount of water that the device will encounter and how forcefully it is expected to enter into the system. Any forceful entry of water will likely soften the grease and lead to washout. To prevent softening, a grease with the right balance of base oil viscosity and polymer additives should be selected (see Section 4.2). For devices operating at lower speeds, the amount of grease fill can be quite high, allowing grease to act as a protective seal. If water ingress is unavoidable, a grease capable of absorbing large quantities of water while maintaining its rheological properties is needed.

3. Relevant Standardized Tests

3.1. Standards Directly Involving Water

Table 1 presents a summary of pertinent standards that describe a grease's resistance to water. It includes ASTM D7342/D8022 (water stability), DIN 51807 (water resistance), ASTM D1264 (water washout), ASTM D4049 (water spray off), and ASTM D1743/D6138/D5969/D7038/D4048 (corrosion prevention). Among these, the most commonly referenced standard for water-contaminated grease is ASTM D1264, also known as water washout. This test involves filling a bearing with grease and spraying a water jet at the bearing shield. Once the test is complete, the amount of grease remaining in the bearing is weighed and the percentage of grease lost reported. This test aims at indicating the ability of a grease to remain within a bearing while being softened by water.

Table 1. Summary of existing standards involving water contamination of grease.

Test	Procedure	Comments
Water stability (ASTM D7342)	Mix grease and water then subject to shear; record initial and final penetration	Mechanical stability also included in the results
Wet roll stability (ASTM D8022)	Add grease and water separately to cylinder then rotate for 2 h; record initial and final penetration	Mechanical stability included in results; does not consider water absorption capacity of grease
Water resistance (DIN 51807)	Dip grease-coated test strip in water; visually inspect for change	Result is not an indication of performance
Water washout (ASTM D1264)	Spray bearing shield with water; record initial and final weight of grease within bearing	Common test; inadvertently tests a grease's ability to retain water
Water spray off (ASTM D4049)	Spray grease-coated plate directly with water; record initial and final weight	Inadvertently tests a grease's ability to retain water
Corrosion prevention (ASTM D1743 & more)	Fill bearing with grease; submerge in water; place into oven; visually inspect for corrosion	Common test; does not fully describe grease's interaction with water

The water spray off test as described in ASTM D4049 is similar to ASTM D1264, but here the grease is sprayed directly with water while it is spread across a flat plate. Once again, the reported result is the percentage of mass loss during the test. This test differs from the washout test since here the grease is sprayed directly with water. This main difference makes this test somewhat controversial, as it is unclear whether the erosive nature of the water jet is more significant than the effects of water contamination [36]. In both the washout and spray off tests, it is possible for grease to increase in weight due to the absorption of water [26]. As a result, the ability of a grease to retain water may be inadvertently included in the results.

The consistency of a grease refers to its firmness. Consistency is directly related to the grease's ability to resist leakage and form stable channels within bearings. If consistency is softened significantly, it can lead to leakage and churning of the grease, yielding poor lubrication performance. Since a grease's consistency is possibly its most important property, measuring how it changes with the addition of water can aid the user to properly select a grease for wet environment. Quantification of consistency is discussed in Section 3.2.

ASTM D7342 is the water stability test, which involves prolonged working of a water-contaminated grease for 100,000 strokes. The consistency before and after is measured by the cone penetration test and the difference between these two is reported as the grease's wet shear stability. Although shear stability is a vital grease property, this test alone provides little information on the consistency change due to water since the grease may have poor mechanical stability without it. In addition, the water concentration in grease is fixed at 10% by weight, meaning that some greases can fully absorb this amount (and potentially much more) while others cannot. Similar disadvantages exist for the wet roll stability test—ASTM D8022—which also involves shearing grease and recording initial and final penetration. A key difference is that in the wet roll stability test, the water and grease are not mixed before shearing begins.

Another standard, DIN 51807, seeks to describe a grease's water resistance by coating a glass plate with the grease and submerging it in water. After some time, the plate is removed from the water and both the grease sample and water are visually inspected for discoloration or other physical changes. The sample is then graded on a scale of 0 to 3, with 0 indicating no change and 3 indicating a dramatic change. This test is somewhat subjective, as the observer's experience would likely affect the assigned grade. In addition, visual inspection does not directly yield meaningful information about the actual performance of the grease.

The remaining set of standards related to water-contaminated grease is intended to describe a grease's corrosion prevention properties. The most commonly referenced is ASTM D1743, but there are numerous other comparable tests. These are typically performed by filling a bearing or test strip with grease, submerging it in water (the Emcor test involves rotating the bearing while submerged), and then maintaining it at an elevated temperature for a prolonged length of time. When the test is complete, the sample is visually inspected for changes due to corrosion and assigned a corresponding grade. The goal of these tests is to determine whether a grease is suitable for use in a wet environment based on how effectively it resists corrosion. In practice, however, it may be preferable to simply select a grease that can easily absorb water to avoid having free water in the first place [9].

It is clear that more standards are needed to adequately describe the degree to which water affects the performance of grease. To this end, many researchers have modified existing standards or developed their own tests.

3.2. Tests Capable of Describing Changes Due to Water

Researchers such as Leckner [26], Mistry [13], Nagarkoti [5,37], and others [12] performed numerous tests given by standards for a contaminated and uncontaminated sample, then compared the results. Other tests, including many by Cyriac et al. [11,38] and Bosman et al. [39,40], were not based on standards or developed in-house. A summary of these tests is provided in Table 2. Some of the standards not discussed are the penetration test [41], roll stability test [42], oil bleed test [43], low-temperature torque test [44], 4-ball weld load and weld scar test [45], Timken OK load test [46], and R2F/FE8 lubricity tests [47]. Tests performed that are not based on standards include yield stress/flow point change observation, film thickness measurement, and water absorption capacity testing.

Table 2. Summary of tests capable of describing the changes induced by water.

Test	Procedure	Comments
Wet penetration change	Record cone penetration of grease; mix grease and water then work for 100,000 strokes; record new penetration	Effects of mechanical shear are included in results
Yield stress/flow point change	Use oscillatory tests in rheometer	Different yield stress definitions (crossover stress vs yield stress [48])
Roll Stability	Record cone penetration of grease; add grease and water separately to cylinder then rotate for 2 h; record new penetration	Effects of mechanical shear are included in results
Film thickness	Film thickness machine used	Thick film does not directly indicate good lubricity
Oil bleed	Place grease above a mesh; apply pressure and record the weight of bled substance	The exact composition of bled substance is unclear
Lubricity	Use 4-ball test machinery, Timken load machinery, or FE8/R2F machinery	4-ball tests are simple, but may not accurately reflect rolling bearing applications
Low temperature torque	Completely fill bearing with grease and allow to reach desired temperature; measure torque to start rotating bearing and torque after 60 min of rotation	Results can be heavily affected by water intrusion
Water absorption	Mix proportioned grease and water for sufficiently long time; look for and remove free water	No standardized test and difficult to find exact point of maximum emulsification

The cone penetration test is likely the most common grease test since it is used to assign a grease its consistency grade. Here, a cone is dropped into a grease sample and the depth it penetrates after 5 seconds is used as an indication of consistency. Another way of indicating consistency is by yield stress measurements. There is no standard for this test, but one proposal appears to yield sufficiently repeatable results [48]. However, the stress corresponding to the crossover of storage and loss modulus in oscillating tests is also frequently used.

The roll stability test involves subjecting a grease sample to relatively low shear rates for 2 h. Before and after this time, the grease consistency is measured by the penetration test, and the change in penetration is recorded as the grease's shear stability.

Oil bleed is induced by applying pressure to a grease sample above a mesh and measuring the amount of fluid that passes through. There are a variety of physical devices designed for this purpose, and tests are typically performed at a range of temperatures.

Low-temperature torque is calculated by completely filling a bearing with grease and allowing it to cool to the desired temperature. When the temperature is reached, the torque required to initially rotate the bearing is recorded as the start-up torque, while the torque required to rotate the bearing after 60 min of operation is recorded as the running torque.

The 4-ball tests provide two main results: the weld load and the wear scar. In this test, a stainless steel ball is pressed and rotated against a base of three others in the presence of grease. The test is continued until they "weld" together, and the bearing is considered failed. After the test, the wear scar on the balls is measured. The applied load at which bearing fails and the wear scar are the essential data obtained by this method. The Timken OK load is a similar test that measures the load required to cause the lubricant film separating a rotating cup and stationary block to rupture, leading to scoring and/or seizure.

Although the 4-ball tests are sometimes regarded as adequate tests of lubricity, there is likely excessive slip to accurately mimic real performance for most rolling bearings [9]. Therefore, tests done on such equipment as the R2F or FE8 tend to give more realistic results. These tests involve rotating loaded bearings under particular operating conditions for approximately 20 days while the temperature is monitored. The temperature increase and wear of the rollers and cage are measured at the end of the test and are used to assess grease performance.

Though the worked stability standard, ASTM D7342, puts forward a method for mixing grease and water using a kitchen-type mixer, researchers have used modified procedures for convenience and potentially for improvement. Leckner [26] and Larsson [27] used a DAC600 SpeedMixer at a high speed to mix water into the grease and then used a lower speed to remove entrapped air bubbles, while Cyriac et al. [11] subjected the grease and water to 1,000 strokes in a grease worker. When using a more thorough mixing process, the grease and water become a more homogeneous mixture. However, this process induces more shear, and thus potentially more damage to the microstructure through mechanical degradation [49]. Since this damage is cumulative and its effect decreases in magnitude, the more a grease is worked before a shear test, the less the consistency is affected (by shear) during the test.

Many tests of grease properties can be evaluated with a rheometer. Perhaps the most important is the evaluation of the flow point or yield stress using oscillatory measurements. Generally, there are two main ways of quantifying this: the first is the crossover point of storage modulus and loss modulus and the second is the onset of nonlinearity in the shear stress-strain relationship [48]. These refer to slightly different points, and therefore, the trends of crossover stress and yield stress can be slightly different. Nevertheless, these are important quantities of a grease that indicate consistency.

Another important quantity in lubrication is the thickness of the lubricating film. This is broadly a function of viscosity, but is more difficult to predict for grease because of its complicated structure. Therefore, tests can be done using specialized film thickness measuring machinery. This test can be configured to measure either the fully-flooded or starved film thickness, which are both important considerations when assessing the performance of a grease.

Finally, a property not quantified by any standard is the maximum capacity of a grease to absorb water. This property is difficult to measure with a high degree of accuracy, but is done by mixing grease with a large quantity of water until it can no longer absorb water. The free water is then removed and the concentration of water is then established. Such a test should be investigated in future work and an effective procedure should be established to quantify this potentially valuable measure of water resistance.

4. Typical Test Results

4.1. Test Results

An overview of general test results for the procedures previously mentioned is given in Table 3. Henceforth, greases will be named by their abbreviated thickener type, since the thickener contributes much more to a grease's overall interaction with water than the base oil [3]. However, the influence of additives—although often significant—will not be considered. Thickener types (and abbreviations) mentioned include calcium (Ca), calcium sulfonate (CaS), lithium complex (LiC), and polyurea (PU).

Table 3. Results of relevant tests: pristine grease samples compared to water-contaminated samples.

Test	Typical Results	Comments
Penetration change with water & shear (wet shear stability)	Most greases show increased penetration with water [12,27]; CaS can show reduced penetration [26]	Effects of mechanical shear are included in results
Yield stress/flow point change	Different trends are obtained even for similar grease types [11,12,26]	Results generally correlate with penetration measurements
Wet roll stability	Most results are similar to wet shear stability results [12,26,27]	Effects of mechanical shear are included in results
Water washout	All samples perform worse with water added [26] CaS typically performs the best [5]	CaS sample increased in mass due to water absorption
Water spray off	Samples generally perform worse with water added, though some perform marginally better [26]	CaS may perform better with water added
Water resistance	Samples often appear unchanged [26,27]	Test does not yield information on performance
Film thickness (flooded)	Adding water generally reduces central film thickness [38]	Contaminated and pristine results are similar
Film thickness (starved)	Numerous greases show marginally thicker films with water [38]	Thick film does not directly indicate good lubricity
Oil bleed	Minimal change with water added, but CaS shows decreased bleed with water [26,38]	Results appear to depend strongly on base oil [27]
Corrosion prevention	Absorbed water may not cause corrosive damage [26]; typically sea/process water yields more damage [12]	Performance may be significantly affected by additives
Lubricity	Samples perform worse: reduced weld load, increased wear scar, higher operating temperature [25,26]	4-ball tests quickly quantify lubricity, but may not accurately reflect rolling bearing applications [9]
Low temperature torque	Greases generally show higher start-up and running torque at lower temperatures with water [13,35]	Results are particularly bad when free water is present
Water absorption	Some greases can absorb up to 80 wt.% water; others substantially less [11]	No standardized test and difficult to find exact saturation point

The results of testing generally indicate that water-contaminated grease performs worse than pristine grease. Overall, water-contaminated grease shows worse lubricity, demonstrated by its decreased load-bearing capacity [13,25,31], increased wear scar [25], and destabilized friction coefficient [25]. Since lubricity describes the ability of a grease to lubricate, negative effects must be minimized.

Some exceptions to the performance reduction include some greases providing thicker starved films with water added and CaS showing decreased oil bleed and less washout with water added. Research shows that the thicker films observed with water added do not necessarily indicate better lubricity [26]. In fact, it appears the lubricity was worse according to the R2F tests. However, CaS greases are frequently used in wet environments due to their unique behavior [17], for they can even show improved performance (in specific tests) with water. These greases are known to absorb large quantities of water and often become stiffer with water added. Interestingly, tests by Hudedagaddi et al. [25] indicate that CaS does not lose load-bearing capacity when contaminated with under 20 wt.% water.

Upon examining the tests and results, it may be concluded that the most meaningful factors likely include lubricity, water washout, consistency change, and corrosion prevention. The other tests either provide little information on performance or are mostly subsumed by those mentioned above. Since good lubricity is ultimately the goal of grease, a test of lubricity change induced by water is arguably the most important in describing the effects of water on the lubricant. Nevertheless, there are other properties affected by water contamination that must be considered in selecting a grease. It is, therefore, a tradeoff among all relevant properties.

4.2. Discussion

Since washout is a predominant concern for wet environments, it is important to consider how a grease may perform better in its standardized test. Good washout and spray off performance is largely dictated by cohesion and adhesion (together forming tackiness), so additives are used to individually increase of these [34]. Tests by Nagarkoti et al. [5] showed that higher viscosity base oil led to better washout performance regardless of the grease type. Another important consideration is adding a high molecular weight polymer or a hydrocarbon resin polymer. These were shown to significantly improve washout performance [5]. In addition, the total base number is believed to determine washout and spray off performance for CaS [5], so increasing the total base number is expected to lead to better washout performance. Since base oil viscosity affects film thickness, using the right viscosity is important. To balance out washout performance with film thickness, the base oil and polymer additives can be modified to produce an ideal balance. Using a higher grade will reduce washout, but can also lead to clogging of supply lines, so finding the right balance is important.

When attempting to manufacture a grease with excellent corrosion prevention properties, it is necessary to include a significant amount of corrosion-inhibiting additives. These additives, however, will often have a detrimental effect on lubrication performance. This is yet another example of where an appropriate balance must be considered.

An interesting result obtained by Leckner [26] was that the LiC grease became so tacky and thick in the R2F test that the test rig eventually stopped working. For such a situation where an inadequate grease is selected, adding water to the grease could actually prolong the life of the machine by reducing the overall tackiness. In another example where water improved performance, Leckner observed a water-contaminated Ca grease actually leading to significantly reduced wear. Despite this finding, however, the other negative aspects of water contamination would likely render long-term operation of an intentionally contaminated setup impractical.

Though examining the change to grease consistency induced by water may prove to be among the simplest ways of assessing the degradation of general performance, most relevant tests—including the wet stability standard—include the effects of mechanical shear. Even in other tests discussed, the process of mixing water into grease likely induces a significant degree of mechanical degradation in the grease. This is partially reflected in the roll stability results, which indicate a lower change in consistency for the water-contaminated grease. Since grease properties change most significantly during the beginning of shearing [49], much of the penetration change is likely due to the shear from the mixing process and not from the water.

Overall, there are many tests capable of assessing the water-resistance of grease, but it is impractical to run every test for every grease formulation. It would be useful, however, for a "water-resistant" grease to be aimed at a particular use and include relevant test results on its data sheet. For instance, equipment operating in below-freezing conditions face the possibility of ice network formation, severely increasing the start-up and running torque needed to operate a bearing. However, if a grease is only intended for use at moderate to high temperatures, performing such a test would be superfluous. Generally, most tests demand access to specialized equipment and significant time investment. Therefore, it is desirable to have simpler, more accessible tests that are still able to provide meaningful results.

5. Future Recommendations

Many of the experiments presented in this paper provide important characteristics of grease samples that are not investigated by grease manufacturers. It is reasonable that most manufacturers do not extensively test the effects of water on their greases since there are few standards directly involving water (those covered in Section 3.1). Therefore, it is recommended that the following be explored so that new tests capable of providing meaningful results can be developed.

5.1. Recommended Tests

Other than those standards discussed in Section 3.1, simply performing general grease performance tests with contaminated and uncontaminated samples then comparing the results is another way that grease water resistance can be quantified. Depending on the intended use of a grease, appropriate tests should be selected and presented on its data sheet. A simple methodology for presenting this data could be standardized as well.

As an indication of change to one of a grease's most basic properties, penetration change induced by water may be the simplest meaningful measure of water resistance. Though a "wet stability" standard exists, this standard inadvertently includes the mechanical stability of a grease. Therefore, it is recommended that a pristine and water-contaminated sample be sheared the same amount before measuring consistency to neglect the influence of mechanical stability. This means that whatever process used to mix water into grease should be performed on a pristine grease to induce a similar amount of microstructural damage from shear. Aside from the consideration of shear from the mixing process, this comparison method is used—notably by the automotive industry [12]—but not ubiquitously so.

It is recommended that new tests be developed, examined for utility, and potentially standardized. Such tests may examine properties such as demulsibility, water saturation point, water absorption potential, water absorption facility, and water penetration depth. A demulsibility test would examine how easily water can be removed from grease. One may consider the influence of grease type, water concentration within the grease, removal method (exposure to air, removal by shear, effects of chemical reactions), and other variables. The water saturation point could be found through chemical analysis or by visual inspection of the onset of emulsification during agitation. The water absorption potential could be found through a method similar to the one used by Cyriac et al. [11] or by a modification of the procedure used by Larsson et al. [27]. The water absorption facility may be found by examining the nature and concentration of surface-active components of grease through inspection of hydrophilic nature or perhaps by quantifying the amount of water absorbed without shear. Finally, the water penetration depth could be explored by examining the depth that water may penetrate into a slab of grease. A procedure may be developed based on the work by Dittes et al. [14].

5.2. Additional Research

There are various areas on the subject of grease water resistance that demand more research. Other than the development of new tests for appropriate quantification of changes induced by water, investigations should be made into the interaction of grease and water. Notably, the transport of water within grease should be examined. More research on the slow and fast diffusion components [27] of water within grease may be linked to a "water penetration depth" over a given time scale. An investigation may also be launched into the reverse, or a "water drying depth" over a given time scale. Examining the composition of the dry layer and considering the amount of water, how much is dissolved and how much is emulsified, and what is the oil composition can give details on the nature of grease lubrication that could be used to improve wet performance.

Rather than to modify existing tests or develop new ones, another option is to improve the data collection. Something as complicated as corrosion can be difficult to quantify for comparison, and results are often reported in terms of a grade given by visual inspection. Since the Emcor test has somewhat poor repeatability—in part due to its grading system—a proposal for a more effective method for quantifying corrosion was put forward by Galary [50]. This is an example of how additional research can lead to improved test results without any modifications to the general experimental procedure.

The main objective of grease is to provide a sufficiently thick film with high lubricity to separate moving parts through a wide range of operating conditions. Even if there is a thick film, highly oxidized or contaminated grease will have poor lubricity and, therefore, provide poor lubrication. As water becomes entrained within grease, its overall lubricity changes, which should be considered when evaluating a grease's water resistance. Since the actual measurement of lubricity is quite difficult and time-consuming, quantitative correlations between overall lubricity and more basic properties—such as consistency, tackiness, and film thickness—should be established. This would facilitate the development of a practical model of grease degradation, which includes the effects of water contamination.

Overall, the criteria for water resistance as a whole must be improved. Nearly every grease type has some formulation marketed as water-resistant, but this is often done without providing a quantitative justification. It is claimed that aluminum complex greases are highly water-resistant [51], though experimental results—particularly those of Authier and Herman [12]—seem to indicate they are not. In fact, these tests showed two different aluminum complex greases to have poor washout performance, low mechanical stability in the presence of water, and poor corrosion resistance. Additional research on the connection between specific water resistance properties and their application to machine performance would help identify which properties are relevant for a given application. After this identification, tests suitable for describing wet performance can be done on a particular grease and presented to consumers so as to justifiably describe the grease as water-resistant.

6. Conclusions

There is a lack of information available to users about the capabilities of greases in wet environments. Since water affects many different properties of grease, it is difficult to describe the overall water-resistance of a grease succinctly. Therefore, numerous relevant properties and corresponding tests for their evaluation have been identified. New recommended tests include demulsibility, water saturation point, water absorption potential, water absorption facility, and water penetration depth tests. In addition to these recommendations, existing grease tests should also be used to compare water-contaminated to uncontaminated samples. These tests are potentially useful in describing the changes to a grease's performance while contaminated with other contaminants or after undergoing some other form of degradation.

Research on the underlying mechanics of grease-water interaction, especially on water transport within grease, would likely provide valuable information on how water causes changes to lubrication performance. Additionally, it is desirable to understand how water affects the overall degradation of grease. An investigation of how water affects mechanical and chemical degradation of grease could yield an effective model for grease life prediction in wet environments. Unlike existing standardized tests, those investigating the effect of water on mechanical degradation should consider that in order to emulsify water, some degree of mechanical shear is required, likely inducing significant structural damage.

There are many properties that are relevant when considering a grease's water resistance, and there is no single definition that determines which grease is the most water-resistant in all applications. In fact, by formulating a grease to perform well in some tests, it is likely going to perform worse in others. Therefore, it is important to understand how a device is lubricated so that the user can identify the most pertinent water-resistant characteristics and seek a grease with the right balance of properties. In short, a water-resistant grease is one with the right combination of properties to best suit a particular wet environment.

Author Contributions: A.G. is the main author of the paper who received significant guidance, insight, and technical assistance from M.K. during writing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Fitch, J. How Water Causes Bearing Failure. In *Machinery Lubrication Magazine*; Noria Corporation: Tulsa, OK, USA, 2008.
2. Duncanson, M. Detecting and Controlling Water in Oil. In *Machinery Lubrication Magazine*; Noria Corporation: Tulsa, OK, USA, 2005.
3. Cantley, R.E. The Effect of Water in Lubricating Oil on Bearing Fatigue Life. *ASLE Trans.* **1977**, *20*, 244–248. [CrossRef]
4. Sedelmeier, G. Managing Water Contamination to Maintain Effective Steel Mill Lubrication. In *Machinery Lubrication Magazine*; Noria Corporation: Tulsa, OK, USA, 2008.
5. Nagarkoti, B.; Johnson, B.; Shah, R. Water Washout Remedies. *NLGI Spokesm.* **2020**, *84*, 75–83.
6. Faci, H.; Haspert, J. Effect of Water on Grease Performance and Lubrication for Life in Sealed Bearings. *NLGI Spokesm.* **2014**, *77*, 8–15.
7. Hink, R. Best Lubrication Practices for the Paper Industry. In *Machinery Lubrication Magazine*; Noria Corporation: Tulsa, OK, USA, 2005.
8. Kaperick, J.; Aguilar, G.; Lennon, M. "Rust Never Sleeps" An Investigation of Corrosion in Lubricating Grease. *NLGI Spokesm.* **2016**, *79*, 8–15.
9. Lugt, P. Modern advancements in lubricating grease technology. *Tribol. Int.* **2016**, *97*, 467–477. [CrossRef]
10. NSK. *Roll Neck Bearing Manual*; NSK: Shinagawa City, Tokyo, Japan, 2015.
11. Cyriac, F.; Lugt, P.M.; Bosman, R. Impact of Water on the Rheology of Lubricating Greases. *Tribol. Trans.* **2016**, *59*, 679–689. [CrossRef]
12. Authier, D.; Herman, A. Calcium Sulfonate Carbonate Greases: A Solution to Water Resistance. In Proceedings of the 25th Annual Elgi Meeting, Amsterdam, The Netherlands, 20–23 April 2013.
13. Mistry, A. Performance of Lubricating Greases in the Presence of Water. *NLGI Spokesm.* **2005**, *68*, 9–15.
14. Dittes, N.; Marklund, P.; Pettersson, A. Mixing Grease with Water. In Proceedings of the European Conference on Improvement in Bearing Technology, Nieuwegein, The Netherlands, February 23–24 2015.
15. DIN 51907-1. *Testing of Lubricants—Test of the Behaviour of Lubricating Greases in the Presence of Water—Part 1: Static Test*; Deutsches Institut Fur Normung: Berlin, Germany, 2020.
16. ASTM D7342-15. *Standard Test Method for Prolonged Worked Stability of Lubricating Grease in Presence of Water (Water Stability Test)*; ASTM International: West Conshohocken, PA, USA, 2015.
17. ASTM D8022-15. *Standard Test Method for Roll Stability of Lubricating Grease in Presence of Water (Wet Roll Stability Test)*; ASTM International: West Conshohocken, PA, USA, 2015.
18. ASTM D1264-18e1. *Standard Test Method for Determining the Water Washout Characteristics of Lubricating Greases*; ASTM International: West Conshohocken, PA, USA, 2018.
19. ASTM D4049-16. *Standard Test Method for Determining the Resistance of Lubricating Grease to Water Spray*; ASTM International: West Conshohocken, PA, USA, 2016.
20. ASTM D1743-13. *Standard Test Method for Determining Corrosion Preventive Properties of Lubricating Greases*; ASTM International: West Conshohocken, PA, USA, 2018.
21. ASTM D6138-19. *Standard Test Method for Determination of Corrosion-Preventive Properties of Lubricating Greases Under Dynamic Wet Conditions (Emcor Test)*; ASTM International: West Conshohocken, PA, USA, 2019.
22. ASTM D5969-11. *Standard Test Method for Corrosion-Preventive Properties of Lubricating Greases in Presence of Dilute Synthetic Sea Water Environments*; ASTM International: West Conshohocken, PA, USA, 2016.
23. ASTM D7038-19. *Standard Test Method for Evaluation of Moisture Corrosion Resistance of Automotive Gear Lubricants*; ASTM International: West Conshohocken, PA, USA, 2019.
24. ASTM D4048-19a. *Standard Test Method for Detection of Copper Corrosion from Lubricating Grease*; ASTM International: West Conshohocken, PA, USA, 2019.
25. Hudedagaddi, C.; Raghav, A.; Tortora, A.; Veeregowda, D. Water molecules influence the lubricity of greases and fuel. *Wear* **2017**, *376–377*, 831–835. [CrossRef]

26. Leckner, J. Water + Grease = Fatal Attraction? In Proceedings of the 25th ELGI Annual General Meeting, Amsterdam, The Netherlands, 20–23 April 2013.
27. Larsson, J.; Ardai, R. The Effect of Water Ingress on the Thickener Structure in Bio-Based Greases. *NLGI Spokesm.* **2018**, *81*, 6–18.
28. Eachus, A.C. The trouble with water. *Lubr. Eng.* **2005**, *61*, 34–38.
29. Noria Corporation. Water in Oil Contamination. In *Machinery Lubrication Magazine*; Noria Corporation: Tulsa, OK, USA, 2001.
30. FAG Kugelfischer Georg Schäfer, A.G. *Rolling Bearing Lubrication*; Publ. No. WL 81 115/4 EA; FAG Kugelfischer Georg Schäfer AG: Schweinfurt, Germany, 2002.
31. Ducom Instruments. *The Effect of Water Molecules on Lubricity of Greases and Fuel*; AZoM: Mona Vale, Australia, 2017.
32. Schatzberg, P.; Felsen, I. Effects of water and oxygen during rolling contact lubrication. *Wear* **1968**, *12*, 331–342. [CrossRef]
33. Echin, A.I.; Novosartov, T.; Kondrat'eva, T. Effect of Water on Lubricating Properties of Synthetic Oils. *Chem. Technol. Fuels Oils* **1983**, *19*, 80–83. [CrossRef]
34. Fish, G. *Calcium Sulfonate Greases: Performance and Application Overview*; Lubrisense White Paper #16; The Lubrizol Corporation: Wickliffe, OH, USA, 2014.
35. Cyriac, F.; Lugt, P.; Bosman, R. The Impact of Water on the Yield Stress and Startup Torque of Lubricating Greases. *Tribol. Trans.* **2017**, *60*, 824–831. [CrossRef]
36. Axel Christiernsson. *H2O, Friend or Foe? Lubrisense White Paper #8*; Axel Christiernsson: Nol, Sweden, 2008.
37. Nagarkoti, B. Water resistance property of greases—An outlook. In Proceedings of the NLGI-India 12th Lubricating Grease Conference, Panaji, India, 28–30 January 2010.
38. Cyriac, F.; Lugt, P.; Bosman, R.; Venner, C. Impact of Water on EHL Film Thickness of Lubricating. *Tribol. Lett.* **2016**, *61*, 23. [CrossRef]
39. Bosman, R.; Lugt, P.M. The Microstructure of Calcium Sulfonate Complex Lubricating Grease and Its Change in the Presence of Water. *Tribol. Trans.* **2018**, *61*, 842–849. [CrossRef]
40. Zhou, Y.; Bosman, R.; Lugt, P. On the Shear Stability of Dry and Water-Contaminated Calcium Sulfonate Complex Lubricating Greases. *Tribol. Trans.* **2019**, *62*, 626–634. [CrossRef]
41. ASTM D217-19b. *Standard Test Methods for Cone Penetration of Lubricating Grease*; ASTM International: West Conshohocken, PA, USA, 2019.
42. ASTM D1831-19a. *Standard Test Method for Roll Stability of Lubricating Grease*; ASTM International: West Conshohocken, PA, USA, 2019.
43. ASTM D6184-17. *Standard Test Method for Oil Separation from Lubricating Grease (Conical Sieve Method)*; ASTM International: West Conshohocken, PA, USA, 2017.
44. ASTM D1478-20. *Standard Test Method for Low-Temperature Torque of Ball Bearing Grease*; ASTM International: West Conshohocken, PA, USA, 2020.
45. ASTM D2783-19. *Standard Test Method for Measurement of Extreme-Pressure Properties of Lubricating Fluids (Four-Ball Method)*; ASTM International: West Conshohocken, PA, USA, 2019.
46. ASTM D2509-20. *Standard Test Method for Measurement of Load-Carrying Capacity of Lubricating Grease (Timken Method)*; ASTM International: West Conshohocken, PA, USA, 2020.
47. Lugt, P. Grease Qualification Testing. In *Grease Lubrication in Rolling Bearings*; Wiley: Hoboken, NJ, USA, 2013; pp. 339–375.
48. Cyriac, F.; Lugt, P.; Bosman, R. On a New Method to Determine the Yield Stress in Lubricating Grease. *Tribol. Trans.* **2015**, *58*, 1021–1030. [CrossRef]
49. Gurt, A.; Khonsari, M. The Use of Entropy in Modeling the Mechanical Degradation of Grease. *Lubricants* **2019**, *7*, 82. [CrossRef]
50. Galary, J. Bearing Corrosion Analysis Using Machine Vision and Computational Algorithms. *NLGI Spokesm.* **2018**, *82*, 16–29.
51. The Timken Company. *Timken Tapered Roller Bearing Catalog*; The Timken Company: North Canton, OH, USA, 2016.