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FULL-SCALE HOPPER TESTING OF LIME FLOWABILITY

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Abstract

The Civil Aviation Authority (CAA) requires that topdressing aircraft are capable of jettisoning 80% of the aeroplane's maximum hopper load within five seconds of the pilot initiating the jettison action. Three different devices were tested for their ability to assess flowability of 13 samples of lime from different quarries. Overall, the 3 test devices (tilting cylinder, upright cylinder with trap door, scale hopper) provided a conservative measure of flowability, in that the lime would get stuck in these devices before flowability in the full-scale hopper testing started to degrade. It was found the compressibility of dried lime correlated with its flowability. As the moisture content of the lime is increased, its compressibility also increases. The average compressibility of the lime samples at flow failure was 20%, which agrees with previously published criteria for good flowability. In order to validate the sampling devices, which used 2-5 kg of lime, comparison testing was performed on two full scale aircraft hoppers, holding 1.2-2.0 tonne of aerial grade lime. Full-scale hopper testing was not able to reproduce bridging and lime holding up in the hopper, but did show a decrease in flowability as more water was added to the lime. Measurements of the 3-axis vibrations in topdressing aircraft in normal operations were recorded. RMS vibration amplitudes of approximately half the acceleration due to gravity were recorded during take-off from a rough airstrip. It is believed that bridging of lime in the full-scale hopper tests was not obtained even with 9% moisture content because the hoppers were not shaken to the same level of vibrations seen in practice.

Keywords

Topdressing, flowability, lime, vibrations

Introduction

A previous project (Post, 2019) examined different devices to determine if any were fit for purpose to test a sample of lime for flowability before the lime is loaded into the airplane hopper. This study found that the 2 kg test cylinder correlated well with the traditional pilot's hand squeeze test for clumping, but there was a need to validate this method with full-scale hopper testing, which led to the current project. Further, the previous study found that the uniformity index (UI) was the parameter of the particle size distribution that best correlated with flowability. The Civil Aviation Authority (CAA) requirement for flowability [Rule Part 137 Subpart C – Special Flight Rules, 137.103 (a)(2)], requires:

> "the aeroplane is equipped with a jettison system that, in accordance with D.5, is capable of discharging not less than 80 percent of the aeroplane's maximum hopper load within five seconds of the pilot initiating the jettison action."

For granulated materials that are nearly uniform in size and of spherical shape, this requirement is not a problem, as such materials have good flowability. Agricultural lime however, is typically a fine powder which can have poor flowability, particularly when wet. Among the complications of testing for flowability is the possibility that a solid fertiliser (or mix of fertilisers) appears satisfactory before loading into the aircraft, but loses fluidity and becomes unsafe after loading, most likely due to vibrations causing compaction as the plane taxis and completes its take-off roll, often on bumpy airstrips. In particular, the vertical accelerations may be significant for load compaction. Thus, the current study also aims to better characterise the vibrations in topdressing airplane hoppers and develop a test procedure that adequately simulates such vibrations.

In 1980 Maber noted “numerous cases where failure to jettison the load was an important contributing factor to the ensuing crash.” and such incidents continue to the present time, as can be found by reviewing CAA’s incident reports where failure to jettison lime is implicated (CAA, 2001; CAA, 2006b; CAA 2008). Maber tested lime flow on a full-scale hopper from a Fletcher FU24-90, which had an outlet size of 440 by 520 mm with the doors fully open. Among the key findings and observations from Maber (1980) were:

- “Changes in moisture content tend to have a more significant effect on flow properties if the lime is very finely ground, particularly when soft limestone rock is used.”
- “Once the hopper has been filled, up to 4 minutes may elapse while the aircraft takes off, climbs and flies to the sowing area.” During this time vibrations of varying frequency and amplitude are imparted to the hopper contents. The effect of these vibrations is to consolidate the hopper contents, thereby reducing the flowability.
- Vibrating the test hopper for 2 minutes severely reduced the amount of material jettisoned in 5 seconds.
- For higher moisture content the effects of vibration on flowability are more severe.
- “The particular variables that most affect the flowability of agricultural lime are moisture content and particle size.”

Yule & Flemmer (2005) recorded vibrations in a hopper, but the amplitude seems very small, only 0.01 g of acceleration, while the more recent measurements of Zanatta et al. (2015) of vibrations experienced by agricultural pilots, show much larger vibrational accelerations, with peaks over 1.0 g.

Materials and Methods

Laboratory Testing equipment

The previously constructed test cylinder had approx. 2 kg capacity and correlated well with a hand squeeze test for clumping. However, this design was questioned as it required the sample to be turned upside to check the flowability, an operation that does not occur in practice. Therefore, a modified cylinder design was introduced that uses a trap door mechanism at the bottom so the lime does not need to be turned around. In addition, a sample-testing device created from a piece of PVC downspout, as shown in Figure 1. This “scale model hopper” holds approximately 5 kg of lime. In total, 3 different devices were used to test the flowability of the lime samples in the lab testing (shown in Figure 2). These devices were also used alongside the full-scale hopper testing.

Figure 1: Three different devices for testing lime samples: scale model hopper made from PVC downspout (left) and two cylinders for testing flow from top and bottom.

Full-scale Testing equipment

Full-scale hopper testing was conducted at two locations: At Ravensdown in Wanganui on 7 Aug 2019, using an extra hopper (Figure 2), and at SuperAir in Hamilton on 20 Aug 2019 using the aircraft shown in Fig. 3. At Ravensdown Websters and Taueru limes were tested, and Supreme lime was tested at SuperAir. At both locations a GoPro camera was mounted facing down towards the hopper outlet. A 10 L water sprayer was used for wetting the lime, and a loader truck and shovels were used for mixing the water into the lime. 0.5 kg samples of the lime taken from the un-used piles were placed in sealed glass jars to be taken to Lincoln Agritech for measurements of moisture content and particle size distribution. Water was added to the dropped lime on the ground in increments of 1% by mass (e.g. for 1 tonne bag of lime this will be 10 L of water).

Figure 2: Full-scale hopper testing at Ravensdown in Wanganui.

Figure 3: SuperAir plane in Hamilton with 1.2 tonne hopper used for testing.

Vibration Analysis

A smartphone with the Phyphox app was used to record vibrations in the aircraft (Fig. 9). It records acceleration in all 3 axes as a function of time, where z is perpendicular to phone, y is along long axis of phone, x is sideways to phone. The accuracy and sampling frequency depends upon the phone being used. Data was taken at 252 Hz (Ravensdown), and 100 Hz (SuperAir). The accuracy of the scale of the measurements is shown in that the average accelerating in the vertical direction is near the expected value of 9.8 m/s^2. Vogt & Kuhn (2013) report accuracy in acceleration measurements with an older model iPhone of 6%. Data was segmented into regions of interest (take-off, in-flight). Average root-mean-squared (RMS) values calculated for each time segment and a Fast Fourier Transform (FFT) analysis used to identify dominant frequencies of vibration in the data.

Results and Discussion

The Webster's lime proved more resilient to moisture addition than the Taueru lime, which was consistent with previous laboratory testing. Both limes had approximately 4% initial moisture content based on laboratory analysis of samples. At the highest moisture level tested with the Webster's lime (10%) quite a bit of lime stuck in the corners (Fig. 4), but in all cases the lime did flow out of the hopper and did not get hung up.

Figure 4: Screen shot of residual lime in hopper for highest moisture level tested (10%) with Webster's lime.

During the testing the scoop of the loader truck was pushed up against the frame for the standalone hopper and the shaker on the loader was used to vibrate the lime-filled hopper. It was noted that the mound of lime at the top of the hopper did not flatten with shaking and the load did not consolidate to any measureable degree due to the shaking. Since it was not possible to measure how long it took for 80% of the load to drop with the equipment available, the time for full load to drop recorded manually with a stopwatch during testing. These values were within 0.5 s of values determined from later analysis of the videos. The CAA jettison test time was then estimated by multiplying the time to drop the full load by 0.8. It was noted that the load dropped was not necessarily 100% of the full load, particularly as at higher moisture levels more of the lime stuck in the corners of the hopper (as in Fig. 4). Figure 5 shows the estimated jettison times as a function of lime moisture content for both limes tested. For most of the cases tested this exceeded the 5.0 s CAA requirement, but in all cases the lime flowed freely from the hopper without hanging or the need for shaking. The Webster's lime exhibited very consistent behaviour up until 75 L of water was added to the 2-tonne pile (7.9% total water content by mass). At this point the lime formed one solid lump when squeezed in the hand (at lower moisture levels it would make 2 or more lumps). The pilot said at 45 L of water added (6.4% water content) he judged the lime to be marginal and would test it in the loader before topdressing it in the field, and he probably would not use the lime at the point where 60 L of water was added to the pile (7.1% total moisture content). The scale hopper test failed at 45 L of water added (6.4% moisture) and the cylinder tests failed at 60 to 75 L water added (7.1-7.9% moisture). The flowability of the Taueru lime degraded more quickly with moisture content than the Webster's lime, and so it was tested to a lower total moisture level. At 45 L of water added (6.1% moisture) it was judged to fail the hand squeeze test (formed 1 lump). It failed both the cylinder and scale hopper tests at 30 L of water added (5.3% moisture).

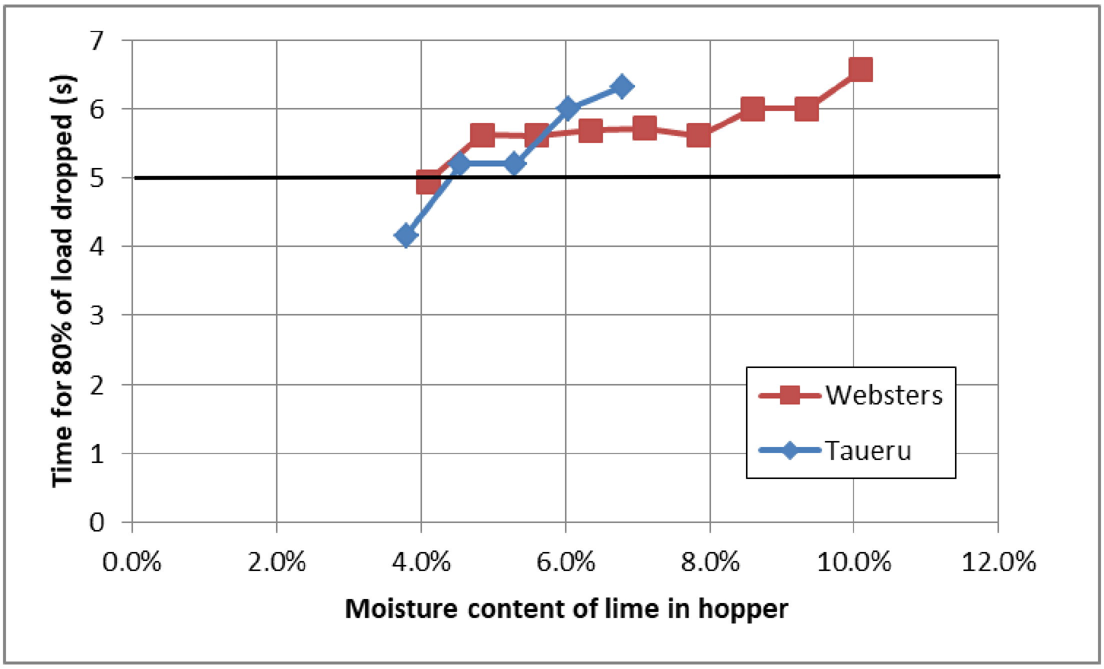

Figure 1: Time for 80% of the load to drop from the hopper as a function of moisture content for 2 different limes tested at Wanganui. Each data point is one measurement.

At SuperAir in Hamilton two 500-kg bags of Supreme lime were used in the testing. It was discovered after the testing by weighing the load in the hopper that the mass of lime used was around 1300 kg. Given that the bulk density of lime is higher than most fertilisers, the bags were likely filled to over the nominal 500 kg mass. The Supreme lime used exhibited the interesting behaviour that the flowability improved after a certain amount of water was added, and then the flowability degraded again above 6% moisture content (Fig. 6). At 50 L of water added to the 1.3-tonne lime load (6.1% total moisture content), the pilot reported that the hopper door was hard to open, but he would still find the lime suitable for topdressing. At 70 L of water added (7.7% moisture), the lime made 1 lump when squeezed. Another pilot who was present at the time said he would not use the lime in that state, and the lime failed to discharge from the scale hopper. At 90 L of water added (9.2% moisture) the lime failed in the test cylinder, and was also difficult to get out of the loader and into the plane, though it still came out of the plane hopper in a reasonable amount of time (6 s).

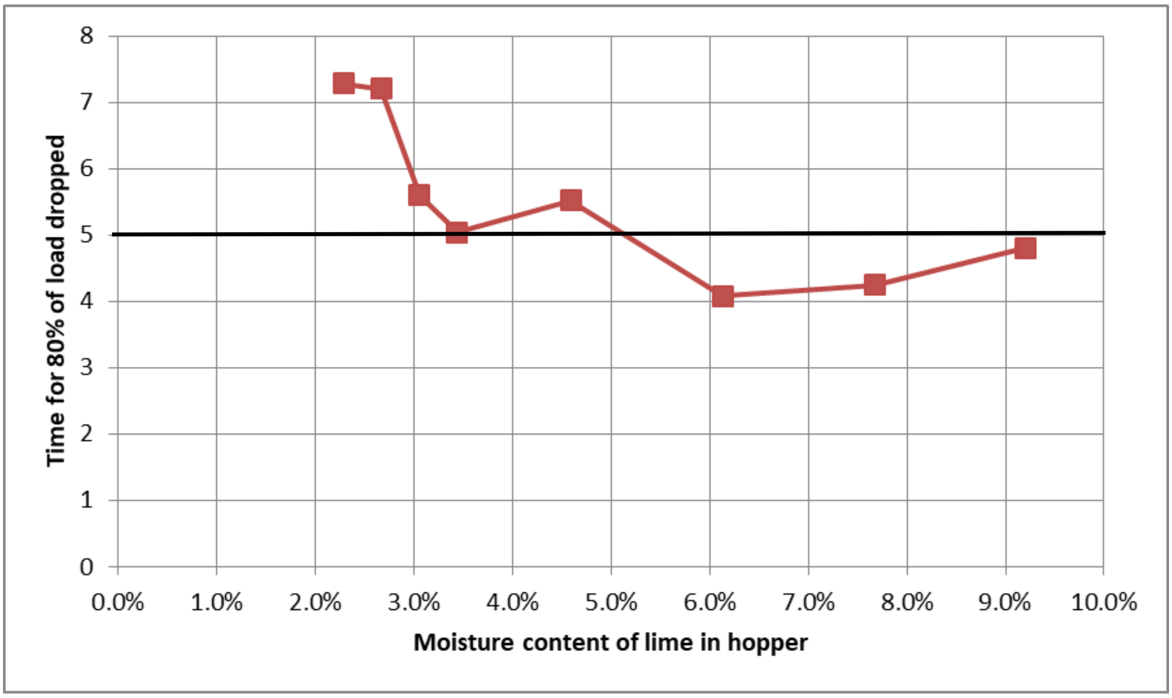

Figure 2: Jettison times for Supreme lime dropped from SuperAir plane in Hamilton as a function of lime moisture content. Each point is one measurement.

Figure 73: Samples of Supreme lime (left) from before start of testing, and (right) after testing.

The unexpected behaviour of the Supreme lime flowability with increasing water content appears to be due to unintended particle agglomeration. Figure 7 shows that the initial condition of the lime was quite different from the final state. Further, after the before and after-samples of the lime were dried, the sieving analysis showed that most of the fine particles of the lime had been removed during the course of the testing. The median particle size increased from 538 to 923 µm, the fraction of particles less than 125 µm decreased from 18.4% to 1.9%, and the uniformity index (UI) also increased from 2.0 to 11.2. A review of the literature suggests wet agglomeration is responsible for the change in particle size distribution. Mehos & Kozicki (2011) and Kale et al. (2011) show that a wet agglomeration process that applies a shear force to the powder can be used to improve the flowability. In a test with powdered potash they found the agglomerated powder had decreased cohesion and wall friction and increased bulk density, all of which serve to improve flowability and reduce chances of arching in a hopper.

Sieving data

Additional samples of lime were analysed in the laboratory to supplement testing from the previous project (Post, 2019). For each lime sample the particle size distribution and bulk density were measured, and the flowability tested with two 2-kg test cylinders. Table 1 shows a summary of the laboratory testing of the 13 lime samples, tested in 2018 and 2019. Unlike the previous testing (Post, 2019), this time the uniformity index (UI) did not show a good correlation with the moisture level at flowability failure. The compressibility continues to show a strong, but not perfect, correlation with flowability, as the less compressible a lime is, the lower its ability to re-arrange its particles to form a cohesive bridge in the hopper. The strongest correlation was with the compressibility of the dried lime sample, with an R^2 of 0.5. This correlation in shown in Figure 8. It is also noted that the UI values here are smaller than what is typically reported from Spreadmark testing. This may be due to (1) limes used for Spreadmark testing are typically not aerial-grade limes, and (2) the sieve set used in this project contains 12 sieve trays, while Spreadmark testing typically only uses 9 compartments, with a smallest division of 0.5 mm since it is designed to analyse larger fertiliser particles, so a more accurate measure of the uniformity index is obtained in the laboratory sieve analysis.

Table 1: Lime properties and testing results. Table sorted by the amount of moisture that must be added to stop flowability for each lime (denoted 'Moisture at flow failure').

Lime Sample	Dry bulk density (kg/L)	Dry tapped density (kg/L)	Median Size (µm)	UI	Fraction under 125 µm	Compressibility at flow test failure	Moisture at flow failure
1	1.20	1.30	252	4.4	18.7%	17.2%	5.1%
2	1.50	1.62	351	4.2	14.3%	22.0%	4.2%
3	1.29	1.37	177	3.9	23.6%	20.0%	4.1%
4	1.35	1.50	166	1.7	36.5%	18.1%	4.0%
5	1.22	1.33	249	3.0	13.8%	22.0%	3.1%
6	1.56	1.70	292	2.0	24.9%	20.0%	3.0%
7	1.61	1.88	451	3.0	17.4%	24.2%	3.0%
8	1.39	1.55	390	1.8	20.5%	12.8%	2.0%
9	1.47	1.64	244	1.8	23.4%	17.2%	2.0%
10	1.68	1.98	376	4.6	21.9%	27.1%	2.0%
11	1.72	1.95	346	3.3	25.2%	21.0%	2.0%
12	1.59	1.90	166	3.5	31.1%	26.1%	1.0%
13	1.45	1.64	199	1.8	33.2%	17.6%	1.0%
Mean	1.46	1.64	281	3.0	23.4%	20.4%	2.8%

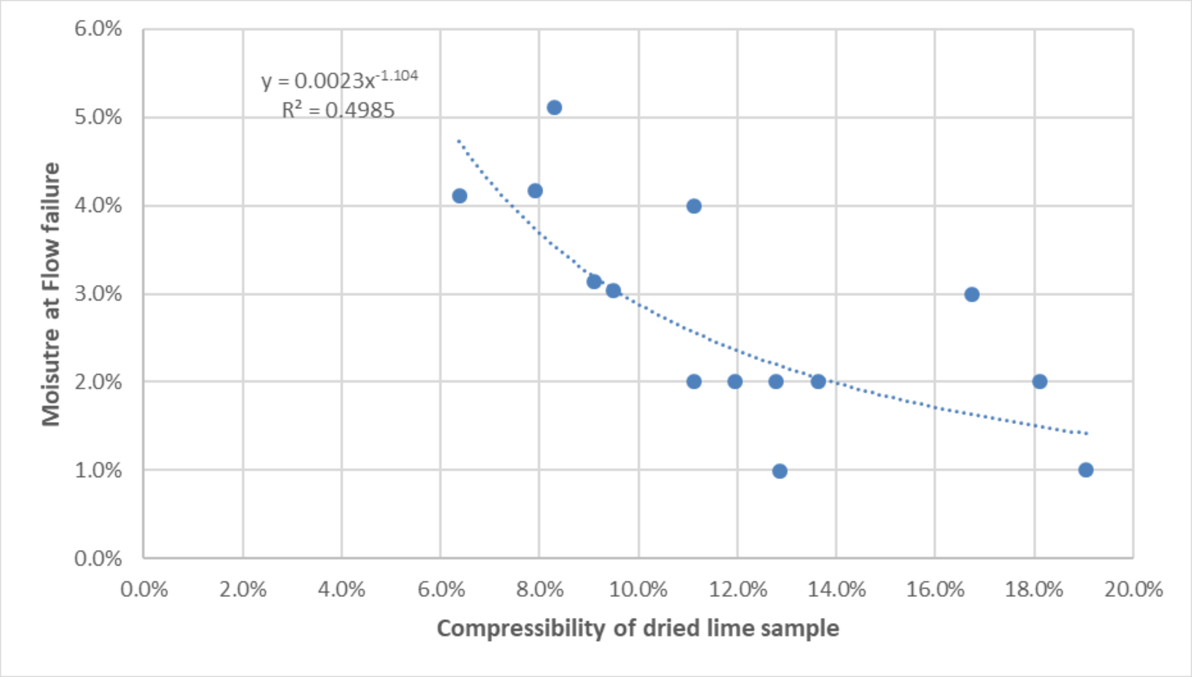

Figure 8: Correlation between the compressibility of dried lime (0% moisture) and the moisture level required for flow failure for all lime samples tested.

Compressibility of lime can be calculated as:

$$Compressibility = \frac{tapped\ density - bulk\ density}{bulk\ density}$$

The average compressibility at flow failure for these twelve limes is 20.4%. This compares very well with the finding in the literature of the previous project that the borderline between free flowing and non-free flowing is approximately 20–21% compressibility (de Campos & Ferreira, 2013).

Figure 9 shows the effects of moisture content on compressibility. It can be seen that increasing the moisture content almost always increases the compressibility. Adding more water causes the lime to “fluff up” and have a lower bulk density, but when the lime is tapped, shaken, or vibrated, it compresses down to its tapped density. A dark line has been drawn across the graph to show the 20% compressibility level that serves as a boundary between good and poor flowability. So another way to assess the flow quality of a lime graphically is the point where its compressibility curve crosses the 20% line. The further to the right (higher moisture content) this occurs, the better the flowability of the lime and resilience to moisture content in the field. In other words, one way to assess quality of lime is how much moisture is needed to increase the compressibility to over 20%. It was found in the laboratory testing of the lime samples that the flowability outcome from the test cylinders and scale hopper was dependent upon the amount of shaking imparted to the lime.

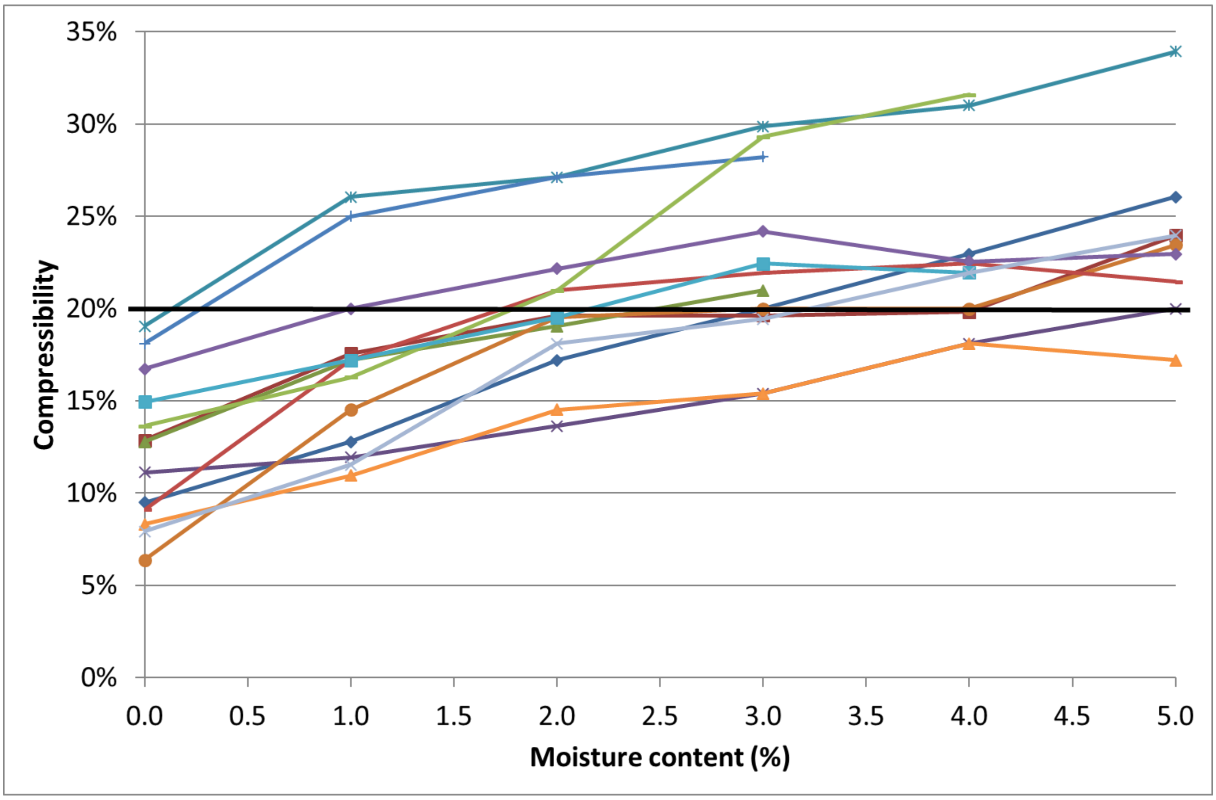

Figure 9: Effect of moisture on compressibility of limes, for same range of samples as in Table 1. Increased compressibility correlates with decreased flowability

Figure 10 shows an example of accelerations measured in the vertical direction during a takeoff event from a sowing run of a Aerowork plane, and Figure 11 the corresponding frequencies from those accelerations. Frequencies were calculated using a standard Fast Fourier Transform (FFT) program in Matlab. For the two takeoffs in the Ravensdown data, the average accelerations were 4.52 m/s^2 and 4.57 m/s^2. For the in-flight recordings the average accelerations from the vibrations were around 3.0 m/s^2. For all the data segments there was a peak in the acceleration at 100 Hz, corresponding to the turbine engine running at 2000 RPM with a 3-bladed propeller (i.e., a propeller blade passes 6000 times per minute = 100 times per second). This matching of measured and expected frequencies in the data give confidence that the plane's vibrations were accurately measured. Data was also recorded for a flight of a SuperAir plane. In this case, the app was turned on in-flight, so no takeoff data was available. For the in-flight data, the average acceleration was also around 3.0 m/s^2, similar to the Aerowork plane.

For the full-scale hopper testing at SuperAir in Hamilton, the average vibrations during the taxiing over the grass near the runway was only 1.2 m/s^2, approximately ¼ the magnitude of that seen during the recorded Aeroworks takeoffs. It was noted that the hump in the lime pile in the hopper did not flatten out after the taxi runs during the Hamilton testing, and the low values of vibrations recorded indicates that sufficient shaking to consolidate the load was not achieved. The condition of the runway for the Aerowork data is not known, but assumed to be a rough grass airstrip from the magnitude of the acceleration. From these recordings, it looks like approximately 20 seconds of shaking around ½ the acceleration due to gravity is needed to simulate the vibration-induced compaction that occurs in topdressing planes in the worst-case scenario of takeoff from a rough airstrip. Examination of videos of topdressing aircraft operations posted on YouTube also confirms 20 seconds is a typical duration of the take-off roll.

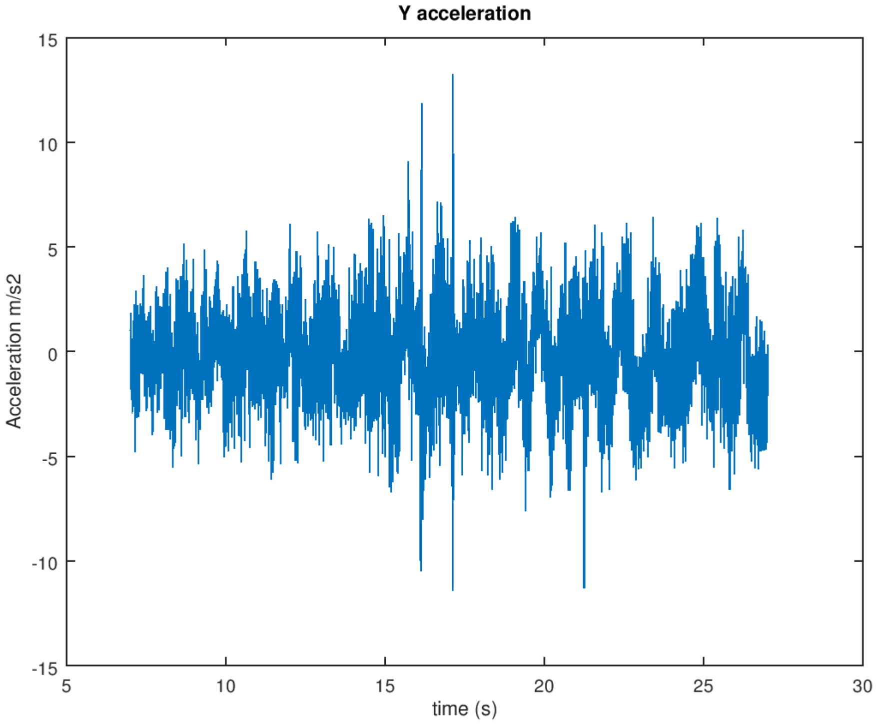

Figure 10: Vertical accelerations for one Aeroworks takeoff run.

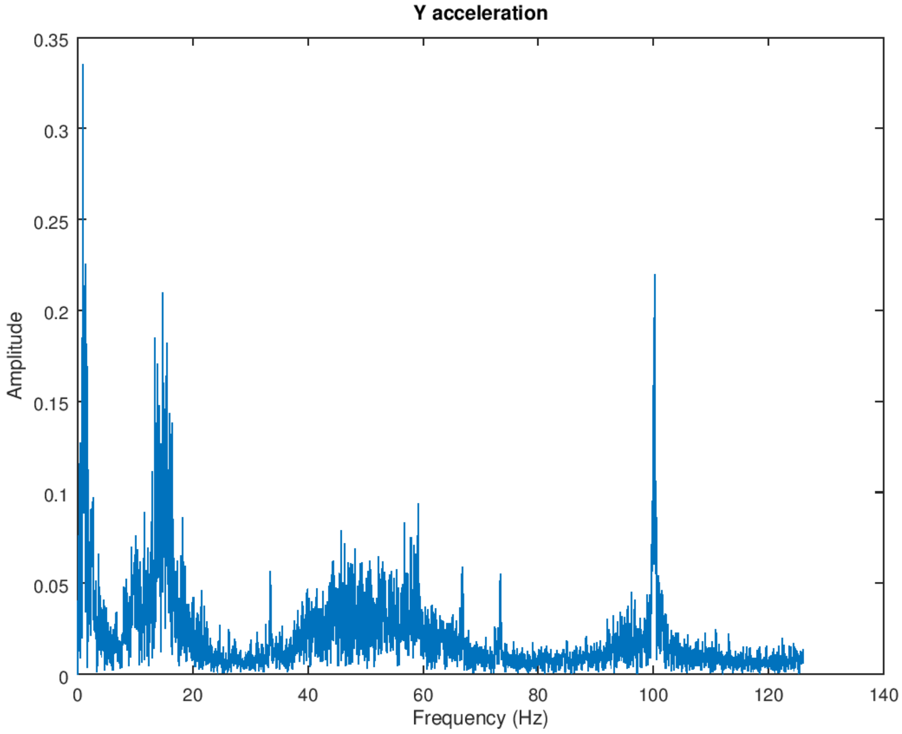

Figure 11: Frequency analysis of vibrations in Fig. 18.

Conclusions

Overall, the three test devices (tilting cylinder, upright cylinder with trap door, scale hopper) provided a conservative measure of flowability, in that the lime would get stuck in these devices before flowability in the full-scale hopper testing started to degrade. Of those three, the scale hopper had the most consistent correlation of showing flow failure at the point when flowability degraded and experienced pilots also said they would not use the lime. The CAA 5-second jettison rule may not be the best measure of flowability, as all of the limes tested were able to be dropped with times reasonably close to 5 seconds, and at no point did the load hang up in the hopper. The primary outstanding question still to be answered is how much the full-scale hoppers and the test devices need to be vibrated to match the worst-case scenario of a plane taking off from a rough airstrip followed by a long flight to the topdressing site.

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