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FLOWABILITY TESTING FOR AERIAL LIME

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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. 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. Two different devices were tested for their ability to assess lime flowability. Lime from six different sources was evaluated. The lime was dried in an oven, and then water added in discrete amounts, so that the flowability of the lime samples could be assessed at moisture levels from 0 to 5% by mass. Tapping and compressing the lime before testing was used to simulate conditions at the bottom of an aircraft hopper. The dried lime samples were also used for measuring the particle size distribution using an Endecotts sieve shaker. From the sieving data, the only particle size distribution parameter that correlated strongly with flowability test results was the Uniformity Index, a measure of the standard deviation of the size distribution.

Keywords
Topdressing, flowability, lime

Introduction

The Civil Aviation Authority (CAA) 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.

As noted in the CAA airstrip safety guidelines (2006a), the flow properties of topdressing products depend on certain physical properties of the granular material, namely: particle size and size range, particle shape, applied compression, and the surface adhesion or stickiness of the material. These properties in turn depend on the source of the lime and how it was ground. While the interactions between these properties are complex, it is known that the finer the grind of lime, the more surface area that is available for adhesion between the particles reducing the flowability and increasing the risk of "bridging" in the hopper. Such adhesion is amplified in wet materials. Also materials that have a wide range of sizes allows the smaller particles to fill in the gaps between the larger ones when the load is vibrated, as occurs during the take-off roll for topdressing aircraft, which further adds to the compaction of the load. Typical guidelines (originally developed by the Ministry of Agriculture and

Forestry) for the particle sizes of agricultural limes are:

- at least 95 percent of the ground limestone to pass through a 2.0 mm sieve
- at least 50 percent of the ground limestone to pass through a 0.5 mm sieve

While coarser limes carry less risk of compaction and poor flowability, there is a trade-off, and larger particles of lime take longer to affect the soil pH (Carey, 2006).

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.

The term "flowability" refers to how well granular materials will move through certain material handling equipment, such as hoppers, but it does not have precise quantifiable definition. There are other material properties that can be quantified that relate to flowability. These include density and compressibility. Compressibility is typically quantified by measuring the bulk density of the freshly poured material, and then the tapped density when the air space between the particles is minimised. It is often recommended to tap the container 100 times to find the maximum tapped density. The Hausner ratio is defined as the tapped density divided by the loose poured bulk density. Higher values of the Hausner ratio indicate poor flowability of the powder. The greater the compressibility of a bulk solid, the less flowable it is. In general, the borderline between free flowing and non-free flowing is approximately 20% compressibility (de Campos & Ferreira, 2013). There are several commercial devices on the market that claim to test flowability, such as Flowdex tester, Aero-Flow Powder Flowability tester, Freeman FT3 tester, and the Hosokawa test kit. There are also basic tests that can be performed on a powder sample such as angle of repose, angle of fall, angle of difference, angle of spatula, and critical velocity. There has been limited success in quantifying flowability with these tests (de Campos & Ferreira, 2013).

There are very few published reports on the flowability of lime specifically, with all the ones that could be found coming from New Zealand due to the importance of lime in the topdressing industry. There has been a sequence of studies at Massey University and two previous studies at Lincoln Agritech Ltd. (LAL) by Maber in 1980, and Praat & Moorhead in 2004. Among the important findings of the work at Massey University is that the moisture content of NZ limes when hammer milled ranges from 0-13% (Grafton & Yule, 2012), and some lime samples taken from airstrips could have moisture content close to 7% (Grafton et al., 2009). Grafton et al. (2011) note the particle size distribution can change based on the age of the crushing hammers. They created a Beverloo device to assess whether lime flowed through different orifices of sizes from 17 to 37 mm. They found when the fine particles less than 300 µm size were removed the lime flowed more readily. The limitations of shear cell testers are that they take a long time to generate the required data curve, which then requires interpretation, and they can also give inconsistent results (Grafton et al., 2012). 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.

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:

- Lime tends to be a less standardised product than other topdressing fertilisers.
- There is no limit on the lime being too finely ground in product specifications.
- "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."
- Hoppers in agricultural aircraft are invariably complicated in shape. "Factors such as outlet size, wall angle, and the surface nature of the wall material affect the way in which a bulk solid will flow from a hopper."
- "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.
- "It is unrealistic to expect to be able to jettison any material that may be put in an aircraft hopper."
- "The particular variables that most affect the flowability of agricultural lime are moisture content and particle size."

Praat & Moorhead (2004) tested 18 samples of lime from 13 sources across New Zealand for flowability. They used 0.2-0.4 kg samples for sieve analysis, 1.2 L for bulk density measurements, and a 2 kg sample for shear testing. Samples were dried at 105 °C for two hours before sieving and to measure the moisture content. They used a Tunra bulk solids shear testing machine, which placed samples between two concentric rings. They also tried a variably aperture flow test to look at how large of an opening was required for various samples to start flowing. In addition, an experienced pilot was also asked to rate the samples for flowability. A summary of their findings:

- Bulk density of the 18 samples varied from 1.1-1.5 kg/L.
- Moisture content of the as-received samples ranged from 0.33-5.33%.
- Sieving analysis found: median particle sizes from 160-640 microns, and Uniformity Index (UI) from 0.89-6.7, and fraction of fines (particles < 125 μm) from 11% to 38%.
- They were not able to correlate the results of the shear flow tester with the pilot rankings.
- Moisture content did not seem to relate to the potential spreadability of the material.
- There was no clear influence of particle size distribution on spreadability either.
- There was a tendency for samples with a higher proportion of fines to be rated less flowable but samples with a higher proportion of small particles were not necessarily rated as more difficult top spread.
- "An objective test for flowability is still required."

The squeeze test often used by pilots (Fig. 1) is a measure of the cohesive strength of the material. Consolidation of a powder with cohesive strength can lead to arching or bridging in the hopper. If the lime stays in a large lump after being squeezed, as is the case in Fig. 1, then it is considered unsuitable for spreading.

Figure 1: Example of squeeze test with a moist sample of lime, from Lincoln Agritech testing in 2004.

Materials and Methods

Testing equipment

A Flodex (Hanson Research, Chatsworth, CA) device was tested. The Flodex is designed for testing in controlled environments such as pharmaceutical laboratories, and for testing the flow of such uniform powders. The device can hold different orifices of size ranging from 4 to 34 mm diameter. A sample of approximately 50 grams size is poured through the funnel into the testing chamber. The sample is to rest in the chamber for 30 seconds with no vibrations, and then the trap door covering the bottom is to be gently lowered. The Flodex is designed to look at the effects of motion along a vertical shear plane. There is no possibility of assessing effects of compression or vibration-induced compaction that is typical in a 2-tonne hopper, as no force can be applied to the powder in the test chamber.

Figure 2: Left – Flodex device; Center – lime sample passing orifice; Right – lime lodged inside (bottom view)

Due to the limitations of the Flodex, and other devices such as shear cells that do not adequately represent the conditions inside an airplane hopper, a new device designated as the LAL test cylinder was developed. It is a PVC cylinder of internal diameter 10.3 cm, and depth 15 cm, with a volume of 1262 mL, holding around 1.5-2.0 kg of lime when filled, depending on the lime density. A removable cap with an opening of size 7.2 cm by 7.2 cm square can be fitted to one end, to simulate the hopper opening on an aircraft. This size is a compromise between getting a small sample that can be quickly tested, but with large enough dimensions to be relevant to topdresser hoppers. A small air hole was drilled in the bottom of the cylinder to prevent vacuum effects. A key feature of the LAL test cylinder is the ability to put a compressive load on the lime.

A typical Cresco hopper has a capacity of 2000 kg and fits within a fuselage of maximum height 1.52 m, with maximum open door dimensions of 1.048 by 0.34 m. This results in an equivalent fluid pressure at the bottom of a hopper with a full load of 22,500 Pa (3.3 psi). For the LAL test cylinder with a diameter of 10.35 cm, the pressure of 22,500 Pa results in a load of 190 N = 20 kg weight on the lime. This can reasonably be applied by a person pressing down on the plate shown in Fig. 3 (left), in order to achieve the same degree of compression in the LAL test cylinder as would be expected in the bottom of a Cresco hopper with a full load of lime.

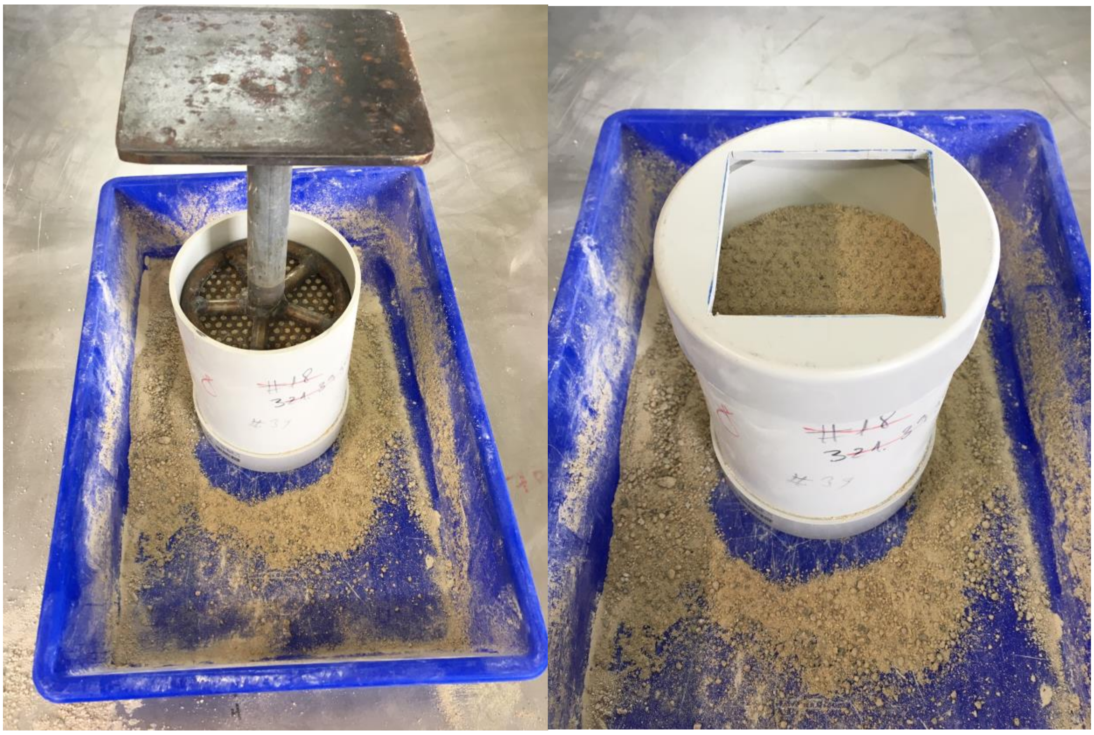

Figure 3: After tapping the side of the cylinder at least 3 times to remove air, a porous metal tool (left) is used to press down on the lime, to simulate the weight of material above it in the hopper, then the amount the lime compresses is measured. The cap is then fit to the open end (right) for the bridging test.

Testing procedure
For each sample of lime the moisture content (on a mass basis) was determined by measuring the mass of the sample as-received, and then again after drying in an oven at 105 °C for at least 2 hours, following the procedure of Praat and Moorhead (2004). A sample of the dried lime (approx. 400-450 g) was sieved using a set of Endecotts pans of diameter 20 cm. The tower was placed on a shaker for at least 5 minutes, again following the procedure of Praat & Moorhead (2004). The dried lime was then tested for bulk density, tapped density, clumpiness and flowability (Fig. 4). Compressibility was calculated from the measured values of bulk density and tapped density. 2 kg was the minimum sample size needed for testing with the LAL test cylinder. After testing the dried lime, water spray was added and mixed into the lime in 1% increments of moisture level by mass, up to 5%, and the lime was re-tested at each moisture level. Wet lime was not sieved as it sticks to the trays.

Figure 4: The packed lime sample is then inverted to check its flowability. If it does not easily flow out (as shown at left) it is considered unsafe to load. This has found to correlate well with clumping of lime in the pilot's squeeze test (right).

For the flowability testing, the cylinder was first filled to the top with lime, levelled off, and then tapped down. Tapping was found to be most effective by dropping the cylinder from a height of just a few cm above the table. While some references report needing 100 taps to find the minimum tapped density, this was judged to be an unrealistic procedure for in-field testing. Instead 10-12 "taps" (dropping of the filled cylinder on its bottom) were used, as it was found this removed most of the trapped air between the particles. After tapping, the lime sample was then compressed in the cylinder using the tool shown in Fig. 3. The pressing down on the sample is critical – if the sample is not compressed, it will be more likely to flow out. After the tapping and pressing, the square orifice cover is placed on the open end of the cylinder (see Fig. 4) and the cylinder is turned over (upside down). If the lime flows out freely of its own accord due to gravity, then the test is considered a "pass" for flowability, but if it requires shaking to dislodge the lime, then it is considered a failure of flowability.

Results and Discussion

The Flodex was difficult to use, as the small orifice size can clog easily even with a reasonably flowing lime, and the trapdoor mechanism can get jammed. It was also found to be sensitive to vibrations during the testing. At times the orifice will initially hold up the powder sample, only to release it when the apparatus is bumped. The Flodex device passed a sample a pilot said he would have rejected. Some stickier limes would not flow through the funnel. So the Flodex was judged not suitable for field use.

In addition to testing for flowability, the LAL test cylinder was also used to measure the bulk density, tap density, and compressibility of the lime samples. As the lime gets wetter, it gets fluffier, and its bulk density decreases and it becomes more compressible (it will pack down more when the cylinder is tapped). The tap density stays nearly constant as moisture is added for a given lime. Figure 5 shows the measured bulk density as a function of moisture content for the limes. The compressibility increases as moisture is added.

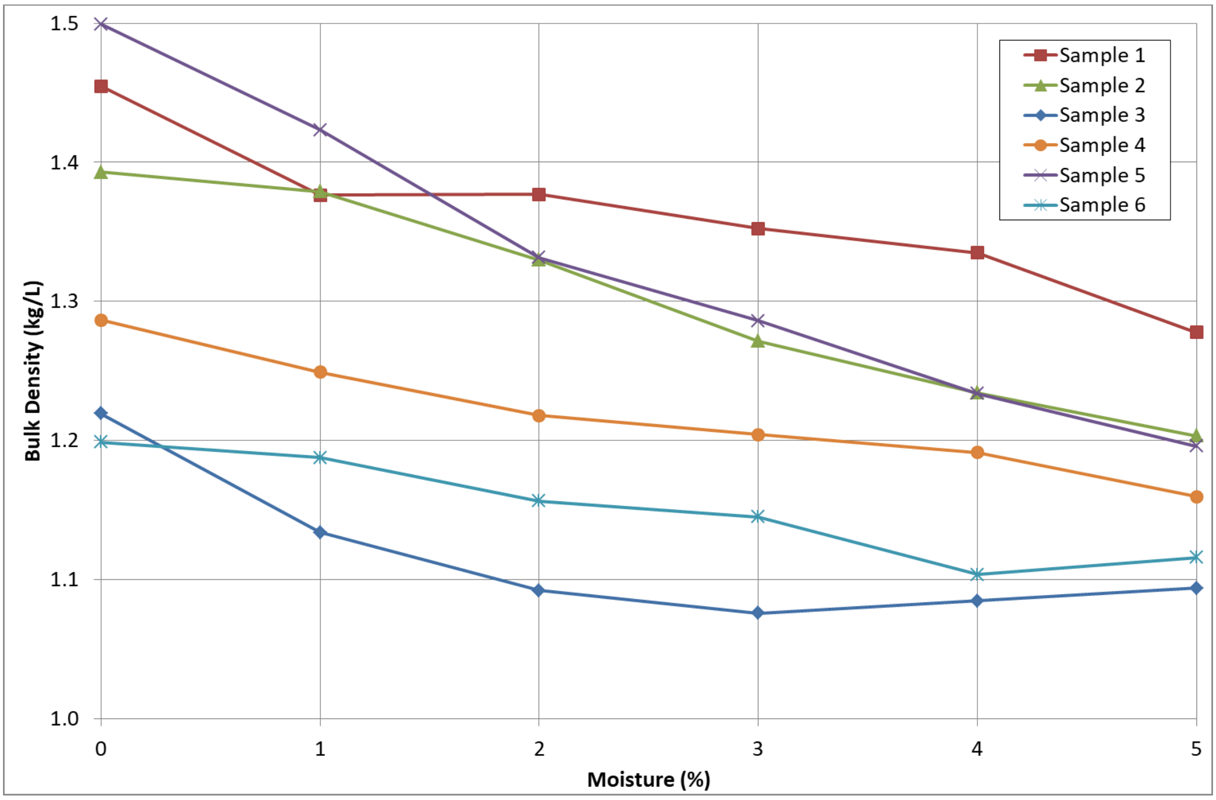

Figure 5: Measured bulk density as a function of moisture content (on a mass base) for the 6 lime samples tested.

Table 1 shows a summary of the testing results with the LAL test cylinder. In addition to the bulk density and the tapped density of the dry lime (0% moisture content), also shown is the compressibility of the dry lime, and the compressibility of the lime-water mixture at the point it fails the flow test in the LAL test cylinder. Failure of the flow test is defined as the lime does not come out on its own when the cylinder is turned upside-down after packing, but requires shaking to loosen the lime. The moisture content when failure occurs is noted, as well as the moisture content when the lime starts forming lasting clumps when squeezed by hand. It was also observed in the testing that as more moisture is added to the lime after the point where it has already failed the flow test, eventually it becomes so sticky it will not dislodge even with shaking.

It was found that the moisture level where the compressibility reaches 20% roughly correlates with when bridging is observed in the tip-over test of the packed-down lime, but the variation seen in Table 1 is large enough that compressibility of the lime cannot be used as a metric for flowability. There is a reasonably good correlation between when the lime fails the traditional pilot's squeeze testing (clumping) and when it fails the test cylinder flow test.

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)	Dry lime compressibility	Compressibility at flow test failure	Moisture at flow failure	Moisture at clumping
1	1.45	1.64	12.9%	17.6%	1.0%	2.0%
2	1.39	1.55	11.1%	12.8%	2.0%	2.0%
3	1.22	1.33	9.1%	22.0%	3.1%	3.1%
4	1.29	1.37	6.4%	20.0%	4.1%	4.1%
5	1.50	1.62	7.9%	22.0%	4.2%	4.2%
6	1.20	1.30	8.3%	17.2%	5.1%	4.1%

Sieving data

The total mass collected after sieving was 99.5% of the mass poured into the sieve tower, indicating no significant errors due to loss of mass in the testing. A stack of 11 Endecotts sieve trays plus the pan was used for the size analysis. All samples were shaken for at least 5 minutes prior to measuring the mass in each tray. Table 2 shows the fraction of mass collected on each sieve pan, for each of the 6 limes tested.

Table 2: Mass fraction retained on each sieve in the measurement stack.

Sieve opening size (mm)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
2.000	4.5%	12.7%	4.2%	6.0%	3.4%	5.7%
1.400	8.3%	10.6%	4.0%	5.6%	8.4%	8.5%
1.000	7.6%	8.2%	4.3%	4.3%	8.4%	7.7%
0.710	7.5%	8.4%	6.1%	4.6%	9.7%	8.3%
0.500	11.9%	13.3%	20.1%	10.7%	19.7%	14.0%
0.355	4.6%	5.2%	11.0%	5.8%	9.3%	6.0%
0.250	7.8%	8.6%	16.5%	12.3%	13.0%	11.1%
0.180	6.3%	6.2%	9.7%	12.4%	7.4%	9.2%
0.125	8.4%	6.3%	10.3%	14.6%	6.3%	10.8%
0.090	9.5%	4.9%	6.2%	9.7%	4.4%	8.1%
0.063	8.4%	4.5%	4.5%	6.7%	2.9%	4.7%
(Pan) 0.0	15.3%	11.1%	3.1%	7.2%	7.0%	6.0%

Figure 6 shows graphically the cumulative mass distribution for each lime, calculated by summing the masses on all trays (shown in Table 2) of equal or smaller sieve size to the indicated size.

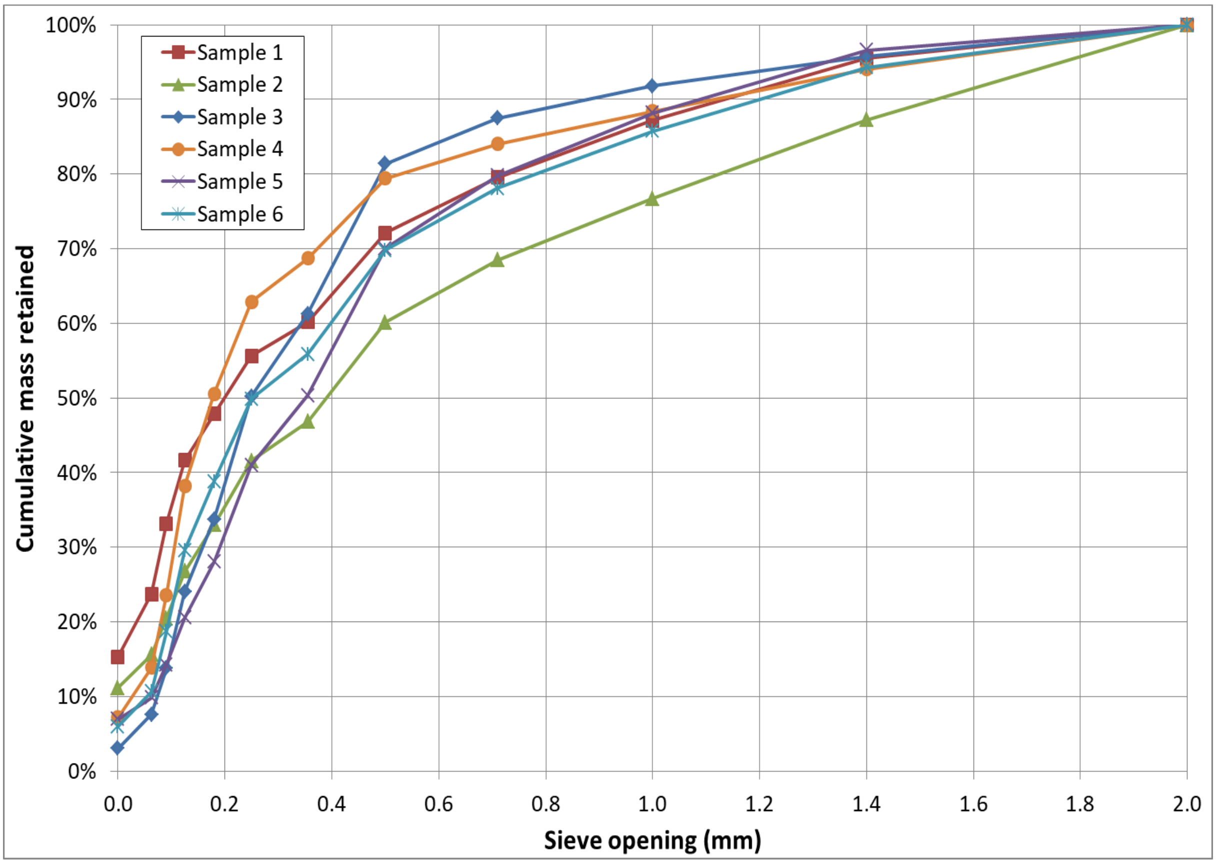

Figure 6: Cumulative mass distribution calculated from sieve analysis.

Statistical analysis of sieving data

From the measured particle size distributions in Table 2, the relevant statistical parameters can be calculated, including the Size Guide Number (SGN), which is an estimate of the median granule size in a fertiliser, the Uniformity Index (UI), which is inversely proportional to the standard deviation, and the fraction of Fines in the lime, using the definition of Praat and Moorhead (2004) as the fraction of particles less than 125 μm (the third smallest sieve size). SGN is calculated by finding the sieve opening (in units of mm) that retains (or passes) 50% of the weight of a fertiliser sample and multiplying by 100. Interpolation is used to find the SGN value between the sieves just above and below 50% cumulative mass. Graphically, SGN can be found in Fig. 6 using the size where the curve crosses the 50% line.

The Uniformity Index (UI) is inversely proportional to the width of the particle size distribution. The higher the value of UI the more uniform the particle sizes, and lower values of UI indicate a greater range of particles sizes. It is calculated by taking the size of the sieve opening that retains 95% of the sample mass and dividing by the size of the sieve opening that retains 10% of the sample mass, and multiplying by 100. The 95% and 10% mass retained values can also be found graphically, using Figure 6. A value of UI = 100 would indicate all the particles had exactly the same size. UI is inversely related to the standard deviation. Table 3 shows the summary statistical calculations from the sieving of each of the lime samples.

Table 3: Summary of statistical properties from sieving analysis of lime samples.

Lime	% < 125 μm	% < 500 μm	Median (μm)	Uniformity Index (UI)	Moisture at flow failure
Sample 1	33.2%	60.2%	199	1.8	**1.0%**
Sample 2	20.5%	46.8%	390	1.8	**2.0%**
Sample 3	13.8%	61.3%	249	3.0	**3.1%**
Sample 4	23.6%	68.7%	177	3.9	**4.1%**
Sample 5	14.3%	50.3%	351	4.2	**4.2%**
Sample 6	18.7%	55.9%	252	4.4	**5.1%**

No correlation appears between the percentage of fines or the median size of the lime particles and the amount of water that has to be added before the lime ceases to have acceptable flowability. However, there is a clear correlation between the uniformity index (UI) and the flowability of the lime. The narrower the particle size distribution (higher values of UI), the better the flowability of the lime.

Conclusions

Novel features of the present work are (1) testing the lime flowability as a function of moisture content for different limes, (2) tapping and compressing the lime before testing to simulate conditions at the bottom of an aircraft hopper, and (3) using the % mass of moisture at failure of the flow test to rank the lime inherent flowability. From this testing procedure, it was determined that the narrower the particle size distribution the better the flowability of the lime and resilience to moisture. Additional work would be required to correlate the test cylinder results with full-scale hopper flows. For such an experiment, it would also be desirable to get accurate measurements of the amplitudes and frequencies of vibrations seen in topdressing aircraft, in order to match the amount of consolidation seen in the hopper during the take-off roll for the sample test procedure.

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