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FLOW OF PARTICULATE MATERIAL FROM A TOPDRESSING AIRCRAFT

A thesis presented in partial fulfilment of the requirements of the degree of Doctor of
Philosophy in Agricultural Engineering
At Massey University, New Zealand

Miles Crispin Ellis Grafton
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Abstract

Fixed wing agricultural aircraft apply approximately 40% of the fertiliser used in New Zealand, the majority of which is applied in hill country. The amount varies from approximately 600,000 tonnes to 1.2 million tonnes per annum.

About 100 fixed wing aircraft of various types are engaged in agricultural operations throughout the country and the safety record has been of considerable concern; the Civil Aviation Authority (CAA) of New Zealand report that there are 12 serious accidents per 100,000 flying hours which result in 4 deaths, almost 2 annually.

Agricultural aviation stakeholders, including, the Department of Labour, Civil Aviation Authority, New Zealand Agricultural Aviation Association (NZAAA) and Federated Farmers are trying to reduce the number of incidents in the sector by establishing guidelines for airstrips, fertiliser storage facilities, their use and application from them.

A large proportion of incidents have, as contributing factors, poor flowing product which cannot be jettisoned in time to avert an accident, collisions with obstructions near the airstrip (20% of all accidents are aircraft hitting fences in proximity to the airstrip) and damage to aircraft due to an inappropriate surface, such as rutting.

The New Zealand topdressing industry handles many products of which only a few are homogenous e.g. Urea and fresh Di-ammonium phosphate. The majority of spreading being undertaken involves products with large variations in particle size

and moisture content producing particles from fine dust to concretions. These characteristics make it very difficult to achieve continuous flow and even spreading from an aircraft. There have been a disproportionate number of accidents and near misses in the New Zealand topdressing industry that have occurred whilst spreading agricultural limestone (lime). Lime has been identified as being particularly problematic and is being used as a focus for this study. Superphosphate, which is used as a flow standard in New Zealand Civil Aviation Authority rules, is used as a comparison in powder flow engineering experiments.

This thesis is a prescribed project concerned with solving specific problems for industry mainly funded by the Fertiliser Manufacturers' Research Association.

Specific objectives/aims of the project:

1. Quantify the flow characteristic of products being spread and identify risks within the system, identifying risk materials and risk situations.

2. Develop a better understanding of material variability in terms of characterising the different deposits used around New Zealand and relating these differences to flow properties.

3. Develop a better understanding of the mechanisms creating the variability in flow properties that relate to production processes, transport and storage and finally loading and spreading with topdressing aircraft of the different limes used in New Zealand.

4. Quantify system performance in terms of economic and environmental impacts.

5. Identify suitable test methodologies that can be used within the industry to determine whether a product is fit for spreading and its flow characteristics. These would be dispatch tests at the lime quarry or fertiliser plant and a flowabiltiy test as the material is loaded onto the aircraft.

6. Identify design criteria that determine the performance of aircraft in relation to safety, flow control and spreading performance. Work with the interested parties to improve work quality and safety associated with agricultural aviation systems.

Flow properties have been quantified using a shear testing regime and engineering design parameters established for mass flow have been calculated from interpreting the powder flow functions. However, as the material from each quarry has variations in particle size distributions caused by factors such as the moisture of the parent limestone, age of the crushing hammers and time being crushed; the results are only an instantaneous solution. All commonly used products except lime are free flowing and shear testing was undertaken on superphosphate samples as a comparison. All the limes tend to be on the cohesive – easy flow boundary.

Limes from throughout New Zealand have been classified by mineralogy, have been analysed by thermal decomposition and have had impurities identified through X-ray diffraction. Although there were differences in the particle size distributions and loose and tapped bulk densities between the limes, helium pycnometry testing showed the limes to have similar particle densities.

In order to achieve free flow conditions with these products they require modification. The simplest modification that proved effective was the removal of fine particles.

This had the effect of reducing the particle size distribution which is important in reducing the packing density and cohesive strength. This was also achieved by only having particles within a narrow particle size range, by removing the fine particles the cohesive strength was reduced and the materials were free flowing.

Although this can be done there is clearly a cost involved, the industry is already struggling with reduced demand and any increase in cost is likely to be unwelcome even though it could help to save pilots' lives and improve the quality of spread achieved.

This thesis considers three aspects of topdressing costs in order to estimate the actual costs of spreading fertiliser and lime. The questions posed are; what are the actual costs of operating the two main models of aircraft flown in New Zealand? What size of aircraft fleet is required to fulfil the spreading requirements? What are the on-farm infrastructure costs that also need to be considered in order to calculate the true costs of servicing the application of fertiliser to our hill country sector?

Topdressing services mainly the sheep and beef sectors which contribute 22.5% of New Zealand's agricultural output. Farm income in this sector is nearly $4 billion. Application of fertiliser is important to sector productivity and the possible collapse of the topdressing industry would have far reaching consequences for these farming sectors and New Zealand's export earnings.

The model finds that there is no financial return on capital invested in the industry. Therefore, the best returns are found by applying fertiliser from old aircraft with aged support vehicles all with little capital value. This is clearly unsustainable as even old aircraft require large injections of capital periodically to maintain airworthiness.

As fertiliser prices have increased, application rates have fallen, which increases application cost per tonne applied. The agreed fixed price charging model is traditionally based on an application charge per tonne. It is likely that farmers perceive increased application charges per tonne as a price increase, whereas it is only compensating the applicator for the additional time of sowing at a lower rate.

It is clear that although farmers buy fertiliser on a cost per tonne basis this is not the activity based cost driver for the aerial applicator. Converting the cost per hour aircraft cost driver, to a cost per tonne for charging farmers; is confusing as application charges alter by rate and product. The industry needs to alter its charging mechanism to a cost per aircraft flying hour activity based charging regime.

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Preface

This thesis is submitted to the University of Massey in partial fulfilment for the degree of Doctor of Philosophy in Agricultural Engineering. The material submitted in this thesis was carried out by the candidate during the years 2007 – 2010 under the supervision of Associate Professor I.J. Yule. All the work was carried out in the School of Engineering and Advanced Technology and the Institute of Natural Resources at Massey University, Palmerston North.

The candidate submits that the thesis has been composed by him and that the work described herein is his own unless otherwise stated in the text.

Nine supporting journal and conference papers which are based on the work presented have been published or submitted to international journals and conferences:

Journal Publications

Grafton, MCE, Yule IJ, Lockhart, JC, 2010, An Economic Analysis of Aerial Topdressing in New Zealand, New Zealand Journal of Agricultural Research (Under Review)

Grafton, MCE, Yule IJ, Lockhart, JC, 2010, A Cost Analysis of New Zealand's On-Farm Agricultural Aviation Infrastructure, New Zealand Journal of Agricultural Research (Under Review)

Grafton, MCE, Yule IJ, Stewart RB, Davies, CE, Jones, JR, 2010, Resolving the Agricultural Crushed Limestone Flow Problem from Fixed Wing Aircraft, Trans. ASABE (Under Review)

Grafton, MCE, Yule IJ, Davies, CE, Jones, JR, 2010, A Comparison of shear Tests using a Carr-Walker and Schulze Annular Shear Cells on Commercial Agricultural Crushed Limestone of New Zealand, Trans ASABE (Under Review)

Conference Publications

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NOMENCLATURE

τ = Shear stress (Pa)

σ = Normal stress (Pa)

P_b = Bulk density (kgm^{-3})

B = Angle between cohesive arch and hopper wall

g = Acceleration due to gravity (ms^{-2})

A_1 = Depth of arch supported by unconfined yield stress (m)

UYS = Unconfined yield stress (Pa)

MCS = Maximum consolidated stress (Pa)

β = Length of narrowest sides of a rectangular orifice (m)

L = Length of longest sides of a rectangular orifice (m)

r_o = Radius of circular orifice (m)

I = Intensity of reflected X-rays

IYL = Incipient yield locus

WYL = Wall yield locus

σ_1 = Maximum consolidation stress (Pa)

σ_1 = Critical applied stress (Pa)

σ_c = Unconfined yield stress (Pa)

CAS = Critical applied stress (Pa)

α = Hopper half wall angle

$H(\alpha)$ = Hopper half angle divided by 60°

δ = Angle of internal friction

δ_e = Effective angle of internal friction

ϕ = Angle of wall friction

$G(\phi_t)$ = Jenike function for funnel flow is 4.3 $\tan\phi$

y = Bulk density multiplied by acceleration due to gravity ($kgm^{-2}s^{-2}$)

P = Pressure (Pa)

ff = flow factor

T = Tensile strength (Pa)

V = Volume (m^3)

K = Beverloo constant for mass flow rate

M = Mass flow rate (kgm^{-3})

k = Beverloo constant multiplier for mean particle size and shape

d = Mean particle size diameter (m)

h = Head or height of bulk solid in a silo (m)
B = Angle between cohesive arch and hopper wall

g = Acceleration due to gravity (ms^{-2})

A_1 = Depth of arch supported by unconfined yield stress (m)

UYS = Unconfined yield stress (Pa)

MCS = Maximum consolidated stress (Pa)

D = Diameter of circular opening and diagonal opening of a square orifice (m)

Chapter 1

Introduction

1.0 Research objectives

The research objectives of this thesis were a prescribed pre-approved project concerned with solving specific problems for the agricultural aviation industry, funded by the New Zealand Fertiliser Manufacturers' Research Association.

Specific objectives/aims of the project:

1. Quantify the flow characteristic of products being spread and identify risks within the system, identifying risk materials and risk situations.

2. Develop a better understanding of material variability in terms of characterising the different deposits used around New Zealand and relating these differences to flow properties.

3. Develop a better understanding of the mechanisms creating the variability in flow properties that relate to production processes, transport and storage and finally loading and spreading with topdressing aircraft of the different limes used in New Zealand.

4. Quantify system performance in terms of economic and environmental impacts.

5. Identify suitable test methodologies that can be used within the industry to determine whether a product is fit for spreading and its flow characteristics. These would be dispatch tests at the lime quarry or fertiliser plant and a flowabiltiy test as the material is loaded onto the aircraft.

6. Identify design criteria that determine the performance of aircraft in relation to safety, flow control and spreading performance. Work with the interested parties to improve work quality and safety associated with agricultural aviation systems.

The objectives cover a range of disciplines such as: mineralogy, rheology, macro and micro economics; and aircraft and airstrip design. The range of disciplines examined required the thesis to be undertaken in sections.

The first describes the background and issues which affect agricultural aviation safety. The second uses engineering techniques, such as X-ray diffraction, thermal decomposition, Helium pycnometry and shear testing to understand the mineralogy and flow properties of bulk solids applied from aircraft. Material modification of agricultural lime was undertaken to improve the flow properties without altering its agronomic properties. The third section examines the micro and macro economics of the agricultural aviation industry. The final section ties these sections together and discusses the conclusions reached from the experiments and investigations undertaken to meet the objectives of the thesis.

1.1 Background

New Zealand's mild climate, led to the development of year round pasture grazing regimes based on a rye grass clover mix. Historically intensive agricultural production began in the nineteenth century and bush clad hills were cleared and put into pasture. This continued with added impetus after World War I as returning veterans were assisted into land blocks which needed developing.

The removal of bush from hillsides resulted in the acceleration of erosion rates. To maintain pasture growth and to stabilise slips on the hillsides requires inputs of fertiliser and pasture seeds.

It was an attempt to control the erosion problem in the hill country which resulted in the New Zealand Public Works Department purchasing a Miles Whitney Straight single engine monoplane to carry out seeding and agricultural aviation trials in May 1938. These included grass seeding on hill sides, cobalt delivery on the soils of the volcanic plateau and lupin sowing on eroding sandy coastal soils of the lower North Island (Geelen, 1983). Each task had been completed with some success which encouraged further investigation.

At the end of World War II some fertiliser spreading trials were undertaken using Royal New Zealand Air Force Grumman Avengers and a Bristol Freighter. It was as a result of these trials that some issues with material flow were first identified. The Grumman Avengers had difficulty discharging dusty non granular superphosphate, and only trials with the most granular super were successful in applying the correct sowing rate. Trials with limestone were more problematic and flow was only obtained by first seeding the hopper with granular superphosphate which initiated flow and allowed the limestone to discharge.

Commercial topdressing began in May 1949 and quickly established nationwide. There were a large number of ex military pilots wishing to continue flying and there were a large number of De Havilland DH 82 Tiger Moths throughout the Commonwealth, see Figure 1.1, which had been used for *ab-initio* pilot training during the war (Geelen, 1983). This aircraft became the mainstay of the topdressing industry until the mid 1950’s when other types with larger payloads and features such as wheel brakes began to replace them and by 1960 the Tiger Moth days had passed.

Figure 1.1: A DH82 Tiger moth topdressing operation from the early 1950's: photo courtesy Wanganui Aero Work (2004) Ltd.

Aerial topdressing is the only practical method of applying fertiliser to New Zealand’s medium to steep hill-country pasture land. Prior to the general acceptance of aircraft delivery of fertiliser and lime to hill-country, bags of fertiliser and seed were sown by hand broadcast either on foot or from horseback, which was labour intensive and expensive. However, by the very nature of the terrain and the high cost of operating aircraft there was a need for a large number of airstrips in close proximity, illustrated in Figure 1.2. This resulted in many strips being less than ideal.

Figure 1.2: Blue dots designate the 380 airstrips located in the 25,600 km^2 of Taranaki, New Zealand

Most hill country airstrips are on plateau hill tops frequently with a gentle down slope; which are sometimes short strips followed by a drop off which enables the aircraft to gain flying speed, Figure 1.3. Turning areas for loading and the width of the strips are also limited. Most airstrips double as grazing paddocks and some have hazards such as fences at the ends of the strips. Many have not had capital expenditure for many decades and most have fertiliser storage bins that are inadequate for modern topdressing aircraft. A modern turbine Cresco can sow up to 300 tonnes of superphosphate on a fine mid summer day, but this is rarely achieved as most farm airstrips have storage facilities of less than 100 tonnes. This often results in considerable down time as the pilot and the loader driver await further deliveries from carriers.

Figure 1.3: Shows a FU24 taking off and landing on hillside plateau strips: source CAA Ag Aircraft Safety Review Dec. 2008.

Most airstrips are plateau strips because there is a limited amount of flat ground. A second reason for using plateau airstrips was that early topdressing aircraft were underpowered when fully laden with a very slow rate of climb. Plateau airstrips allowed them to sow from the top down and then climb back to the strip empty. Nowadays most topdressing aircraft used in New Zealand are still piston powered but better performing turbine aircraft are replacing them and these have the performance to utilise valley floor airstrips, where hazards of short, sloping plateau airstrips can be avoided.

The main disadvantage of plateau airstrips is access for delivery of fertiliser and the loader truck which loads fertiliser to the aircraft and carries aircraft fuel for operations. Access is generally some considerable distance from the main road and the farm tracks are often only bulldozed and graded, although some are gravelled. As the tracks age some have vegetative growth and most are seasonal and only useable when dry. It is common for aircraft loaders to be trapped on plateau strips from autumn through to spring. It is also common for airstrips to be unserviceable and jobs left unfinished, as bins of an inadequate size are emptied. These can’t be replenished as the access tracks are impassable. On some occasions large four wheel drive tractors have towed trucks to the airstrips, but, trucking firms are reluctant to condone this practice. Valley strips close to main roads overcome the access difficulties as access is available year round.

A common problem with airstrips is caused by wear due to the quick turn around time of agricultural operations and the number and frequency of take-offs and landings. When sowing limestone an aircraft may make about 15 take off and landings per hour and this will result in an aircraft landing in a similar place on the airstrip up to 150 times in a day. Should the airstrip not be completely dry and compacted it may rut and break up similar to a bowler’s run on a cricket pitch. This will adversely affect take off speeds and can lead to undercarriage wear and damage. These situations are common as most farmers wish to have their superphosphate sown between February and June, during autumn after their main farm income has been received, when moisture is present to allow the fertiliser to become active and prior to the end of their financial year which is usually June in the North Island of New Zealand and May in the South Island.

1.2 Specialised Aircraft

New Zealand’s unique topdressing conditions of sowing bulk solids from short narrow airstrips in hill country soon led to a search for a suitable aircraft. In most other agricultural nations, agricultural aircraft sow liquids or dust insecticide on crops grown on flat land and take off and land from long suitable airstrips.

In 1952 the NZ Civil Aviation Department set out a 23 point specification for an ideal topdressing aircraft suitable for NZ conditions (Geelen, 1983). The specifications included (Maber, 2007):

- An ability to operate off short airstrips in variable weather with a 1,000 1b (454 kg) fertiliser load
- Good ground handling qualities
- Safety for the pilot in the event of a crash
- A fully laden climb rate of 1,000 ft (300 m) per minute

Some items such as the climb rate have only been met with the introduction of turbine powered aircraft since the 1980's. However, in 1953 Mr. Wendell Fletcher of Fletcher Aviation Corp. arrived from the USA with a prototype topdressing aircraft which met most of the Civil Aviation Department specifications. The aircraft was demonstrated from several air fields and was the feature of an air-show in Hamilton where its manoeuvrability and handling were demonstrated. New Zealand manufacture under license began soon afterwards at Hamilton.

About 300 Fletchers were constructed between 1955 and 1980 and about 70 are still in service although many of these have been repowered with turbine conversions. Although a few Fletchers were sold overseas and have operated in Australia, Turkey and Bangladesh, New Zealand is the only country which has adopted this aircraft type as its main agricultural fixed wing aircraft.

In 1980 the Fletcher manufacturer Pacific Aerospace Corporation (PAC) replaced the aircraft with a larger aircraft with the same silhouette with a turbine engine instead of a reciprocating engine which increased the power from 400 hp (298 kW) to 600 hp (447 kW) and then 750 hp (559 kW) when the Pratt and Whitney PT6-34-Ag replaced the Lycoming LTP 101 engine as standard. In addition to a more powerful engine the payload was increased from 1 tonne to 2 tonnes. There are about 20 operational (some are always undergoing major overhaul) Cresco topdressing aircraft operating in New Zealand, see Figure 1.4.

Both the Fletcher and Cresco have a combination of features which makes this design unique in the agricultural aircraft product range:

The hopper is behind the pilot which minimises windscreen dust and enables easier loading of bulk solids. All other agricultural aircraft have the pilot behind the load, which pilots consider to be safer as the cockpit isn’t sandwiched between the engine and the load. Aircraft hoppers have a window which allows a pilot to view the hopper and therefore will see a hung load. The window on the Cresco is behind the pilot’s head and is not readily visible unless the pilot removes his shoulder harness to enable him to view.

The tricycle undercarriage on the Fletcher/ Cresco offers more manoeuvrability on airstrips with a turning nose wheel when compared with the conventional undercarriage featured on nearly all other agricultural models of a small wheel at the back of the aircraft. It also enables better visibility on airstrips and loading areas and on take off on narrow airstrips as the pilot has a horizontal perspective. The undercarriage system has independent air shocks which are useful on rough airstrips. Other aircraft such as the Air Tractor and Thrush series of models have a wishbone system connecting the main wheels, which is more rigid and produces bounce.

The Cresco’s monocoque construction enables lightweight construction and it has an empty weight of 1,400 kg as compared to an Air Tractor AT 502 Figure 1.5, an aircraft with the same engine and propeller with an empty weight of 1,915 kg. The latter has a tubular airframe and the body is a cheap-to-repair selection of fairing parts. The Air Tractor has the same payload as it has a larger wing with a 52' (16 m) wingspan (aircraft are in US customary units) compared to the Cresco 42' (13 m). It is therefore, less manoeuvrable, turns less tightly and is more inclined to wing stall in tight manoeuvres. The Cresco has a shorter takeoff distance of 315 m compared to 364 m when fully laden at sea level.

Quite clearly, an aircraft hopper has to fit in an airframe. As aircraft have become more powerful, hoppers have become rounder to occupy a greater volume within the available space over the aircraft centre of gravity. Thus the hopper wall angles have become less steep and mass flow becomes less likely. However hopper outlets have become larger; although the mechanism for operating some of these is less ergonomic as they are heavier. Earlier designs used a ‘clam shell’ door, in which two doors opened and closed similar to shutters with no contact with the load within. The latest Cresco hopper requires the pilot to operate a cantilevered door in which a proportion of the door must enter the hopper to reveal the opening. In addition shelves which allow hang ups and bridging to occur exist because, for structural integrity of the aircraft, the wing spar is at the centre of gravity too.

Figure 1.4: A Cresco agricultural aircraft with tricycle undercarriage being loaded with bulk solids on a grass airstrip. Source: Wanganui Aero Work (2004) Ltd Website

Figure 1.5: An Air Tractor 502 a conventional agricultural aircraft set up for spraying with CP nozzles. Source: Air Tractor Inc. Website

The latest PAC topdressing aircraft introduced is the Cresco 750 XL; this aircraft featured a $3m^3$ hopper; compared to a $2m^3$ in the standard Cresco, on an onboard load cell which gave the pilot a cockpit read out to prevent overloading. However, all three built have been removed from service as topdressing aircraft and have been converted to parachute work. The aircraft hopper assembly and load cell readout was a compulsory feature for certification as the pilot has no view of the hopper. This proved to be unreliable and in combination with undercarriage problems, which aircraft engineers assumed to have occurred as it is a heavier aircraft than the original Cresco. The extra wear that resulted, led to the withdrawal of this aircraft type. PAC no longer produce any topdressing aircraft which will impact on the NZ topdressing industry in the future as new aircraft will by necessity be of different types.

1.3 Identified Hazards in NZ Topdressing Aircraft

In response to the accident rate the NZ CAA and the Department of Labour jointly published "*Safety Guideline Farm Airstrips and Associated Fertiliser Cartage, Storage & Application"* in December 2006. Since this publication the CAA have completed an *"Agricultural Aircraft Safety Review"*, published in December 2008. The first deals with hazard identification and the supply chain responsibility from manufacture to application. The aim is to provide a standard guideline that will prevent delivery of fertiliser to inadequate facilities which will lead to deterioration of fertiliser products and prevent them from flowing freely. It also provides a guide to pilots to prevent them from loading unsuitable products which have flow properties that fail to meet the legal dump requirement and or use airstrips which are not of a suitable standard and therefore provide unnecessary risk to the pilot and aircraft. It refers to statutory requirements and provides guidelines for best practise for airstrip owners, farm access ways, cartage firms, fertiliser manufacturers and the aerial applicator. The "Safety Review" summarises occurrences and the numbers and types of incidents by common aircraft types.

The Department of Labour is responsible for investigating work place accidents, whilst the CAA is the aviation regulator and the investigator of most General Aviation accidents. They state in the Guideline that in the event of an occurrence it would be used when considering the investigation. This implies that if factors such as airstrip shortcomings, or inappropriate storage and handling of materials directly contribute to an accident then those responsible may be prosecuted.

Below in Table 1.1, the typical costs of applying a 2 tonne load of superphosphate are shown when the aircraft; that is operated at NZ$1,200 hr^{-1} total time, has to ferry the load 2, 5 and 10 km from the airstrip in a Cresco or AT 502 turbine topdressing aircraft. The costs explain why there are a large number of airstrips in reasonably close proximity, which has meant that most strips only service at most a few farms. Therefore, there are only a few users to invest in airstrip infrastructure and storage facilities.

The author can cite an example of a covered bin with walls, doors and sliding roof capable of storing 400 tonnes of superphosphate which cost NZ$400,000 to construct. Fertiliser can be protected much more cheaply using tarpaulins which is the preferred method over inadequate bins. In addition farm access tracks require grading, shell-rock and maintenance of culverts.

Table 1.1: Cost comparisons of applying a two tonne superphosphate load by Cresco at varying distances from an airstrip. It assumes a rate of 250 kg per hectare, using a 20 metre swath, or bout width, which are typical for the industry.

Ferry distance (km)	Sowing Speed 200 kmh^{-1}	Ha sown per min.	Sowing time (min)	Turning time (min)	Loading time (min)	Ferry time and return (min)	Turn around time (min)	Cost per trip hour total time ($)	Cost ferry ($)	% ferry
10	200	6.67	1.2	.67	1	6	8.87	177	140	79
5	200	6.67	1.2	.67	1	3	5.87	117	70	60
2	200	6.67	1.2	.67	1	1.2	4.07	81	28	34

Although the hazards identified and the means to eliminate, minimise and mitigate them are well covered through the supply chain some seem impractical in the work environment. Those guidelines suggesting a carrier not deliver fertiliser to a farmer’s bin if it is not of a suitable standard seem unlikely to occur, unless of course the carrier became culpable. A carrier would then be expected to return and store the material at their own expense until the facility is improved and would certainly not be paid for the non delivery. However, if the guidelines are followed it will certainly improve the safety of agricultural aviation operations and reduce the number of occurrences.

The Agricultural Aircraft Safety Review is a substantial document of 400 pages including appendices and is a comprehensive examination of agricultural fixed wing occurrences and attempts to find the reason that the accident rate for this branch of General Aviation has been increasing since 1994, whilst the rate is falling for all other types. It is a compilation of works by mainly three authors and 200 pages of appendices detailing various legislation, (current and former), occurrence reports and parts of accident investigations which are referred to by the authors.

There are three main issues explored:

- The increase in the accident rate since agricultural overload provisions changed, with rule changes in 1994, and whether this is the cause.
- There have been a number of turbine conversions on Fletcher aircraft, most of these have taken place since 1994; and whether this has contributed.
- Through examining occurrences by category in a database compare the Fletcher and Cresco occurrences with all other types of agricultural aircraft.

The first section identifies that the legislative changes did not provide for compulsory changes to manoeuvring speeds with loads above maximum certified take off weight (MCTOW). To summarise increases in load leads to fatigue load on an airframe. Taking loads above the certified weight need to be combined with manoeuvring restrictions to prevent damage to the airframe. This is logical and as turbine conversions to Fletcher aircraft have resulted in 50% increase to horsepower the aircraft is able to manoeuvre and carry a legal agricultural load above MCTOW and stress an airframe through greater gravitational force than was possible prior to the conversion. The review discusses whether allowing aircraft to have replacement turbine engines fitted on a supplementary type certificate (STC) rather than a separate change in aircraft type is best practise, when in fact a separate aircraft type does result. This has enabled a cheap turbine option to be available to operators and has hindered the penetration of new turbine aircraft fully certified as a separate type in the market as a cheaper engine replacement has been approved. In addition some conversions have also involved installing larger hoppers up to 2 m^3 for the purpose of allowing a full load of urea to be sown from the aircraft as urea has a bulk density of about 660 Kg/m^3 and thus a legal load may be sown from a hopper this size in a turbine Fletcher. However, the increased volume from 1.39 m^3 makes overloading with more dense material possible.

CAA database queries of incidents by category showed a higher rate of undercarriage occurrences for Cresco and Fletcher aircraft than for foreign manufactured other types. The author is a little concerned that Fletcher and Cresco aircraft are compared to all other aircraft types in this manner. Firstly the other types can't operate on the same rough airstrips as they mostly have a sprung wishbone suspension and a conventional undercarriage (Pers. Comm., R. Hartnell, Chief Engineer, Wanganui Aero Work (2004) Ltd). Secondly New Zealand topdressing aircraft have a large number of take off and landings compared to overseas aircraft which mainly operate as sprayers; between ten and fifteen an hour, compared to one or two an hour for crop sprayers. However, types designed for overseas conditions have less undercarriage incidents reported to CAA than the New Zealand built aircraft, which is an anomaly if it isn’t related to the airstrips used.

Furthermore, there have been CAA approved modifications introduced to strengthen the axles which were prone to cracking on the Cresco (pers. Comm., R. Hartnell Wanganui Aero work

(2004) Ltd.). It is also difficult to differentiate rough airstrip damage with overloading damage. It is the latter that has been assumed.

The reported incidents of undercarriage bolts breaking may be as a result of landing using propeller Beta (to change the pitch of a variable pitch propeller to a flat blade with no pitch which produces drag and rapidly slows the aircraft down) without flap to speed turnaround time, something not considered in the report. This type of landing approach frequently results in an aircraft dropping rapidly on to a strip which is likely to stress an undercarriage more than a slower approach using flaps (Pers comm., R. Hartnell, Chief Engineer, Wanganui Aero Work (2004) Ltd.).

1.4 Bulk Solid Flow Issues

Material flow issues are of concern to fixed wing agricultural aircraft operators and their clients in respect of safety and accurate deposition of fertiliser at the desired application rate.

There are on average 13 topdressing accidents and about 4 deaths per 100,000 flying hours in New Zealand, currently one pilot is killed every 215 days (Civil Aviation Authority of New Zealand, AISU 2008). The number of fixed wing flying hours undertaken each year varies between 30,000 and 50,000 (Lewis *et al*, 2008).

Crushed agricultural limestone (lime) is present in a disproportionate number of these accidents. The failure of lime to flow out of the aircraft when desired is one cause of some accidents. Actual statistics of lime accidents have not been kept in the CAA database, but flow problems discharging lime has been established as a probable cause of some accidents.

Lime is required to flow out either when spreading, or as an emergency discharge due to other difficulties encountered by the pilot. This is especially relevant on take-off when pilots are sometimes required to discharge some of their load to affect a take off. Twenty percent of all topdressing accidents occur on take-off, when aircraft hit obstructions such as fences or trees, or fail to get air-borne (CAA, 2006). As with all types of aviation most accidents occur on take off or landing a situation accentuated in New Zealand agricultural aviation with an average of about twelve take offs and landings per productive flying hour.

The requirement to dump part of the load in order to take off is a frequent occurrence during operations as there is a tendency to overload aircraft for the conditions (Lewis *et al*, 2008). Overloading with lime is more likely than with other commonly applied bulk solids as it has a greater bulk density.

Bulk density measurements were undertaken on eleven commercial limes as received at Massey University as part of a series of experiments and the limes had a loose – tap density range between 1,200 and 1,750 kg m^{-3}. The AT 502 and Cresco have hopper capacities of 1.9 m^3 and 2.0 m^3 respectively and most limes have a density which allows aircraft to be loaded with material which exceeds the maximum take off weight including the allowable agricultural overload which is about 2.2 tonnes of bulk solid. However, the safe aircraft load is dependent on the weather conditions and the airstrip and is often less than the maximum permissible load.

Aircraft loaders are equipped with hydraulic load cells which are certified for accuracy every six months. The aircraft load is usually now determined by radio communication between the pilot and the loader driver and is often adjusted after fuel is requested which is required every

1-2 hours depending on the aircraft type. In earlier times communication was maintained with hand signals. Therefore, the tendency to overload is entirely dependent on the ability of the pilot to make a judgement about how much lime remains in the hopper before it is reloaded. Judgement is affected by the pilot's ability to see into the hopper, which may be dark and cloudy, whether the residual load adheres to the part of the hopper the pilot can see; and the margin of error around such murky observation, which is unknown. There may be other factors that mean visual observations are rushed or omitted such as anxiety about impending weather or time available, in addition to the positioning of the window behind the pilot's head. Also, the commission based rates of pay do not promote careful checking of the hopper before loading, but rather reward haste.

Flow tests on lime undertaken by John Maber in 1979 (pers. comm) using a Fletcher hopper were done to establish dump times on several limes when the hopper was at varied angles. A 15° tilt backwards was used to simulate take-off conditions which would be experienced by an aircraft rotating to leave a long airstrip. This was used as it is a typical situation and it is at take off that the pilot is most likely to dump his load. A no tilt dump was also undertaken as was a 3° forward tilt to simulate a sowing attitude. The 15° was the slowest as the back wall of the hopper supported the lime and the material that dumped came from in front of the hopper door. It is a concern that the aircraft dump is impaired in a take off attitude when this is when it is most likely to be needed. On the alternate strips which the aircraft drops off the end and maintains a controlled fall until flight speed is reached the dump is inhibited by the fall reducing the gravitational acceleration g. Where, for free flowing bulk solids the rate of flow is proportional to the $\sqrt{g}$ (Deming and Mehring, 1929). So if overloaded on this type of strip the rate of dump will be reduced the faster the rate of descent.

The lime flow problem is described anecdotally by the industry as three distinctive issues; bridging of dry particles, adhesion to the aircraft and cohesion between particles of damp lime. In all instances the pilot has difficulty jettisoning his load. In the case of adhesion to the aircraft several hundred kilos may be left in the aircraft. When the next legal load is placed in the aircraft it becomes overloaded. Section D5 of Part 91 of the Civil Aviation Rules state; ‘ the aircraft must be fitted with a jettison system which is capable of discharging 80 percent of the aeroplane’s maximum hopper load within five seconds of the pilot initiating the jettison action’ (CAA, 2006). However, D5 of the rule (CAA, 2007), prescribes that the jettison tests are undertaken using superphosphate which is very free flowing when dry and properly matured, as specified below.

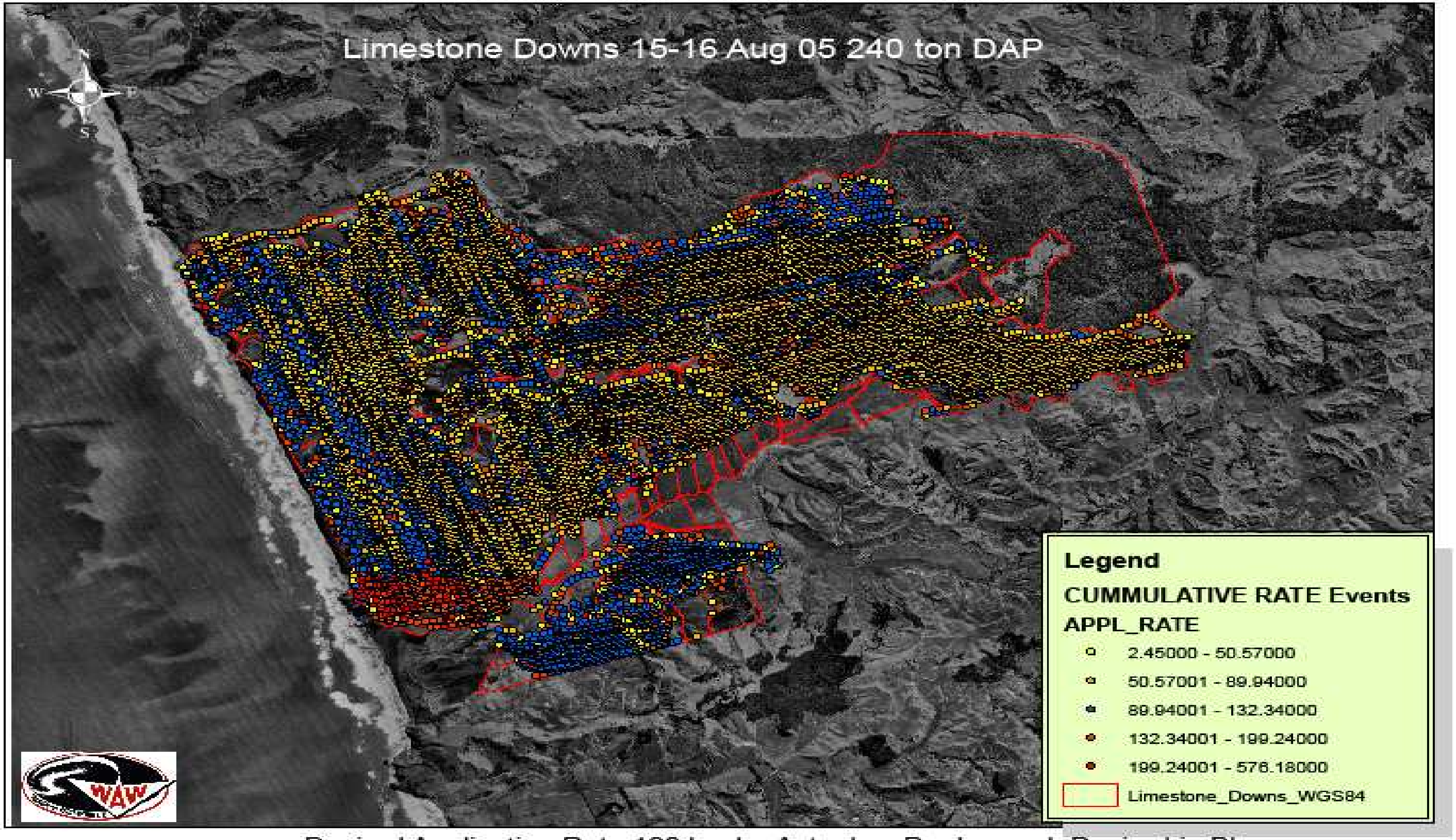
‘A jettison system must be—
(1) Simple to operate; and
(2) Designed so that once the control is selected by the pilot the load will fully discharge without requiring the pilot to continue holding the control.
(b) The capability of the jettison system must be—
(1) Demonstrated by a flight test using—
    (i) the maximum permitted load of Superphosphate specified in the flight manual; and
    (ii) when specialised role equipment is fitted, the maximum permitted load of the agricultural material typically used when that role equipment is fitted; and
(2) Specified in the aeroplane flight manual.’

Little work has been completed to evaluate the evenness of flow from topdressing aircraft (Yule *et al*, 2008).

The work that has been done requires collecting data, which has been accomplished on small scale applications through collecting samples in collection trays to establish the application rate.

A full farm commercial application has been used to establish evenness of spread by calibrating the flow rate of a non cohesive granular fertiliser Di-Ammonium Phosphate (DAP) through a hopper opening and then estimating the flow from the hopper based on opening and relating this to the position of the aircraft through a Differential Global Positioning System (DGPS) operating at 5 Hertz. The cumulative total of the estimated application was within 3% of the total fertiliser applied, Figure 1.6. The estimation was made from measuring the hopper opening using a potentiometer and the DGPS reading and logging both readings. The calibration was made on the ground by calibrating the flow rate from an identical hopper on the ground at a fertiliser store. Kriging was used to calculate a coefficient of variation of 77% on this job. Kriging estimates the probability of a concentration or rate in an area based upon the spatial evidence adjacent to the point. Figure 1.7 shows the application rate in a 3 dimensional analysis after the Kriging is run. The work was undertaken in August 2005, and the data was analysed independently by the author and Massey University (Yule *et al,* 2008).

The desired rate is within the blue zone of both Figures 1.6 and 1.7. The desired rate was 120 kg per hectare although this was rarely achieved. The largest proportion of the farm received a rate less than was desired, the areas in the lighter colours. However some areas received an application rate considerably higher than was required, shown as the darker shaded areas.



Desired Application Rate 120 kg. ha Actual as Per Legend, Desired in Blue

Figure 1.6: Modelled application rate obtained by calibrated hopper linked to Differential Global Positioning System at 5 Hertz, figure Grafton, 2005.

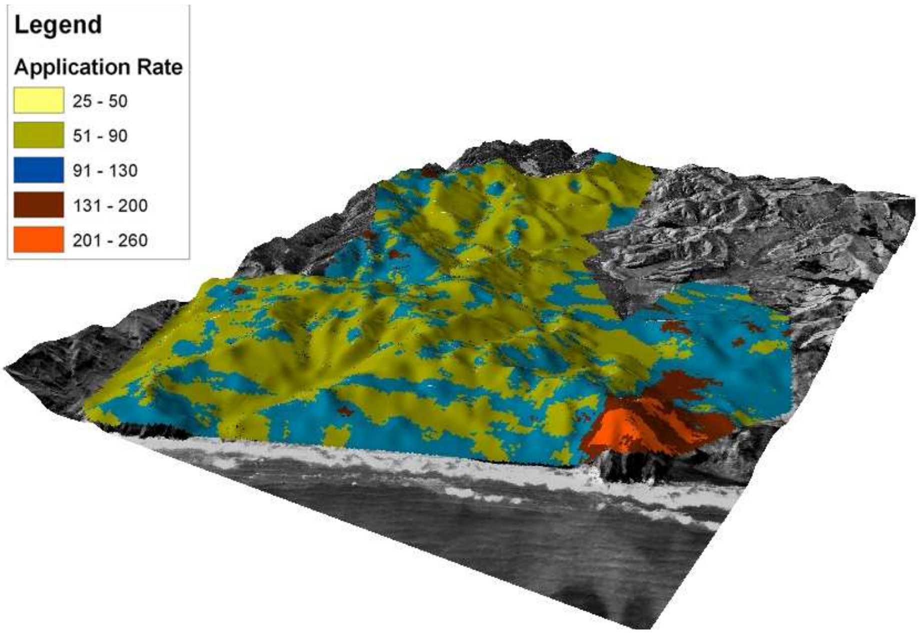


Figure 1.7: Krig of data application rate depicted in Figure 1.6 figure courtesy M.E. Irwin Massey University, 2009.

Flow trials with commercial agricultural lime through a full scale aircraft hopper and through a model hopper with variable opening and side wall angles demonstrated that none of the commercial limes tested was free flowing. Some frequently bridged forming cohesive arches as shown in Figure 1.8 (Grafton *et al*, 2009a).

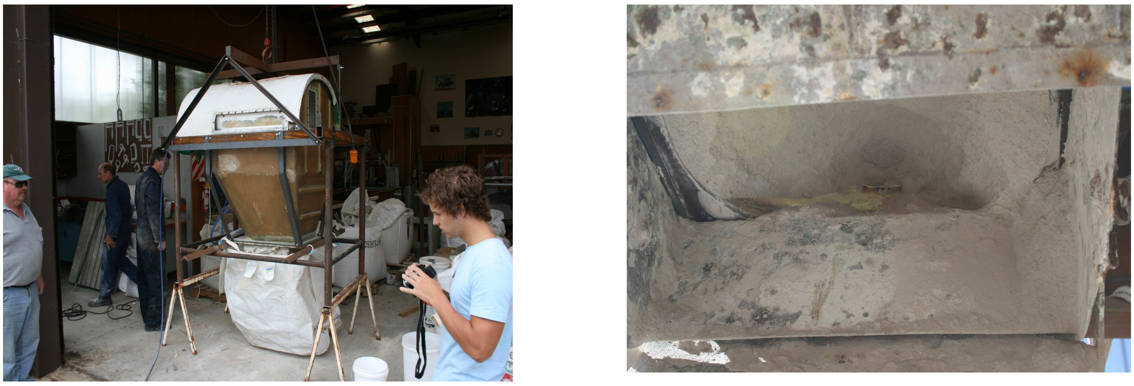


Figure 1.8: Shows an agricultural lime bridging in an aircraft hopper during flow trials, (Grafton *et al*, 2009b)

Lime is defined by Fertmark® the NZ Federated Farmers fertiliser quality standard and quality assurance programme as a substance that must be at least 65% calcium carbonate by weight, and which 95% by weight of the particles must pass through a 2 mm sieve and 50% by weight through a 0.5 mm sieve.

However this standard is rather a generic description of the range of products mined and crushed throughout New Zealand which are all marketed as agricultural lime. These deposits were formed from recent Plio-Pleistocene through to ancient very pure calcium carbonate deposits from the Ordovician epoch (Christie *et al*, 2001). They also vary in character from Ordovician pure marble deposits, Plio-Pleistocene through to Miocene sandy coquina through to Oligocene argillaceous micritic limestone (muddy limestone).

Flow tests (Grafton *et al*, 2010) and shear tests undertaken at Massey University on commercial limes suggest that the sandy coquina deposits tend to flow more freely than the micritic limestone (Grafton *et al*, 2009b). In addition, the removal of fines improved flow and decreased the bulk density of the limes. The removal of particles less than 300 microns produced a lime with a similar bulk density to superphosphate. If a similar product was commercially available to aerial applicators the chances of overloading would be reduced and the material would be less cohesive.

1.5 Summary

It is clear that the CAA is determined to improve the safety of fixed wing topdressing operations in New Zealand. They have invested considerable time and resources to produce an airstrip and supply chain guideline which has been distributed free of charge to all airstrip owners and operators. They have also tried to identify factors which have contributed to the deterioration in the safety record over the last 15 years so they can reverse this trend.

It is likely that a work place accident that results from materials that won’t flow, or due to unsuitable airstrips will lead to prosecutions under the Occupational Safety Health Act administered by the Department of Labour and or the CAA if an aerial operator has contributed to the incident.

The contributors to the Agricultural Aircraft Safety Review concluded that overloading is common and that a means of accurately recording each load and recording it for audit purposes is desirable. That the overloading has led to undercarriage occurrences in PAC manufactured aircraft. That if aircraft operating above MCTOW do not compensate by reducing the manoeuvring speed and maximum velocity then the airframe may be stressed beyond its certified limits. That it may have been a mistake to allow reciprocating engines to be replaced by much more powerful turbine engines in Fletcher aircraft on a STC, when a separate type certificate would have been more appropriate as the aircraft is more accurately described as a separate aircraft type. That by allowing this, it has disadvantaged manufacturers of new aircraft certified as different types, thus encouraging operators to take a cheap option of modifying an old airframe rather than purchase a replacement aircraft. The granting of the STC is based on the extra power not being used to exceed the permissible g load and manoeuvring speeds. It is likely if the aircraft was certified as a separate type that the airframe would require strengthening.

The review failed to address the issue of material flow problems which prevent aircraft dumping their loads but merely discussed the range of bulk densities of commonly sown materials in regard to overloading.

It also failed to address the human factors which lead pilots of agricultural aircraft to overload for the conditions. It seems likely that factors include the means of remuneration, over confidence in their own ability and a blasé attitude to the actual risks which they face, probably due to their continuous exposure to these risks.

It seems inevitable that CAA will modify its rules in respect of all matters raised in this paper. Certainly in the future turbine conversions will be more difficult to have certified. That a compulsory means of accurately recording aircraft loads that will prevent overloading by allowing those engaging in the practise to be prosecuted will be required.

Preventing overloading will certainly prevent some problems but will not address the flow problem when a load fails to discharge, nor the problem of a partially hung load which leads to an accidental overload when another legal load is added.

It is difficult for pilots and their loader drivers who are at the end of the bulk solid supply chain, to assess the flow properties of the material they will load and sow. It is also not reasonable to expect each load to be identical to a previous one. For example a load on the bin floor may have been subjected to moisture seeping through as may material near a bin wall. Issues of compaction and fine segregation are also likely to occur, which will produce variable loads. Agricultural lime has a large particle size range from less than 38 microns through to particles larger than 2 mm. In addition the percentage of fines can alter quite dramatically depending on the age of the crushing hammers. Therefore, under the inevitable vibration of loading and cartage from the quarry through to loading in an aircraft and take-off on a farm airstrip, compaction and load consolidation is likely to occur. Materials with a wide range of particle sizes are prone to segregation and consolidation as the smaller particles pack between the larger ones and bridge which cause materials to cohere and prevent flow (McGlinchey *et al*, 2005).

Although, the CAA has discharge requirements for bulk solids there is no simple method of ensuring that all loads comply. This is not an issue with some materials such as Urea or well stored superphosphate and Di Ammonium Phosphate, however for materials such as agricultural crushed limestone there will need to be changes in the standards for aviation use to enable certainty of flow compliance.

Aircraft delivery systems have remained largely unaltered since the inception of agricultural topdressing. A door is manipulated via a series of connecting rods to a door or a clam shell opening. The pilot has to attempt to deliver the correct application rate by controlling the door opening and the swath or bout width, between sowing runs. DGPS assists in improving quality by giving the pilot a read-out of area covered in each run. A light bar integral with the system, outside the cockpit enables the pilot to guide the aircraft to the correct pre set swath spacing. These systems have been developed since the early 1990's and are not new technology, however are only fitted to a minority of agricultural aircraft in New Zealand, which means most operators continue to apply fertiliser by eye.

Some work has been undertaken to control the application rate through the DGPS system with some success (Yule *et al*, 2008). In addition work has been undertaken to control application rate by measuring the mass flow from the aircraft over time. Pacific Aerospace Corporation fitted a g-meter to a load cell suspending the hopper over the outlet, in their agricultural versions of the XL Cresco, so that the mass flow rate could be known at any time; despite changes in gravity due to aircraft manoeuvre and contour flight. However, the systems were unreliable and subject to failure. Manufacture of this type of aircraft has ceased and all three which entered service in New Zealand have been withdrawn.

It is not possible for pilots operating a manual system to apply fertiliser at accurate application rates whilst contour flying over hill country. This type of flying results in changes in aircraft speed and consequently rate (see Figure 1.9). The only practical means of overcoming this difficulty is to automate the delivery system based upon information received from the DGPS and if possible a means of measuring the rate of material discharge from the hopper.

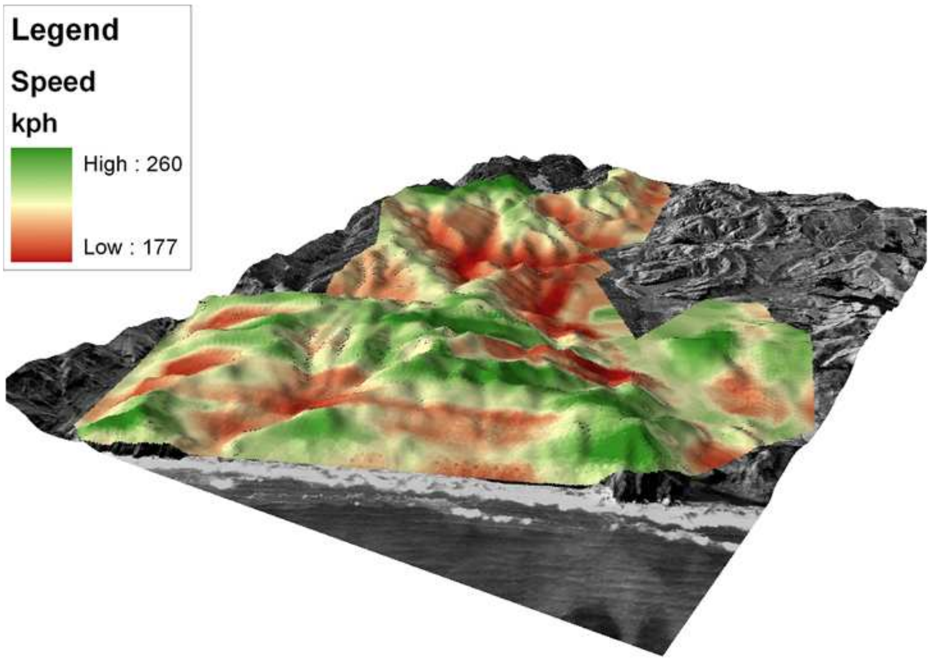


Figure 1.9: Speed ramp spatial display from DGPS data of topdressing job Limestone Downs

It is necessary to examine the economics of the topdressing industry to understand the choices that have been made in respect of aircraft choice. Financial reasons may also be a factor in the quality of the spread and the safety record of the industry.

Chapter 2

Literary Review

2.1 Introduction

Fertmark® was established in 1996 by NZ Federated Farmers and the major NZ Fertiliser manufacturers to establish a quality assurance regime for fertiliser manufacture and use in New Zealand. The aim has been to give New Zealand farmers confidence in the quality of fertiliser and the associated advertising (www.fertqual.co.nz).

Agricultural lime is defined in the Fertmark Code of Practise as: ‘Ground limestone rock with a minimum lime equivalent of 65% by weight of $CaCO_3$. Not less than 95% by weight shall be able to pass through a 2.00 mm sieve, and not less than 50% by weight shall be able to pass through a 0.5 mm sieve (www.fertqual.co.nz). Fertmark® limes are characterised by declared values of calcium carbonate equivalence using a standard method which involves a titrimetric method of acid neutralisation. All declared values are subject to independent audit at least biennially by qualified Fertmark® auditors.

The purpose of this section of the review is to examine the physical make up of lime materials to see if there are common factors or differences among limes which influence their flow properties; to meet objective 2 *“Develop a better understanding of material variability in terms of characterising the different deposits used around New Zealand and relating these differences to flow properties”*.

It is possible that some of the clay impurities in agricultural lime may contribute to problems associated with the spread of lime by agricultural aircraft in New Zealand, if present in sufficient quantity. Clays have a tendency to adsorb water molecules and dissolved ions readily, which may be a factor in some limes being cohesive. Another objective was to establish actual $CaCO_3$ levels by Thermal Gravimetric Analysis (TGA) and compare these with the values published by the fertiliser manufacturers to Fertmark®. The declared value involves a titration to neutralise HCl and is reported as a $CaCO_3$ equivalent (Cunniff, 1999). The titration therefore does not definitively measure the calcium carbonate in a sample but rather measures its total acid neutralising effect. Acid neutralising hydroxides associated with clay were considered possible impurities which may adversely affect flow and differences between the TGA and declared values may indicate their presence. The TGA also provides information on the thermal decomposition of both carbonates and hydroxides.

2.2 Origin and Mineralogy of Limestones in New Zealand

The distribution and general properties of New Zealand limestones for economic uses is summarised by Christie *et al* (2001). Most agricultural limes in New Zealand are sourced from mid-Tertiary (Oligocene) limestone deposits. This includes limestones found in Northland, Waikato, Taranaki and Canterbury through to Southland. The exceptions are Poverty Bay to Wairarapa where the limestones are of Plio-Pleistocene age and in the Nelson Region where lime is also obtained from Ordovician Takaka Marble.

There are regional differences amongst the various limestone sources. In Northland the bulk of the lime is obtained from the so-called [hydraulic] limestones of the Mahurangi Formation O'Connor (1999), which comprises Oligocene argillaceous grey/white, intensely-sheared, usually bioturbated, relatively hard argillaceous lime mud. Approximately 60% is muddy matrix (consisting of roughly 70% carbonate nanofossils), about 20% is clay minerals, and the remaining 20% consists of variable quantities of quartz, feldspar, calcite (veins), pyrite, and glauconite, along with siliceous and carbonate microfossils. Carbonate contents vary between 60% and 80%, with rare examples greater than 90% O'Connor (1999). On the eastern side of Northland minor quantities of lime are obtained from the carbonate-cemented shelly limestones of the Whangarei limestone. Both sources are of similar age and it is likely that the muddy limestone is the deep water facies equivalent of the Whangarei limestone O'Connor (1999).

The limes obtained in Waikato are derived from crystalline limestones comprising fragments of carbonate macro- and microfossil shells. They are mostly hard as a result of secondary calcite cementation and are contiguous with the crystalline limestones at Whangarei.

The East Coast North Island limestones are softer and less cemented, consistent with their younger, Plio-Pleistocene age. They comprise dominantly fragmented barnacles. At Havelock North a travertine deposit was worked for industrial lime but the shelly Awapapa limestone is quarried for agricultural product. A similar limestone (Totaranui) is quarried east of Pahiatua.

In the north Canterbury region Oligocene-aged argillaceous to sandy limestone forms the raw material for agricultural lime. In South Canterbury the main limestone exploited is the Otekaike Limestone, a partially crystalline Oligocene-aged unit comprising shell fragments and microfossils. In Southland slightly younger Miocene-aged crystalline shell fragment limestones are worked Christie *et al*, (2001) and O'Connor (1999).

On the West Coast the Oligocene-aged algal Waitakere limestone near Westport (Lever, 2001) has been extensively quarried for both cement production and agricultural lime. Elsewhere in Westland crystalline shelly limestones of similar age are also exploited for agricultural lime.

In the Nelson region Takaka marble has been used for high grade agricultural lime as well as for its better known use as a building stone. It is a hard, crystalline rock in which the original sediments have been recrystallised to coarse calcite.

2.3 Background

The New Zealand topdressing industry handles many products, of which only a few are homogenous e.g. Urea & fresh DAP; the majority of spreading being undertaken involves products with large variations in particle size and moisture content which comes from fine dust to concretions. These characteristics make it very difficult to achieve either continuous flow, or even spreading from an aircraft. Lime has been identified as being particularly problematic and is being used as an initial focus for this study, but other materials are to be considered once the factors crucial to good flow-ability are identified and quantified.

The lime flow problem experienced by the industry comprises three distinct issues: *viz* bridging of dry particles, adhesion to the aircraft hopper wall and cohesion between particles of damp lime. In all three instances the pilot has difficulty jettisoning his load. In the case of adhesion to the aircraft hopper several hundred kilos may be left in the aircraft hopper. When the next legal load is placed in the aircraft hopper it becomes overloaded as the bulk density of lime is such that an aircraft may become overloaded whilst the hopper is not full. Some fatal accidents and many near misses have occurred as a result of pilots being unable to jettison any of their pay-load of agricultural lime.

There is a correlation between increasing bulk density and reduced flow-ability (Ganesan, *et al*, 2005). However, confusingly the inverse can be true as indicated in the multifaceted approach developed by McGee & McGlinchey (2005). Some of the aspects of the multifaceted approach will be revisited later in this chapter, which looks at several aspects of bulk powder properties and weights these to determine flow properties.

With a wide range of particles of mixed sizes there may be a tendency for the smaller particles to percolate (Mehta, *et al*, 1993) especially in the low intensity shaking environment encountered in a truck or aircraft until they jettison. It is not know if this is contributing to the problem, but it may have the greatest effect near the hopper wall and therefore change the particle wall dynamic by altering the angle of wall friction. It is known that small powder particles are cohesive (Ganesan et al, 2005) and due to their large surface area, are more inclined to adsorb moisture, which is the property most obviously affecting the cohesive strength and hence the arching ability of bulk materials (Johanson, 1978). However, particle flow is multidimensional and is a function of many factors elegantly described by Ilari (2001*)* “*Through our experience, we suggest understanding that the concept of flow is at the centre of a cobweb from the origins, having connections with civil engineering, laboratory characterisation, rheology of solids, mechanics of fluids, process engineering, sensory analysis, behaviour studies, physics, mathematics and statistics”*. Freeman *et al*, (2007) observes that powders are complex, not least because a given mass of powder can contain variable amounts of air which can radically change its flow properties, perhaps by a factor of 100 or even 1,000.

The science of bulk solid storage and flow was developed to overcome a range of problems relating to these matters in a wide range of industries and situations. Bulk solids are extremely important in solid energy production, process engineering, food technology, grain storage and other situations in addition to fertiliser and lime storage.

The science of predicting powder flow was developed from soil mechanics and is useful in designing hoppers to discharge powders in a controlled manner to suit the process purpose.

There are a range of flow types from no flow to funnel flow to mass flow (see Figure 2.1). The no flow situation occurs when the powder has enough strength to support its weight by forming a cohesive arch. These arches may be momentary and collapse or may be induced to break by hammering or vibrating a hopper, in an aircraft this is achieved by bunting which is the practice of manoeuvring an aircraft to change the gravitational force to aid the jettison of a load.

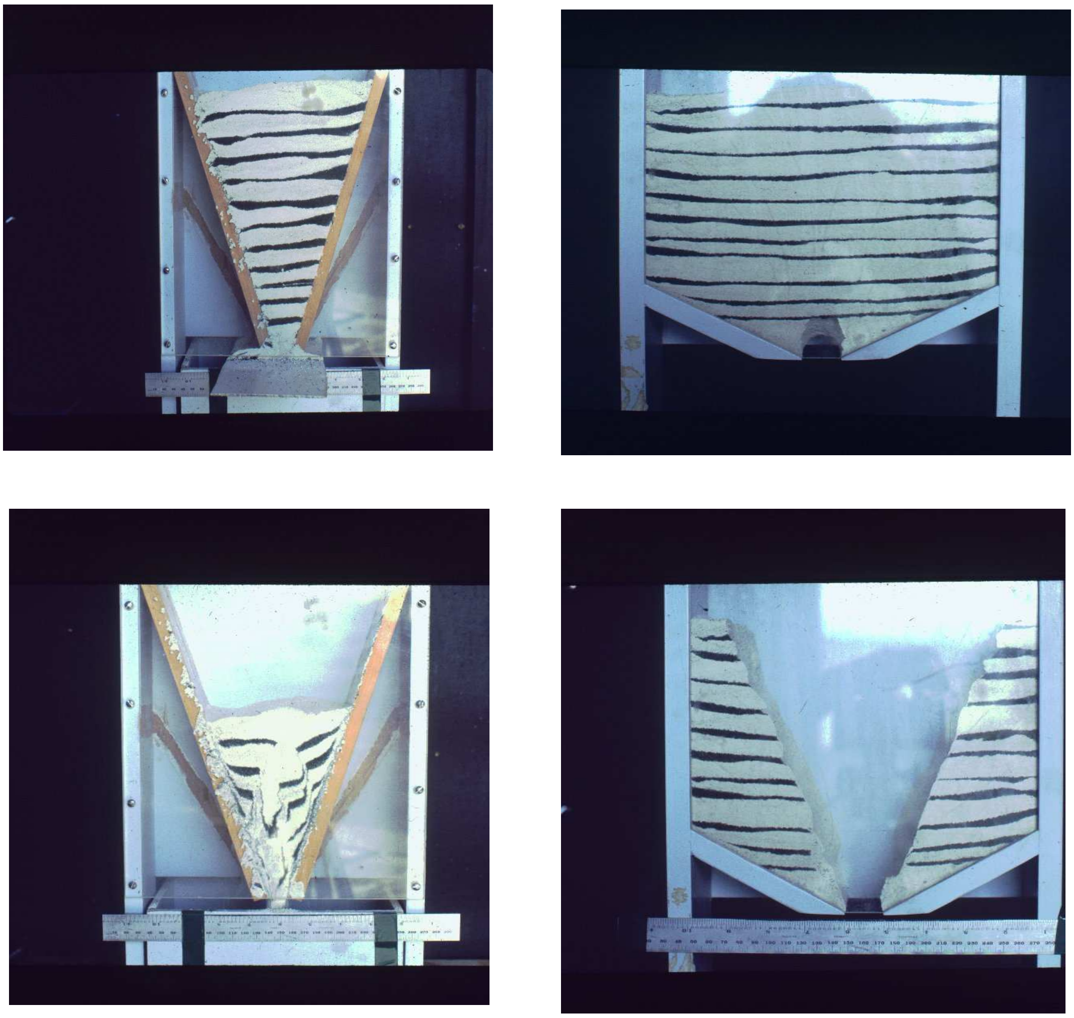


Figure 2.1: shows from top left clockwise; mass flow, no flow and cohesive arch, funnel flow and mass flow again. Photographs courtesy of John Maber.

2.4 Measuring Flow Properties

In order to be able to better predict flow we must first develop a better understanding of the material’s key physical properties which determine the type of flow achieved in a given situation. The main/only method of achieving this is through shear testing (Jenike, 1964). A range of shear testing apparatus has been developed, mainly through experimentation related to a wide range of materials from coal to pharmaceutical materials; this has lead to the development of a range of shear testers suited to those materials. The methods of analysis are described later in this chapter as well as a review of the different shear testing apparatus.

Shear testing is suitable for materials which are not free flowing. Free flowing materials conform to the analysis provide by Beverloo *et al,* (1961) and their flow can be calculated through the Beverloo equation. Free flowing materials have no ability to form a cohesive arch, (As illustrated in Figure 2.1). Shear testing may be used to determine how large a cohesive arch the material can form, with this understanding, the handling equipment used to transport and store the material can be designed so that good flow can be maintained.

One of the pioneers of this work was Jenike who developed a shear cell in order to characterise materials. The shear cell operates by pulling the top half of the material across the bottom half causing the material to shear; this is completed with different normal loads on the material. The Jenike tester, along with approved testing procedure, can produce consistent results and is the industry standard. It has proved difficult to use as different operators often got different results, the cell was also small and only suited to a very limited range of unmodified materials. A number of annular or rotational shear cells have been developed. These have been found to be easier and less time consuming to use de Silva (2000) and Freeman *et al,* (2007). Again the shear tests are completed with a number of normal loads applied.

The flow properties which can be determined by shear testing are related to the frictional properties of the material which influence the cohesiveness of the material. Shear testers measure the stress required to cause the material being tested to fail or shear under a normal stress after the material has been compacted by a known consolidating normal stress. By taking readings at a range of normal stresses a series of points can be graphed. The shear stress relation at failure / normal stress applied; which when linked by a best fit curve provides a line of powder failure, known as a yield locus at the known initial compaction consolidation Jenike, (1964). This information by itself is not very useful to agricultural aviation as most material flow properties relate to ensuring certainty of gravity flow of bulk solids from storage vessels or silos.

Material flow properties from storage vessels are affected by the interaction of the wall and the material stored. They are also influenced by the size and shape of the outlet and the steepness of the hopper wall, (see Figure 2.1). Material can be sheared along wall material in a similar manner as to shearing against itself, by replacing one half of the material being sheared by wall material. This provides a failure locus, known as a wall yield locus.

Bulk solid materials stored in a silo do not exert a significant normal stress on the opening as most of the stress is radial and applied on the silo’s hopper walls. This changes when flow initiates as the weight of material above the hopper forms a vertical stress as material discharges (Jenike, 1964). Once the hopper is opened the material will flow if the opening is larger than the radial stress field at the opening of the hopper (Jenike, 1964). If the bulk solid has greater strength than the radial stress at the opening flow will not initiate (see Figures 2.1 and 2.2).

A shear testing regime can provide the data so that the required opening and wall angle can be established to ensure gravity flow from a silo given the bulk solid and wall material being tested are representative of the silo and material being stored.

Powder strength is measured by shear testing, (see Figure 2.3), at a known pre-consolidation stress which is at a known consolidated normal stress less than or equal to the pre-consolidation stress. Several readings are taken at a range of normal stresses, less than the pre-consolidation stress, for each pre-consolidation stress to obtain a yield locus and then a family of yield loci, (see Figures 2.4 and 2.5).

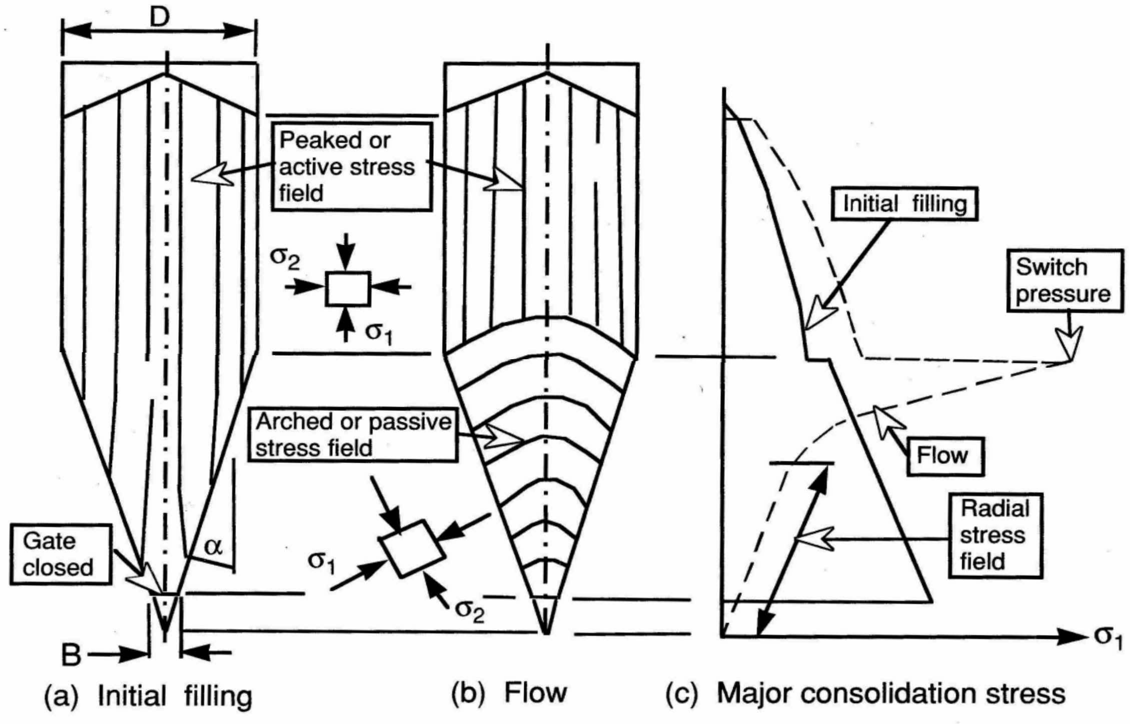


Figure2.2: Stress fields at hopper outlet from (Robers, A. W, McGlinchey Edit., 2005)

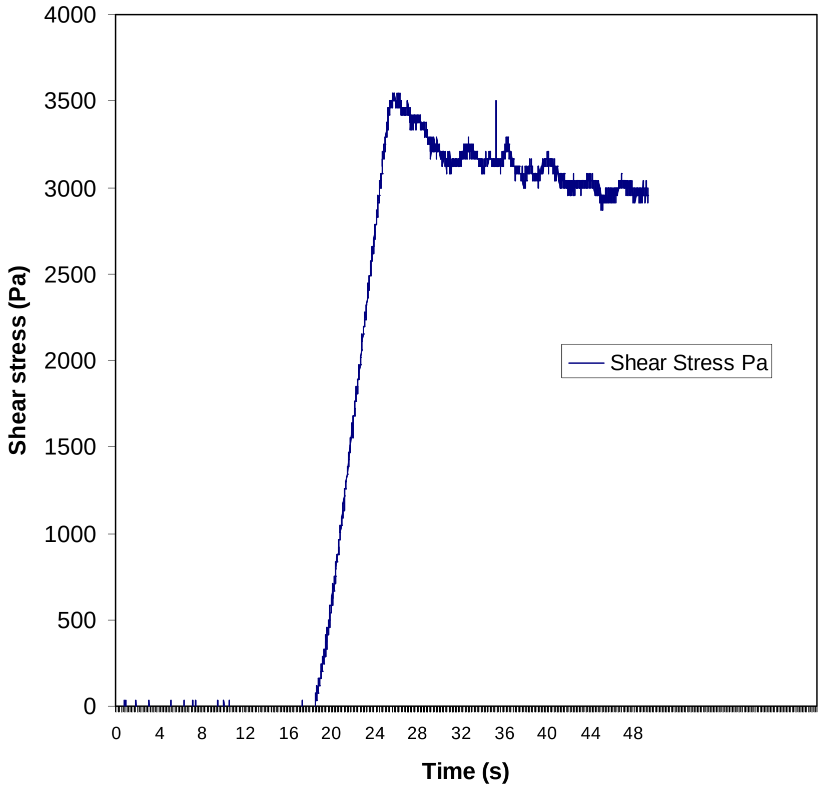


Figure 2.3: A shear test select maximum for Incipient Yield Locus (3,500 Pa)

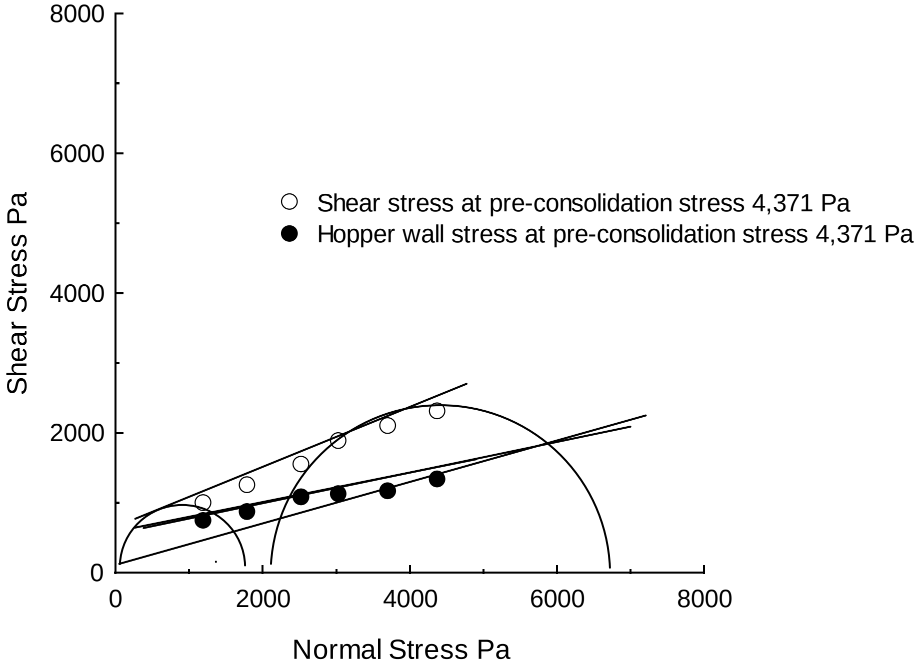


Figure 2.4: Mohr circle construction yield locus and unconfined yield stress (UYS) and maximum consolidated stress (MCS) and hopper wall yield locus; as received Westport lime.

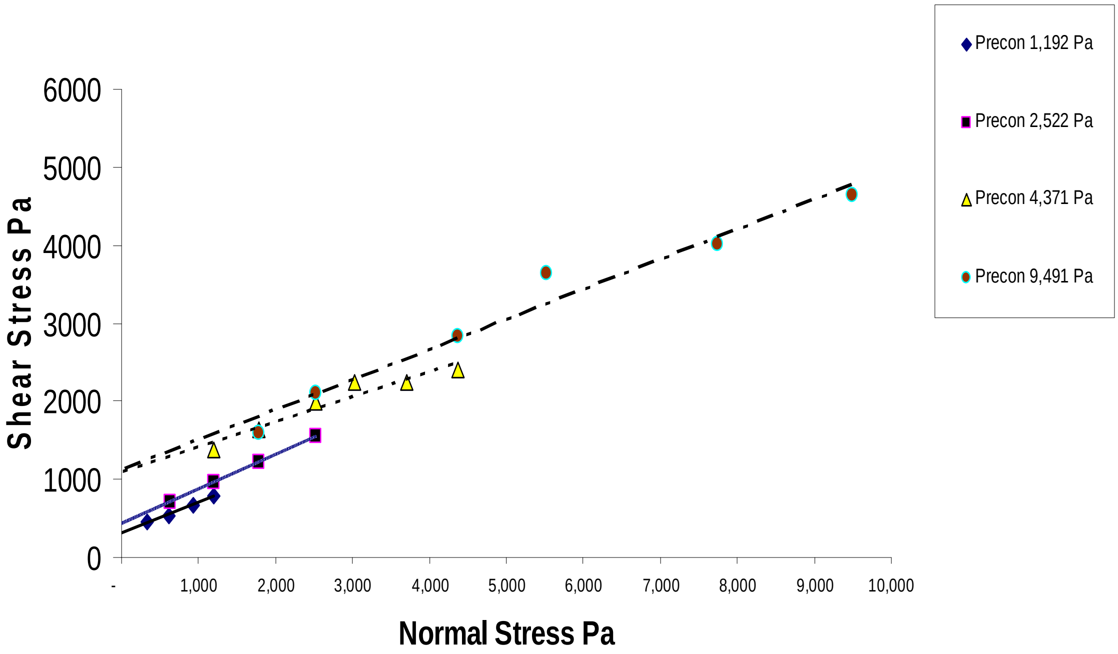


Figure 2.5: Yield loci (Walker shear cell) as a function of pre-consolidation stress; as received Westport lime, 0.9% moisture by total mass.

A wall yield locus is also required which is measured by shearing the powder against a sample of the wall material.

The data is analysed using Mohr circles which is applicable to powders. Shear tests are undertaken on powders, as large particles are free flowing although are capable of bridging and shear testers are limited by their size and the physical nature of the shear plane which is only a few particles thick (Jenike, 1964). For example the Jenike shear cell is limited to particles less than 4.5 mm in diameter. The reason Mohr circle analysis is applicable is that stress analysis is being undertaken, rather than force analysis. Force is a vector measurement with a (x,y,z) component. Stress is Force/ Area and as a result has nine components and is a tensor rather than a vector. These stresses operate as complimentary pairs 90° to each other and once the eliminating and substitution is applied using the double argument rule we finish up with:

$$(\cos^2(\theta+\tau) - \sigma) + (\sin^2(\theta+\tau)) = R \qquad (2.1)$$

this is an equation which defines a circle (Nedderman, 1992).

The initial pre-consolidation stress can be obtained by following the instructions of the IChE Guide (IChE 1989) which is based upon the bulk density of the material being tested (Table 2.1). The initial pre-consolidation σ_{p1}, removes the material history and eliminates voids in the powder. By pre-consolidating prior to each shear test, which are all undertaken at a lower normal stress than the pre-consolidation stress, the shear stress values can be established for a shear locus at a set pre-consolidation.

Table 2.1: Recommended Normal stresses as per IChE standard Jenike shear test method (IChE, 1989).

ρ_b (kg/m^3)	σ_{p1} (kPa)
< 300	approximately 1.5
300 – 800	approximately 2.0
800 – 1600	approximately 2.5
1600 – 2400	approximately 3.0
> 2400	approximately 4.0

The test consists of acquiring 3 or 4 points between 20 – 80% of the pre-consolidation σ_p, kPa. Once completed the test is undertaken at σ_{p2}, σ_{p3}, σ_{p4}, which are at 2, 4 and 8 times σ_{p1}. Mohr circles can then be drawn within the yield loci data lines to obtain the unconfined yield stress and the major consolidating stress. The unconfined yield stress is the strength the powder has when it is not confined and is the stress required to break its structure McGee and McGlinchey (2005), whereas the maximum consolidated stress is the strength the powder can obtain when is confined and will alter under failure as the consolidating pressure changes. In a silo situation this pressure will alter as the level changes and also over time under storage at a head of pressure, see Figure 2.2.The yield loci lies tangential to the Mohr circles. The main rules of drawing these loci by hand is to make sure the X axes and the Y axes are the same scale otherwise the intersects of the Mohr circles are meaningless, as the circle is only valid at the same scale. The angle of internal friction is obtained by the angle created by a line drawn tangential to the Major Minor consolidated stress Mohr circles from each of the pre-consolidation stresses as in Figure 2.6 below. Each point of the Mohr circles comprises a shear stress and a normal stress value at the pre-consolidation Normal stress value for each locus (Nedderman, 1992).

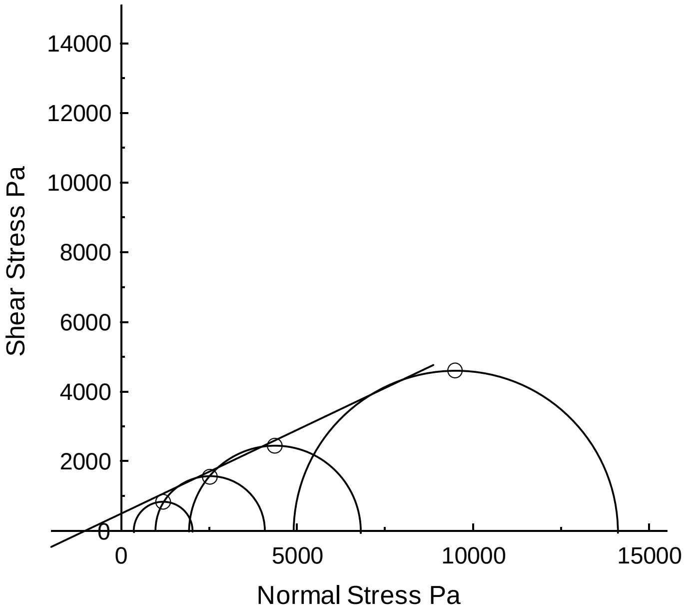


Figure 2.6: Incipient Yield Locus showing angle of internal friction (δ) 26º, as received Westport limestone

The arch strength is based upon the Unconfined Yield Stress a property of cohesive bulk solids and represents the maximum compressive stress that can act along a free surface (Nedderman, 1992). Bulk solids gain strength from a mixture of physical means which may contribute depending on the material.

These Include:

Dissolution: Moisture may cause materials to cake as particles dissolve and form agglomerates which become cohesive cakes, common with sugars. Caking is common in situations when cementation occurs as the dissolved material crystallises when the solvent, usually water, evaporates. Dissolution may also decrease cohesion by removing fines (McGlinchey, 2005).

Polar Bonds: Interstitial moisture may help particles cohere through electrostatic attraction (McGlinchey, 2005)

Van der Waals Forces: These are intermolecular attractions caused through polar molecules creating fluctuating dipoles as electrons make one part of a molecule negative as they move around the atoms temporarily creating polar attractions by attracting the opposite pole from neighbouring atoms (McGlinchey, 2005).

Bridging: This is a function of particle size distribution and particle shape. Particles may form bridges by interlocking amongst themselves and is quite common with particles of angular irregular shapes and those with a wide particle distribution similar to the requirements of tablet formation (McGlinchey, 2005).

The material in a hopper has strength that may vary as a result of several of these factors and this strength will vary with time as conditions alter and also independently of conditions by time alone (McGlinchey, 2005). Bulk solids tend to gain strength with time (Jenike, 1964) as the material reaches equilibrium and consolidates under its own weight. The material is also influenced by the hopper wall – particle interface which effects the hopper half angle required to let the material flow along the wall contemporaneously with those not in contact with the wall. It is the relationship of hopper half angle and hopper opening that ensures mass flow.

The minimum opening equation is based upon finding the intersection of two simultaneous equations, one which quantifies the supporting force of a cohesive arch and the other the normal force acting on the arch, where the normal force is greater than the supporting force the arch will collapse (Nedderman, 1992). This assumes that the weight of material acting as the normal force is only that supported by the unconfined yield stress, all other material above this concentric outer arch has no influence, which is the case as we are establishing the maximum diameter of a self supporting arch. The stress below the arch is zero, which from the Mohr analysis means that the stress above the arch is the opposite end of the Mohr circle along the x axis, which is the UYS. Figure 2.7 is a schematic of a cohesive arch from which the equations are derived, annotated in the terminology of this thesis but based on Jenike’s model for the formation of an arch (Nedderman, 1992).

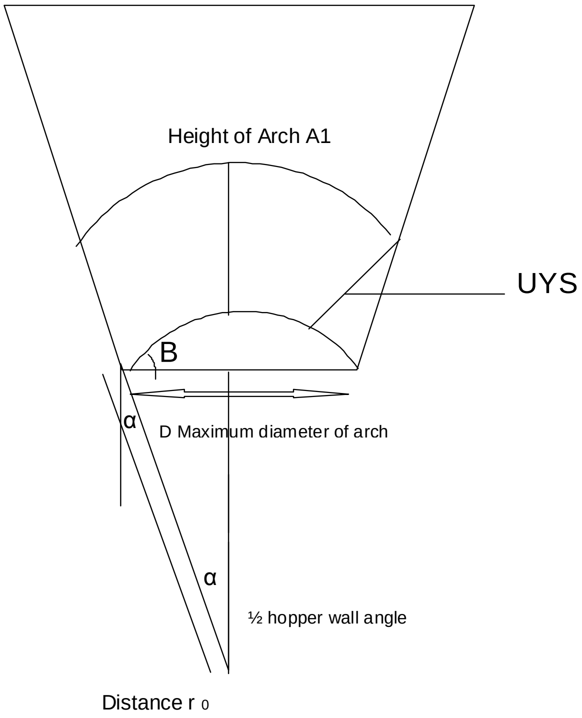


Figure 2.7: Jenike's Arch Formation Schematic

The normal force acting to break the arch is:

$$\pi(r_0 \sin\alpha)^2 \ \rho \ g \ A_1 \qquad (2.2)$$

This provides the force by weight which is calculated from the normal stress, on the arch multiplied by the area, using the elements of the depth of material, its bulk density and gravitational acceleration and the radius of the arch.

Whereas the width of the arch is $2(r_0 \sin \alpha)$ and the force supporting the arch is:

$$2\pi(r_0 \sin \alpha) A_1 \cos B \text{ UYS } \sin B \qquad (2.3)$$

This comprises the horizontal and vertical components of the unconfined yield stress multiplied by the height of material supported, and the circumference of the arch.

This can be expressed through the use of the double angle formulae rule where $2\sin B\cos B$ can be substituted for $\sin 2B$ as ($\pi\ r_0 \sin\alpha$ UYS $A_1 \sin 2B$). This has a maximum when $\sin 2B = 1$ which occurs when 2B is 90º, when B is 45º. In practise this will vary with the angle of internal friction, and will generally be less than the maximum.

We can see from simple geometry that the maximum distance D is $2(r_0 \text{ Sin}\alpha)$ and also the maximum diameter occurs when the normal force acting on the arch equals the force supporting the arch. Therefore:

$\pi(r_0 \sin\alpha)^2 þ g A_1 = \pi\ r_0 \sin\alpha \text{ UYS } A_1.$

Which simplifies to:

$\text{UYS} = r_0 \sin\alpha þ g,$

$D = 2\ \text{UYS}/þ g$ (by substitution).

It is from this base that the minimum opening diameter used for the calculation to produce mass flow is derived.

$D = H(\alpha)CAS / \rho g$ (2.4)

D is the opening (m)

$H(\alpha)$ is the hopper half angle over 60º

ρ is the bulk density of the powder.

The flow factor (ff) is obtained to establish the Critical Applied Stress (CAS). The critical applied stress is the consolidating stress required to break a cohesive arch and the consolidating stress must be greater than this value to ensure mass flow. The value is derived from solving radius stress field equations which plot changes in wall yield locus WYL and the hopper ½ wall angles for various Incipient Yield Loci at fixed angles of internal friction. These are calculated from simultaneous equations which plot changes in values to these parameters based upon differentiating geometric coordinates along a Mohr circle tangential to an IYL with a WYL plotted within it as WYL is always less than the IYL Figure 2.9. It is the ratio of the stress during flow to the maximum consolidated stress (Roberts, McGlinchey Ed., 2005).

$$\text{ff} = \frac{\sigma_1}{\bar{\sigma}_1} \qquad (2.5)$$

$\bar{\sigma}_1$ = CAS at the point of intersection of the flow factor and the powder flow function

Thus by rearranging (2.5), recognizing that D may be obtained from (2.4), the flow factor may be established from:

$$\text{ff} = \frac{\sigma_1 H(\alpha)}{\rho g D} \qquad (2.6)$$

Fortunately these radial stress calculations have been completed and have been published by Jenike (1964), Arnold *et al* (1978), and others in a series of charts and thus as stated earlier, it is not necessary for the experimenter to calculate these for themselves. Such calculations require iterations; at small increments which require computerised algorithms for good accuracy Nedderman, (1992).

However, once the angles of internal friction (δ) and wall friction (ø) are known the hopper half wall angle (α) can be found using Jenike's equation (Roberts, McGlinchey, Ed., 2005) which establishes bounds between mass and funnel flow from his work on flow in converging channels.

The hopper half angle equation:

$$\alpha = \frac{\pi}{2} - \frac{1}{2}\cos^{-1}\frac{(1-\sin\delta)}{2\sin\delta} - F \qquad (2.7)$$

Where $F = \frac{1}{2}\left[\phi + \sin^{-1}\left(\frac{\sin\phi}{\sin\delta}\right)\right]$

The term 90° can be substituted for π/2 for results in degrees rather than radians. The hopper wall half angle is much more sensitive to changes in the angle of wall friction than to changes in angle of internal friction.

The information gleaned does not consider mass flow rates in the design parameters for silos. A theoretical solution to this problem was developed in 1965 by Dr. Jerry Johanson, a colleague of Jenike's (Johanson, 1965) with the steady flow rate equation (8):

$$M = \rho D^{(1+m)} L^{(1-m)} \left(\frac{\pi}{4}\right)^{m} \sqrt{\frac{Dg}{2(m+1)\tan\alpha}\left[1-\frac{ff}{ff_a}\right]} \qquad (2.8)$$

m=0 for plane flow hoppers

m=1 for conical hoppers and axi-symmetrical hoppers

D = width of slot or diameter of opening

L= length of slot for plane flow hopper

α = hopper half angle

ff= critical flow factor

$ff_a = \sigma_1 / \sigma_c$ = MCS/UYS = the actual flow factor.

This is a development of the equation developed by Derning and Mehring (1929):

$$M = k\rho D^{(1+m)} g^{\frac{1}{2}} L^{(1-m)} \left(\frac{\pi}{4}\right)^{m} D^{\frac{1}{2}} \qquad (2.9)$$

This was later modified by Beverloo *et al* (1961) and Brown and Richards (1960) when they independently discovered that flow of free flowing material was based upon a relationship between the aperture and the diameter of the particle and that this constant was relatively stable for all free flowing substances.

As this is a steady flow equation for free flowing bulk solids it has limitations, as many of these solids require some assistance or take some time to initiate and reach a steady flow. The flow rate also alters with the height of the bulk solid in plug flow, *i.e.* non mass flow or funnel bins (Roberts, MacGlinchey ED., 2005).

The use of funnel flow bins is not recommended except for; the storage of hard abrasive solids which would damage the hopper walls, as there is little movement of the material against the hopper wall with these bins, (see Figure 2.1). However, these bins may also be used without problems if (Jenike, 1964):

- segregation is not going to occur as the particles are uniform in dimensions and density.
- deterioration does not occur over the time being stored.
- the outlet is large enough to allow solid flow without flow promoting devices.

The minimum outlet size and the required head (height of bulk solid) to ensure continuous flow can be calculated (Jenike, 1964).

For a circular opening the diameter of the opening is given by (10):

$$D = CAS\ G(\phi_t)/\gamma \qquad (2.10)$$

Where $\gamma = \rho g$

$G(\phi_t)$ is a function calculated by Jenike as a function of the instantaneous or incipient time yield locus angle as shown in Figure 2.6, of the bulk solid: $G(\phi_t)$ as a function of (ϕ_t) is represented in Figure 2.8 (Jenike, 1964) and is 4.3 $\tan(\phi_t)$ (Roberts, McGlinchey Ed.,2005).

D is also the diagonal measurement of a square outlet, but for rectangular outlets equation (2.4) is also necessary so that a minimum width can also be calculated.

The effective head for the chosen maximum consolidated stress σ_1 is simply (2.11):

$$h = \frac{\sigma_1}{\gamma} \qquad (2.11)$$

The head height will be less than this when the hopper is discharging as the consolidated stress will be less than the maximum, and flow will continue whilst $h > h_0$ when flow stops.

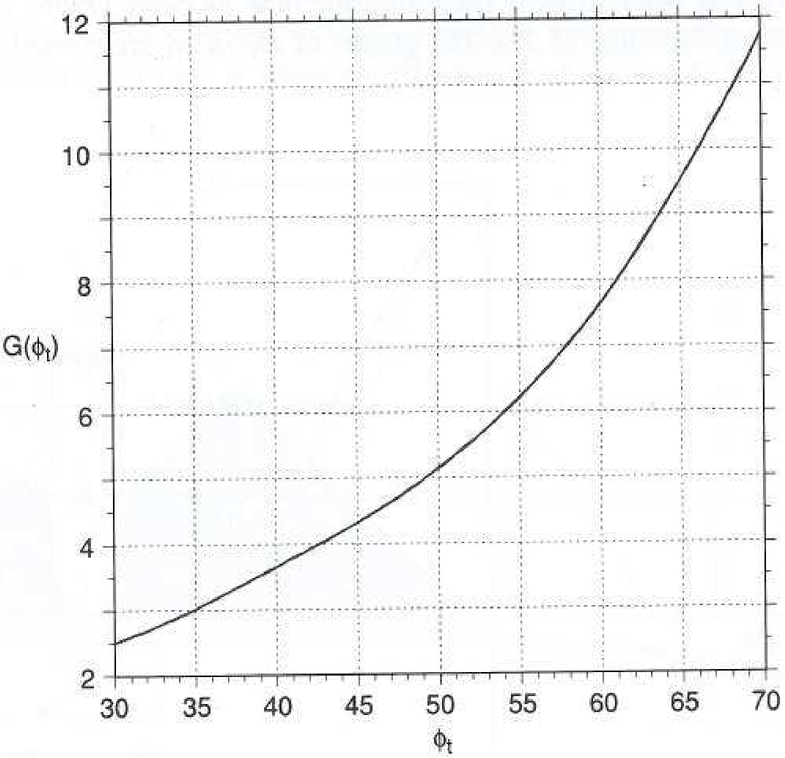


Figure 2.8: The G(ø) function: From Jenike (1964)

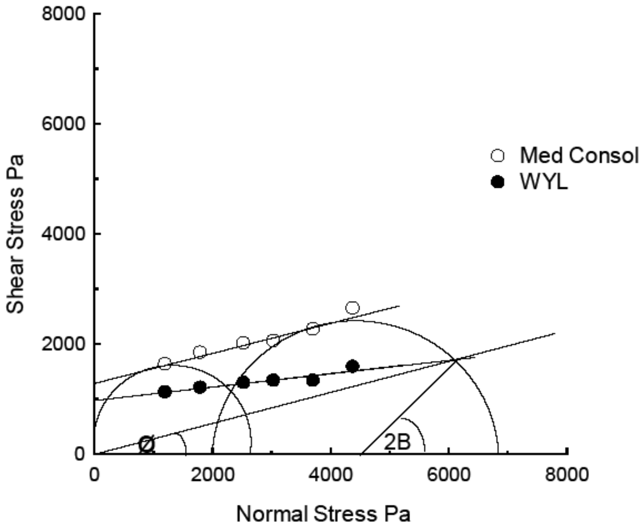


Figure 2.9: Mohr circle analysis shows relationship of wall yield locus and B which is the angle between the radial stress field and a tangent to the hopper wall (see Figure 2.7).

The powder flow function is obtained by plotting the unconfined yield stress against the maximum consolidated stress for each of the yield loci as in Figure 2.10.

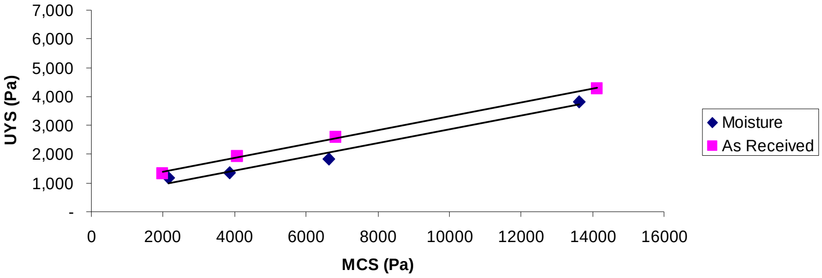


Figure 210: Powder flow functions for as received and 5%moisture added Westport lime.

The inverse of the slope of this line is the Jenike flow index (Jenike, 1964), which is a measure of flow-ability of a powder (see Table 2.2). If the flow function is permanently above the flow factor then mass flow is easily obtained. If the flow factor is permanently below the flow function then a no flow situation exists. Generally bulk solids gain strength when stored over time and samples are left under consolidation for some time on a time consolidating bench before shearing to provide time yield loci (Jenike, 1964). Should the flow factor intercept the instantaneous flow function, but not that of the time yield function then one needs to introduce some agitation or vibration to initiate flow if the material has been left in the silo for some time e.g. over the weekend.

Table 2.2: Flow Index values (Jenike, 1964)

Flow-ability	No-flow	Cohesive	Easy flow	Free flow
Flow index	FI <2	<2 FI <4	<4 FI <10	FI > 10

Shear testers:

There are several types of shear testers but all are designed to provide the information just described; which is required to manage powder flow. The original shear cell is the Jenike shear cell, (see Figures 2.11, 2.12 and 2.13).

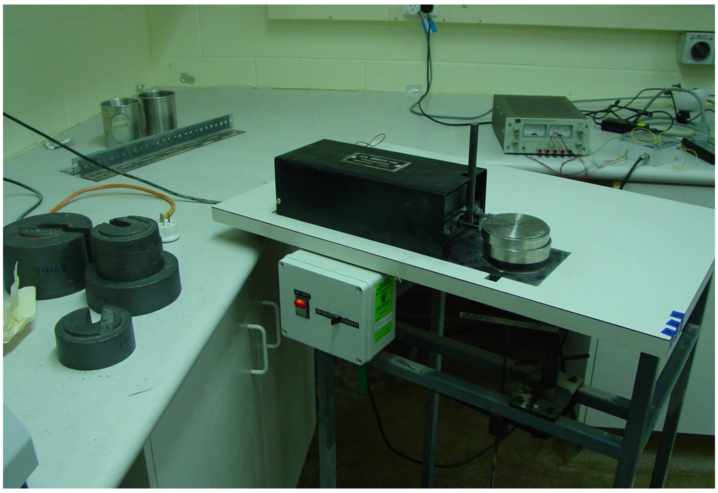


Figure 2.11: Jenike shear cell

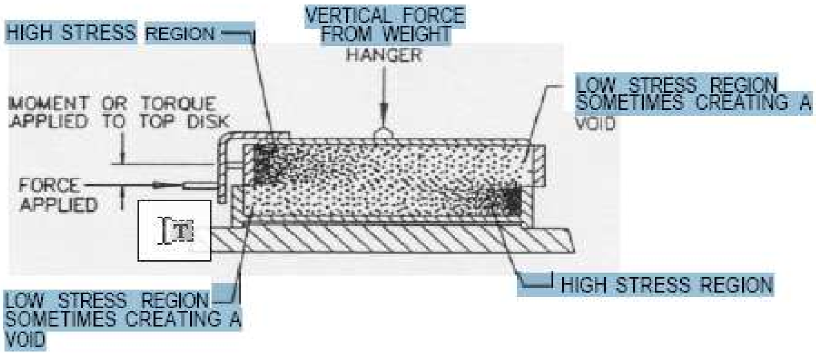


Figure 2.12: Schematic of a Jenike Shear Cell Showing Uneven Stress Distribution, Johanson, (1992).

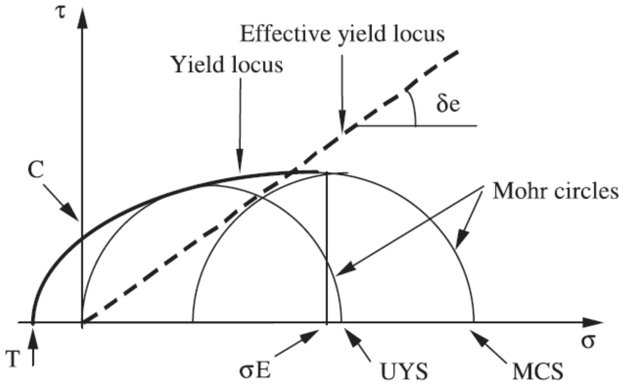


Figure 2.13: A drawing from Fitzpatrick *et al*, (2004) which illustrates the idealised yield locus.

C is the cohesiveness of the material, without any normal stress. It is where the Yield Locus crosses the Y axis, measured in Pascals as the Y axis is the shear stress value

δe the Effective Yield Locus is the angle of internal friction of the bulk solid, from origin to tangent of MCS Mohr circle

MCS is the Maximum Consolidated Stress derived from a Mohr circle drawn from a tangent to the pre-shear point of the yield locus and where the x axis is crossed is the MCS measured in Pascals as this axis is the Normal stress.

T is tensile strength in Pa.

σe is the pre-shear consolidation point

UYS is the unconfined yield stress, the strength the solid has with no consolidating stress applied, derived from Mohr circle from origin which is tangential to the yield locus, where circle crosses the x axis at the UYS point is the value.

The above have been explained in the chapter, the conceptual theory derives from soil mechanics and is derived from soil strength failure work. The incipient yield locus is used in this work rather than the effective yield locus as the effective yield locus is different for each locus for materials with cohesive strength, whereas the incipient locus is the same for all normal stresses and it is more correct to seek the point of failure, than the steady state which alters with normal stress (Nedderman, 1992).

Although the Jenike shear cell is well proven it has two major drawbacks, one being the time it takes to complete a series of tests as it may take a week or two to undertake a complete set of loci. In reality the writer has found that each point takes between 45 minutes and two hours to achieve depending on ones ability to achieve a critical consolidation. A locus should require at least three points, preferably four and each point should be repeated twice. We then have between 9 – 12 points for each locus and a family of loci consists of four loci at different pre-consolidations, we can see that the time is between 40 and 96 working hours to complete a full test. The other problem is that the shear tester requires particles more than 5% of the cell diameter to be removed (IChE, 1989). This makes it unsuitable for bulk solids with particles with a significant portion greater than 4.5 mm for the standard Jenike cell. Jenike, (1964) suggests that larger particles are free flowing and their removal allows a shear test to proceed after sieving. However Carr and Walker (1967) found that the results obtained by this method with coal powder at Portishead coal generating power station at Bristol U.K. gave hopper openings which were smaller than those required in practise.

Carr and Walker (1967) developed an annular shear cell, Figure 2.14, which they claimed gave more accurate openings than the Jenike shear cell when applied to the coal powder they were using without requiring the material to be sieved. The tests were also quicker to undertake and the results were supported by flow from the storage devices at the power station (Carr and Walker, 1967).

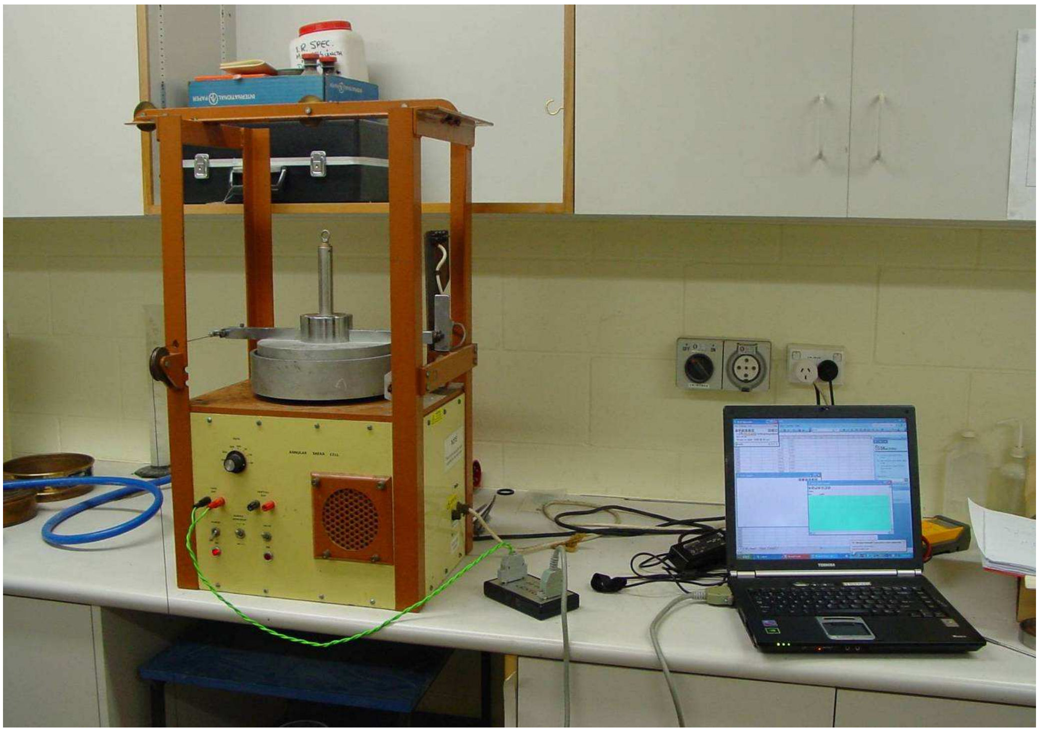


Figure 2.14: An annular shear cell in calibration mode from Carr and Walker (1967).

The annular shear cell produces very repeatable results as long as the test method is closely followed. Tests undertaken to measure the accuracy and repeatability of annular shear cell tests demonstrated that results for both peak and steady state shear tests were repeatable within a loci data range between; 1.5% - 3.5% depending on the pre-consolidation stress Berry and Bradley, (2007). In addition Berry and Bradley (2007) established that 5 point shear loci were very closely approximated with 2 point, end point loci for tests that could be undertaken with time constraints. Their results were less variable than the 5% tolerance deemed acceptable for the Jenike limited displacement direct shear cell and the time to undertake the tests was much less; results are obtainable in hours which would take days using a Jenike shear cell.

Another advantage of the annular shear cell chosen is that it is large enough to take a 2 kg powder load. This enables a representative sample of agricultural limestone to be used, without removing the particles with a diameter greater than 4.5 mm, which is a prerequisite of the Jenike shear cell and some other shear cells with a much smaller capacity. The yield loci produced in the Walker annular shear cell tend to be more linear than those produced from the other shear cells Carr and Walker, (1967) and Berry and Bradley, (2007).

Since 1967 a number of shear cells have been developed some of which are fully automated, but all are unlimited displacement rotational shear cells (Schmitt and Feise, 2004). The Schulze ring shear tester, (Figure 2.15) and the Peschl rotational shear tester (Figure 2.16), are two examples of fully automated shear testers which are attached to computers with proprietary software that provides the operator with a yield locus and powder flow functions. Examples of the result display of an automated shear test using a Shulze cell can be seen in Figures 2.17 and 2.18. Figure 2.16 shows a pre-consolidation and shear test at predetermined normal stresses ramped upwards from the lowest normal stress, whereas Figure 2.18 shows a computer generated yield locus and Mohr circle analysis from the data in Figure 2.17.

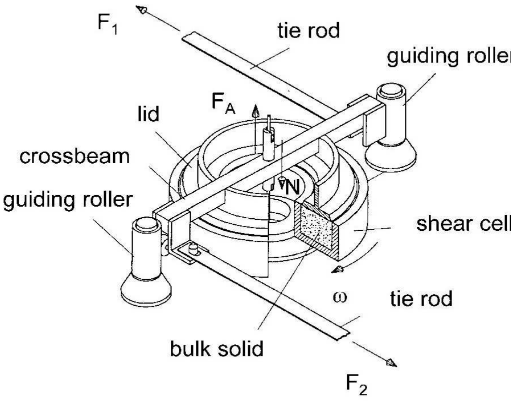


Figure 2.15: Schulze ring shear tester (schematic from Schmitt and Feise, (2004))

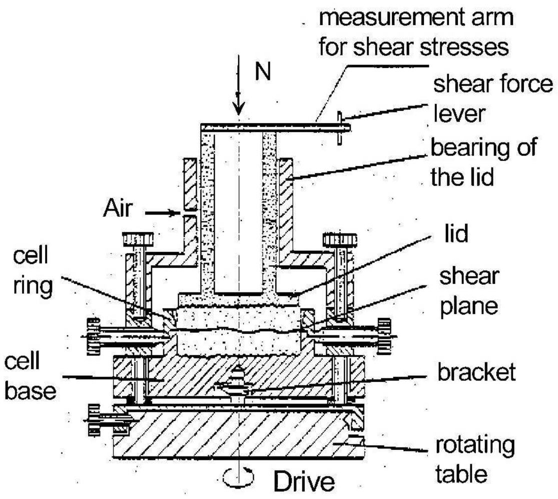
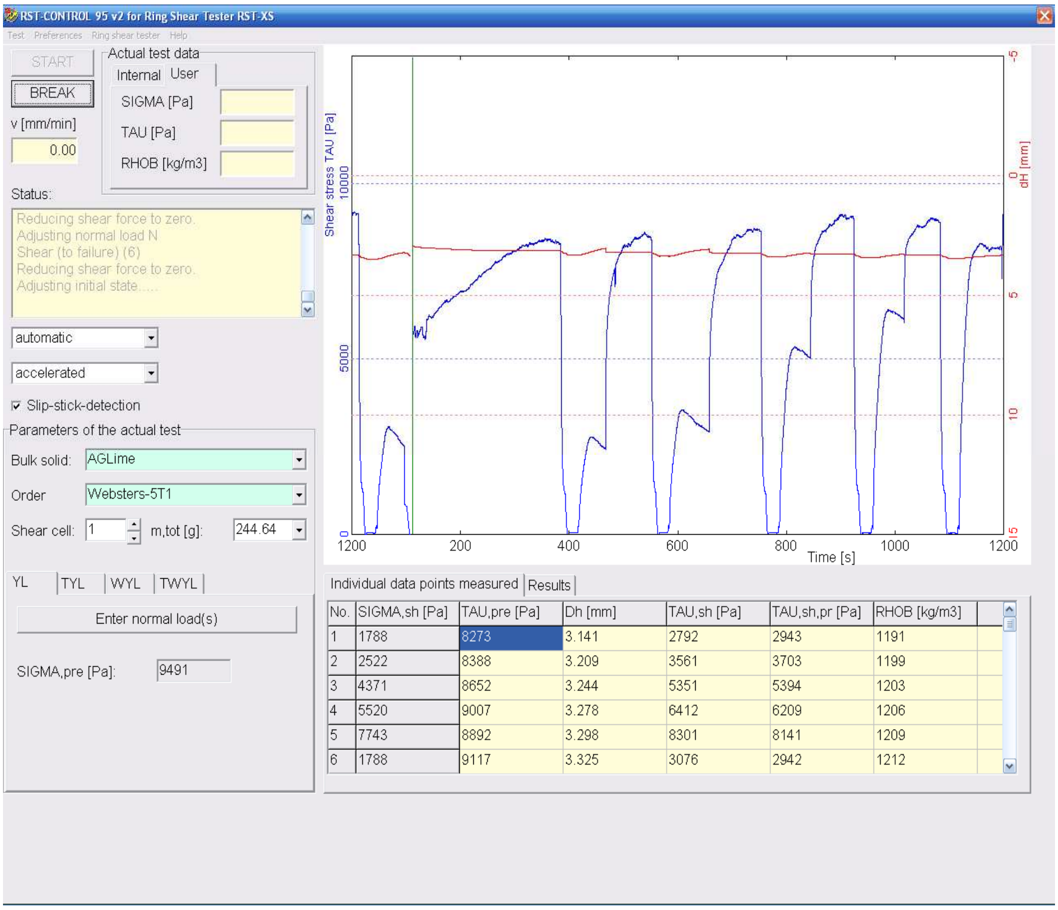


Figure 2.16: Peschl rotational shear cell (schematic from Schmitt and Feise, 2004))



SIGMA [Pa]

TAU [Pa]

RHOB [kg/m3]

v [mm/min] 0.00

Status:

Reducing shear force to zero.
Adjusting normal load N
Shear (to failure) (6)
Reducing shear force to zero.
Adjusting initial state.....

automatic

accelerated

☑ Slip-stick-detection

Parameters of the actual test

Bulk solid: AGLime

Order Websters-5T1

Shear cell: 1 m,tot [g]: 244.64

SIGMA,pre [Pa]: 9491

No.	SIGMA,sh [Pa]	TAU,pre [Pa]	Dh [mm]	TAU,sh [Pa]	TAU,sh,pr [Pa]	RHOB [kg/m3]
1	1788	8273	3.141	2792	2943	1191
2	2522	8388	3.209	3561	3703	1199
3	4371	8652	3.244	5351	5394	1203
4	5520	9007	3.278	6412	6209	1206
5	7743	8892	3.298	8301	8141	1209
6	1788	9117	3.325	3076	2942	1212

Figure 2.17: A set of shear tests which produced a loci on the Shulze automated shear tester Ngarua limestone preconsolidation stress 9,491 Pa.

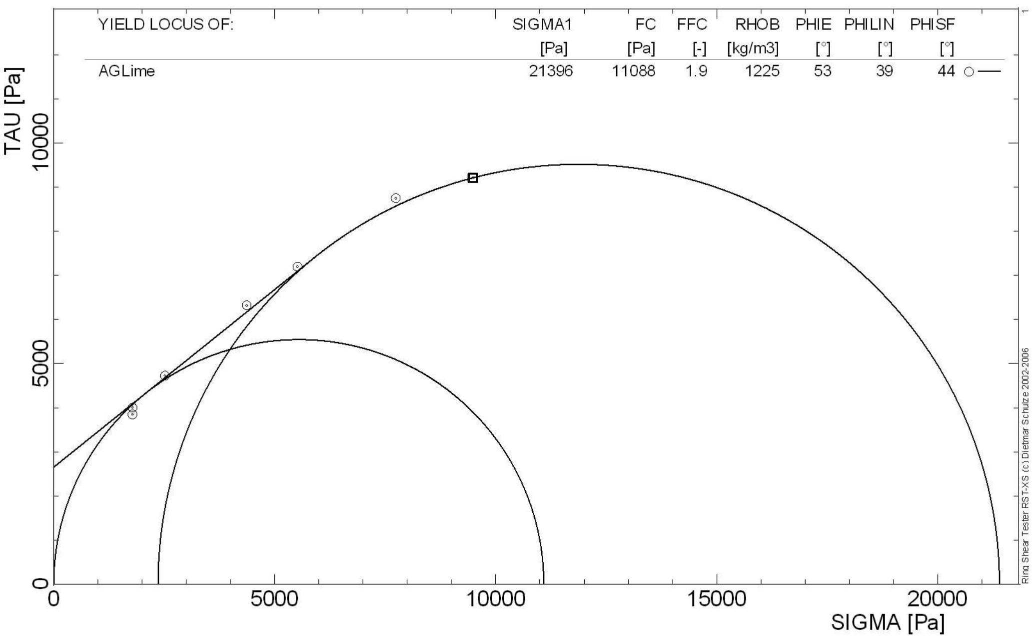


Figure 2.18: The yield locus and Mohr circle analysis of the data from Figure 2.16

Comparisons of the results from three types of rotational shear cells described showed some significant differences in the shear loci produced by these machines, using the same normal stresses on standard powders used for the Jenike shear cell ASTM Standard D 6128 (Schmitt and Feise, 2004). In their experiments they found that the Schulze fully automated tester produced loci within the range found for the Jenike shear cell on titanium oxide, a cohesive test powder used in ASTM Standard D 6128. That all the shear testers replicated the Jenike results on free flowing powders except the Walker shear cell (annular shear cell Figure 2.13), which gave these powders greater cohesion than the smaller automated shear cells. They recommend that this type of shear cell not be used on fine powders. However the TiO_2 powder which they described as fine had a mean particle diameter of 0.6 micron, which is an extremely fine powder.

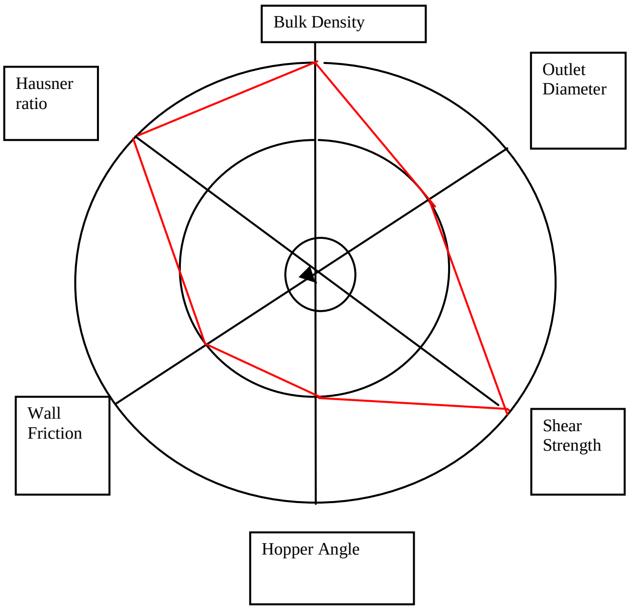
In theory all these shear testers should produce similar results. However, the Walker's size makes it more suitable for coarser materials, which is what it was designed to measure. The tester geometry does influence the results and a tester should be chosen that is suitable for the material being tested. The Jenike shear cell, which is a standard for shear cells, whose results are closely replicated by the Shulze automated shear cell, nevertheless gave erroneous results when used on coarse materials (Carr and Walker, 1967). This may be as a result of the material being altered by removing the coarse particles as required in the Jenike standard method. No particles larger than 5% of the diameter of the shear cell should be present in the shear tester, for a standard Jenike this requires the removal of those greater than 4.5 mm in diameter and for the Shulze those greater than 3.5 mm.

Mcgee and McGlinchey (2005) claim that to try and describe a powder's flow behaviour with a single number or even a flow function inevitably gives a limited view. They suggest examining several facets, giving equal weight to the following: bulk density (rating the lower the bulk density the worse the flow, the critical opening required for mass flow, shear strength, the hopper wall angle (measured from the horizontal) however in this thesis it has been converted to angle from the vertical which is Jenike's convention which is used throughout, angle of wall friction and Hausner ratio, which is the ratio of the tap density over the loose poured density. From a set of tests on a number of substances they set parameters of 3 categories for all 6 facets, easy, average and poor flow. However there isn't a single set of parameters for all powders; the parameters are set for classes of powders depending on their behaviour. Therefore, the parameters for $TiO_{2,}$ differ from pharmaceutical powders and most probably crushed agricultural limestone.

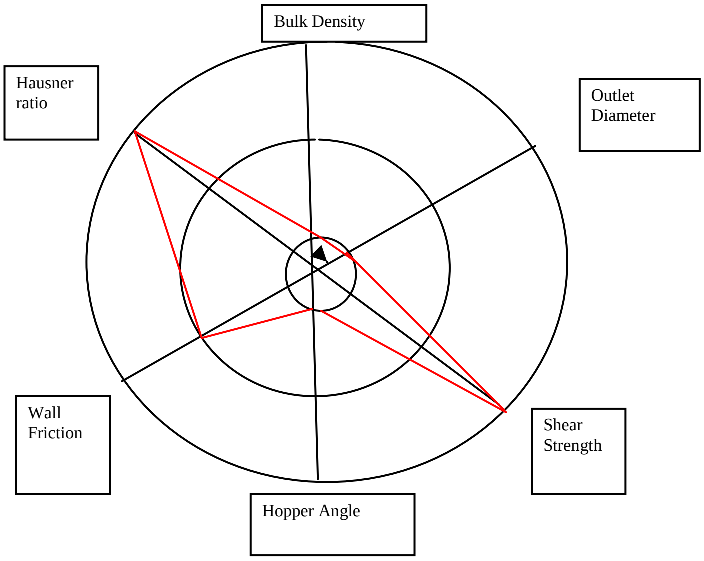
Their method is depicted by 3 concentric circles intersected by 3 lines of diameter equally spaced, each of the six points representing one of the six facets, (Figure 2.19 and Table 2.3). The inner circle represents easy flow, the middle average and the outer circle poor flow. A line is drawn from each facet's flow parameters to the next and the area enclosed represents the flow characteristics. The resulting diagram looks like a spider web and is known as a spider diagram.

Table 2.3: Flow Parameters for multifaceted approach (McGee and MacGlinchey, 2005) where the inner circle represents 'Easy Flow', middle 'Average' and outer 'Poor Flow'.

Circle	Wall Friction (deg)	Shear strength (Pa)	Hausner ratio	Outlet size (cm)	Bulk Density (kg/m^3)	Mass flow wall angle
Easy flow	<20	300	1.1	15	1200	25
Average	25	1000	1.25	50	800	17
Poor flow	>30	2000	1.5	100	400	10



Poor flow spider diagram



Easy flow spider diagram

Figure 2.19: Spider diagrams based on the flow facets in Table 2.3. Note all these parameters may not be correct for crushed limestone, shear strength and bulk density may need to be adjusted to better reflect limestone properties.

A feature of the spider diagram approach is that it should be customised to the powders under investigation. Although all the relevant data for the limestone is known, each had similar characteristics which would make spider diagram analysis impossible as each diagram would be indistinguishable from another.

2.5 Other Rheometers:

The earliest of these was developed around the Carr indices Carr, (1965). The Hosokawa Powder Characteristics rheometers® Ilari, (2001) and measures the angle of repose, the angle of spatula, the compressibility of the material and its cohesiveness. It produces a flowability index in a scale of 1 – 100 (see Figure 2.21).

The Carr indices are a combination of parameters which provide an indication of the flow properties of a bulk solid.

The angle of repose is the angle that forms between the horizontal and a static pile of bulk solid that has been dropped from a height. However, there is also a poured angle of repose which is the angle the material forms when a container is emptied through an orifice smaller than the container’s diameter. These angles are often not the same, the poured is generally steeper than the dropped, the steeper the angle of repose the less free flowing a bulk solid usually is. Materials with an angle of repose less than 35° are usually easy flowing.

Figure 2.20: The Hosokawa Powder Characteristics Tester

The angle of spatula is the angle formed by a bulk solid on a flat blade when it is lifted vertically through the bulk solid. Materials with angle of spatula less than 40^{o} are generally easy flow materials.

Compressibility of a material is another indicator of powder flow properties. The more compressible a bulk solid or powder is the more likely there will be flow problems. The standard measure of compressibility is obtained by dividing the tap density by the loose poured or aerated bulk density. The tap density is found by either tapping a sample in a tap tester until the volume stops reducing, or by manually tapping a sample in a container vertically for at least 100 times from a height of about 2.5 cm until the volume ceases to reduce. A loose poured density is found by filling a container from above gently usually by means of a hopper and screening off, the over fill, the mass is then divided by the volume. This ratio tap density/ loose bulk density is known as the Hausner ratio (Table 2.4).

Table 2.4: The Hausner ratio and corresponding flow properties

Hausner Ratio	**Flow-ability**
> 1.4	Very difficult
1.25 - 1.4	Difficult
1.1 -1.25	Medium flowing
1.0 - 1.1	Free flowing

The Hosokawa Powder Characteristics tester uses a uni-axial shear test to measure the cohesiveness of the powder based upon an idea by Carr, (1965). A column of powder is supported on all sides and consolidated by a normal stress. The supporting walls are removed and the column is sheared by a normal stress. The stress required to shear the unsupported column is the unconfined yield stress UYS σ_c. If this stress is greater than 0.25 of the consolidation normal stress σ_1 then the material is considered to be cohesive. This coincides with the Jenike flow index in Table 2.2, which is the inverse of the flow function. Hence the 4 rating which is the cohesive measure of the Jenike index coincides with $\left(\frac{\sigma_c}{\sigma_1}\right) > 0.25$ which is the measure of cohesiveness provided by the Carr index.

Similarly the Johanson Indicizer® uses an automated patented uni-axial cell to measure 8 indices using three machines (Figure 2.22). Table 2.5 below summarises the indices taken from Johanson, (1995). Cohesion is measured in this instrument with a hang up cell. The cell is used to consolidate the load, the bottom withdraws and the powder sheared by a normal stress on the cell, the sheared powder falls through the cell bottom of the shear cell.

Table 2.5: Johanson Indices and their applications (Johanson, 1995)

Index	(length)	Repose segregation potential and capsule fill weight variations
Rat-hole Index	RI (length)	Predicts: rat-holing hang-ups, lump formation and flushing potential
Hopper Index	HI (degrees)	Predicts: hopper slope angles required to cause flow at the walls, chute segregation potential and hopper wall angles for clean out
Flow Rate Index	FRI (wt/time)	Predicts: limiting feed rates from hopper outlets, fluidization and air current segregation potential, flushing potential, de-aeration time in containers, pre rate limits and capsule till rate limits
Bin Density Index	BDI (wt/vol.)	Predicts: bin gravimetric capacity and loads on bin walls
Feeder Density Index	FDI (wt/vol.)	Predicts: feeder gravimetric rates and, when compared with BDI, gives the range of densities possible at tableting presses.
Chute Index	CI (degrees)	Predicts: build-up in chutes, feeders, conveyors and press feed shoes.
Springback Index	SBI (percent)	Predicts: special hang-up problems with elastic wind-up.

There are at least two companies producing automated rotational shear cells, Freeman’s apparatus (Freeman et al, 2007) has produced automated powder flow data within a few minutes over a wide range of materials (Figure 2.21). These shear cells have a helical blade and have an aerating conditioning phase that claims to remove the product history of the material being tested. They then measure the force required to move the blade through the material and have computer algorithms that relate these measurements to flow characteristics from the torque measured. A similar device is available from Stable Micro Systems, a ‘Powder Flow Analyser’, and is operated as an attachment to their Texture Analyser, (Figure 2.23). This device measures the work done by plotting the area under a Force / Distance graph. In both cases the indices measure an increase in cohesion and caking by a larger number which is the opposite of the Jenike Flow Index, Table 2.6.

All the automatic rheometers claim to be able to produce replicable results with important flow/ no flow information on bulk solids in a matter of minutes rather than weeks which makes them a practical, commercial necessity in assessing material flow properties in industry.

Table 2.6: A Table comparing Stable Micro Systems Powder Flow Analyser Cohesive

Cohesive Index (CI)	**Flow Behaviour**
>19	Hardened/Extremely Cohesive
19 – 16	Very cohesive
16 – 14	Cohesive
14 – 11	Easy flowing
<11	Free flowing

Figure 2.21: The Freeman FT4 Powder Rheometer

The automated rheometers are all supplied with proprietary software which enables them to produce a test result independent of operator influence. However, except for the Shulze and the Peschl automated shear cells, which are unlimited displacement direct shear cells based on the principles of Jenike (1964) and Carr and Walker (1967), the others can not be used for bulk solid study from first principles.

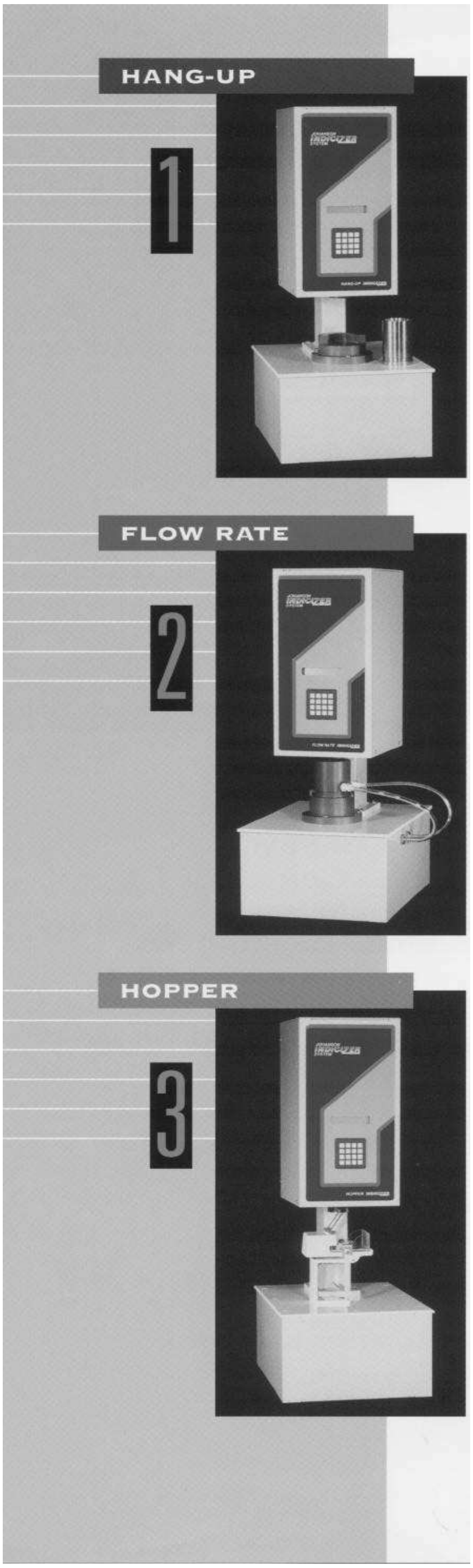


Figure 2.22: The 3 Johanson Indicizers

Figure 2.23: The SMS Powder Flow Analyser

Chapter 3

Investigating the Physical and Chemical Characteristics of Agricultural Limestone.

3.1 Introduction

The physical and chemical characteristics of agricultural limestone samples taken throughout New Zealand have been examined. Fertmark® lime samples were selected as they are subject to an audited quality assurance scheme and have declared calcium carbonate values.

The internal quality control data for the quarries was also made available, see Figures 3.1 and 3.2. They chart the particle size distribution, acid neutralising equivalence as a percentage of $CaCO_3$ and moisture content of lime from each quarry over time. The information collated is directly relevant to the Fertmark® lime standard described in Chapter 2.

The limes in this investigation have similar particle size distributions and mean sizes in the range 150-300 microns; see Figure 3.3. However, although the quarries comply with the Fertmark standard, actual size distributions can change significantly when the crushing hammers on the size-reduction mills are changed. Typically, the proportion of fines, *i.e.* material measured in quarry quality assurance tests, particles smaller than 125 microns, can increase from ~20% by mass to ~40% by mass as in Figure 3.1. Quality assurance measurements are made from a 20 kg grab sample taken once a month for the purpose of assuring compliance, no statistical analysis is undertaken by the quarry owner.

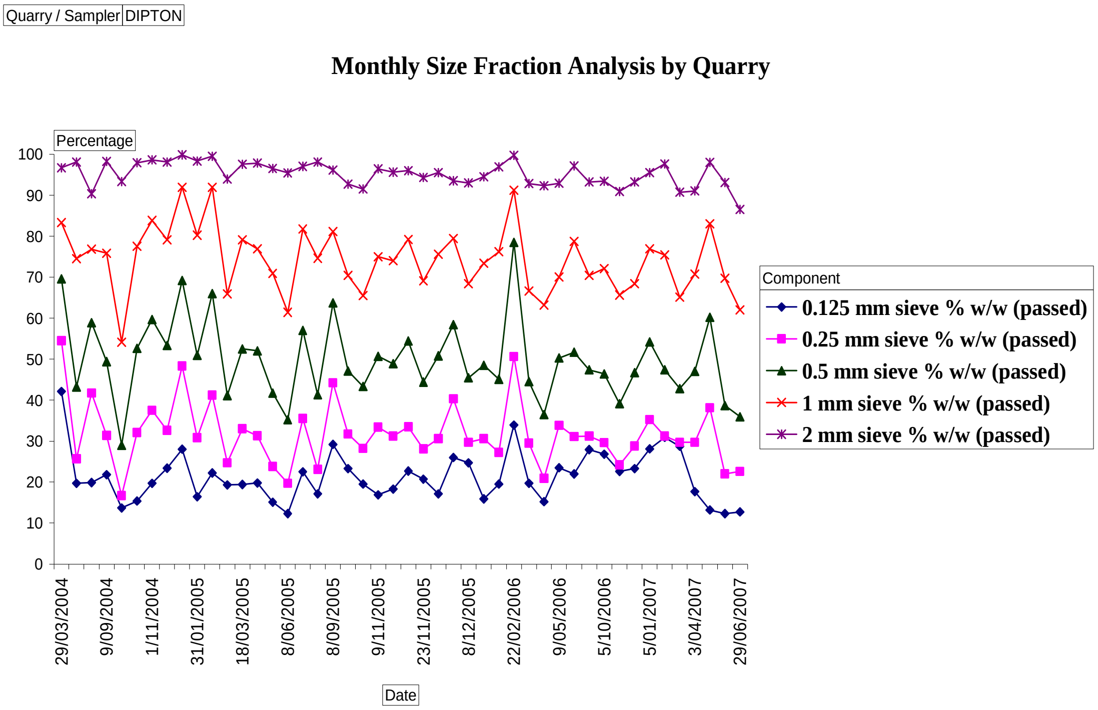


Figure 3.1: The particle size data from Fertmark registered quarries, in this case Dipton quarry. Courtesy of Ravensdown Fertilser Co-operative Ltd.

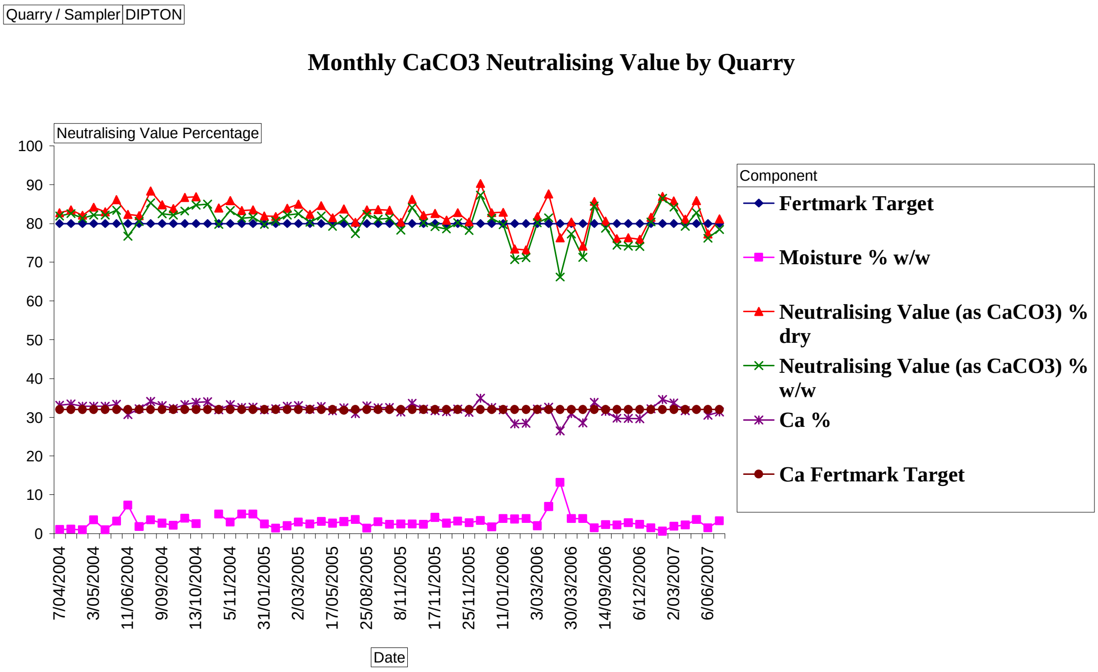


Figure 3.2: Quality assurance data, moisture content and acid neutralising equivalence, from Dipton quarry. Courtesy of Ravensdown Fertiliser Co-operative Ltd.

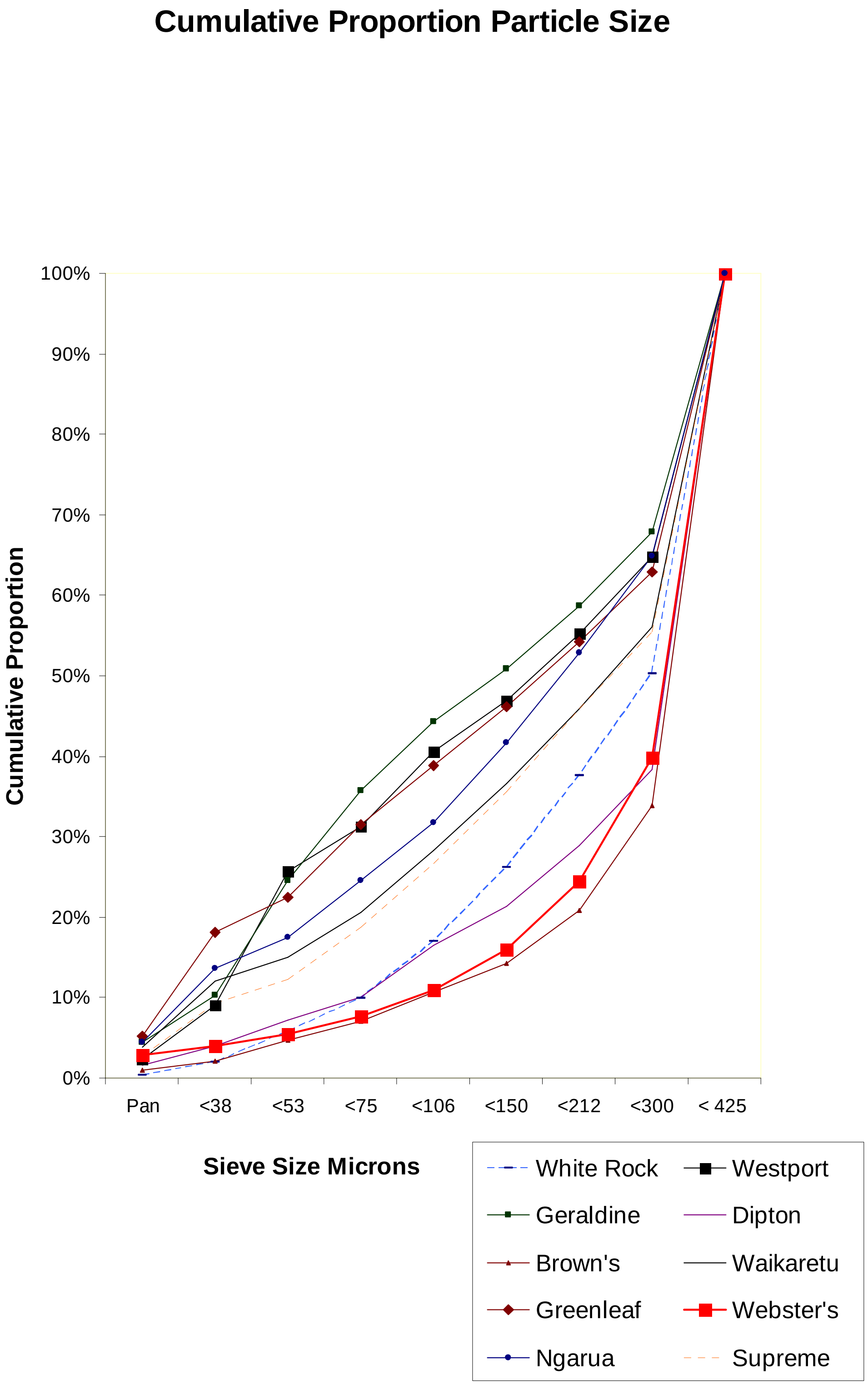


Figure 3.3: Cumulative particle size distribution of Fertmark limestone samples from quarries examined. Dry sieved to BS 410-2:2000.

The high proportion of fines in the crushed limestone is as a result of ensuring that the Fertmark particle size distribution standard is met at all times through the life cycle of the crushing hammers. The Fertmark standard is taken from a former Ministry of Agriculture and Fisheries limestone standard; which states 95% of particles by weight to be less than 2 mm and 50% below 0.5 mm. The minimum calcium carbonate equivalence level of 65% is to ensure acid neutralising effectiveness. The particle size distribution standard is as a result of the insolubility of calcium carbonate. Fine particles have a high surface area per volume and therefore, for a substance with a low solubility this is a preferable trait from an agronomic perspective. In Table 3.1 comparisons are made between the particle densities and loose/ tap densities of the limestones investigated. As the particle densities are similar differences in bulk density are probably due to the particle size distributions in the received samples.

Table 3.1: Tap density and particle density established by Helium pycnometry (Quantachrome Ultrapycnometer 1000)

Limestone	*Loose Bulk Density kgm^{-3}	*Tap Density kgm^{-3}	% Tap Density/ Loose BD.	Particle Density kgm^{-3}
Brown’s	1,419	1,647	116	2,663
Dipton	1,306	1,453	111	2,661
Geraldine	1,184	1,488	127	2,580
Greenleaf	1,257	1,553	124	2,529
Ngarua	1,518	1,910	126	2,723
Supreme	1,350	1,448	107	2,595
Waikeretu	1,477	1,757	119	2,658
Webster’s	1,325	1,555	117	2,580
Westport	1,313	1,522	116	2,667
Whiterock	1,100	1,403	128	2,694

*** loose and tap densities were undertaken with 10 replicates the CV range (standard deviation / mean) 0.3% - 1.1%.**

Hausner ratio is defined as $\rho_b tapped / \rho_b loose$ which is a measure of compressibility of a bulk solid. Granular materials which compress by more than 23% often have cohesive strength and poor flow properties as percolation of small particles pack into and occupy the air spaces which are present in the aerated loose poured state (McGlinchey, 2005). Loose poured density is the bulk density of a material in the expanded condition that results when it is poured or caused to flow into a rigid vessel. Tapped density is the bulk density of the material obtained when it has been compacted by tapping the vessel containing it, on a hard surface.

Helium pycnometry is a means of obtaining a skeletal particle density. Quantachrome ultrapycnometer 1000, which was used to find the particle density of the limestones is a gas expansion pycnometer. It measures the volume the particles of a known mass occupy in a vacuum with no interstitial spaces. The sample is placed in the sample chamber which is then evacuated to create a vacuum, thus drying the sample simultaneously. The pycnometer measures the pressure drop when Helium gas occupying a known volume in an adjacent chamber is released by opening a valve so as to occupy both chambers. The chamber in which the sample is placed is calibrated by placing a stainless steel calibration sphere in the sample chamber at a known temperature to record a reference volume. The volume of the sample is calculated thus:

$$V_s = V_c + \frac{V_r}{1 - \frac{P_1}{P_2}} \tag{3.1}$$

Where:

V_s is the sample volume

V_c is the volume of the empty chamber

V_r is the reference volume

P_1 is the pressure of Helium in the empty gas chamber prior to release

P_2 is the pressure of Helium when it is allowed to occupy both chambers

The machine runs a minimum of 5 tests and to a maximum set by the operator or until the standard deviation of the particle density measured is less than .001%.

A high proportion of fines tend to produce a cohesive powder especially in the presence of moisture, through pendular bridges between particles and capillary bonding (McGlinchey, 2005). However, these forces may also act to bind large numbers of fine particles into an agglomeration that behaves as a large particle, which is the basis of granulation (McGlinchey,. 2005). About half of the lime used in New Zealand is applied by aircraft due to the terrain of the pasture land in production. The flow properties of lime are of interest as a number of accidents have occurred as a result of the lime failing to discharge from the hoppers of aircraft applying it. The value of applying fine particles by aircraft must also be questioned. These particles have a high drag coefficient and may be carried for many kilometres by wind or even thermals, thus are likely to land outside the target application area (Jones *et al*, 2008).

Experimental investigations were undertaken to establish the chemical makeup of the impurities within the limestone deposits from the various mineralogy’s. The type of impurities within the deposits may influence the material flow properties, given that for certification they may be up to 35% of the material by weight. By necessity, the flow properties need to be studied under varying moisture conditions as found in the field.

3.2 Chemical Characterisation Methods

As the definition of lime is generic it is important to examine the physical composition of lime materials to see if there are common factors which influence their flow properties. The presence of clays, which have a tendency to readily adsorb water molecules and dissolved ions, may be a factor in some limes being cohesive. The actual $CaCO_3$ levels were established by thermal gravimetric analysis, TGA, and these were compared with the declared values stated by the fertiliser manufacturers as provided to Fertmark. The Fertmark standard method is by titration which does not definitively measure the calcium carbonate in a sample but rather measures the total acid neutralising effect of the sample (NZ Fertiliser Quality Council Codes of Practice, 2004). Acid neutralising hydroxides associated with clay are possible impurities which may adversely affect flow, and differences between the TGA and declared values may indicate their presence. TGA also provides information on the thermal decomposition of both carbonates and hydroxides. Impurities were identified using x-ray diffraction analysis.

Thermal gravimetric analysis

Thermal gravimetric analysis identifies the materials comprising the test matter by the profile of the thermal decomposition and the temperatures and amplitude of the thermal peaks. It is known that most of the limestone should comprise the calcite form of $CaCO_{3,}$ with additional moisture, silicate and clay impurities. Calcite is a rhombohedral crystal, and is the most stable polymorph of calcium carbonate below 50°C (Mackenzie *et al*, 1970). Accordingly the thermal decomposition of calcite to CaO was taken as the actual percentage of $CaCO_3$. Impurities were identified from profiles of material decomposition, however, as these materials occur in small amounts, and are often close in thermal decomposition range, actual composition is difficult to confirm and complementary data was obtained by x-ray diffraction (Montoya *et al.* 2003).

Differential thermal analysis

A Q600 thermal analyser (TA Instruments, New Castle, Delaware, USA) was used to provide simultaneous differential thermal analysis, DTA, differential scanning calorimetry, DSC, and heat flow analysis of the 10 limes studied. The analysis comprises measuring changes in percentage mass as a proportion of initial total mass with temperature change over a preset range. In this study the range was; 40°C – 1,200°C at a ramp rate of 20°C/ minute. Simultaneously a DSC, which measures the endothermic and exothermic reactions as they occur in temperature change in °C/mg and, the heat flow as energy per gram in W/g of material. For an example of a printout from this machine see Figure 3.4.

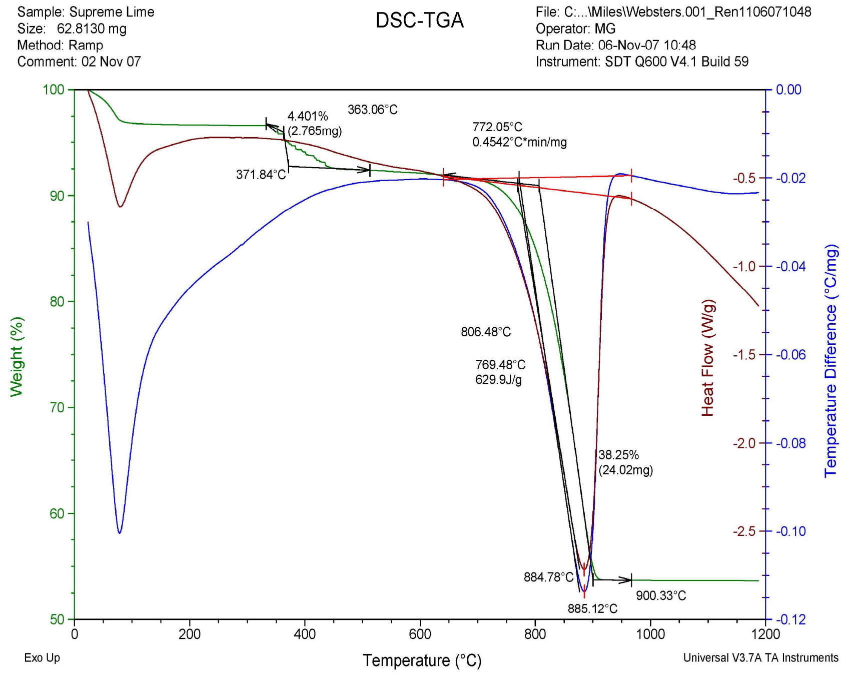


Figure 3.4: Supreme Lime sample run showing thermal decomposition of hydroxides of 4.401% of mass from 371.84°C and decomposition of carbonate of 38.25% by mass % CO_2

X-ray diffraction

The second part of the investigation was to identify the actual composition of the impurities using XRD and to establish the proportional composition of the limes. These results, along with the nature of the parent limestone may indicate links between mineralogy, the composition of impurities and the proportions of each impurity found in each limestone.

Powder cohesion

The SMS cohesive index and Hausner ratio are both indicators of the cohesiveness; and flow properties of the powder being tested and can be determined relatively quickly; they enable comparisons between batches of input or product rather than quantitative measures of design or flow variables.

The SMS cohesive index requires a powder testing machine made by Stable Micro Systems,(Godalming, Surrey, UK), and is determined by proprietary software from measurements of the force required to turn a paddle through a sample of material; the calculation requires the additional inputs of loose poured bulk density and Hausner Ratio.

Cohesion and caking were investigated using a Powder Flow Analyser by Stable Micro Systems, SMS, Godalming, Surrey, UK. Hausner ratios were measured by manual tap testing samples with 100 taps, with 10 replicates and comparing the tap density to a loose pour density averaged over 10 replicates, coefficient of variation, which is the standard deviation over the mean was between, 0.3% and 1.1%.

The SMS cohesive index and Hausner ratio are indicators of the flow properties of the powder being tested and can be determined relatively quickly; they enable comparisons between batches of input or product rather than quantitative measures of design or flow variables. The SMS cohesive index is determined by measuring the force required to turn a paddle through a sample of material and calculating the work done from the area under the curve of a plot of Force versus Distance travelled by the paddle through the powder; this work is converted to an index which measures cohesiveness. However, for definitive answers to powder flow solutions and estimation of hopper design parameters, a shear testing regime based upon powder flow mechanics is required. Table 3.2 compares values of flow properties of Hausner ratio and Stable Micro-Systems powder flow analyser, cohesive index.

Table 3.2: The SMS Cohesive Index; alongside the Hausner Ratio, and flow-ability.

Cohesive Index (CI)	**Flow Behaviour**	**Hausner Ratio**	**Flow-ability**
>19	Hardened/Extremely Cohesive	> 1.4	Very difficult
19 – 16	Very cohesive	1.25 - 1.4	Difficult
16 – 14	Cohesive	1.1 -1.25	Medium flowing
14 – 11	Easy flowing	1.0 - 1.1	Free flowing
<11	Free flowing		

3.3 Annular Shear Cells

An annular shear cell, (Figure 2.13), which is a copy of the cell built by Walker and Carr to undertake shear tests on bulk coal at Portishead in 1967 was used (MacMillan, 1971). The method is that adapted by Nedderman, (1992) from Carr and Walker (1967). The actual method is comprehensively described in chapter 2. The annular shear cell was chosen for the shear testing because it is large enough to take a 2 kg powder load which enables a representative sample of agricultural limestone to

be used; without removing the particles with a diameter greater than 4.5mm, which is a prerequisite of the Jenike shear cell (IChE, 1989) and some other shear cells with a much smaller capacity. It produces very repeatable results as long as the test method is closely followed. The results were less variable than the 5% tolerance deemed acceptable for the Jenike direct shear cell, Berry and Bradley (2007) and the time to undertake the tests was much less; results are obtainable in hours which would take days using a Jenike shear cell.

The loci obtained by Carr and Walker using their annular shear cell were lower i.e. the material sheared at lower stresses at the same normal stress than those obtained using a Jenike shear cell Carr and Walker, (1967). The loci also fitted a straight line approximation better than those obtained using a Jenike shear cell. Carr and Walker reported that the hopper design calculations, described as “the critical blocking apertures obtained from these loci gave fair agreement to those occurring in practice” Carr and Walker, (1967).

In recent years there has been considerable work developing automated annular shear cells to replace the cumbersome and slow Jenike shear cell as a means of accurately measuring powder strength characteristics. One of these shear cells is the Schulze RST-01.pc; which has been compared to the Jenike shear cell using standard titanium dioxide test material European Union (EU) tests. Eleven laboratories produced loci using this shear cell with the test material; their loci were all within the range obtained from the EU wide tests using the Jenike shear cell (de Silva, 2000) and (Shmitt and Feise, 2004).

In a study comparing the Walker cell, three different sized Schulze shear cells, 0.9 litres, 0.2 litres and 0.03 litres and another small annular shear cell, the Peschl cell 0.05 litre, the Carr-Walker cell produced loci lower than the other cells with cohesive powders and higher loci for free flowing powders although with the latter accompanied by a lot of scatter and a low level of confidence (Schmitt and Feise, 2004). The Walker shear cell Schmitt and Feise (2004) used had a 12 kg lid and they found it difficult to manage.

This contrasts with the very repeatable linear loci produced and reported by Carr and Walker (1967) and Berry and Bradley (2007). Some of the results obtained from shearing commercial agricultural crushed limestone were compared to those using a fully automated Schulze RST-XS 200 ml annular shear cell which was made available for use by the authors at Glasgow Caledonian University, see Figure 3.5. The method used in the operation of the Schulze RST-XS 200 ml annular shear cell is that prescribed in the operating manual (Schulze, 2006).

Figure 3.5: The Schulze annular shear cell, photograph Schulze operating instructions

3.4 Experimental

Fertmark registered limes were used in all experiments as these products are prepared to a known standard. They were delivered by the Ravensdown quarries which the lime samples are named after and the quality assurance data from the internal auditing was also supplied.

Thermal Gravimetric Analysis and Differential Scanning Calorimetry

Ten limes from quarries throughout New Zealand. A small grab sample of about 200 g was taken from the middle of the one tonne samples of each lime sample supplied. These were ground in a mortar and pestle and the crucible of the thermal analyser filled to the correct depth with a sample of approximately 50 mg. Not withstanding the difficulty of obtaining a representative sample, replicates produced similar results; for example Waikeretu limestone samples taken on 6 November and 12 November 2007, had 29.6% and 31.3% mass decomposition of carbon dioxide respectively.

The STD Q600 Thermal Analyser combines two separate machines in one device, a thermal gravimetric analyser and a differential scanning calorimeter, and runs these tests simultaneously. It is attached to a computer and is controlled by software which allows the operator to select the types of tests, temperature range and speed of the temperature ramp. The thermal analyser was calibrated and a simultaneous set of TGA, DSC and heat flow results were obtained. The actual calcium carbonate content of the limes was established by measuring the percentage mass of carbon dioxide lost through thermal decomposition and then compared to the Fertmark declared values as established by the standard method described in the Fertmark Code of Practice (www.fertqual.co.nz).

X-Ray Diffraction Analysis

Forty gram samples of all ten limes were dissolved in 38% HCl, washed and vacuum filtered to remove the soluble salts, predominantly $CaCl_2$. The residue was then used for x-ray diffraction analysis with a GBC EMMA Diffractometer by GBC Scientific Equipment, Dandening, Victoria, Australia.

The atomic spacings (d-spacings) in Angstrom units of crystallographic planes in the mineral are determined from the analysis and these can be diagnostic for the mineral concerned. The intensity (I) is also determined to discriminate (using I ratios) amongst the various d–spacings measured. The impurities in the limes were identified from the patterns obtained from the x-ray diffraction. The patterns measure peaks (intensity) of reflected x-rays and the spacing between the peaks. There are charts of patterns created by common minerals and by this means minerals may be identified.

Hausner ratio

Loose bulk densities were obtained by pouring the limes through a funnel on to a feeding belt which discharged into a cylindrical container 150 mm in diameter, of known volume (1.1 litres) measured by filling with distilled water with a known density at 19.1ºC the water temperature at the time; the surface was levelled and the mass of limestone in the container determined by weighing. Each experiment was replicated ten times for each material using a fresh sample; all sets of lime samples had a coefficient of variation of less than 1.1%.

Tapped densities were obtained by tapping a known mass of material in a measuring cylinder. A known mass of approximately 170 ml was placed in a measuring cylinder and manually tapped 100 times; typically, the tapped volume changed by about 15%. These were also replicated ten times.

Annular Shear Cell

The lime samples were sheared in a Carr Walker annular shear cell at moisture levels as received from the ten quarries, which are at levels typically less than 3%. However, lime samples taken from some airstrips, where they had been stored for a few weeks, had moisture levels on occasion greater than the as received samples, and were found to be close to 7%. To simulate the moisture levels found in the field, moisture was added by slow application of distilled water via a household window cleaner aerosol sprayed directly and along the sides of a plastic bag holding the material with a re-sealable closure concentric within a similar bag to maintain moisture once sealed. Care was taken to minimise disturbance of the samples to prevent granulation. Moisture was added to the contents by weight on an electric balance to increase the moisture level by mass by approximately 5%. Samples of two limes of different mineralogy a sandy coquina and a micritic lime; had further samples with moisture added by mass to increase the moisture content by; 2.5%, 7.5% and 10% of total mass. Each sample was left to equilibrate for four weeks. A 0.2 kg sample of the material used to fill the shear cell was dried at 130ºC for at least 19 hours to determine the moisture content of lime being used as suggested by the ASTM C25 - 06 standard.

$$\text{Moisture content (\%)} = \left(1-\left(\frac{Mass\ sample}{Mass\ sample\ and\ moisture}\right)\right)\times 100 \qquad (3.2)$$

All the samples as received and with moisture added were sheared in the annular cell and Mohr analysis was undertaken to produce hopper design parameters for mass flow, which is flow in which all particles move in the hopper and none are in stationary zones along the hopper wall, Jenike (1964). Yield loci were obtained for the ten limes at pre-consolidation normal stresses of 1.25kPa, 2.5kPa, 4.3kPa and 9.5kPa. Wall yield loci were obtained at a pre-consolidation normal stress of 4.3kPa using fibreglass cut from a hopper wall of a decommissioned Fletcher 950. As a comparison shear tests were undertaken on a freshly manufactured and mature superphosphate. This provides a comparison with yield loci obtained from the test material specified by CAA for the jettison requirements (CAA, 2007). In addition it provides a comparison with the results obtained by MacMillan (1971) using the same shear cell, which in 1970 was calibrated to a proving ring, whereas the authors used a calibrated shear cell connected through a Pico data logger to Pico software in a computer.

From this information angles of internal friction, wall friction, hopper half angles, powder flow functions, Jenike flow index, which is the inverse of the slope of the powder flow function, see chapter 2 Table 2.2 and the minimum openings required to prevent cohesive arching were calculated.

Similarly five samples of the materials tested in the Walker shear cell were tested in the Schulze shear cell using the same pre-consolidation stresses and the wall yield loci were produced using a piece of fibreglass cut to fit the Schulze cell from the same aircraft hopper used for the wall material of the Walker tests. The Schulze shear cell tests were limited to one replicate as time was limited at Glasgow Caledonian University where the tests were undertaken.

This enabled a direct comparison, between the shear cells; of the calculated angles, critical blocking apertures, and their Jenike flow index to be made.

3.5 Results

Thermal gravimetric analysis

Six of the ten limes had similar or greater calcium carbonate levels from TGA analysis than that determined by acid neutralisation, refer to Table 3.3. The four limes which had lower actual calcium carbonate levels by TGA than declared value Dipton, Supreme, Waikaretu and Whiterock, showed evidence of hydroxide thermal decomposition between 350°C and 580°C. In this range there are several likely compounds which thermally decompose that have an acid neutralising effect and, therefore, a calcium carbonate equivalence. They are the clay aluminous silicates which are impurities within the limestone units.

The Thermal Analyser graph, Figure 3.4 shows a 63 mg sample of Supreme Lime shows thermal decomposition of hydroxides of 4.401% of mass from 371.84°C and decomposition of carbonate of 38.25% by mass % CO_2. The graph clearly shows the simultaneous running of tests which allows the operator to see an overlay of weight loss, temperature, exothermic – endothermic reactions and energy flows. The results of the thermal gravimetric analysis are tabled in Table 3.3. Replicates were limited by restricted access to the thermal analyser as it is in constant demand. Three samples had replicates undertaken which were within 1.7 % CO_2, emitted. Figures tabled are as reported from the machine.

Table 3.3: DSC-TGA analysis of 10 Ravensdown limestones from throughout New Zealand compared with declared values for carbonate content.

Lime	mass $CaCO_3$ %	Hydroxide %	Moisture mass %	Mass $CaCO_3$ net moisture % by TGA	Declared Value $CaCO_3$ to Fertmark %
Brown's	86.18	0.00	3.75	89.51	88
Dipton	72.12	4.39	2.50	73.97	80
Geraldine	72.56	0.00	5.81	77.03	78
Greenleaf	68.48	0.00	4.00	71.34	68
Ngarua	96.60	0.00	1.00	97.57	97
Supreme	87.00	4.40	3.00	89.69	91
Waikaretu	71.08	7.54	2.00	72.53	78
Webster's	90.07	0.00	4.54	94.35	89
Westport	88.34	0.00	1.00	89.23	90
Whiterock	83.45	1.72	2.50	85.59	87

Mineralogy and x-ray diffraction

The age description and mineralogy of the various limes is described in Table 3.4, alongside the SMS powder flow analyser (PFA) cohesive index and Hausner ratio for the samples from the ten Fertmark registered quarries.

The age and description of the limestone deposits are described in a mineralogy commodity report (Christie *et al*, 2001), whilst the dominant non carbonate mineralogy was found by x-ray diffraction by the method already described.

Table 3.4: The relationship between residue mineralogy, quarry location, age and type of limestone; alongside the cohesive index from the Powder Flow Analyser and the Hausner ratio for 10 commercial limes.

Quarry	Location	Region	Age	Type (Christie et al 2001)	Dominant Non-carbonate Residue Mineralogy	PFACohesive Index	Hausner Ratio
Brown’s	**Coonoor**	**North Wairarapa**	**Plio-Pleistocene**	**Coquina**	**Quartz, minor chlorite, halloysite and feldspar**	**14.50**	**1.16**
Dipton	**Dipton**	**Southland**	**Miocene**	**Algal, coquina**	**Quartz, minor chlorite**	**12.22**	**1.11**
Geraldine	**Geraldine**	**South Canterbury**	**Oligocene**	**Semi-crystalline coquina**	**Quartz, minor mica**	**16.21**	**1.26**
Greenleaf	**Dargaville**	**Northland**	**Oligocene**	**Argillaceous**	**Quartz, minor feldspar and chlorite/smectite**	**16.08**	**1.24**
Ngarua	**Takaka Hill**	**Nelson**	**Ordovician**	**Marble**	**Trace of mica**	**18.07**	**1.26**
Supreme	**Hamilton**	**Waikato**	**Oligocene**	**Crystalline coquina**	**Quartz, minor smectite**	**15.45**	**1.07**
Waikaretu	**Waikaretu**	**Waikato**	**Oligocene**	**Crystalline coquina**	**Quartz, chlorite/smectite, minor feldspar**	**14.87**	**1.19**
Websters	**Havelock North**	**Hawkes Bay**	**Plio-Pleistocene**	**Coquina**	**Quartz, minor feldspar and chlorite/smectite**	**19.15**	**1.17**
Westport	**Westport**	**Westland**	**Oligocene**	**Algal**	**Quartz, kaolinite, mica**	**28.61**	**1.16**
Whiterock	**Loburn**	**North Canterbury**	**Oligocene**	**Sandy coquina**	**Quartz, chlorite, montmorillonite**	**13.62**	**1.28**

Walker annular shear cell

The annular shear cell produces loci that tend to be linear with less curvature than those obtained for the Jenike shear cell and also provides less conservative hopper opening solutions Carr and Walker (1967) and Schmitt and Feise (2004). The limes were shear tested by the method described and the following obtained: the angle of internal friction, the angle of wall friction and a powder flow function.

The radial stress equation solutions provided in charts by Jenike (1964) were used to obtain the hopper half angle and the flow factor. These results are displayed in Table 3.5.

There was a full range of cohesive changes in response to the added moisture as evidenced by the flow function results for the limes tested. These ranged as in Figure 3.6 from no change, to no change in slope but an increase in the unconfined yield stress as in Figure 3.7, to an increase in cohesiveness with moisture Figure 3.8, to a decrease in cohesiveness with added moisture Figure 3.9. The two limestones which had moisture added in a linear progression, Geraldine and Westport, had little difference in their powder flow functions between the amounts of moisture added, as shown in Figures 3.10 and 3.11.

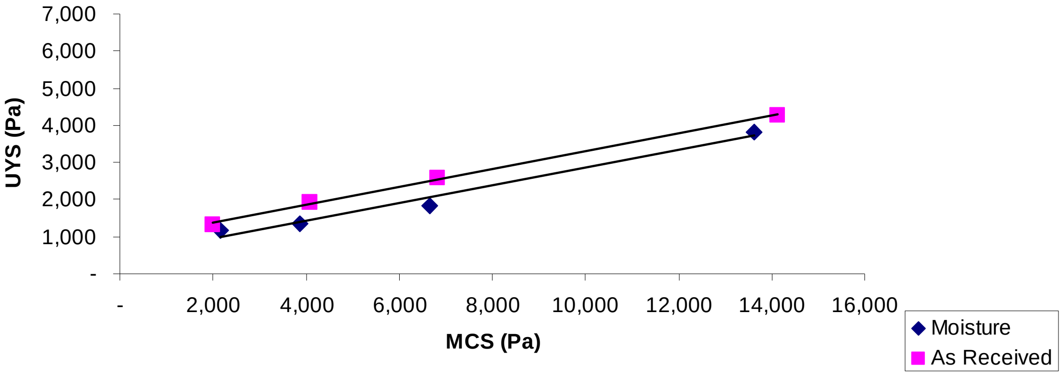


Figure 3.6: Powder flow functions for as received and 5% moisture added Westport limestone.

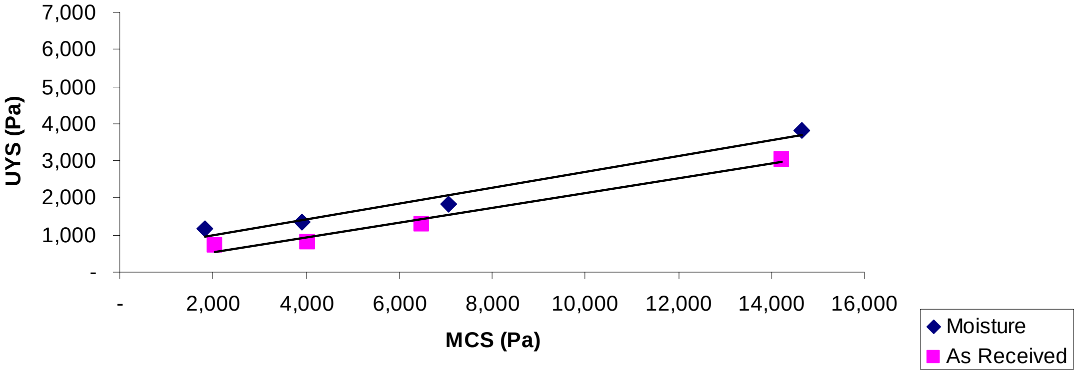


Figure 3.7: Powder flow functions demonstrating same slope but higher unconfined yield stress with 5% additional moisture by weight Supreme limestone.

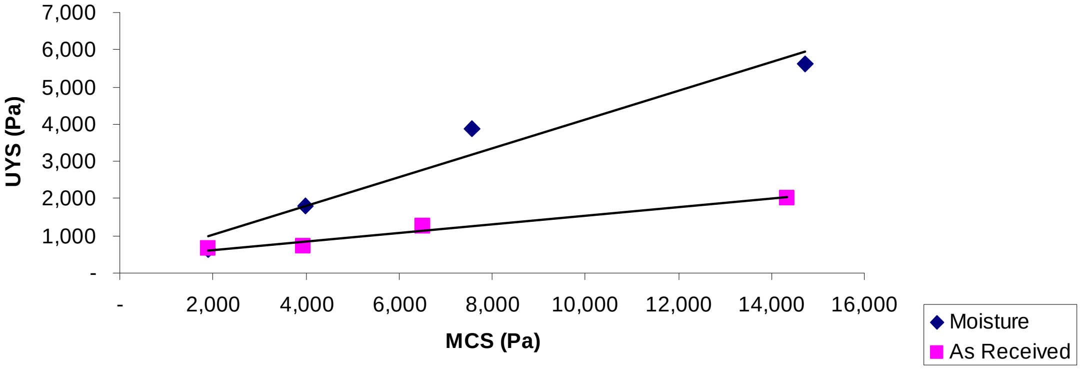


Figure 3.8: Powder flow functions demonstrating an increase in cohesion with 5% added moisture Dipton limestone.

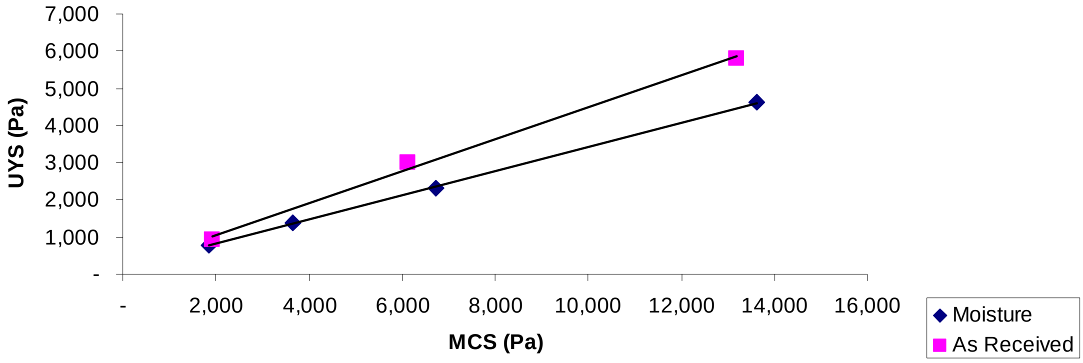


Figure 3.9: Powder flow functions demonstrating a decrease in cohesion with 5% added moisture Geraldine limestone.

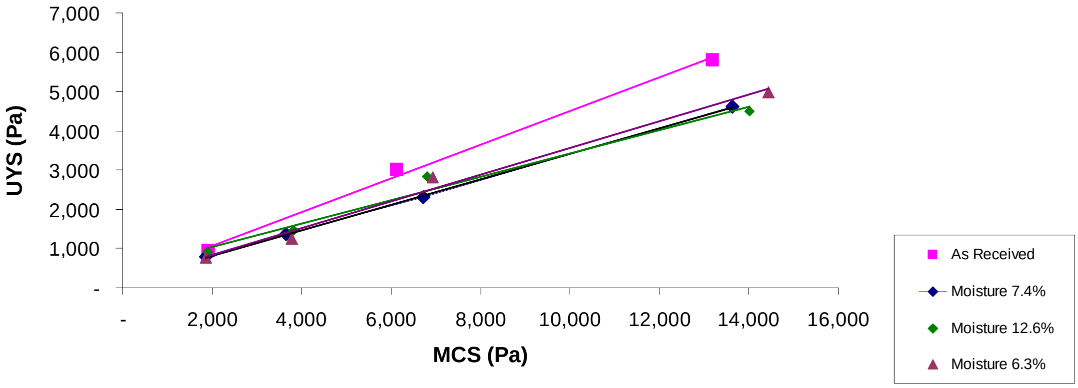


Figure 3.10: Powder flow functions of Geraldine limestone with linear progression of added moisture

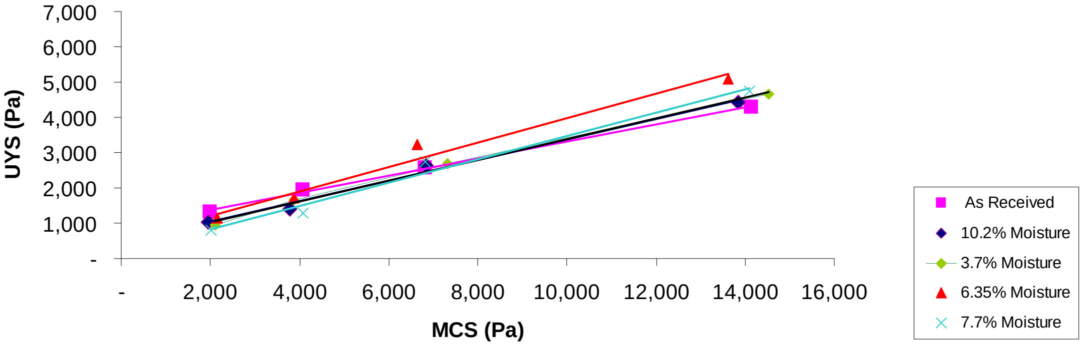


Figure 3.11: Powder flow functions of Westport limestone with linear progression of added moisture

Section D5 of Civil Aviation Rule 91 of New Zealand specifically states that an aircraft must be able to jettison 80% of its maximum allowable payload in five seconds when filled with superphosphate. Therefore, it is relevant to compare the results obtained with limestone with those obtained with superphosphate.

Table 3.5: Summary of results of shear tests on Commercial Agricultural Limes

Lime	% H2O	Flow Index	UYS/MCS r^2 of the slope of the UYS v MCS plot	Internal Friction (°)	Wall Friction (°)	Conical Opening (m)	Plane-flow Opening (m)	Hopper ½ Wall Conical (°)	Hopper ½ Wall Plane (°)
Browns	0.91	4.31	.90	24.8	7	.151	.145	25	22
Browns + H_2O	5.86	5.12	.986	30.7	19	.123	.127	27	31
Dipton	1.74	8.65	.97	29.5	25.2	.064	.067	19	25
Dipton + H_2O	8.39	2.6	.952	31.5	20.3	.057	.059	25	31
Geraldine	4.3	2.34	.996	21.3	19.5	.048	.05	25	31
Geraldine + H_2O	6.3	2.90	.99	29.8	20.5	.03	.03	24	30
Geraldine + H_2O	7.36	3.54	.97	29.5	16.4	.035	.035	31	30
Geraldine + H_2O	12.6	3.4	.98	31.0	22	.089	.092	23	29
Greenleaf	4.4	3.69	.962	37.2	25.2	.123	.123	17	28
Greenleaf + H_2O	8.54	2.6	.991	29.6	22.3	.014	.012	21	29
MacDonalds	0.95	7.08	.867	23.7	15.2	.178	.26	32	40
MacDonalds + H_2O	5.89	3.72	.957	29.4	17.8	.112	.115	28	32
Ngarua	0.3	5.00	.959	22.8	11.5	.038	.04	12	21
Ngarua + H_2O	5.48	4.91	.977	29.8	19.8	.108	.11	25	31
Supreme	1.3	5.05	.984	27.3	17.4	.034	.034	30	32
Supreme(2) + H_2O	6.76	4.71	.97	31.6	14.6	.113	.123	32	45
Supreme Aerial	2.2	3.74	.907	31	18	.004	.004	28	32
Waikeretu	1.3	3.53	.965	30.1	16.1	0	0	31	40
Waikeretu + H_2O	6.94	3.93	.979	23.1	15.2	.152	.163	32	45
Websters	1.67	3.87	.968	30.5	18.4	.082	.083	28	31
Websters + H_2O	6.7	3.06	.985	26.3	19.5	.046	.039	25	31
Westport	0.9	3.29	.994	26.2	16.0	.089	.087	31	32
Westport + H_2O	3.7	3.12	.98	29	21.5	0.11	0.12	22	29
Westport + H_2O	6.35	3.96	.996	21	26.4	.154	.16	15	20
Westport + H_2O	7.7	3.01	.98	25.6	20.1	.03	.03	25	31
Westport + H_2O	10.2	3.43	.99	31	15.9	.08	.09	10	25
Whiterock	1.1	5.44	.965	25.5	24.9	.167	.175	18	25
Whiterock + H_2O	6.84	4.33	.923	27.9	17.2	.1	.1	29.5	30

Wall yield loci for the as received limes undertaken with Perspex, whilst those with added water undertaken with fibreglass aircraft hopper wall.

Statistical analysis on best fit lines with four points shows an r^2 range between 0.9 and .99. However this is insufficient points to be of great significance, given that 2 points provides an r^2 of 1.

To this end a comprehensive shear test study was undertaken on superphosphate in 1970 by MacMillan (1971) using the same annular shear cell, but with the stress measured against a proving ring which measures the stress to achieve ring distortion, rather than the load cell used in this series of experiments.

In the MacMillan experiments a range of flow indices was established for superphosphate manufactured at the Hornby plant in Christchurch, New Zealand from freshly manufactured through to mature superphosphate 14 weeks from manufacture. MacMillan obtained Jenike flow indices (FI) between 5.45 and 41.60. Freshly manufactured superphosphate was more cohesive than mature superphosphate. It had surface moisture, a sticky feel and a green tinge compared to mature superphosphate's dry feel and grey colour.

Shear tests were undertaken on a one day old superphosphate and a mature six week old superphosphate, for a comparison with the limestone shear tests and to provide contemporary results to compare with MacMillan.

Both samples were very granular with little fines; 95% of particles between 1mm and 6 mm, less than 5% by weight less than 0.5mm. Shear tests were undertaken to obtain flow functions and a Jenike flow index. The flow index for the fresh superphosphate was 8.1 and the mature superphosphate is free flowing, it had no unconfined yield strength and the flow function lies along the abscissa. The results obtained are shown in Table 3.6. The minimum opening is thus four times the largest particles which are 6 mm to prevent mechanical bridging; see for example (Davies and Desai, 2008).

Table 3.6: Summary of shear tests on freshly manufactured and mature superphosphate.

	1 day old	*5 Weeks Old*
Superphosphate Product	8.8	7.3
Flow Index	8.14	∞
UYS/MCS r^2 of the slope of the UYS v MCS plot	0.936	N/A
Internal Friction (°)	32.1	N/A
Wall Friction (°)	18.1	N/A
Conical Opening (m)	0.203	N/A
Plane-flow Opening (m)	0.209	N/A
Hopper ½ Wall Conical (°)	28	N/A
Hopper ½ Wall Plane (°)	32	N/A

Schulze automated annular shear cell

The yield loci comparisons between the Schulze and Walker annular shear cells showed higher yield stresses for the Schulze than those using the Walker consistently for all pre-consolidation stresses as shown in Figure 3.12. Powder flow functions, critical blocking apertures, hopper half angles and the Jenike flow index, which is a measure of powder flow-ability; developed from these loci are compared, see Figures 3.13 and 3.14 and also Table 3.7. No comparison is available for the added moisture Westport sample as the Schulze cell can not produce a yield locus with this material unless slip stick detection is turned off, there is no resulting powder flow function nor wall yield locus.

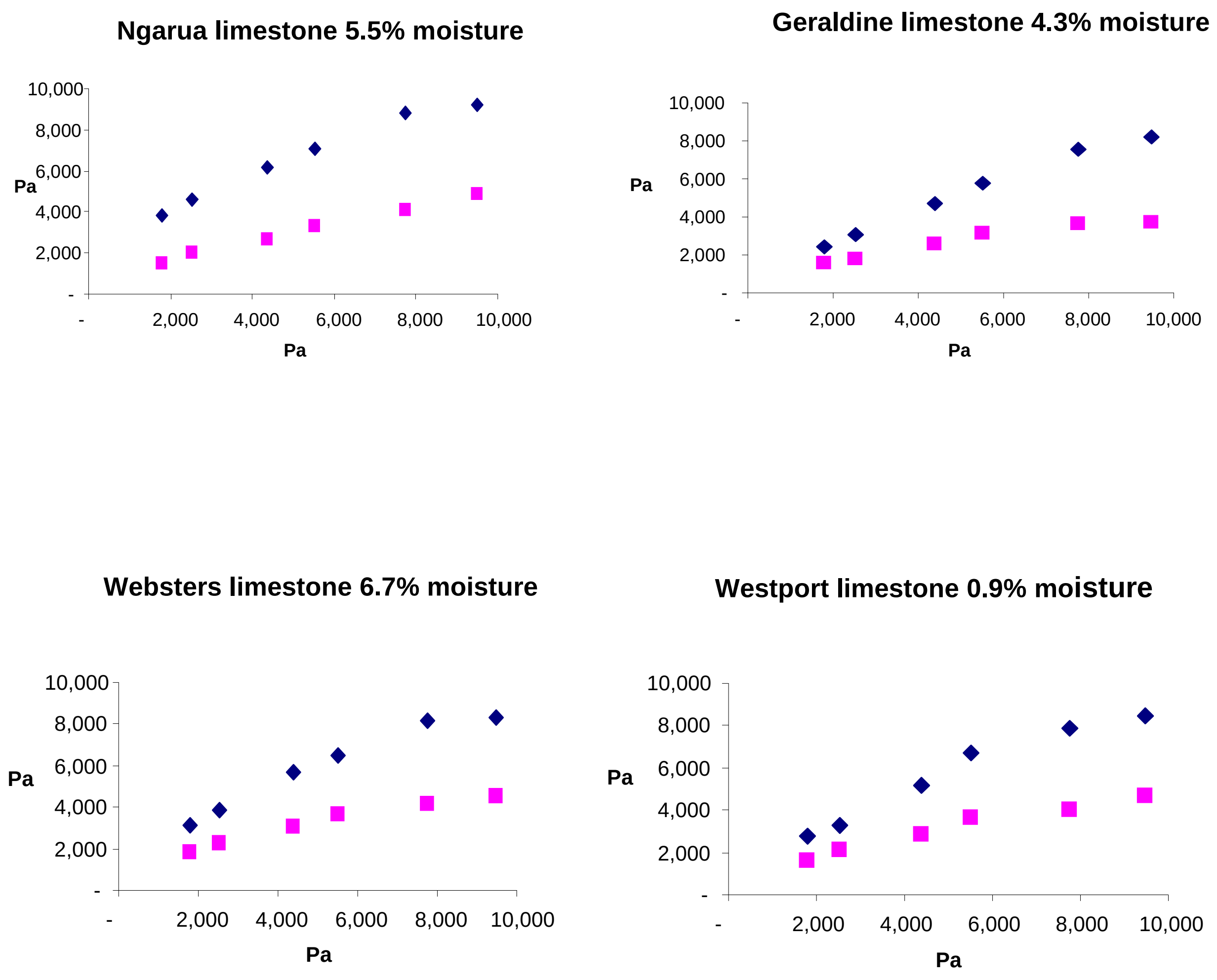
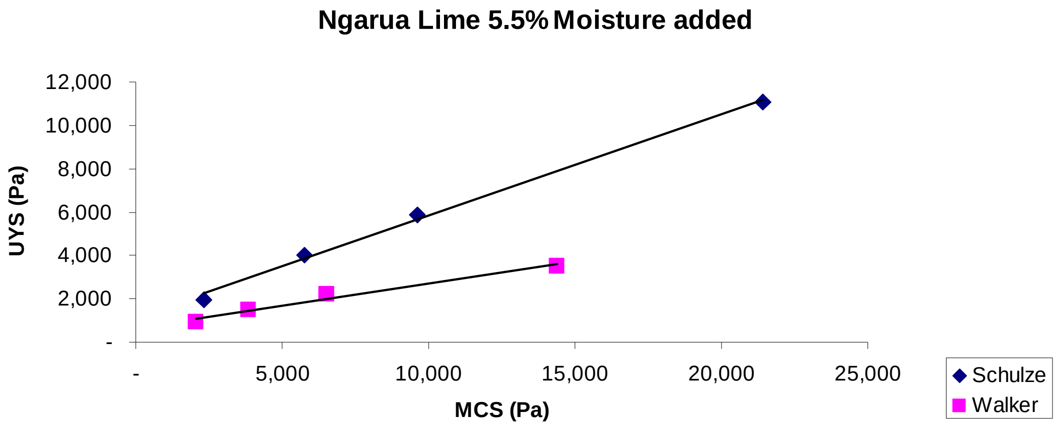
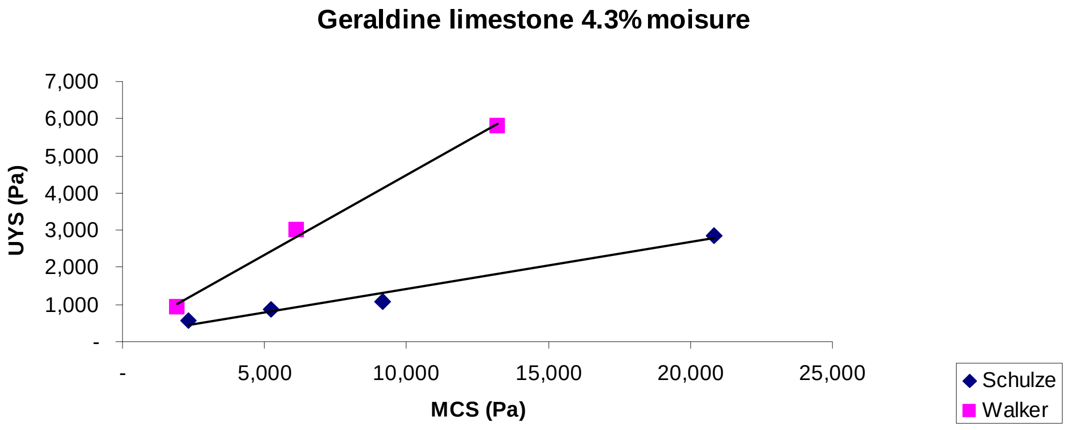
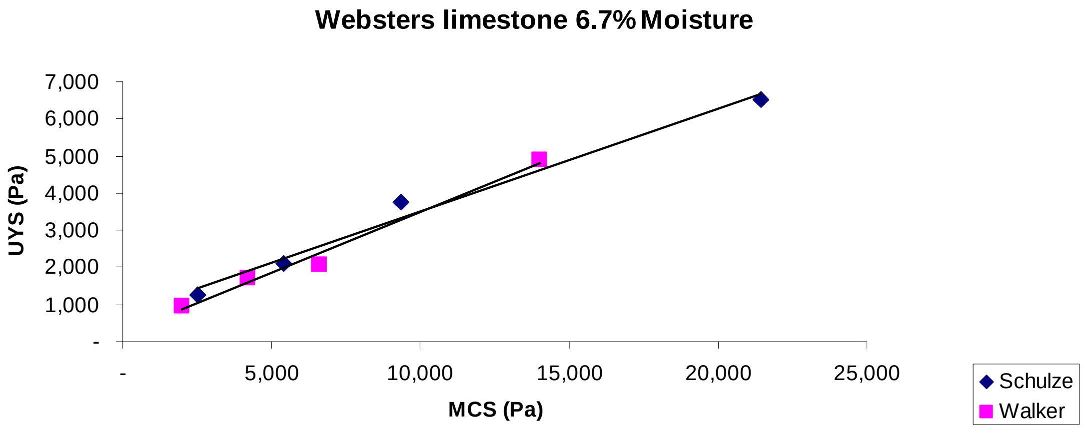


Figure 3.12: Shows yield loci stress comparisons at 9.5kPa pre-consolidation between Schulze ◆ and Walker ■ shear cells.


Ngarua Lime 5.5% Moisture added


Geraldine limestone 4.3% moisure


Websters limestone 6.7% Moisture

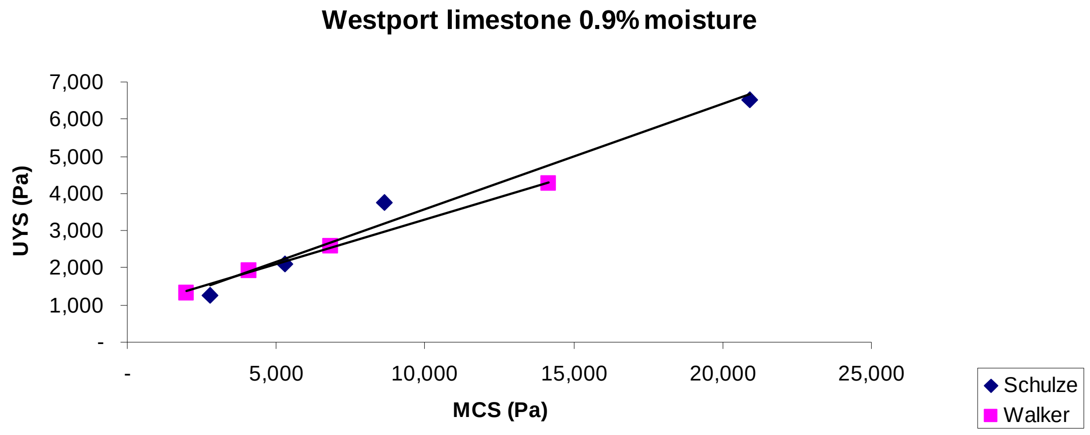


Figure 3.13: Powder flow functions derived from the yield loci unconfined yield stress versus, maximum consolidated stress of each locus between Schulze ◆ and Walker ■ shear cells.

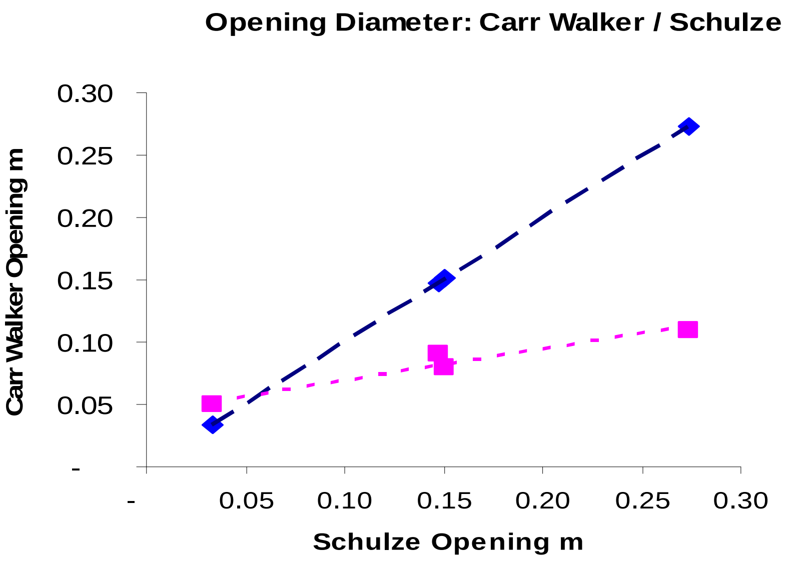


Figure 3.14: Critical blocking apertures comparisons between Schulze ◆ and Walker ■ shear cells.

Table 3.7: Hopper design criteria developed from the powder flow functions and wall yield loci for Schulze and Walker shear cells.

Schulze Lime	*Opening (m) ß*		*Hopper ½ angle α*		*Wall friction angle Ø*		*Jenike Flow Index*	
	Schulze	Walker	Schulze	Walker	Schulze	Walker	Schulze	Walker
Ngarua	.27	0.11	7	25	29	20	2.1	4.9
Geraldine	.03	.05	27	20	19	16	7.9	2.3
Webster	.15	.08	16	28	26	20	3.6	3.1
Westport (1)	.15	.09	13	31	17	16	3.5	4.2
Westport (2)	-	0.15	-	15	-	26	-	4.0

Westport (1) as received from quarry, Westport (2) with added moisture

3.6 Discussion

The tests undertaken demonstrate that the limes have a wide range of cohesive properties which vary between becoming easier flowing through to becoming more cohesive with the addition of 5% moisture by weight. This is consistent with the mineralogy and geology of the limes, which shows them to be different substances which only have in common calcium carbonate content greater than 65% and approximately the same particle size distribution (NZ. Fertiliser Quality Council, (2004).

The suitability of the Jenike flow index as a sole means of gauging flow-ability must also be questioned (McGee and McGlinchey, 2005). The result of the powder flow functions for Supreme lime as shown in Figure 3.7, demonstrates that the addition of moisture increases the unconfined yield stress, yet does not change the rate of increase with increasing major consolidated stress, therefore leaving the Jenike flow index unchanged.

The reason why some limestone types became less cohesive when moisture was added is most likely due to agglomeration. In this process the effective particle size distribution is altered as fine particles adhere to each other and to larger particles thus increasing the size of the particles which results in a more free flowing bulk solid.

The shear stress measured with the Walker cell is less than those obtained by the Schulze cell, at the same normal stress. This mirrors the results gathered by Carr and Walker when their results were compared to those obtained with a Jenike shear cell

(Carr and Walker, 1967). This is expected given the similarity in results obtained by Schulze, with the Schulze shear cell and the Jenike shear cell Schulze *et al*, 2001).

The powder flow functions comparisons obtained from the yield loci are less distinguishable as to which shear cell is used, as can be seen in Figure 3.14. The critical aperture openings and hopper half angles are generally more conservative when calculated from the data obtained from the Schulze than when calculated from the Walker cell, which is also consistent with the results obtained by Carr and Walker (1967) and Schulze *et al* (2001).

The powder flow functions obtained for Geraldine and Ngarua limestones are very different between the shear cells, whereas those obtained for Webster and "as received" Westport lime are similar.

The Schulze cell data obtained in Glasgow from two loci sets suggests that Ngarua is the most cohesive of the limes, whereas the Walker cell suggests that it is the freest flowing of the limes. Whilst the Walker cell data suggests that Geraldine is the most cohesive of the limes, whereas the Schulze cell data suggests that it is the freest flowing. Furthermore, yield loci and a wall yield locus are obtainable for Westport limestone with added moisture, whereas the Schulze automated shear cell failed to produce a locus without the slip stick detection being removed. Consequently the yield loci obtained have the staircase appearance of a slip stick material; neither did the machine complete a yield locus at the lowest pre-consolidation stress of 1.2kPa. The machine did not complete a wall yield locus either and the powder flow function had no reasonable degree of confidence as there is a stair case effect which has the points well above and below the line of best fit, see Figure 3.15.

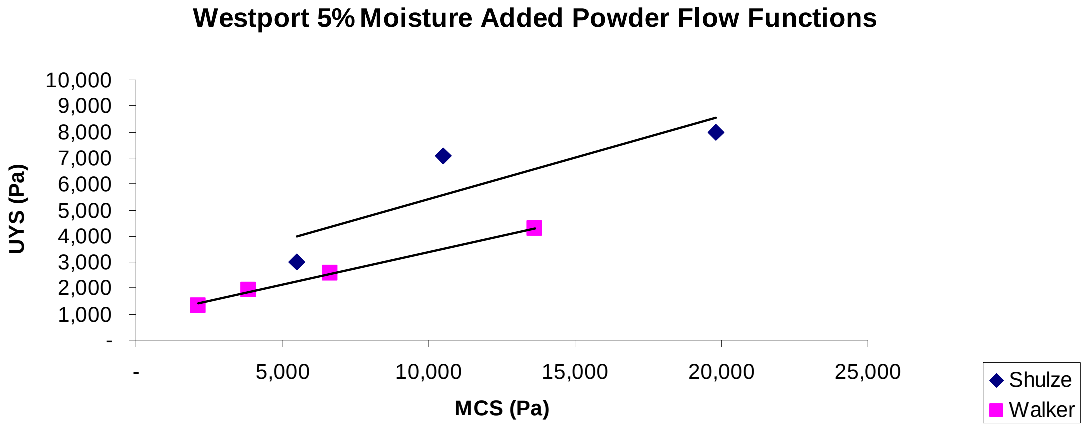


Figure 3.15: Powder flow function for Westport (2) sample between Schulze ◆ and Walker ■ cells.

Shmitt and Feise compared several shear cells including the Schulze and the Walker; finding that with free flowing Aluminium oxide the Walker cell's results suggested the material was more cohesive than any of the other shear cells (Shmitt and Feise, 2004). Whilst with cohesive Titanium dioxide their results with the Walker shear cell suggest that this material is nearly free flowing. They recommended that the Walker cell not be used for free flowing substances and postulated that due to its size and the weight of the lid that this machine is problematic (Shmitt and Feise, 2004). Their study did find a good degree of repeatability with their use of the Walker shear cell and did not have scatter in the data that Shmitt and Feise experienced. Although it is well documented that the Walker cell will suggest that material that are cohesive are more free flowing than the results obtained from the Jenike shear cell, it may also be that similarly to Shmitt and Feise findings, that the Walker cell shear data suggests that free flowing substances are more cohesive than the results obtained from other shear cells (Shmitt and Feise, 2004). This may partially explain the results obtained from testing Ngarua and Geraldine limes.

Another possible cause of the divergent results obtained with a Schulze and a Walker shear cell is the phenomenon of spontaneous compaction (Nedderman, 1992). This is where the particles pack into a more compacted mix with increased cohesion. This appeared to occurr whilst conducting shear testing on Geraldine lime with the Walker cell. This limestone tended to have two levels of compaction, at one level producing results which suggest it is a free flowing substance and suddenly increasing strength after some time to a cohesive material. Thus, if each shear point is taken with a fresh sample producing a locus suggesting a free flowing substance, or if each locus is derived from a single fill, it required a long pre-consolidation until a second compaction occurred as in Figure 3.16. The Schulze shear tester is fully automated and undertakes shear tests once a consistent pre-consolidation shear is established, therefore, it is probable that the results for Geraldine lime were obtained at the first rather than the second level of compaction.

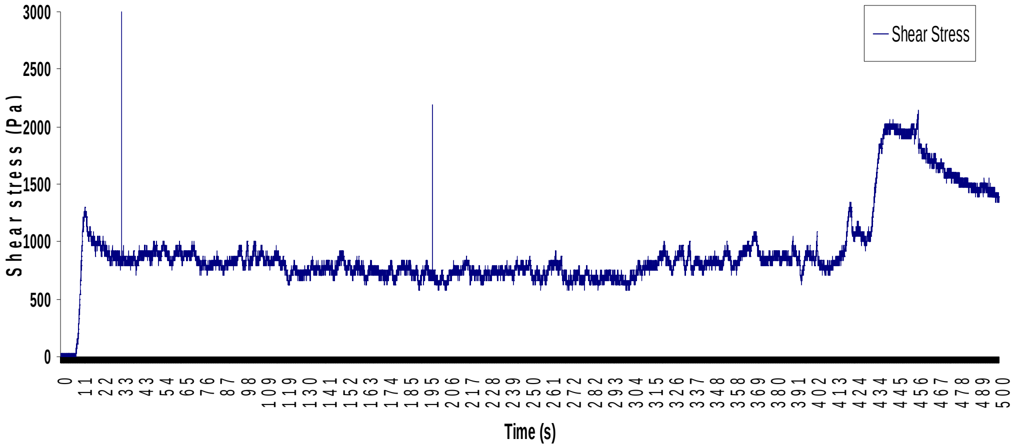


Figure 3.16: Geraldine lime shear test demonstrating spontaneous compaction

The Walker cell was able to produce yield loci and a powder flow function with Westport lime with added moisture, whilst the Schulze cell was unable to as it found this material to have slip stick properties. One possibility for this may be because of agglomeration and the difference in size of the shear cells. It is possible that particles agglomerated due to added moisture and interfered with the shear plane in the Schulze cell. The standard method of shear testing for the Jenike cell states that all particles greater than 5% of the diameter of the shear cell should be removed for this reason (IChE, 1989). This means that all agglomerated larger than 3.5 mm in diameter would need to be removed from the Westport lime sample to comply. These agglomerates were not removed as like samples were compared for all materials, which may be the reason that the Schulze shear cell found this to be a slip stick material. As the Walker cell is ten times larger than the Schulze shear cell it is able to cope with agglomerates in the material.

3.7 Conclusions

It is apparent that the Fertmark standard for lime does provide a quality assurance process in respect of acid neutralisation and in the provision of a particle size distribution. Due to the parameters of the scheme it does not actually examine the chemical compounds contained within. The impurities which include clay materials have a tendency to be cohesive with ionic attraction and as a result an attraction to moisture. These compounds may therefore, have a significant bearing in the flow problems associated with lime (Jiao *et al*, 2007).

The flow problem is multi dimensional and is affected by more than just the physical characteristics such as moisture content and particle size distribution. The geology and mineralogy of the limestone also has a bearing which means that limes behave differently when parameters such as moisture content are altered, with a range of findings between poorer flow, and improved flow. Moisture content will be extremely difficult to control once the lime leaves the quarry as on farm storage facilities are often not weather proof.

The aircraft currently engaged in sowing bulk solid agricultural lime in New Zealand in many instances have difficulty initiating flow, and maintaining a steady flow and as a result are unlikely to meet the jettison requirements within Section D5 of Part 91 of the Civil Aviation Rules. All limes tested were more cohesive than mature superphosphate; and generally were more cohesive than the freshly manufactured superphosphate, certainly at the same moisture content, which is often described as problematic by both aerial and ground spread applicators.

The experimental work undertaken on the lime samples suggests that the argillaceous (muddy) limes are more problematic and gain strength in the presence of moisture, whereas the coquina (sandy) limes and marble limes are less sensitive to moisture gains and are less inclined to gain cohesive strength in the presence of moisture and will, therefore be a safer option for agricultural aviation use.

The Walker shear cell produces yield loci that are less conservative for cohesive materials than shear cells which more closely mimic the Jenike shear cell. This attribute of the shear cell has been evident since its development in 1966 (Carr and Walker, 1967). However the design criteria developed from the yield loci derived from the Walker cell were found to give a fair agreement to those found in practice (Carr and Walker, 1967). The results obtained in this study comparing results obtained by a Walker cell and a Schulze fully automated shear cell with cohesive materials; were consistent with these findings as the Schulze cell produced higher yield stresses from the same normal stress.

The result with Geraldine limestone was inconsistent with the other results as the Walker cell found this material to be more cohesive than the results obtained with the Schulze cell. It is possible that this may be as a result of Geraldine limestone being prone to spontaneous compaction, a phenomenon recorded with the Walker cell.

Because of its size the Walker cell is better suited for measuring materials with a proportion of large particles as the standard method prescribes the removal of particles greater than 5% of the diameter of the shear cell. In the case of the Schulze cell used in these experiments that would be 3.5 mm, or for a standard Jenike shear cell, 4.5 mm (IChE, 1989). The Walker cell because of its size is suitable for particles up to 12.5 mm in diameter.

The results from both shear cells confirm that the limestone material may be classified as either cohesive or easy flowing (i.e. not free flowing) and therefore, have cohesive strength. This is a concern in respect of agricultural aircraft operators and there is little doubt that it is the reason that lime has problematic flow properties from their aircraft.

That there are a number of different shear cells and granular materials that require strength measurements and design criteria for silo storage. It is unlikely that any one shear cell will be suitable for all materials. Therefore, selecting the shear cell best suited to the material should be a consideration in any silo or hopper design calculations.

Chapter 4

Improvement of flowability of crushed agricultural Limestone by removing a Fines Fraction

4.1. Introduction

About half of the agricultural lime used in New Zealand is applied by agricultural aircraft. As this equates to several hundred thousand tonnes and the flow properties are not satisfactory it is essential to engineer a solution.

Agricultural limestone has a wide range of particle sizes and there may be a tendency for the smaller particles to percolate Mehta *et al,* (1993) especially in the low intensity shaking environment encountered in a truck or aircraft. We do not know if this is contributing to the problem, but it may have the greatest effect near the hopper wall and therefore change the particle wall dynamic by altering the angle of wall friction. The value of applying fine particles by aircraft must also be questioned. These particles have a high drag coefficient and may be carried for many kilometres by wind or even thermals, thus are likely to land outside the target application area Jones *et al*, (2008), calculating their actual drift would require further dispersion modelling which would need validation.

The presence of a large proportion of fine material is largely an agronomic one due to the low solubility of calcium carbonate Nye and Ameloko, (1987).

It was postulated that the large range of particle sizes from less than 38 microns to about 2 mm, with 50% by weight less than 0.5 mm, to meet the Fertmark® quality assurance scheme particle size distribution standard, may lead to particles packing through percolation creating cohesive materials. One possible solution could be the removal of fines.

If the removal of fines is to make a significant difference to the flow properties, then the modified material must be shown to be free flowing. It has been shown that the flow rate of a free flowing granular material through a square edged circular orifice in the bottom of a cylinder is proportional to the diameter of the orifice to the power of 2.5 (Deming and Mehring, 1929), in the form of the equation:

$$M = K\rho g^{\frac{1}{2}} D^{\frac{5}{2}} \qquad (4.1)$$

Where M is the flow rate of the bulk solid by mass

ρ is the bulk density

g is the acceleration due to gravity

K is a constant for the particular material

This has been further refined by Brown and Richards (Brown and Richards, 1960) and independently by Beverloo (Beverloo *et al*, 1961) to have two constants rather than one, the second relating to the mean diameter of the material flowing through the orifice. This reduces the variability of the main constant K and was conceived from observing that there was very limited material flow adjacent to a sharp edged orifice reducing the actual available orifice opening (Beverloo *et al*, 1961). The modified flow equation is:

$$M = K\rho g^{\frac{1}{2}}(D - k\bar{d})^{\frac{5}{2}} \qquad (4.2)$$

Where k is a constant related to particle size and shape

$\bar{d}$ is the mean particle size diameter of the free flowing granular material

It was also noted through experimentation that the maximum orifice diameter D_o should be no more than 0.45 times the diameter of the cylinder D_c so that the material construction of the wall is not of influence to the flow tests (Brown and Richards 1960).

That $\frac{D_o}{\bar{d}}$ should be greater than 20 (Beverloo *et al*, 1961).

That the flow rate is unaffected by the head h of the material within the cylinder whilst $h > D_c$ (Franklin and Johanson, 1955).

Brown and Richards noticed that as particle size decreases k increases (Brown and Richards, 1960). In addition; Davies *et al.* (1995) found k to be 1.32 for perfectly spherical particles, steel ball bearings, with a diameter 3.175 mm.

To test the postulate that removing fines from lime would reduce percolation packing and therefore produce a free flowing modified material; an easy flowing lime from the Whiterock quarry with a Jenike flow index in the range 4.3 – 5.3 (see Table 2.2), was selected. Two samples with a particle size distribution between 300 and 425 microns and between 425 microns and 2 mm were selected for flow testing through sharp edged orifices at the bottom of a cylinder. The flow data would be compared to that of the unmodified material, which was to act as a control. Then determine whether any of the materials behave as cohesionless materials obeying equation (2). For any cohesionless materials found both K and k would be determined.

4.2. Materials and Method

The two samples with different particle size distributions were created by sieving Whiterock agricultural crushed limestone, which has a mineral composition as per Table 3.4 and flow properties as per Table 3.5; using BS 410-2:2000 standard method and sieves using an Endecott Test Sieve Shaker model EFLI MkII. These sample distributions comprised particles less than 2 mm but greater than 425 microns; and particles greater than 300 microns and less than 425 microns. These particle size distributions were chosen as the first removes all particles less than 425 microns leaving a minimum particle size. The second, as it produces particles of a similar size which, therefore will not percolate and pack, whilst maintaining the same mean particle size as the unmodified control sample, see Figure 3.3. A 20 litre bucket of each sample was used for flow experiments through a Perspex cylinder 406 mm long by 139.5 mm diameter; the test apparatus is illustrated in Figure 4.1. A third control sample consisting of as received Whiterock agricultural crushed limestone was also tested. All three samples were taken from the same 1m^3 bag of limestone.

Mean particle size $\bar{d}$ for material >425 μm < 2mm $\approx$ 1.3mm **Sample 1**

Mean particle size $\bar{d}$ for material >300 μm < 425μm $\approx$ 365μm **Sample 2**

Mean particle size $\bar{d}$ for material as received $\approx$ 365μm **Sample 3**

Figure 4.1: The perspex flow cylinder on frame resting on a 50 kg button load cell calibrated in LabView 8.2 student addition

Five orifice sizes were made with the following diameters: 55.8 mm, 37.0 mm, 25.4 mm, 21.6 mm and 16.4 mm. The orifices were covered with packing tape when bolted in place to allow the cylinder to be gently filled to overflowing and then screed off. The cylinder was filled *in-situ* on a frame which could be lowered by turning a screw on to a Bongshin 50kg compression load cell model 50 CRES calibrated to tare weight via an amplifier and data acquisition card to a computer programmed in LabView 8.2 student edition. Flow was measured by a digital stop watch which was started once the packing tape sealing the orifice was removed, whilst the LabView data collection programme was running. Both the programme and digital stop watch were stopped once the head of material reached a mark 140 mm from the base of the cylinder which is the mark where the head is the same as the cylinder diameter "$h = Dc$", thus allowing a volume of 4 litres to discharge. The stop watch was used because the material was essentially in full flow when the 140 mm mark was reached.

Four replicates were taken at each orifice setting and the flow rate was established from an average of the results which were typically within a 4% range of each other for each setting.

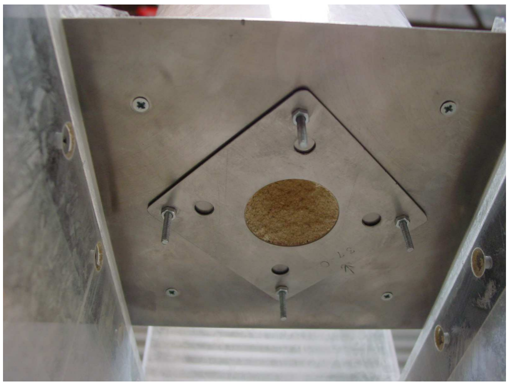
The load cell was fitted to the frame for use with previous experiments and the results obtained had considerable noise. The use of a single load is not recommended in bulk solids application. Unlike liquids, bulk solids do not keep a level surface and flow may not be axisymmetric. This leads to uneven and unpredictable loadings.

As the mean particle diameter of sample 1 is 1.3 mm and given that the ratio of the orifice opening to mean particle size "$\frac{D_o}{\bar{d}}$"should be greater than 20, then for this sample; the 16.4 mm diameter orifice was not used. In order that each sample had the same number of readings, then for samples 2 and 3; the 55.8 mm orifice was not used.

Bulk density was measured by the method of loose filling the cylinder and then to screed off the excess, the cylinder which has a volume of 6.2 litres was tapped to compact the material to prevent spilling and the container was weighed on a digital balance. The bulk density of the sieved materials was the same 1,074 kgm^{-3} whereas the bulk density of the "as received" limestone was 1,232 kgm^{-3}.

4.3. Results

Flow was not achieved with the control, as received limestone for all four orifices used with the material immediately forming a cohesive arch over the orifices as shown in Figure 4.2.



Figures 4.2: Overview of Beverloo device no flow, bridging over 37 mm orifice

The modified limes had no difficulty flowing through the selection of orifices as shown in figures 4.3.

Figures 4.3: Lime between 300 and 425 microns after flow test

The flow profiles were measured both by stop watch and electronically via a load cell and the measurements graphed to demonstrate the “Beverloo” relationship of a free flowing material.

Both the modified materials flowed freely through the orifices and values for K and k could be determined.

Values for these constants were found by regression analysis by plotting the flow rate to the power of 0.4 against the orifice diameter, so that the slope is $(K\rho g^{\frac{1}{2}})^{\frac{2}{5}}$ and by extrapolating through to a sealed orifice the intersection on the y axis gives $(K\rho g^{\frac{1}{2}})^{\frac{2}{5}} k\overline{d}$. Flow rates and times are shown in Table 4.1 and are graphed in Figure 4.4.

This type of analysis when applied to free flowing bulk solids consistently produces r^2 values close to 1; which was the case in this analysis within 5 decimal places, Brown and Richards (1960), Beverloo *et al*, (1961), Davies and Chew, (1983).

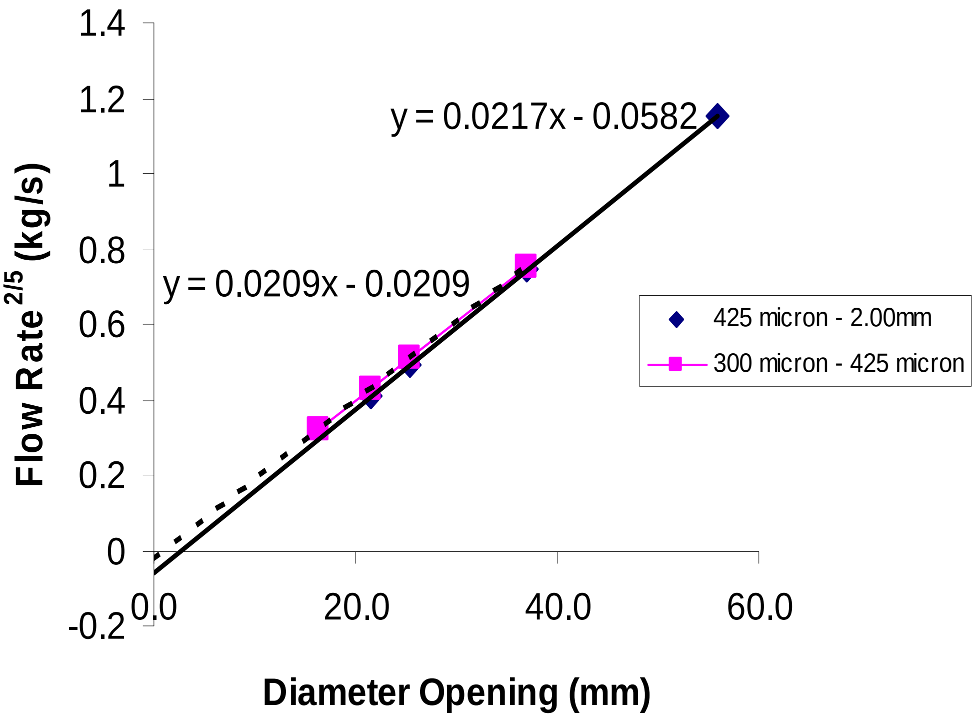


Figure 4.4: The plot of flow rate$^{2/5}$ against orifice opening from data Table 4.1

Table 4.1: Flow data from modified limestone samples

	Sample 1		Sample 2	
Opening mm	**Time s**	**Flow rate kgs^{-1}**	**Time s**	**Flow rate kgs^{-1}**
16.4			73.18 74.39 74.31 74.43	0.059 0.058 0.058 0.058
21.6	39.65 40.61 40.66 41.04	0.11 0.11 0.11 0.11	35.85 36.13 36.16 36.25	0.12 0.12 0.12 0.12
25.4	25.58 25.16 25.11 24.99	0.17 0.17 0.17 0.17	23.81 23.62 23.50 22.89	0.18 0.18 0.18 0.19
37.0	9.22 9.01 8.89 8.85	0.47 0.48 0.48 0.49	8.95 8.93 8.82 8.80	0.48 0.48 0.49 0.49
55.8	2.96 3.05 3.07 3.15	1.45 1.41 1.40 1.37		

The values of *K* and *k* for the free flowing modified limestone comprising samples 1 and 2; see Table 4.2.

Table 4.2: Solution table for samples 1 and 2

Sample	Mean particle size $\bar{d}$ m	K	k	Bulk density P_b kgm^{-3}
1	0.0013	0.64	2.10	1,074
2	0.000365	0.59	2.74	1,074

The modified limestone samples that had fines removed were clearly free flowing and their flow rate was proportional to the orifice diameter$^{5/2}$. That these samples were produced from the same bag of Whiterock crushed agricultural limestone as the control, and were merely modified by the removal of fines, demonstrates that the presence of fines less than 300µm gives the "as received" material cohesive strength.

The values for K and k obtained are within the range obtained by Beverloo *et al*, (1961) with their work, although the results for k are greater than their results obtained for agricultural seeds, but are less than what they obtained for sand. They are also similar to those obtained by Davies and Chew (1983) with their work with casein and lactose. This suggests that the method and results are valid.

4.4 Discussion

It has been shown that crushed agricultural limestone's flow properties can be improved and given the hazard to pilots it poses in its present unmodified state, this should be considered by the industry. This work demonstrates that modifying the particle size distribution could be an effective means of improving the flow properties of this product. In both modified samples produced, free flow conditions were established and their flow rate followed the original equations established by Deming and Mehring (1929). The flow rate would be entirely predictable from the aircraft and improved hopper design could be considered in order to apply these products more accurately.

Further samples need to be considered to ensure that this approach achieves consistent benefits over the whole range of agricultural limes quarried in New Zealand. These benefits include, improved flow-ability of product, application control and aircraft safety.

Modifying agricultural lime products will have an additional cost for limestone millers and alternative uses for the fines, such as road packing material, which is a use currently employed, will have to be found. There could be possible additional costs for aerial operators as the bulk density of the material is reduced and they are paid on a per tonnage basis. However, it would be argued that that these products are still sufficiently dense that the maximum safe load can be achieved within the hopper and the improved flow properties will actually improve the efficiency of flying as less time will be spent trying to overcome problem situations where lime bridges in the hopper. Variation in flow properties may be a contributing factor to agricultural aircraft having difficulties discharging their payload of this material.

4.5 Slot Hopper

As there was no flow from the “as received” limestone, a model slot hopper as shown in Figure 4.5 was used to compare the flow rates of “as received” limestone, with the modified limestones used in the orifice flow experiments already described. In addition another unmodified limestone (MacDonald’s 15% 2mm – 6mm chip) which is marketed as suitable for aerial application was flow tested as a comparison.

Johanson (1965) developed equation (4.3) in to a form for calculating a predictive flow for bulk solids from a hopper, as described in Chapter 2 from work on flows from converging channels (Johanson, 1965).

$$M = \rho\beta^{(1+m)}\, L^{(1-m)} \left(\frac{\pi}{4}\right)^{m} \sqrt{\frac{\beta g}{2(m+1)\tan\theta_e}\left[1-\frac{ff}{ff_a}\right]} \qquad (4.3)$$

m= 0 for plane flow hoppers

m= 1 for conical hoppers and axi-symmetrical hoppers

B = width of slot or diameter of opening

L= length of slot for plane flow hopper

θ_e = included half angle of the flow channel

ff= critical flow factor

ff_a = σ_1 / σ_c = MCS/UYS = the actual flow factor or Jenike Flow Index

Figure 4.5: Slot hopper used for flow testing

The Perspex hopper in Figure 4.5 has adjustable wall angles which are set by placing a template machined to set angles and tightening screws to fix the walls at this angle. The width of the opening is then measured by Vernier callipers; the length of the opening is 150.31 cm.

A 50 kg load cell as shown in Figure 4.6 was calibrated to tare weight via an amplifier and data acquisition card to a computer programmed in LabView 8.2 student edition, in a similar manner to the flow cylinder used to establish the flow formulae of the modified limestones.

Flow is initiated by releasing a trap door and the rate of flow measured at 50 Hz in the "LabView" programme see Figures 4.7 and 4.8. Each test for all opening widths and hopper half angles were undertaken four times and average flow rates and standard deviation were recorded in Table 4.3. These are compared to the theoretical flow rates based on the critical flow factor and Jenike flow index values as calculated using the

Walker shear cell; as shown in Table 3.6 in Chapter 3. These are all tabled with the maximum possible flow rate, which occurs when $(ff / ff_a = 0)$.

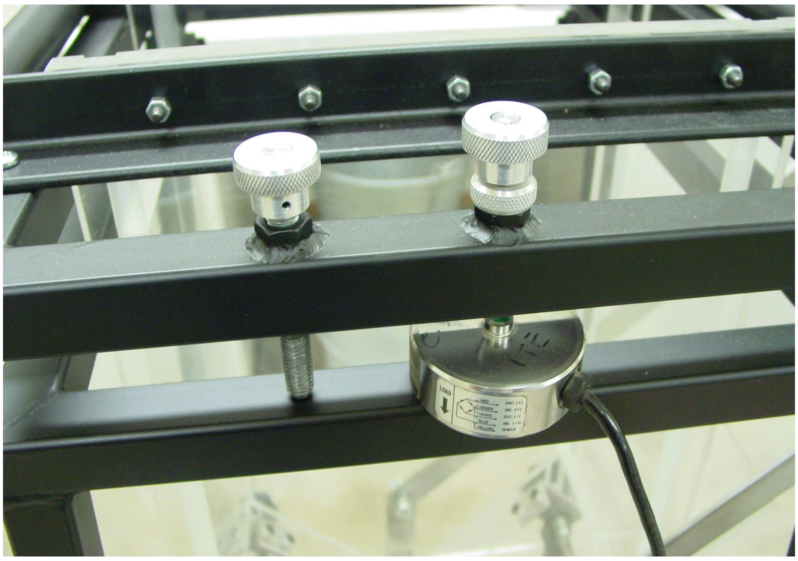
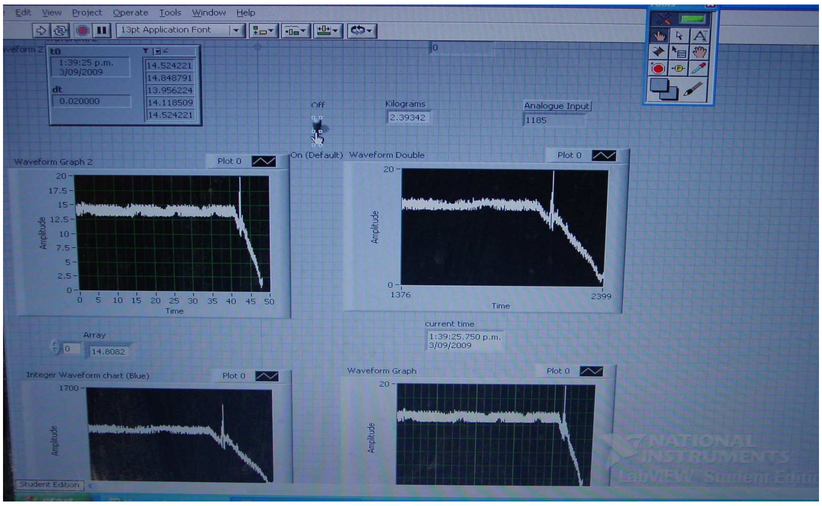


Figure 4.6: Bongshin CRES 50; 50 kg button load cell recording mass change

Figure 4.7: trapdoor that initiates flow


t0
1:39:25 p.m.
3/09/2009
dt
0.020000
Y
14.524221
14.848791
13.956224
14.118509
14.524221

Kilograms
2.39342

Analogue Input
1185

current time
1:39:25.750 p.m.
3/09/2009

Array
0
14.8082

Figure 4.8: LabView display showing rate of flow

Table 4.3: Results of flow tests from the slot hopper

Lime	*Hopper ½ angle °*	*B Width cm*	*Area cm^2*	*Max Flow rate kgs^{-1} $Ff/ff_a=0$*	*Theoretical Flow rate ff & ffa as per Walker shear result.*	*Actual Flow rate Kg/s*	*Std dev Actual rate*
Whiterock>300<425µm	15	6.37	95.75	11.10	10.46	6.40	.28
Whiterock>300<425µm	25	4.70	70.65	5.33	5.03	3.75	.16
Whiterock > 425µm	15	6.37	95.75	11.10	10.46	5.51	.12
Whiterock > 425µm	25	5.38	80.87	6.53	6.16	4.46	.15
Whiterock > 425µm*	25	4.70	70.65	5.33	5.03	3.35	*
Whiterock As Received	25	4.90	73.65	6.51	4.98	1.93	.13
MacDonalds15% (2-6)mm chip	25	4.90	73.65	7.61	5.47	2.34	.05

***Test had no replicates, it was used to compare same slot opening as previous run**

The results displayed in Table 4.3 are represented as a percentage of maximum possible flow rates in Table 4.4.; alongside the theoretical flow rate based on the flow functions obtained with the Walker cell (Table 3.5).

Table 4.4: Actual flow rates as a percentage of theoretical flow rates.

Lime	*Hopper ½ angle °*	*B Width cm*	*Actual Flow Rate as % of Maximum flow*	*Actual Flow Rate as % of Theoretical flow*	*Theoretical Flow Rate As % of Maximum flow*	*Hopper ½ Angle for Critical aperture*
Whiterock>300<425μm	15	6.37	58	61	94	*NM
Whiterock>300<425μm	25	4.70	70	75	94	*NM
Whiterock > 425μm	15	6.37	50	53	94	*NM
Whiterock > 425μm	25	5.38	68	72	94	*NM
Whiterock > 425μm	25	4.70	63	67	94	*NM
Whiterock As Received	25	4.90	30	39	76	25
MacDonalds15% (2-6)mm chip	25	4.90	31	43	72	32

***NM not measured as proven free flowing material**

4.6 Discussion Slot Hopper:

The modified free flowing materials flow rates were less than the theoretical flow rates established using equation (4.3). These are close to the theoretical maximum for materials with a free flowing Jenike flow index (Jenike, 1964); in this case the theoretical value is 94% of the theoretical maximum flow rate.

Flow rates for the modified materials are closer to the theoretical flow rates at 25° than at 15°. This is as a result of the influence of $2\tan\theta_e$ in the denominator. The increase in flow as the hopper half angle is reduced can be almost accounted for by the increase in the opening area, which suggests that for these experiments the influence of the hopper half angle is less pronounced than the calculations of equation (4.3), using this apparatus. This is probably due to the fact that the two longest walls are vertical and the sloping walls run along the narrower breadth of the hopper see Figure 4.8.

The apparatus is easy to set at an angle by inserting the steel template but it is extremely difficult to repeat an orifice opening once the settings have been altered. Unfortunately this was not discovered before a setting was changed which meant that at 25° there are three different width settings.

However, the modified materials did flow much faster than the unmodified material and the MacDonald’s aerial limestone. The standard deviations of the flow rates were small and the actual flow rates were significantly different between the modified and as received material. Although using Johanson’s equation (4.3) as a means of predicting flow was not applicable to the apparatus used. The size of the experiment was limited by the amount of sieved material available, which is due to the time it takes to sieve reasonable size samples using Endicott 200 mm sieves and shakers.

4.7. Conclusions

Fines were removed from an easy flow limestone to produce material with a particle size distribution greater than 425 microns and one with a material greater than 300 microns and less than 425 microns. These modified granular materials were shown to be cohesionless by gravity flow through a series of sharp edged orifices between 16.4 mm and 55.8 mm, in the centre of a cylinder 406 mm by 139.5 mm from which the flow took place. The unmodified material would not flow through apertures of 37 mm or less.

Quite clearly lime's flow properties can be improved and given the hazard to pilots it poses in its present unmodified state, then there is cause to modify the particle size distribution. This will also reduce the nuisance of dust drifting off site.

Lime fines are sometimes applied in suspension with as little as 20% moisture content from fixed wing and helicopter agricultural aircraft in New Zealand at present. It may be that this method be used for a quick response to increase pH of soils, whereas a screened limestone without fines; be applied as a free flowing granular material for a slow release solution. The removal of fines also decreases the bulk density of the limestone material and consequently also reduces the risk of overloading aircraft.

One of the issues with agricultural limestone is its inability to meet the Civil Aviation Authority rule Part 91 and 137 dump requirement of 80% of the load in 5 seconds (CAA, 2007).

As stated in Chapter 1 as the capacity of agricultural aircraft have increased the hopper's have become very rounded to fit the tubular fuselage and as a result the hopper half angle has reduced.

Equation (4.2) for a rectangular orifice is represented as:

$$M = K\rho g^{\frac{1}{2}} L(B - k\overline{d})^{\frac{3}{2}} \qquad (4.4)$$

An approximate dump rate can then obtained by placing the values of *K* and *k* which have already been established with the opening dimensions of an aircraft hopper.

The Cresco aircraft (described in Chapter 1) has a rectangular orifice with dimensions of L = 1.048 m and B = 0.34 m.

For these dimensions the theoretical discharge flow rate as calculated from equation (4) is:

For the modified Whiterock material with a particle size distribution between 300 microns and 425 microns the theoretical discharge rate is 413 kgs^{-1}.

For the modified Whiterock material with a particle size distribution greater than 425 microns but less than 2mm the theoretical discharge rate is 455 kgs^{-1}.

The Cresco aircraft has a $2m^3$ hopper which means that theoretically both the modified limestones would meet the CAA dump requirement.

A continuous commercial sieve is needed to produce large samples of sieved material for full scale experimentation in further field trials using agricultural aircraft for dump testing.

4.8 Concluding Remarks from Experimental Work

At this stage it is appropriate to relate the experimental work with the first three objectives of the thesis. The Specific objectives/aims of the project are:

1. Quantify the flow characteristic of products being spread and identify risks within the system, identifying risk materials and risk situations.

2. Develop a better understanding of material variability in terms of characterising the different deposits used around New Zealand and relating these differences to flow properties.
3. Develop a better understanding of the mechanisms creating the variability in flow properties that relate to production processes, transport and storage and finally loading and spreading with topdressing aircraft of the different limes used in New Zealand.

In terms of Objective 1 this research has concentrated on risks associated with unblended fertilisers or approved safe blended mixes. In some situations pilots have been asked to spread fresh mixes of superphosphate and Nitrogen products such as urea, which chemically react producing a mix which will not flow. Chemically reactive mixes are not prepared by the fertiliser manufacturing companies at their plants or stores. These blends are a known risk and the industry has taken all practical steps to eliminate the risk. On rare occasions some farmers have purchased fertilisers separately and created a mix on farm with the aim of reducing application costs, this risk can only be mitigated by farmer education and by the applicators being vigilant and examining the product that they have been asked to sow and assessing the flow properties.

Nitrogen fertilisers such as urea and Di-ammonium phosphate are extremely free flowing and of the products applied by aircraft, pose no risk, as long as the code of practice is followed in terms of transport and on farm storage. The main phosphate fertilisers sown are superphosphate, sulphur superphosphate and reactive phosphate rock. The most common of these is superphosphate which is sometimes reported as being problematic when it is sown before it has matured. There is a risk of sulphur fire in mixes containing this element, however the risk is well understood and the manufacturers eliminate the risk by mixing molten sulphur within the superphosphate manufacturing process so that fine granules are contained within the superphosphate granule (Ravensdown, 2010). Therefore, there is no free elemental sulphur to ignite. In this process the elemental sulphur is no greater than 21%, well within the safe limit set at 30% by the Ministry of Transport, Department, Civil Aviation Division (CAIC, 1986).

Crushed agricultural limestone has anecdotally been reported as the most problematic of the materials commonly sown from fixed wing aircraft. The research undertaken for this thesis supports these findings. Comparisons between freshly manufactured superphosphate, also reported as somewhat problematic to sow evenly; and the ten limes tested show that whilst these tended to be on the cohesive-easy flow boundary, the fresh superphosphate was near the easy flow – free flow boundary of the Jenike Index.

The first four chapters complete objectives 1-3. The problematic nature of the flow of the crushed limestone deposits relates to the range of particle size distributions, which varies continuously within each quarry depending on the time spent in the hammer mill and the age of the crushing hammers. The effects of moisture and mineralogy seem to make less difference to flow properties, although these effects do differ amongst deposits. The most significant difference was achieved; by either eliminating fines which will pass through a screen of 425 microns, or by reducing the range of particle sizes to within the 300 and 425 micron range; in both circumstances a free flowing lime can be produced. No further experiments were conducted to examine the sieve size below which the benefit was not achieved, but is likely to be a function of the particle size distribution within the material. The key was to reduce the particle size range; as material with the same mean diameter as the original non-sieved sample achieved free flowing conditions. This was also supported by a simple tap test which would reveal that the Hausner ratio also changed to a level where flow was predicted to be free flowing.

Removing fines from lime can be achieved quite cheaply by screening, although this is only possible if the milled lime is dry enough to prevent the screen blocking. Crushed limestone is a low value product which may limit investment in storage facilities to store separate batches of limestone for different uses; or to provide a store of product milled in dry conditions which has had the fines removed. The finer the screen the slower the process is as the screen needs to be cleaned, to clear the mesh. One Fertmark ® quarry does produce a crushed limestone for aerial application by screening fines below 2 mm from the product. A screen mesh smaller than this would slow the manufacture down considerably and increase the amount of time spent clearing the mesh (Pers. Comm, Mike Rorison, CEO, Rorison Lime).

To manufacture large quantities of crushed limestone with particle size distributions smaller than those that are practicable using screens will mean investing in more advanced technology. Centrifugal sorters and positive pressure blowers are available that will prepare a size fraction from material such as crushed limestone.

There seems little logic in a situation where the most hazardous products to spread (lime) because of their density and flow properties are not required to meet the jettison requirement of D5 of Part 91 Civil Aviation Rules. If the CAA were to decide that all products are required to meet that standard then most, if not all of the lime spread in New Zealand would have to be modified as this is the only way the jettison requirement could be met.

Objective 5 of the study was to: Identify suitable test methodologies that can be used within the industry to determine whether a product is fit for spreading and its flow characteristics. These would be dispatch tests at the lime quarry or fertiliser plant and a flow-ability test as the material is loaded onto the aircraft.

It is clearly easier to determine if a product is free flowing or not, this could be achieved by a simple cylinder test as described relating to the Beverloo equation. A cylinder with an orifice of about 50mm diameter and a quick release door opening could establish the flow properties of materials. If the cylinder delivered the required volume in a certain time, say 3 seconds with the cylinder used in the experiment reported in this thesis, then the legal CAA discharge requirement could be met for a Cresco. A standard cylinder and method would be able to be used along the supply chain from quarry despatch through to pilot.

Simple tap tests would also help confirm whether a material was free flowing. The tests undertaken showed that the Hausner ratio of the modified sample materials did indicate the material was free flowing when the original material had a Hausner ratio of 1.28 (Difficult).

Objective 6 refers to design criteria surrounding the performance of the aircraft; and is as follows:

Identify design criteria that determine the performance of aircraft in relation to safety, flow control and spreading performance. Work with the interested parties to improve work quality and safety associated with agricultural aviation systems.

Chapter 1 deals with the issues in objective 6 as far as it is possible within the scope of the research. Aircraft have become more powerful, the hoppers have become more cylindrical to maximise the volume within the tubular fuselage. This has reduced the hopper half angle. For materials which have problematic flow properties, steep smooth hopper walls are often required to ensure discharge. Hopper designs and door openings vary amongst aircraft types. In a global perspective most agricultural aircraft discharge liquids on crops grown on flat arable land. Therefore, the shape of the hopper makes little difference to the flow of liquids. New Zealand is quite unique in that most of the work undertaken by fixed wing agricultural aircraft is with bulk solids on easy to steep contoured pasture land. As New Zealand no longer manufactures agricultural aircraft and is a very small market, it is very difficult to imagine there will be any aircraft design changes to meet the market. Any design changes are likely to significantly reduce the carrying capacity of the aircraft for all materials not just the problematic ones. Any changes would have to have CAA approval and certain materials would still not be able to pass the CAA jettison requirement. Therefore, it is advocated that flow problems must be solved by modifying the bulk solid.

Spreading performance has generally been left to the judgement of the pilot. On board Differential Global Positioning Systems (DGPS), with the ability to load boundary files and with touch screen pilot interface have been installed in 25% of the aircraft operating nationally. These systems enhance a pilots ability to apply fertiliser at a desired rate as the pilot can read how many hectares has been sown at the bout width or swath width, with a known load each sowing run. The pilot must manipulate the hopper door opening if he intends to adjust the rate for speed and contour and this is done by pure guesstimate derived through experience. Unless the material is free flowing; it is extremely difficult to predict flow rate from the hopper and automated systems of door opening simply would not work. Systems which automatically adjust door opening to achieve a consistent application at varying speeds would also not work unless the material being sown was free flowing. Although a digital overlay can be produced to show the area of the farm that fertiliser was applied to, it does not show at what rate it has been applied. Validation of actual on ground application is extremely expensive and difficult in the terrain aircraft operate. The only whole farm validation work undertaken, applying 240 tonnes of Di-ammonium phosphate, on 2,180 ha, produced an in field coefficient of variation of 77% for the application rate once Kriging had been undertaken, by the author. Although, an overlay of the data from the aircraft DGPS would show that all the area which should have fertiliser applied to it, did have fertiliser applied to it.

There is obviously some benefit in applying the fertiliser at the desired application rate, which is generally established as a result of recommendations based upon soil tests with consultation with a farm advisor. Uneven distribution results in some areas gaining more than the desired rate, whilst others receive less although the total amount applied is as recommended. The law of diminishing returns applies in this situation, where those areas which receive fertiliser rates greater than that is required will benefit, but less than the proportional extra fertiliser applied.

No real work has been done to analyse the accuracy of aerial topdressing in New Zealand; however Murray (2007) did find that significant improvement in productivity could be gained by applying exactly the right amount of fertiliser to every point in the landscape. Perfect quality using “Variable Rate Application” (VRA) technology was modelled to produce a 23% improvement in productivity.

Clearly if the technology could be improved to deliver better outcomes for farmers then aerial operators may be able to improve margins. This is unlikely at the present time as sheep and beef prices are generally depressed and returns are low for this farming sector.

The aerial topdressing industry is in a position where there is over capacity, lack of profitability; and as a result an almost total lack of investment in new technologies to improve the quality of service provided. The focus for farmers and contractors has been in cost reduction.

Objective 4 deals with environmental and economic impacts of topdressing, and is as follows:

Quantify system performance in terms of economic and environmental impacts.
Chapters 5 and 6; deal with objective 4 in respect of examining economic impacts. There is also little doubt there is an environmental impact in applying fertilisers. However, in respect of agricultural aviation this is almost impossible to measure but one aspect to consider is off target application. Although it is known that between 600,000 and 1,000,000 tonnes are applied annually, the quantity varies depending upon the price of fertiliser and the sheep and beef price schedule. There is no record of how and where it is spread, except in the minority of cases a DGPS print out which shows where the hopper was open. It is spread over 8.5 million ha and mainly comprises superphosphate and lime, although some reactive phosphate rock, urea and di-ammonium phosphate are also spread.

Aircraft applying fertiliser provide a visual spectacle which can be seen from some distance, depending on the location. Small particles can clearly be seen to drift some distance and in hot conditions may even be carried upward in thermals. This is a very obvious type of off target application but is not seen as a significant environmental issue by the Regional Councils which are required to manage water quality and ensure sustainable land use.

The main agricultural fertiliser pollution problems being addressed by the Regional Councils are nitrogen and phosphate run off from intensive dairy farming. These farmers are required to have nutrient management plans and in some regions the amount of nitrogen being applied is limited. High prices for milk solids over recent years has driven farm conversions from other uses such as forestry, sheep fattening and other arable land uses. Deterioration of some catchments monitored by Regional Councils has been evident after changes in land use to dairying or dairy support, leading to increased regulation. Whereas the main issue of concern on hill country pastoral land, the land use type which requires aerial topdressing; is top soil erosion. If the fortunes of the hill farming sector were to be improved and economic circumstances warranted much more intensive farming then additional fertiliser would be required. High levels of fertiliser input on steep ground with high rainfall is bound to become a cause for concern and improved control of fertiliser application and application rate is likely to be required.

Chapter 5

An Economic Analysis of Aerial Topdressing in New Zealand

5.1 Introduction

Fixed wing agricultural aircraft apply the majority of fertiliser used on hill country sheep and beef farms in New Zealand. This type of aircraft use was pioneered in New Zealand some 60 years ago by people such as; Aussie James and Waiouru farmer Wally Harding who converted Tiger Moths for aerial topdressing. Hill country farms currently consume 40% of the conventional (NPK) fertiliser used in New Zealand. While annual demand varies with both the price of fertiliser and the profitability of this land use type; as much as one million tonnes are applied per annum by the agricultural aviation industry.

Currently 116 fixed wing aircraft of various types are engaged in agricultural topdressing operations. Unfortunately the safety record is of considerable concern. For this reason insurance has become the major non-finance related fixed cost for the aerial operator.

Traditionally farmers have negotiated a fixed price per tonne of fertiliser applied with their preferred operator. However, the cost of service provision is driven largely by variable cost. The variable costs of operating an aircraft are highly dependent on the hours flown, and hence the volume applied each financial year. It also follows that the further the aircraft has to carry its payload the greater the cost of application.

Therefore, maximising the hours flown per year will minimise fixed costs, while variable costs should reflect flying distances, turn-round times and other job variables. For the fixed pricing model to operate successfully the agreed price must exceed the marginal cost of application over the whole property, including the operator’s margin, and cover the proportion of fixed costs.

Over the past two years the cost of fertiliser has increased significantly reducing demand for both the products and aerial application services. The agricultural aviation industry has been thrown into crisis, putting further pressure on application pricing. Downward pressure on pricing further compromises the fixed pricing model assumptions as applicators marginally price to cover their operating variable costs, leaving their margins and fixed costs to chance.

There is little doubt that the New Zealand fixed wing aerial application industry is in difficulty. The New Zealand Agricultural Aviation Association (NZAAA) Conference of 2009 was themed “Industry in Crisis”. The keynote presentation and report to the Association was an industry structural analysis (structure, conduct, performance) conducted by Lockhart (Lockhart, 2009).

The report concluded that the industry is failing to achieve an adequate margin that allows for replacement of existing equipment and is, therefore, consuming the capital invested in existing plant and machinery. In short, the industry was identified as failing to meet the cost of capital. Evidence of this being included low replacement rates of aircraft (only two replacement aircraft have been introduced into New Zealand within the past three years), and price competition in the absence of technological change (Lockhart, 2009). To raise load capacity and, therefore, reduce marginal costs the industry has been re-powering existing aircraft, constructed between 1968 and 1984, with turbine engines instead of purchasing new aircraft (CAA, 2008; Lockhart, 2009). In some cases the repowering has exceeded the original airframe's design envelope.

Furthermore, the difficulty of achieving reasonable returns appears to eventually lead to operator failures. Pilot safety is being, unwittingly, compromised and puts at risk an essential service to the hill country farming sector of an agriculture dependent nation. The two major fertiliser manufacturing cooperatives identified the financial risk to their hill country shareholders and have vertically integrated their businesses by purchasing agricultural aviation companies. Services to their farmer shareholders are then assured in the short-term, providing that the cooperative members support the cross subsidisation of this service.

5.2 Method

Operating costs appear to vary from operator to operator as aircraft vary in type, age and capacity. Similar variability in cost appears to confront loading equipment. Variation in costs can also be attributed to pilot skill, their attitude towards risk, and their diligence in meeting farmers' requirements. Each aircraft generally has two or three loading trucks, which are strategically placed to allow an aircraft to operate off more than one strip due to limitations of local weather; the travel time differential between road and air; and access problems with freight cartage firms delivering fertiliser to farm airstrip bins (Grafton *et al*, 2009). The broad pattern of repair and maintenance costs would appear to be similar for other classes of machinery. With agricultural machinery such as tractors for example, a number of large surveys have been completed and repair and maintenance functions derived with some confidence when a large sample size is used, Yule (1995) described a number of these models. The most commonly used one is the ASABE Standard D230.2. Due to the lower numbers of machines involved with aerial topdressing it is not feasible to derive robust functions through this approach. With aircraft the scheduled maintenance procedures are well prescribed and to some extent these are reasonably predictable. However, repair work, as opposed to maintenance, prior to an inspection cannot be predicted.

The two most popular agricultural aircraft used in New Zealand are the Pacific Aerospace Corporation "PAC" Cresco and Fletcher aircraft. These are both single engine monoplanes with a tricycle undercarriage and similar silhouette, the Cresco replaced the Fletcher and is a larger turbine variant of the Fletcher design, as illustrated in Figures 5.1a and 5.1b.

Figure 5.1a: Fletcher FU 24 spreading superphosphate on North Island Hill country (from Wanganui Aero Work (2004) Ltd website).

Figure 5.1b: Cresco 08-600 spreading superphosphate on North Island hill country (from Wanganui Aero Work (2004) Ltd website).

There is a constant trade off between investing capital in new equipment and the cost of maintaining depreciating plant and machinery equipment. This trade-off also applies to agricultural aviation. Those operators with older plant and equipment substitute the cost of capital employed with higher maintenance costs and reduced utility through more frequent breakdowns. These costs can be accumulated very differently by agricultural aviators depending on machinery, its age, and their propensity to invest. For example, the cost of engine maintenance between the PAC Cresco 08-600 powered by a 559 kW (750 hp) Pratt and Whitney PT6-34Ag turbine engine; and the PAC Fletcher FU 24 powered by a 298 kW (400 hp) Lycoming IO 720 reciprocating engine are reported in Table 5.1. Many FU 24 aircraft have been repowered by turbine engines, but for this example the engines fitted at the time of airframe manufacture are compared. The Cresco can be operated with a superphosphate payload of approximately 2 tonnes, whereas the Fletcher is operated with a payload of about 1.2 tonnes.

The financial model is based on the following assumptions:

- The aircraft operate for 600 hours per year at 50 hours per month
- The Cresco sows 20 tonnes of fertiliser per operating hour
- The Fletcher sows 12 tonnes of fertiliser per operating hour
- The Cresco is serviced by two new loader trucks
- The Fletcher is serviced with two, thirty year old trucks
- The value of a Cresco is $1,300,000
- The value of the Cresco’s loader trucks are $250,000 each
- The value of the Fletcher is $130,000
- The value of the Fletcher IO 720 hire engine is $120,000
- The value of the Fletcher loader trucks are $40,000 each

Engine Maintenance

The cost of purchasing a new PT6-34Ag engine, running it for 5,000 hours and trading the engine at this time with the manufacturer using the "Agricultural Enhancement" scheme Pratt and Whitney offers, is compared with the cost of a power by hour engine hire option with an IO 720, an option frequently used by FU 24 owner operators. All operators have a variety of Civil Aviation Authority approved maintenance regimes and sometimes choose to undertake the cost of extra inspections and maintenance to extend their turbine engine hours beyond 5,000 hours; and, accept a reduced engine trade amount as a result; or to own, operate and overhaul their own IO 720 engines or repowered turbine replacements. Other well defined costs are added to identify the engine operating costs of both aircraft (Table 5.1). Taking account of the model's operating capacity (600 hours per annum), these costs can be identified as $4.65 per tonne for the Cresco and $5.90 for the Fletcher.

Table 5.1: Example of engine operating cost comparisons between Cresco and a Fletcher for 50 hours per month (NZ$).

P&W PT6-34Ag	**Hour**	**Lycoming IO 720**	**Month**	**Hour**
Engine replacement *	57	Monthly hire	140	
Hot section inspections	10	Power by hour		65
Eng. gearbox, shrouds liners	21			
P&W outwork				
100 hour check engine labour	5	100 hour check oil		3
Hourly engine operating costs	**93.00**			**70.80**
Engine operating costs per tonne applied	**4.65**			**5.90**

*Note: Assumes a US$304,000 engine traded for US$103,000 at 5,000 hours at NZ$ = US70c.

Airframe Maintenance

The other maintenance and outwork expenses vary considerably from year to year for each aircraft. Maintenance intervals may also vary depending on the operator's CAA approved maintenance programme. However, items such as wings and propellers have a compulsory overhaul life. There are also required maintenance inspections and defect rectification. Maintenance costs can also vary because of the age of the aircraft: older aircraft tend to have more defects and the way the aircraft is flown, landed and the conditions it is operated in, also have an effect. Indicative maintenance costs are presented in Table 5.2. Fleet operators with their own maintenance facilities ought to be able to reduce labour costs.

Table 5.2: Cresco and Fletcher airframe maintenance cost comparison (NZ$).

	Cresco		Fletcher	
Maintenance Item	Monthly	Hourly	Monthly	Hourly
Airframe & lifed wing	860	15	1,400	
Labour 100 hour checks		40		40
Outwork defects		30		45
Propeller	42	3	42	3
Annual cost of Operating 50 hours per month	63,624		70,104	
Airframe Maintenance cost per tonne applied		5.30		9.74

Insurance

Differences in operator approach to insurance have also been found from an annual aggregate deductible to full cover fixed excess. Operators face industry risk as well as shared risk by aircraft type and operator experience. The actual cost of insurance can vary as operators can trade premium off against cover through mechanisms of excess and annual aggregate deductibles. However, premium is invariably expressed as a percentage of aircraft hull value. The actual cost of the insurance must include the uncovered deductibles within the policy. Assuming the industry claims costs reflect the 12 accidents per 100,000 flying hours (Lewis et al, 2008). There are up to 50,000 flying hours flown per year, which equates to six accidents. Assuming that each of these accidents costs 75% of the hull value, which from aircraft operators' experience is a reasonable deduction; and, add to these the minor incidents that are not claimable and the insurer's margin (8%) of an aircraft's hull value then the industry's average insurance cost is predictable (refer to Table 5.3).

Table 5.3: Insurance cost comparisons Cresco and Fletcher (NZ$).

Insurance Costs	Cresco	Fletcher
Hull Value	1,300,000	250,000
Insurance 8%	104,000	20,000
Insurance cost per hour at 600 hours per annum	173	33
Cost per tonne applied	8.66	2.78

Note: Fletcher insurance covers hire engine. The engine owner has first call on the insurance payout at an agreed value.

Fuel

The Cresco and Fletcher in this comparison run on different fuels. The turbine Cresco engine runs on a kerosene mix Jet-A1 and the Fletcher on 100-130 octane Avgas. Fuel prices differ from region to region as cost of delivery varies and larger fleet operators typically receive a volume and/or prompt payment discount. Fuel costs for a Cresco and Fletcher, based on those from a lower North Island provincial centre (Shell Oil, 2009) are provided in Table 5.4.

Table 5.4: Fuel cost comparisons Cresco and Fletcher (NZ$).

Fuel costs	Cresco	Fletcher
Avgas pump price per litre		1.65
Jet-A1 pump price per litre	1.26	
Litre Burn per hour including 16% ferry to - fro jobs	240	120
Cost per productive hour	302	198
Cost per tonne applied	15.12	16.50

Loading Equipment

The last of the direct operating expenses examined are wages and vehicle costs. It is assumed that both aircraft operate with two loading trucks, have one pilot and one loader driver for this analysis.

For this example it is assumed that the Cresco is operating with two near new loader trucks with a value of $250,000 each and the Fletcher with two thirty year old trucks with a value of $40,000 each. The cost of loading equipment for a truck is around $130,000 and although the thirty year old trucks would have little residual value the loading equipment does at the replacement cost. Loading trucks do not travel a high mileage but do spend much of their working life in acidic superphosphate dust. The cost of operating the older trucks will be higher, as much as $25,000 per annum per truck to keep road worthy (pers. Comm. R.M. Harding, Operations Manager, Wanganui Aero Work (2004) Ltd.), than the new ones, although non-cash depreciation on the new trucks will be greater.

The loader driver's wage is assumed to be the same for both scenarios. The pilot's remuneration does differ, depending on aircraft flown, which is the case in reality. The fleet operators and some individual aircraft owned by groups of farmer co-operatives invariably pay pilots either a percentage of total sales or on a per tonne basis. Owner operators naturally take the residual and variable income from operations. For this case scenario we assume the remuneration for a Cresco pilot is $88,000 per annum and for a Fletcher pilot $55,000. These pay rates are indicative of the industry for the tonnages sown. The operating costs for vehicles and staff remuneration are shown in Table 5.5.

Table 5.5: Direct costs for salaries and support vehicles Cresco and Fletcher (NZ$)

	Cresco		**Fletcher**	
	Month	**tonne**	**Month**	**tonne**
Fuel vehicles & road user	767	0.77	767	1.28
Maintenance vehicles	800	0.80	4,000	6.66
Insurance	167	.17	100	.17
Pilot pay	7,333	7.33	4,583	7.64
Loader driver pay	3,750	3.75	3,750	6.25
ACC	460	.46	346	.58
Total per monthly tonnage	13,277	13.28	13,546	21.58

Miscellaneous Fixed Costs

At this stage of the financial model direct operating costs which are required to be met for marginal cost pricing are known. Some items such as vehicle insurance and ACC may be arguably included as overhead, they are included here as they may not be avoided and to link vehicle and wage related costs in one table.

The hours flown and tonnages sown are less than optimal but reflect the current state of the industry with less fertiliser being sown, generally by applying a reduced application rate over the same area as previously, rather than the same rate over a reduced area. This increases the cost per tonne applied. The marginal cost per tonne of superphosphate applied by Cresco and Fletcher aircraft by including all of the cost elements above is $46.51 per tonne for the Cresco and $56.51 for the Fletcher.

Any price achieved in excess of the marginal cost contributes to the overhead; although the breakeven turnover is achieved a loss is inevitable.

To enable marginal price analysis the marginal operating cost for 600 hours was divided into a variable and fixed component, by separating the monthly fixed maintenance, the insurance cost and driver’s pay as the fixed cost component. The fixed cost contribution is $13.50 per tonne for the Cresco and $11.83 for the Fletcher.

Overhead costs

The next step is to produce a hypothetical budget for the overhead costs based upon realistic assumptions, see Table 5.6. The cost to the business is $27.78 per allocated hour. In the case of the Cresco this works out to an estimated cost of $1.30 per tonne applied and $2.32 for the Fletcher.

Table 5.6: Typical Overhead costs assuming 600 hours of annual use per plane. (NZ$)

Overhead	**month**	**hour**
Telephone	125	2.50
Rent-Landings	200	4.00
Licenses Permits CAA	180	3.60
Subscriptions	30	0.60
Utilities	120	2.40
Stationery	24	0.48
Advertising/ marketing	30	0.60
Professional Fees	300	6.00
Building repairs	100	2.00
Accommodation/ travel	100	2.00
General/Other	180	3.60
Total:	**1,389**	**27.78**

Combining these costs allows us to present the operating costs before depreciation, interest and return on assets employed, see Table 5.7.

Table 5.7: Marginal cost before cost of ownership at 600 hours per annum. (NZ$)

	Cresco			**Fletcher**		
	month	**hour**	**tonne**	**month**	**hour**	**tonne**
Marginal operating cost	47,900	958	47.90	35,298	706	58.83
Including Overhead						
Fixed component	14,890	298	14.89	8,490	170	14.15
Variable component	33,010	660	33.01	26,808	536	44.68

Agricultural aircraft operators in New Zealand have a wide range of financial arrangements and debt service requirements. The cost (or benefit) of ownership is examined as a percentage return on total assets employed. Because aerial topdressing is a very risky business - nearly two percent of pilots engaged in the activity die each year - financial returns should reflect that risk. High physical risk of the equipment being damaged or written off also increases costs. There is also considerable financial risk in respect of high fixed costs which can only be recovered from operating machinery with extremely high variable operating costs. However as the industry is in crisis for this exercise a minimum return of total assets of fifteen percent is sought (Lockhart, 2009) whereas 20-25% would be a more realistic expectation.

Depreciation

Although depreciation is a non taxable expense, aircraft and trucks must be replaced. Non-cash depreciation expenses should be retained for asset replacement (Lockhart, 2009). The depreciation rates for agricultural aircraft and the loading equipment are the same 12.5% straight line, (SL) or 18% diminishing value, (DV) (IRD, 2007). To minimise costs the straight line depreciation option is used in this analysis (see Table 5.8). In reality due to New Zealand Generally Accepted Accounting Practices, “NZGAAP”, the maintenance costs for time life components, should be depreciated over their life as per Tables 5.1 and 5.2 and, therefore, in this model comprise some of the depreciation, these are deducted from the depreciation totals (NZIAS 16, 2005).

Table 5.8: Cost of ownership Cresco and Fletcher comparison for 600 hours per annum (NZ$)

Aircraft	*Assets Employed*	*Required Return Per annum*	*month*	*hour*	**tonne**
Cresco	1,800,000	270,000	22,500	450	22.50
Fletcher*	210,000	31,500	2,625	53	4.38
	Assets Employed	**Depreciation**	**month**	**hour**	**tonne**
Cresco	1,800,000	225,000	18,750		
Less provided maintenance Table 2			(902)		
Less maintenance provided Table 1			(2,850)[++]	(57)	
Total Depreciation			14,998	300	14.99
Fletcher	210,000	26,250	2,188		
Less maintenance provided Table 2			(1,540)		
Total Depreciation			648	12.96	1.08

***Fletcher has a hire engine so aircraft value $130,000, which is less than the insurance value**

[++] This is not a monthly charge but is based on the hourly rate and is included to balance.

The total cost of operating the aircraft in this analysis are now known and these are tabled and separated in to fixed and variable components for analysis, in Table 5.9.

Table 5.9: The cost of operating a Cresco and Fletcher at 600 hours per annum in fixed and variable components (NZ$)

	Cresco			**Fletcher**		
	month	**hour**	**tonne**	**month**	**hour**	**tonne**
Total operating cost including overhead	85,398	1,708	85.40	38,571	771	64.29
Fixed component	52,388	1,048	52.39	11,763	235	19.61
Variable component	33,010	660	33.01	26,808	536	44.68

The breakeven cost of operating a Cresco for 600 hours per annum sowing 12,000 tonnes of superphosphate is $85.40 a tonne, whilst for the Fletcher with a lease engine, sowing 7,200 tonnes over 600 hours is $64.29 per tonne, as summarised in Table 5.10.

Table 5.10: Operating cost per tonne applied of Cresco and Fletcher aircraft.

	Aircraft Type	
Expense Item	Cresco	Fletcher
Engine operating	4.15	5.91
Airframe maintenance	5.30	9.74
Insurance	8.66	2.78
Fuel	15.12	16.50
Salaries and support vehicles	13.28	21.58
Overhead	1.30	2.32
Ownership (including depreciation)	14.99	1.08
Return on capital at 15%	22.50	4.38
Total operating and fixed cost per tonne	85.40	64.29

The fixed operating cost for a Cresco is $52,388 per month and variable component of $660 per hour, whilst the Fletcher's has a fixed operating cost of $11,763 per month and variable cost of $536 per hour.

Sensitivity Analysis

Sensitivity analysis was undertaken to establish the breakeven number of productive flying hours required to breakeven financially over a range of pricing regimes, as per Table 5.11.

Table 5.11: Sensitivity price analysis for breakeven hours. (NZ$)

	Cresco			**Fletcher**		
$/ tonne	**Monthly hours**	**Annual hours**	**Revenue required per annum ($)**	**Monthly hours**	**Annual hours**	**Revenue required per annum ($)**
60	97	1,164	1,396,800	64	768	552,960
65	82	982	1,276,600	50	600	468,000
70	71	850	1,190,000	39	465	390,242
75	62	744	1,116,000	32	388	349,165
80	56	672	1,075,200	28	333	319,719
85	50	600	1,020,000	24	292	297,576

The variance analysis demonstrates that the best returns are obtained by applying fertiliser with obsolete equipment. The Cresco example requires $85 per tonne to breakeven over 600 hours whereas the Fletcher only $65 per tonne.

5.3 Results

At present typical application charges per tonne of superphosphate are between $60 and $70 per tonne, although some predatory pricing as low as $45 per tonne has been reported. These charges appear to have risen quite dramatically to the farmer over the past three years, when in 2006 typical industry rates were between $45 and $60 per tonne. However, as the price of fertiliser has doubled the amount applied per hectare has typically dropped from 250 kg/ha to 160kg/ha. The price of superphosphate fertiliser which is the main input by aerial application, has fluctuated greatly moving from a little over $220 per tonne in 2007, to a peak of $510 per tonne in July 2008; and is $311 per tonne in early 2010 (Ravensdown, 2010).

The application rate is calculated from the Ministry of Agriculture and Forestry, sheep and beef farm expenditure models, for this example the lower North Island figures are selected (MAF, 2009). The tonnage cost is calculated by adding the spreading charge per tonne ($70/t) to the fertiliser cost and calculating the application rate per ha. The flying time to apply at lower application rates increases; thus increasing the cost of application. The increased application charge per tonne is not an increase in revenue to the aircraft operator, it merely appears to be so as the method of charging for the hours flown is per tonne applied.

The cost of application using a Cresco flying at its breakeven charge out rate of $1,700 per flying hour, at various rates based on the distance the load needs to be carried from an airstrip is shown in Table 5.12. Note there is a urea example as this is sown at lower application rates and due to its low bulk density a smaller load by mass is carried as the Cresco 08-600 has a $2m^3$ hopper. This information is used to express spreading cost per tonne as a function of the distance from the airstrip as shown in Figure 5.2. Sowing swath widths are 20m for superphosphate and 24m for urea, typical “spreadmark” certified swath widths (NZ Fertiliser Quality Council, 2009).

Figure 5.2 demonstrates the affect of the lower bulk density of the Urea fertiliser in increasing application costs, the effect of reducing application rates is also demonstrated. This occurs because aircraft have to spend longer in the air to deliver the tonnage required. At current application charges; the breakeven delivery distance for superphosphate is within 4 km of the airstrip, at 160kg/ha at $70/ tonne.

Table 5.12: Application cost variance analysis with rate and distance from an airstrip for Cresco, 600 hours per annum.

Application Rate super 2,000 kg load	Sowing time (min)	Turning time (min)	Ferry distance (km)	Ferry time and return (min)	Turn around time (min) (2)	Cost per trip at $1,700 per hour flying time	Cost of flying Empty ($)	% Empty
250	1.2	.67	10	6.0	8.87	223	170	76
250	1.2	.67	5	3.0	5.87	138	85	62
250	1.2	.67	2	1.2	4.07	87	34	39
160	1.9	.67	10	6.0	9.55	242	170	70
160	1.9	.67	5	3.0	6.55	157	85	54
160	1.9	.67	2	1.2	4.75	123	34	41
Sowing rate urea 1,400 kg load (3)								
60	2.92	1.34	10	6.0	11.26	291	170	58
60	2.92	1.34	5	3.0	8.26	206	85	41
60	2.92	1.34	2	1.2	6.46	155	34	22

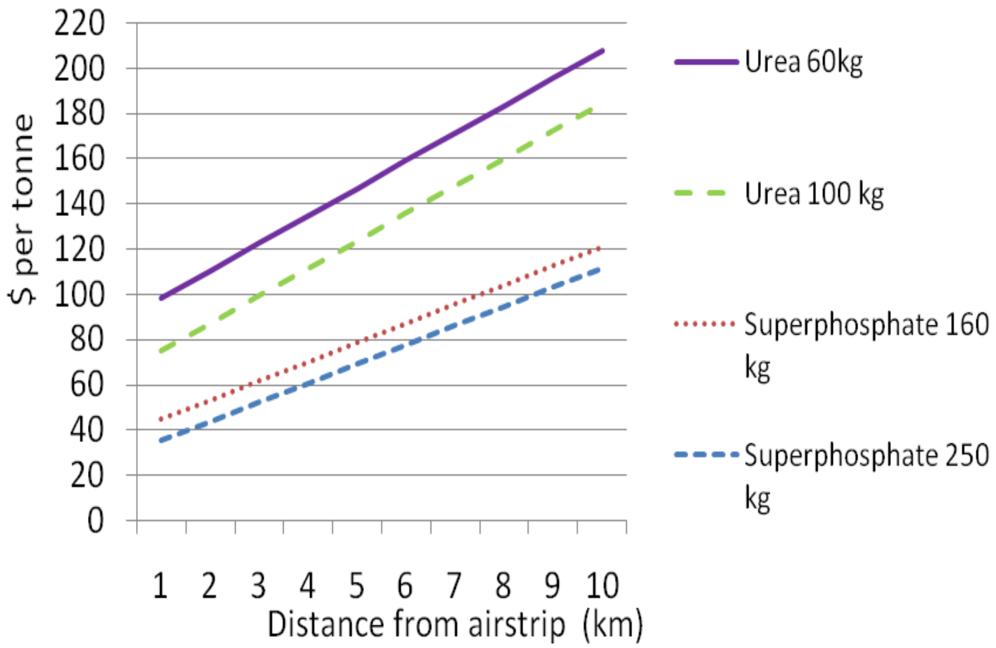


Figure 5.2: Fertiliser Application cost against distance from airstrip

Therefore, the breakeven turnover can be met by sowing a high percentage of the superphosphate within 4 km of the airstrip, thus increasing the number of tonnes sown by hour. The quality of the job must be compromised and suggests that an even distribution over the entire property will not be attained. The fact that every load of fertiliser carried over 4 km will result in a net loss, must be a behaviour driver for the operator. The variable cost driver for superphosphate; being $8.5 per kilometre from the airstrip and over $12 for urea, which means that the average charge is heavily loaded towards application within proximity of the airstrip.

This behaviour over time must lead to a transfer of fertility as areas close to the airstrip receive luxury application of fertiliser whilst those furthest away receive less than that which has been contracted to be sown. In time this may lead to farm decisions being made erroneously due to incorrect assumptions of farm area fertiliser history.

Figure 5.3 shows the cost of spreading a property when the average cost within the boundary is illustrated, this is perhaps more useful for the operator costing jobs. Again it is based on the assumption of a perfectly circular farm property; the same basic trends exist as in Figure 5.2.

Where the property does not require all areas to be sown, for example areas of bush; this has the effect of reducing the average application rate, which again increases the cost per tonne spread.

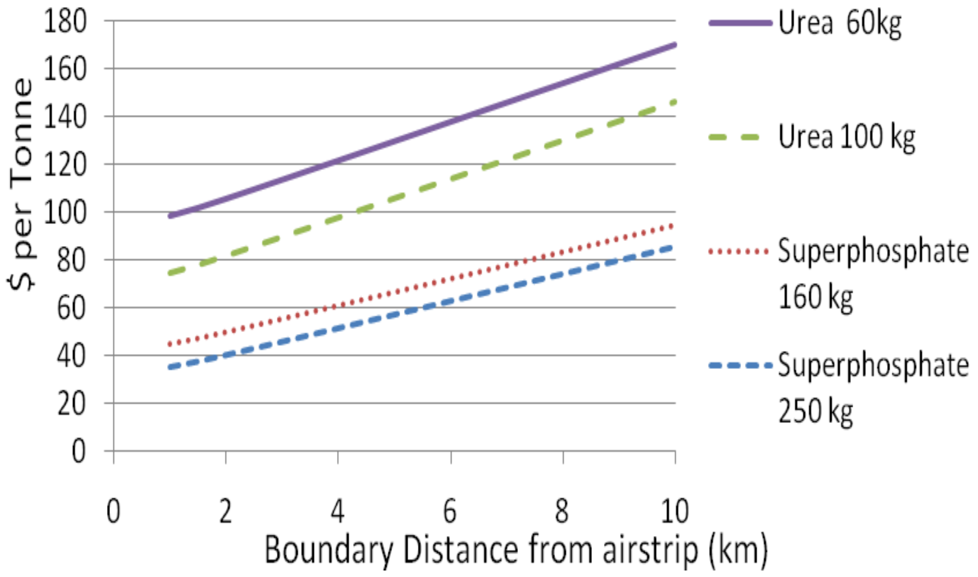


Figure 5.3: Average fertiliser application cost against boundary distance from airstrip

5.4 Discussion

The Cresco's greater capacity gives this aircraft an advantage over the Fletcher, up until the full costs of ownership are considered. Although the Cresco remains competitive after depreciation is recovered it cannot provide an adequate return on investment at current charge-out rates. The Fletcher appears to have a financial advantage because it is fully depreciated. This scenario, namely, a thirty year old aircraft with a hire engine, being loaded by thirty year old trucks, is a common practice in New Zealand. Regrettably it is not sustainable. Aircraft are subject to certificate of airworthiness checks as are trucks to certificate of fitness checks. Many of these machines have already been re-engined, re-skinned and re-sparred. Their remaining working life-spans are increasingly limited.

Although aircraft overhauls have been budgeted in this paper, these costs occur at periodic intervals. For example, a Cresco wing has a life of 16,000 hours and a Fletcher wing is overhauled after eight years. Operators are compelled to overhaul their aircraft and since 1997 some have chosen to re-power their Fletcher aircraft with turbine conversions, these aircraft are much cheaper to obtain than new aircraft, a turbine conversion and overhaul "re-skinning" is about $500,000 whereas a new turbine aircraft is about $1,400,000 (Lewis *et al*, 2008). However, the accident rate of these aircraft has been higher than aircraft which have not been turbine converted or new turbine aircraft. A number of concerns from the industry were reported by the CAA (Lewis *et al*, 2008), regarding the practice of re-powering dated aircraft with more powerful engines.

It is clear as there is no return for investment in the industry there is a reluctance to invest capital (Lockhart, 2009). The Fletcher turbine conversion is a compromise in capital to reduce the ownership costs of a new turbine aircraft, and to reduce the variable operating cost of the Fletcher prior to conversion. This compromise is, however, not only motivated by financial considerations but is also compromising safety in an already high risk industry.

Similarly, loading equipment is being removed from unserviceable trucks and is being installed on more modern replacements, in preference to purchasing new loading equipment. The rationale behind this is that the truck becomes obsolete before the loading equipment. However, some of this equipment is over thirty years old and although the pilot is protected by a safety bar on the loading equipment it is not reasonable to expect this equipment to remain serviceable indefinitely.

5.5 Conclusions

The purpose of this chapter is to provide a model to help explain the financial constraints of operating fixed wing agricultural aircraft in New Zealand, which is perceived as being in crisis by those engaged in it.

A macro-economic industry overview has been undertaken by Lockhart (2009), which explains why the industry is lacking investment and why the investment that has occurred has been via vertical integration from the major fertiliser manufacturing and distribution companies.

It also explains why the independent farmer - agricultural aircraft co-operatives; that are not fertiliser manufacturers, which supply a large customer base per aircraft can survive in the short-medium term as they can guarantee a large number of flying hours that consequently reduces the fixed costs per flying hour. It should also be considered that if the operation provides a deficit the owners have to supply capital. There is also the consideration of quality, co-operative’s generally operate so that the customer, who is also the owner must have his fertiliser sown when it suits the applicator not the customer to maximise efficiency.

The modelling undertaken in this chapter supports the conclusions reached in the Lockhart report (Lockhart, 2009). The lack of investment and new entrants is entirely due to the lack of profits which provide no returns on investment, on an industry level. Although, as Lockhart points out that this does not preclude those operating in a profitable niche sector from making a commercial return (Lockhart, 2009).

This chapter illustrates a further difficulty for the industry that it is often servicing clients with large farms, this becomes less efficient due to the distance fertiliser has to be ferried by aircraft before it is spread. In a competitive market the pressure is to discount these larger clients but in reality they are more expensive to service, assuming adequate airstrips are provided, due to the increased flying distances involved. Farmers are also requesting reduced application rates which mean that the application cost per tonne is increased as the aircraft have to travel further in order to spread the same tonnage.

This chapter does not consider the on-farm cost of providing an airstrip, roads to the airstrip and on-farm storage facilities; these are further costs which must be borne by the farmer.

Chapter 6

A Cost Analysis of New Zealand's On-Farm Agricultural Aviation Infrastructure

6.1 Background

New Zealand's hill country sheep and beef farming systems are largely based on animal production from ryegrass and clover swards. Easier topography exhibits higher concentrations of both while harder hill country swards are dominated by poorer species. New Zealand's temperate climate allows year round outside grazing. In the most severe environments, such as that created by altitude, animals are typically grazed on lower and better soils during winter and early spring. Especially through lambing and calving in the South Island, and to a lesser extent the North Island's central plateau.

Sheep and beef farming systems comprise 8.6M ha out of 15.6M ha farmed in New Zealand (MAF, 2009a). There are about 12,200 farms in this sector with an average farm size of 705 ha (MAF, 2009b) which excludes non-commercial lifestyle properties. The sheep and beef sector contributes NZ$2.6 billion in beef production of which 83% is exported and some NZ$2.2 billion in sheep meat exports of which 90% is exported. A further NZ$440 million is earned through wool exports. This sector contributes 22.5% of New Zealand's agricultural output (MAF, 2009a). Farm gate income from this sector is some NZ$3.9 billion which includes some support for the more lucrative dairy industry, from over wintering dry cows and heifers to the purchase of surplus progeny – both bulls and heifers (MAF, 2009b).

Prior to the introduction of commercial fixed wing agricultural aviation in 1950 application of fertiliser and crushed agricultural limestone was by hand, and often from horse back. At present about half of the one million tonnes of fertiliser and half million tonnes of crushed limestone applied on sheep and beef farms is applied by aircraft, generally on the land that is not accessible to fertiliser spreading trucks (MAF, 2009b). It is applied from aircraft operating from 3,670 airstrips throughout the country. This equates to one airstrip per 3.5 farms or some 2,360 ha is being serviced by each strip.

6.2 Introduction

Low returns for spreading and a reduced demand for fertiliser in the sheep and beef sector in recent years has meant that many agricultural aviation companies are operating at a loss.

In addition to operators eroding the capital value of their equipment (planes and loading-trucks) the on-farm facilities required for aerial topdressing are also being consumed. There has been a lack of capital investment in infrastructure for the aerial topdressing for some decades. If aerial topdressing is to have a future then significant re-investment is required. Aircraft operating costs presents one side of the equation (that of fixed-wing agricultural aviation in New Zealand), the other side is on-farm facilities including access roads, bulk bins, and airstrips.

Due to the operating cost structure of aerial application, it is not an option to simply have fewer airstrips. As demonstrated in the previous chapter, costs escalate – markedly - as distance from the airstrip to spreading site increases. This outcome, by sheer virtue of the technology being employed, has also led to criticism of aerial topdressers.

Grafton *et al*, (2009) identified many of the difficulties and limitations with existing on-farm facilities. The first generation of airstrips were built for underpowered aircraft where taking off, downhill, from an elevated location was desirable. Early site locations often created additional problems as access roads became impassable for trucking in and loading fertiliser, particularly in wet conditions. Storage facilities were often primitive, or non existent and lack of capital investment and maintenance mean that many are now in a very poor state of repair.

If aerial topdressing is to have a future in New Zealand then an economically viable system must be developed to deliver fertiliser and lime to the hill country. This chapter attempts to identify the level of on-farm investment required to achieve this and assesses the true cost of delivering fertiliser to hill country properties.

6.3 Method

The operating cost of two typical aircraft types under New Zealand conditions has been described in detail in Chapter 5. Table 5.10 summarises those costs and calculates a cost per tonne spread. The costs are based on spreading superphosphate and urea and are based on an assumed annual workload of 600 hours.

Assumptions around work load used to calculate these costs are drawn from New Zealand's Civil Aviation Authority (CAA) report (Lewis *et al*, 2008). The total hours flown annually typically varies between a low of some 30,000 hours to a peak of 55,000 hours flown by all types of aircraft. However, in 1994 when sheep prices were extremely low only 15,000 hours were flown nationally. The variation in hours flown mostly relates to changes in demand for fertiliser by this farming sector which is, in turn, influenced significantly by price relative to farm returns. Since January 2007 the price of superphosphate has fluctuated from $220 per tonne, through to a peak of $510 per tonne in July 2008 (Ravensdown, 2010) and is currently $312 per tonne in January 2010.

When superphosphate prices are high, the least productive hill country tends to be the first to have fertiliser application reduced or withdrawn. Sheep and beef farmers tend to reduce the application rate to meet their budgets, and are more inclined to maintain application rates on their flatter more productive areas, as one would expect from the law of diminishing returns.

The CAA statistics (Lewis *et al*, 2009) show that in 2006, a relatively poor year when only 37,000 hours were flown, 11,000hrs were by Crescos, of which there are 22 in New Zealand (500hrs/ aircraft /year) and 23,000hrs by Fletcher's, of which there are 70 (328hrs/ aircraft/ year). However some of the latter aircraft have been decommissioned or are currently in a state of restoration. The remaining 3,000hrs were flown by all other aircraft types. Six hundred hours, therefore, represents a fair assumption of industry practice. The effect of the variation in the number of hours flown per year, on total operating costs per hour is presented in Figure 6.1.

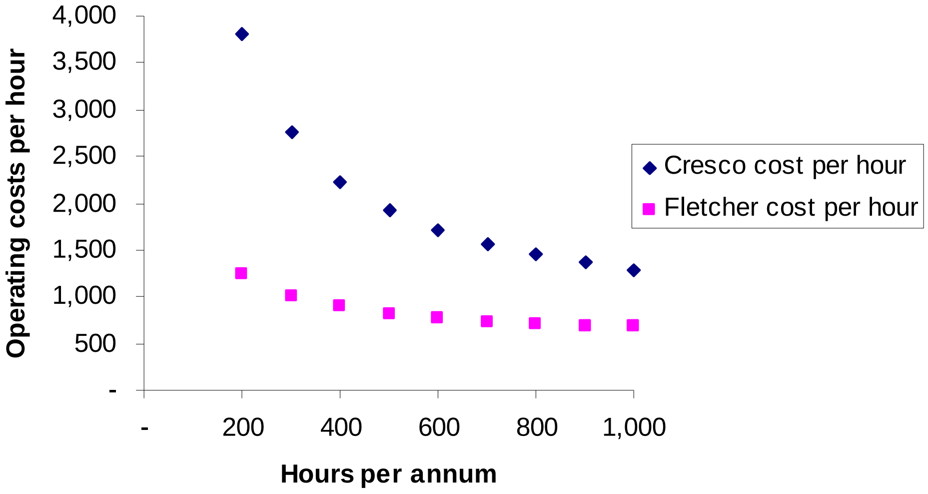


Figure 6.1: Aircraft operating costs per hour against utilisation per annum

Weather permitting the New Zealand agricultural aviation industry has the capacity of applying close to a million tonnes of fertiliser and lime annually. However, because the industry is immediately affected by changes in the price of fertiliser it operates at the margins of farmers' diminishing returns in spite of its necessity.

6.4 Fleet capacity

In most areas of New Zealand an agricultural aircraft can, weather permitting, operate for a thousand hours per annum. Hence at current operating hours aircraft are under utilised and operating costs per tonne applied are greater than the revenue obtainable (Grafton et al, 2010). The problem is not uncommon, and is to a large extent *the* classic mechanisation problem. Namely, at what capacity to run machinery to cover the work required at least cost. The difference here is that demand for machinery (aircraft flying hours) is set by farmers not the operators themselves, unless they choose to compete on price.

A number of factors have an effect on the actual capacity achieved by each operator. These are, to a large extent, organisational considerations around ensuring the aircraft is loaded effectively when on a job; ensuring that sound logistical practices between jobs (making sure that all equipment, staff, and materials required are in place); and, operating in appropriate weather conditions at the site (which may be some distance form the home base location).

Wind conditions are a major factor in agricultural aviation in New Zealand. Winds over four metres per second may prevent accurate aerial topdressing. However, ground conditions, both to deliver material to the airstrip and ensure that the airstrip is in a condition to receive many take-offs and landings in one day; need to be considered. Damage to the airstrip can create problems at a later date if the airstrip is left in even a mildly rutted condition – to say nothing about that from livestock, especially heavy cattle.

Since 2008 many hill country farmers appear to have cut back on their application rates. This means that the application cost per tonne must be increased because the flying distance required per tonne is increased. The effect of distance from the airstrip has been identified (see Figure 5.3). Operators flying off larger properties often have distances of up to 10 km to cover. Although large farmers may expect discounted prices because of bulk purchases it is actually more expensive for the aerial operator to service these properties. Providing of course the marginal cost of flying the greater distances involved is more than the cost of relocating plant and machinery to the next site.

A recent practice, particularly in the South Waikato and King Country is for farmers, agricultural aviation companies and fertiliser companies to co-invest in consolidated all weather facilities. However, the additional costs of operating aircraft over extended distances from these strips appear to be ignored.

6.5 Farm infrastructure issues

The location of all New Zealand airstrips is shown in Figure 6.2. The North Island strips are shown in more detail in Figure 6.3, as there are more than twice the number of airstrips here, than the South Island. The coverage obtained within a seven kilometre radius from each of these strips is depicted in Figure 6.4 (flying 7km from each strip would cover 15,394ha). The large number of airstrips provides good coverage and ensures that aircraft are not required to carry their payload any great distance, which would increase the cost of application. Note that this concentration of airstrips has been achieved over the last 50 odd years entirely intuitively by the farming community. However, this outcome is suspected to be more a function of the low investment required in first generation strips; farmers' desire for independence; and now dated capacity requirements than consideration of optimal sites at an aggregate level.

In New Zealand there is currently one strip for every 2,358ha of hill country pasture (say one strip for every three farms). Therefore, a circular coverage of some 2.7km from each airstrip is required to cover the land being farmed.

The cost involved in bringing airstrip facilities up to the standard largely depends on their location in respect of public roads; the facilities that are currently present; and, the amount of fertiliser applied from the airstrip. The approximate cost of producing an all weather shell-rock road with drainage is about $10,000 per kilometre; the cost of a covered weatherproof 200 tonne bin is around $70,000; while an all weather airstrip costs around $90,000. Although the requirement for an all weather strip is not essential in the guide (cost indication through Pers. Comm. Mike Manning, General Manager Key Clients and R &D, Ravensdown Fertiliser Co-op Ltd, 2009).

If it is assumed that 90% of airstrips don't meet either the; "*Safety Guideline Farm Airstrips and Associated Fertiliser Cartage, Storage & Application*" standards in the guide, or have a fertiliser bin of an adequate size, the level of investment required to meet the standard is considerable. If all airstrips were to have adequate storage facilities, then the need for all weather access tracks is reduced, providing that the aircraft loader can access or has accessed the airstrip. Either way there is some $231 million to be immediately spent on farm infrastructure.

In a poor (low demand) year some 205 tonnes are flown off each strip while in a good year some 400 tonnes will be flown off each strip. The actual infrastructure costs would then need to be spread over applications of 300t per annum. The cost of maintenance is reflected by depreciation rates (likely to be underestimated), which are 4% for buildings of this type, and higher for tracks and strip surfaces. The actual costs, in terms of tonneage applied, return on investment and, therefore, cost per tonne applied are presented in Table 6.1. Comparisons are provided between an all weather strip and its ongoing maintenance with that of a new bin purchase on an existing strip.

Table 6.1: Required strip hire charges for implementing the New Zealand Farm Airstrip Guide.

Airstrip Type / Cost	**Maintenance / Depreciation ($)**	**Tonnes Applied from Strip**	**Return On Investment At cost of credit 9% ($)**	**Strip hire charge ($$T^{-1}$)**
All Weather $200,000	8,000	500	18,000	52
Bin Purchase $70,000	2,800	300	6,300	30

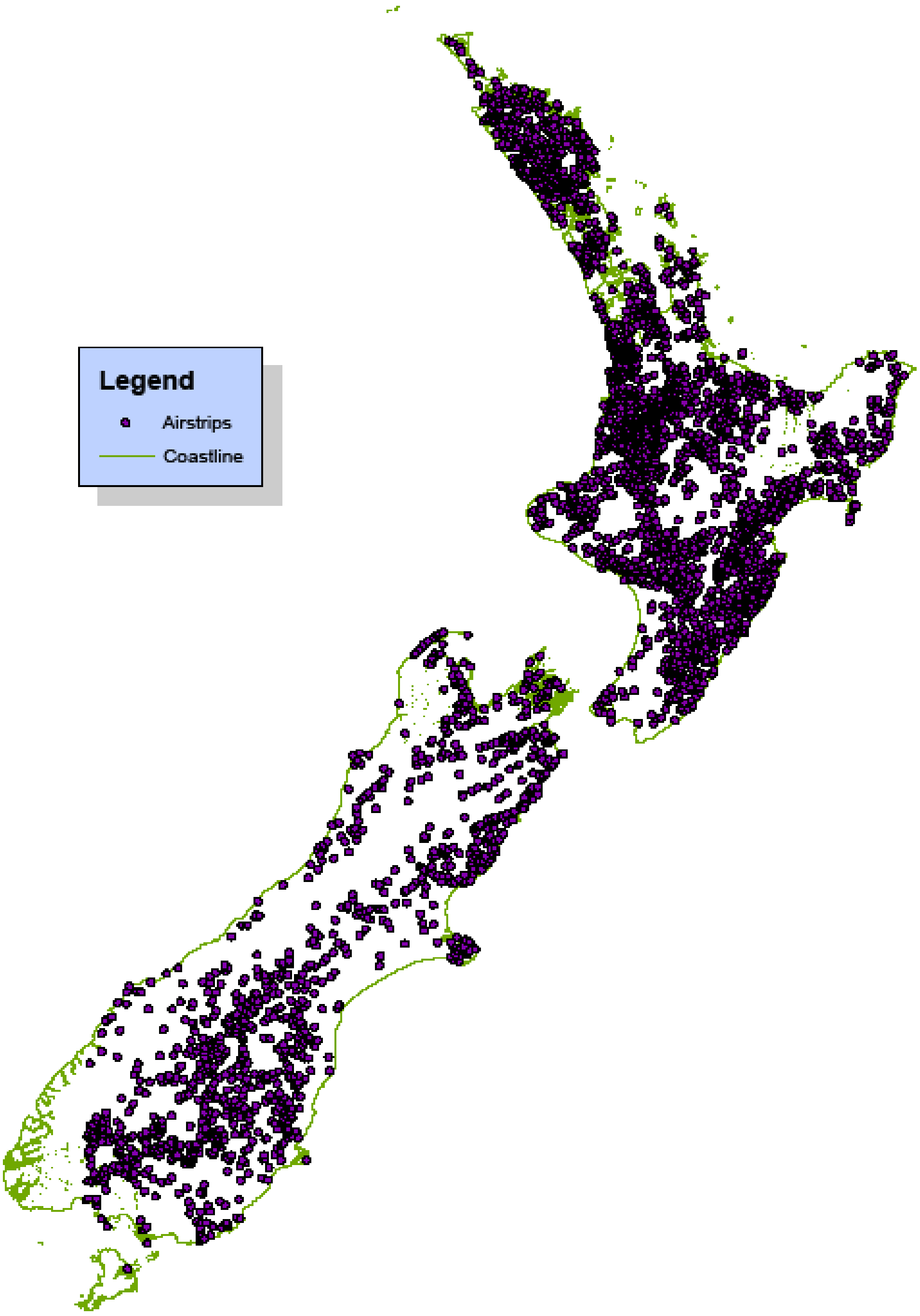


Figure 6.2: Spatial representation of New Zealand's 3,600 airstrips

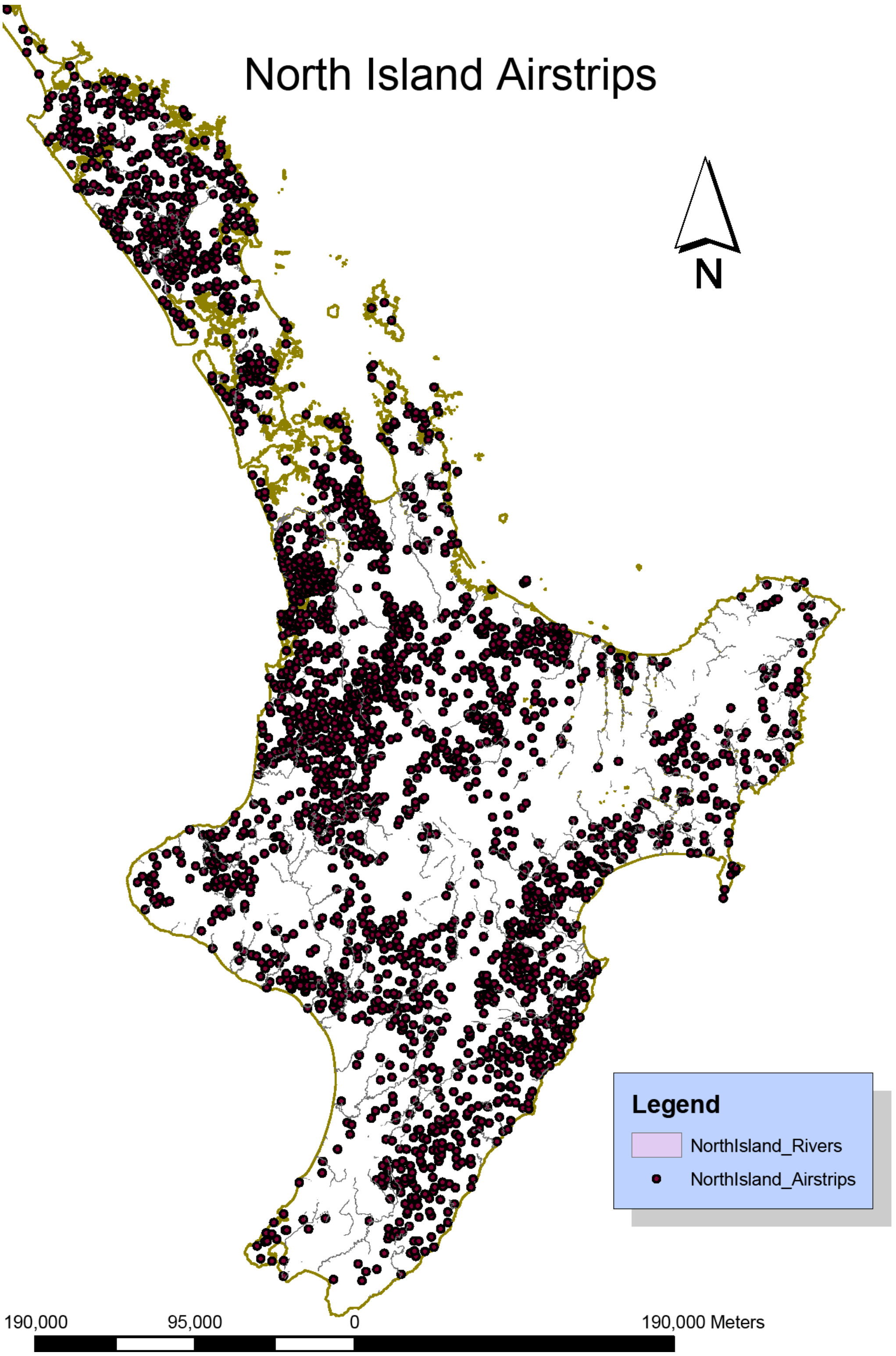


Figure 6.3: Spatial representation of the 2,545 North Island Airstrips (Data from Eagle Technology).

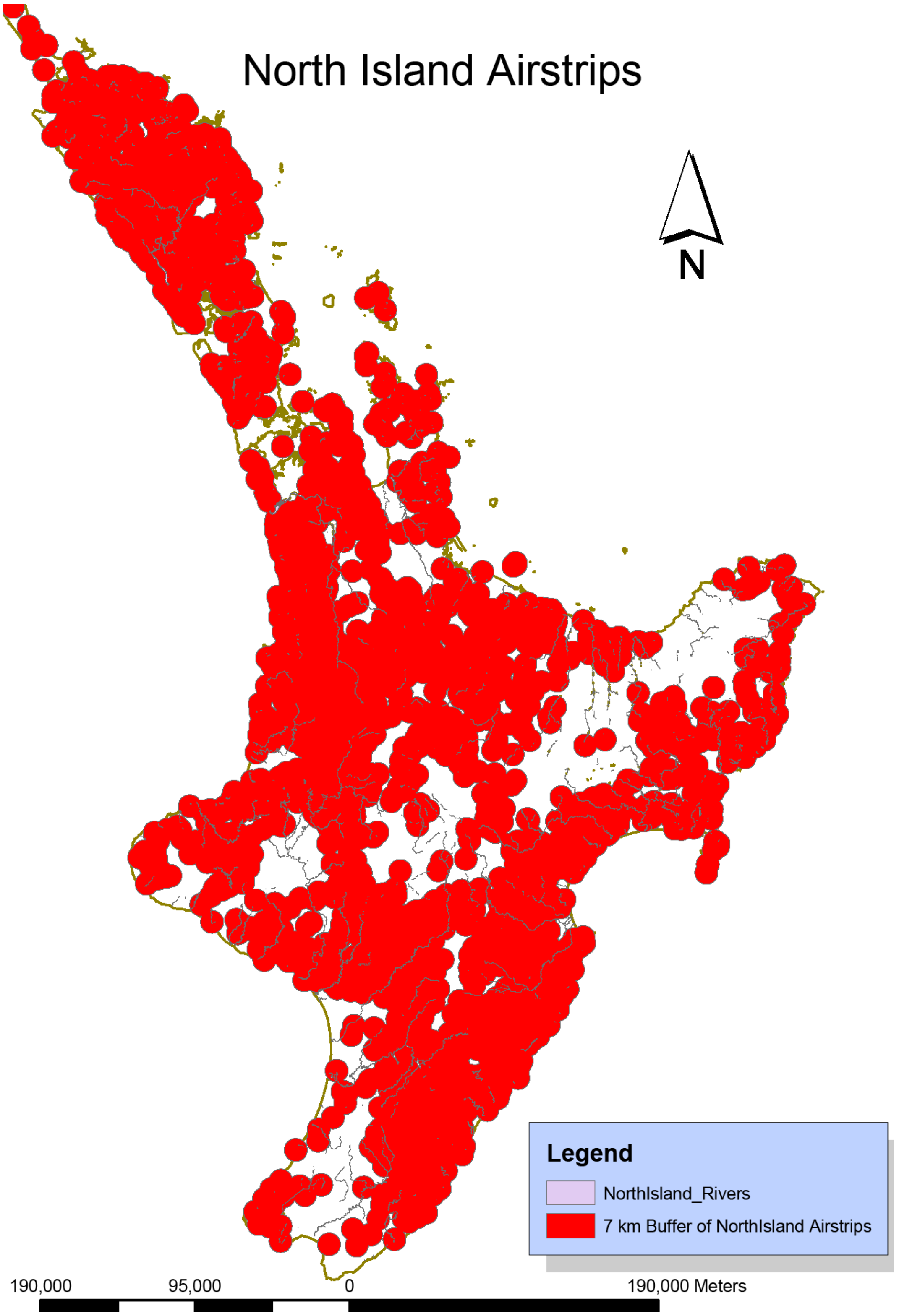


Figure 6.4: North Island Airstrips with 7 km buffer around each.

At present strip hire charges for using another farmer's airstrip range from \$2 to \$10 per tonne for a general grass strip through to an all weather airstrip. These charges are significantly lower than that required to sustain the investment required. A realistic price per tonne could well be \$30 per tonne, assuming a desired ROI of 9%, using the current number of strips (if 90% of them were to be rebuilt). The relationship between strip hire costs and the tonnes applied from a strip are presented in Figure 6.5.

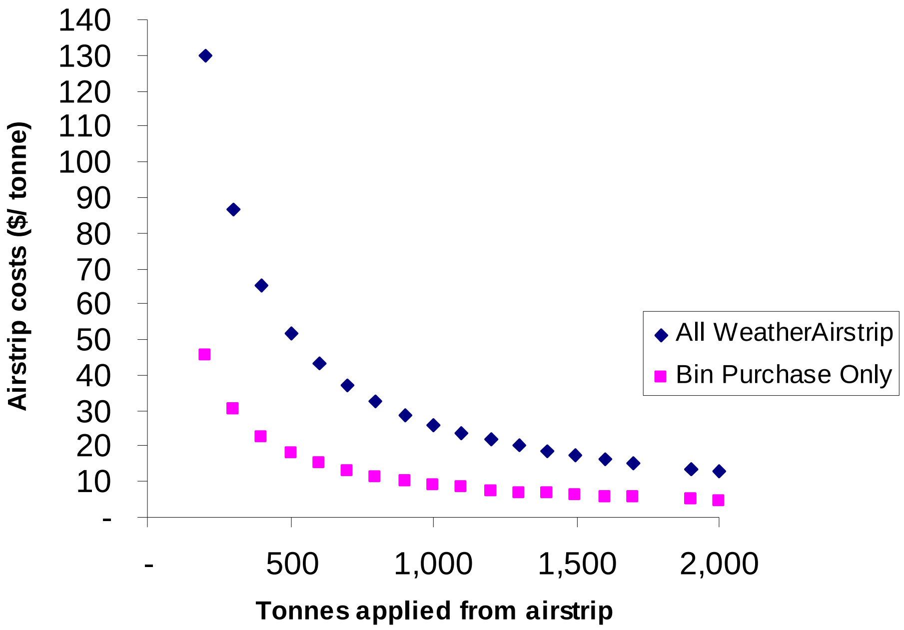


Figure 6.5: Strip hire costs per tonne applied

6.6 Results

Both the aircraft operating costs and the cost of on-ground facilities have been calculated. It appears that in both cases the industry is operating well short of meeting the cost of capital. The problem now is to attempt to represent actual individual situations and examine possible scenarios for the future. The balance between greater aircraft flying hours and the number of airstrips needs to be identified in broad terms.

If the aircraft was to service the farming area immediately around the strip then a simple optimisation could be achieved. An estimate of aircraft costs and on-ground costs on that basis is presented in Figure 6.7. Assuming an application rate of 160 kg /ha for superphosphate the total cost is represented by the average cost from the airstrip which is $5.6x + 38.53$, where x is the boundary distance from the airstrip in kilometers. The cost of the airstrip can be represented by the tonnage off it divided by the area covered assuming 800,000 tonnes, the midpoint between a poor and a good year, is spread per annum within New Zealand. For a bin only purchase airstrip the cost against distance spread is $312x^{-2}$. By differentiating the addition of these equations the cheapest total cost occurs at 4.8 km, covering a circular area of 7,238 ha. If each strip were to service this land area the aerial topdressing requirements of New Zealand could be met by 1,192 strips, less than half the number currently in existence, which are 2,545 in the North Island and 1,114 in the South Island. However for an all weather airstrip the airstrip cost against distance spread is $892x^{-2}$. This results in a minimum at 14.34 km which would leave 123 airstrips servicing 70,200 ha from each strip at a cost of $123 per tonne at an application rate of 160 kg/ha. The all weather airstrip is clearly cost prohibitive.

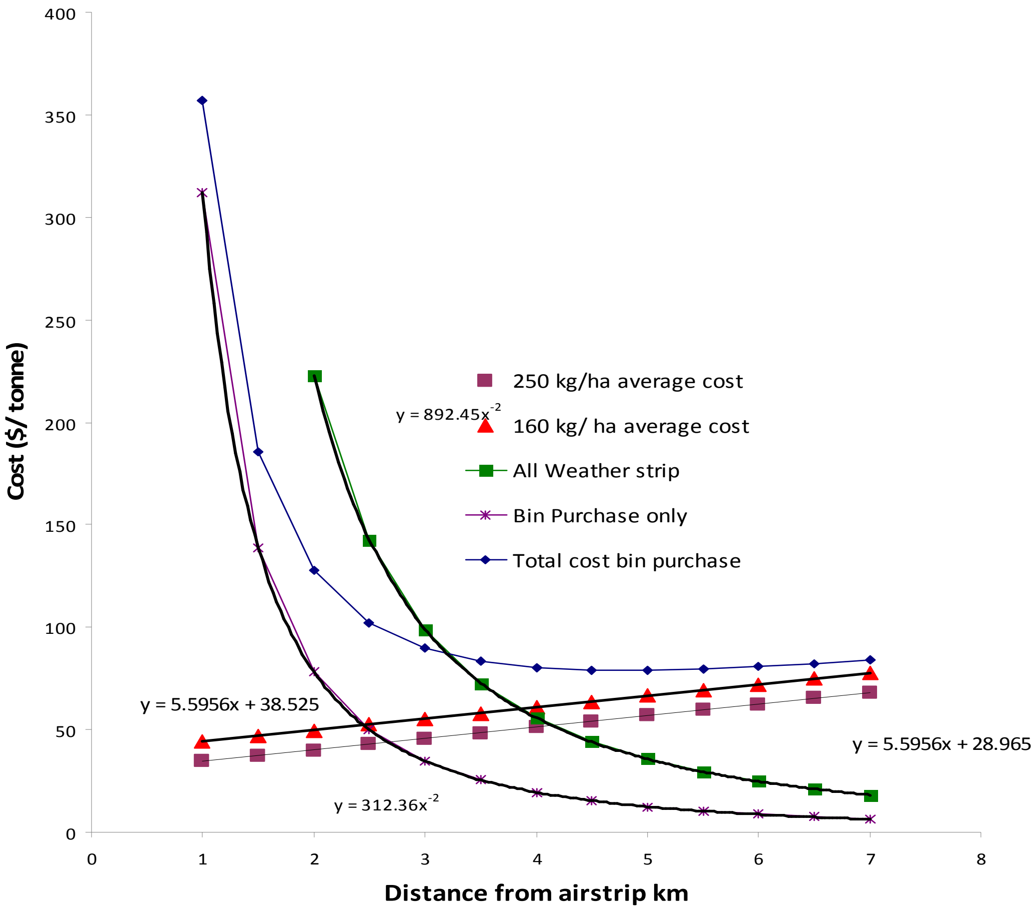


Figure 6.6: Average cost of application and strip charges from an airstrip

This scenario is somewhat unlikely in the short term. But the cost of servicing a farm lying between four and seven kilometres from the airstrip can be calculated. Assuming the airstrip was servicing a number of farms the on-ground cost per tonne could be calculated and added to the aircraft operating costs. Another way to look at it would be to decide what proportion of the area requires application of fertiliser and use that as the basis for cost calculation. This approach could help in planning the number of airstrips required, given land use and topographic requirements.

The mathematics taken to develop this economic model, are not complex and can be easily represented on a spreadsheet. Some flexibility can be developed to allow for the planning of on-ground facilities.

Further simple calculations, based on the annual use of each aircraft of 1,000 hours, suggest that at the present level of fertiliser application to this farming sector a fleet of 54 aircraft would be sufficient, this would mean retiring a significant number of the current, dated fleet.

6.7 Conclusions

The cost to New Zealand farmers of bringing 90% of the 3,600 airstrips up to an adequate standard and then maintaining them is simply too great if those costs were to be recovered through strip hire fees. However, the deteriorating safety record of the agricultural aviation industry suggest that something needs to be done, and with increasing urgency. The lack of on-farm investment; and the poor safety record of agricultural aviation need to be addressed.

Present requirements for topdressing in New Zealand could be satisfied by as few as 30 – 40 Cresco aircraft or turbine equivalents. If today’s fleet were rationalised it would mean the 22 Crescos, 2 Air Tractor 402 aircraft and about 30 turbine Fletchers would cope with a peak demand of 1 million tonnes spread. This is much more than is being spread at the moment, which would mean a significant downsizing of the industry and a significant number of businesses closing. This process may take place in a relatively short period as a number of operators have ageing aircraft and support vehicles. Operators faced with major overhaul costs and or engine replacements are likely to exit the industry rather than undertake these costs with little hope of a return from the investment.

In order to achieve economically optimum performance, the fleet of 54 aircraft; are likely to operate from around 1,200 airstrips that adhere to the standard suggested by the CAA. Rather than service 2,300 ha, each one will service up to 7,240 ha and as application rates continue to decline this area is likely to increase. The likely application cost per tonne of product applied will be in the region of $80 per tonne at the present application rate.

This analysis makes no attempt to assess if this is a cost that can be sustained by the industry. The true cost of fertiliser application has not been factored in for many years, perhaps decades, and the capital within the industry has been eroded. If the true cost cannot be sustained, then significant reductions in the productivity of the hill sheep and beef sector can be expected.

Chapter 7

Conclusions

7.1 Summary

This study examined the flow properties of products spread from agricultural aircraft in order to better understand their behaviour and assess the possible performance of aerial topdressing systems going into the future. One key requirement is to have products which can be discharged in a controlled manner to achieve the desired application rates. This is necessary in order to achieve the best financial and environmental outcomes for the farmer. The study found that only free flowing materials could be controlled adequately in order to provide an opportunity to achieve predetermined application rates on the ground. The flow properties of agricultural lime, is of particular concern. It has been found that the Fertmark standard description for lime which was developed for agronomic reasons may actually contribute to the problem.

All the quality assurance samples from 10 Fertmark registered quarries met this standard in terms of particle size distributions over the five years of measurement. Most samples met the standard easily and had much higher percentages of fines than is required to meet the standard. Therefore, it is probable that limestone is crushed more than is required to ensure that it is always met which is problematic.

This is because the wide particle size distributions created by crushing hammers breaking limestone into agricultural lime produce a compressible bulk solid; which gain strength as fines and small particles pack between the larger ones. On occasion the limes can gain enough strength to bridge an aircraft hopper opening and preventing discharge, which is extremely dangerous for the pilot.

The fixed wing agricultural aviation sector is the only branch of civil aviation in New Zealand with a deteriorating safety record. Pilots being unable to discharge their pay-load of lime; has been identified as a probable cause in several accidents.

The agricultural limes used for experiments in this thesis represent the major deposits from throughout New Zealand. Although there were differences in their mineralogy they had similar particle densities. Differences in bulk density are caused by differences in particle size distributions. Particle size distributions vary continuously as time spent in the hammer mill and the age of the mill hammers alters. However, all the limes tested met the Fertmark standard.

All the limes in their as received state were subjected to various cohesion and flow-ability tests; using a Stable Micro Systems Powder Flow Analyser, bulk density comparisons for the Hausner ratio and a shear testing regime using a Walker cell and some were also tested on a Schulze automated shear cell. All tests showed the materials to be on the cohesive – easy flow boundary which shows the material to have difficult flow properties. These findings didn't alter significantly with the addition of moisture from 2.5% - 10% by weight.

A non compressible free flowing lime was obtained by removing fines less than 425 µm; and also by removing all particles smaller than 300 µm and larger than 425 µm.

The latter particle size distribution maintained the same mean particle size distribution of the as received material and therefore complied with the Fertmark standard. Flow tests showed that both materials obeyed the “Beverloo” equation and the Hausner ratios were close to one.

The New Zealand fixed wing agricultural aviation industry services mainly the sheep and beef farmers, who farm the more marginal hill country land which can not have fertiliser applied by vehicles. This land is the least productive pasture land farmed and when sheep and beef prices are low, or when fertiliser prices are high is the first land where inputs are withheld. Although this sector comprises about 55% of all land farmed in New Zealand it produces only 25% of the total value of farm outputs.

In recent years fluctuations in sheep and beef prices and fertiliser prices has resulted in an elasticity of demand for agricultural aviation contractor services. In about half of the last 20 years demand for services has been low and aerial contractors have been unprofitable, which has placed this vital service sector in difficulty.

In an environment where the focus has been on economic survival, farmers’ decision tree in respect of fertiliser application for hill country farmers has merely been one of whether to apply fertiliser or not; based upon fiscal restraints rather than farm fertility requirements or nutrient budgeting.

7.2 Concluding Remarks and Future Study Directions

The Civil Aviation Authority in conjunction with the Occupational Safety and Health Office, of the Department of Labour in consultation; and with the assistance of stakeholders including Federated Farmers and NZ Agricultural Aviation Authority; has produced a farm airstrip safety guideline. This document specifies the responsibilities of all those in the supply chain from fertiliser manufacture or quarry, through delivery by carrier, the farm infrastructure and access to the fertiliser storage facility; the airstrip standard and the pilot's responsibility whether to undertake, or refuse to undertake operations.

The guideline sets the standard for investigations into work place accidents that occur as a result of agricultural aviation operations. It can be concluded that modern health and safety standards are required and that farm airstrips are a workplace like any other; and carriers and pilots using airstrips are contractors.

This exposes airstrip owners to prosecution risk should their airstrip or facilities be a contributing factor in a workplace accident. As 20% of agricultural aviation accidents involve collisions with obstructions adjacent to airstrips such as fences this is a real risk. As many airstrips service several farms this risk may be unpalatable if it is being used by a neighbour; employing contractors independently of the strip owner.

New Zealand has over 3,600 farm airstrips which, enables most hill country properties to be serviced relatively cheaply as aircraft do not need to do much unproductive flying. However, the number of airstrips reflects the historic lack of financial barriers in setting them up. Most do not meet the standard and once airstrip owners are prosecuted then many will be withdrawn from use. Those that remain will require on going maintenance and investment and realistic charges for the use of these airstrips will be a necessity.

Owners of airstrips which service several farms are likely to arrange different forms of airstrip ownership, such as transferring the airstrip into some type of lease arrangement with a holding company; to distance themselves directly from responsibility for the actions of contractors, not associated with their farm. Charges for the airstrip and maintenance upkeep; will become the responsibility of the lessee.

The CAA has signalled changes to Part 137 rules; and in the latest draft amendments have altered the jettison wording by removing “superphosphate” and clearly defining the jettison requirement; that 80% of the payload must discharge within 5 seconds applies to all products that are used. This has huge implications for the aerial topdressing industry and the lime quarries. They have also referenced the farm airstrip safety guide in the proposed rule changes, which clearly increases the responsibility of pilots to ensure the airstrips, products being sown and facilities are suitable.

It is almost certain that the proposed rule changes will occur. It is also likely that aircraft operators and strip owners will be prosecuted for accidents that occur directly relating to the unsuitability of the product being sown or the strip. One likely consequence of such actions may be the declining of insurance claims; policies generally have a caveat that operators must be complying with CAA regulations.

The proposed change to the jettison requirement will mean that lime will not be sown in its present form. Those quarries supplying lime for agricultural aviation operations will either need to screen out all smaller particles at the limit of economic screening about 2mm and forego the Fertmark standard; or invest in cyclonic separators and or positive pressure elutriation to make a lime that complies and flows freely by having a very narrow particle size distribution. Farmers requiring very fine lime particles will be able to have application through a suspended slurry liquid application.

It is quite clear that pilots are not able to accurately apply fertiliser by means of a lever operated hopper door outlet. DGPS has improved accuracy by providing the pilot with an average rate per run, the computer records the hectares covered at the planes swath width. The pilot is then able to adjust the distance covered to maintain the correct overall application rate.

Development of variable rate application technology has occurred (Murray, 2007). However, commercialising the technology has not proceeded at this stage. Commercialisation is likely to proceed, once the parameters for establishing prescriptive maps for fertiliser placement are available at an individual farm level. This will require knowledge of soil type, weather, aspect, farm contour and fertility status. It will also require some investment in service infrastructure to initiate, which will only be undertaken if farmers perceive value and are willing to pay for the service.

It is likely that the use of automated hydraulic hopper doors that can control the rate of discharge to maintain the desired application rate will be commercialised prior to variable rate technology. Aircraft DGPS can be loaded with farm paddock information or a boundary can be flown and loaded by the pilot. The DGPS systems have a predictive boundary detection system which allows the hopper door system to be activated and deactivated at a preset proximity to the boundary.

Any use of automation to improve the quality of application will require the bulk solids being sown to be free flowing. Only free flowing substances can have flow rates that are predictable. For hygroscopic materials such as superphosphate this will be assisted by the new farm airstrip guide; and the requirement to properly store fertiliser, throughout the supply chain. There are two possible routes to bringing about change, change the materials being spread or change the aircraft hopper design. Even with extensive changes to the aircraft the study reveals that the problem would remain and while the risk of bridging in a hopper may be reduced it unlikely to be eliminated. Modifying the materials spread is suggested as the most effective means of improving accuracy in spreading and safety for pilots. In both cases the farm safety guidelines would also need to be enforced.

We can conclude that the cost of aerial application of fertiliser will increase and that this is required to improve the safety record of the industry. This also creates an opportunity to add value as properly stored products manufactured to be free flowing will be applied more accurately and only then can concepts such as variable rate fertiliser application realistically be achieved This should lead to productivity gains which may well be greater than the added cost of application as indicated by Murray (2007).

7.3 Future experimentation

Due to cost constraints only small amounts of modified limes were produced. Further experimental work could be usefully completed to ensure that the approach suggested has benefits over the complete range of agricultural limes available in New Zealand. Methods of screening lime could be investigated to examine how finer material could be removed in a cost effective way. It would also be useful to establish the range of particle size which are required to be removed in order to produce free flowing material from parent material at various moisture levels and if kiln drying is essential for particle size separation.. Once these parameter are established the required industrial processes could be investigated and the costs calculated.

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