AN ASSESSMENT OF THE EFFECT OF GRADING OF PERLITE ON ULTIMATE STRENGTH IN LIGHTWEIGHT CONCRETE

ADRIAN JEREMY WINTER

A RESEARCH REPORT SUBMITTED TO THE FACULTY OF ARCHITECTURE, UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG, FOR THE DEGREE OF MASTER OF SCIENCE IN BUILDING.

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CONTENTS

SYNOPSIS

This research project is an investigation into the effect of the grading of perlite lightweight aggregates on the resultant concrete strengths.

Lightweight concretes are reviewed.

Perlite, as a lightweight aggregate, is assessed.

Grading theory for aggregates and in particular lightweight aggregate is analysed.

A series of mix designs are proposed with manipulation of the grading of the perlite as the only variable. This is so that variations in compressive strength and density may be assessed in terms of the grading of the perlite.

Those mixes are undertaken and tested for compressive strength and dry density.

In this research project compressive strength is considered a benefit, while mass is considered a disadvantage.

The performance of a lightweight concrete is assessed firstly in terms of the Power Factor. The Power Factor is the compressive strength divided by the dry density of a concrete.

The performance of lightweight concretes produced with Perlite aggregate is assessed secondly in terms of the Cement Content Factor. The Cement Content Factor is the Power Factor divided by the Cement Content. This factor has the effect of creating a common denominator of the cement content.

An evaluation of the results yields the conclusions detailed in chapter Eight, the principal two being:

- The optimal perlite grading tested was a monodisperse, single size fraction, of between 600 and 1180 microns.

- The most practical measure for manufacturers to improve the performance of lightweight aggregate in concretes is to screen out all particles above 2360 microns.

DECLARATION

I declare that this research report is my own work.

It is submitted for the Degree of Master of Science in Building, at the University of the Witwatersrand, Johannesburg.

It has not been submitted before for any degree at any other university.

30th day of November 1998

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MR STEFAN MAKOVY

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INTRODUCTION

Concrete producers and precast concrete manufacturers face the dilemma of balancing strength, density, and cost.

Generally, concrete strengths of between 20 MPa and 40 MPa are appropriate in the construction industry, and conventionally manufactured concretes in this range typically have densities of 2300 kg/m³ to 2500 kg/m³.

If concretes of these strengths and appropriate quality could be made lighter, several immediate benefits would arise:

Decreased applied loads on structures
Reduced transport costs
Larger elements could be possible for the same mass

Regrettably, the principle reasons why lightweight concretes are not generally well utilised in the precast and construction industries are:

- The aggregates required may be more expensive than traditional sand and stone, in some cases specialised equipment and additives are necessary. Very often lightweight concretes are cement rich.[1]

- Shrinkage in lightweight concretes is generally greater than in conventional concretes.[2]

- Protection of reinforcing steel against corrosion is inferior to "normal" concretes, and hence durability is poorer in lightweight concretes.[3]

At the pilot study stage the most immediate discovery was of a lack of "science" regarding the use of perlite as an aggregate. The printed material received from the supplier included a general description of perlite, its physical and chemical characteristics, and a list of uses of the various grades available. Particle sizes used for the grading analysis was non-standard. There was no printed batching information.

Pondering the nature of lightweight aggregates used in the manufacture of low density concretes, led to the notion that, assuming the perlite adds little or nothing to the compressive strength of the concrete, perhaps the particle size and distribution (grading) would **influence the strength in some other way** than that of regular aggregates in conventional concretes. For example, the comb of the honey bee has evolved its relatively uniform structure in response to the need to support a maximum mass of honey for a minimum of wax. If a honeycomb had a distribution of cell sizes, it would not be as efficient in its use of wax, as a comb with single sized cells.[4]

Before any product is accepted for construction or manufacturing purposes, all aspects of its performance must be fully understood. It is in the light of this quest for increased knowledge, regarding the potential applications for perlite, that this project is undertaken.

There will always be further characteristics of a material that could be examined. They remain the subject of other reports.

LIST OF TABLES

CHAPTER FIVE

CHAPTER SIX

CHAPTER SEVEN

LIST OF FIGURES

CHAPTER ONE

CHAPTER TWO

CHAPTER THREE

CHAPTER FOUR

CHAPTER ONE

LIGHTWEIGHT CONCRETES

LIGHTWEIGHT CONCRETES

CONCRETE

Conventional concretes used in the construction and precast industries generally utilise crushed or weathered rock as aggregate. Commonly used South African aggregates, typically have relative densities of around 2.7 and the resultant well compacted concretes will exhibit densities of between 2350 kg/m³ and 2450 kg/m³ (ave 2400kg/m³).[5]

Concretes consist of aggregates (fine and coarse) and bonding paste, made up of Portland cement and water. The density of a concrete may be varied by the use of the aggregates from differing parent material.

Aggregates typically make up almost half the cost of a mix and therefore the cheapest acceptable aggregates, appropriate to the use envisaged, are always used.

When the relative density of the material, used as the aggregate in a concrete mix, is known the density of the resultant concrete may be calculated.

Common South African aggregates, used in conventional wet cast concretes, and the resultant well compacted concrete densities, for a given cement content and w/c ratio, are tabled below. An example of this calculation is detailed in Appendix One.

Table 1
Rock commonly used as Aggregates - Some densities

Rock Type	Relative density Average[5]	Theoretical concrete density Kg/m³
Basalt	2.9	2 513
Andesite	2.8	2 444
Granite	2.7	2 374
Sandstone	2.6	2 305

The theoretical well compacted concrete density is based on the absolute volume mix design procedure as laid out in Fulton's Concrete Technology manual. The predicted density is based on a water cement ratio of 0.75, aggregate of 19mm stone, and sand of the same type (see Appendix One).

Special aggregates of higher or lower relative density are used to produce concretes of higher or lower density. Usually these special aggregates are more expensive than conventional aggregates and so are employed only when the advantages of the sought after density are worth the additional cost to the designer.

ADVANTAGES AND DISADVANTAGES

Lightweight concretes may offer many advantages, if adequate performance is obtainable. Invariably, as the density is lowered, compressive and tensile strengths can only be maintained with substantial increases in cement content.[1]

Assuming that concretes could be produced with, at the very least, appropriate strengths then many benefits would flow, including:

- Lower applied load on structures and hence cheaper foundations.
- Reduced transport and handling costs for precast elements. Lower capital investment in equipment, and hence fewer barriers to entry, leading to increased competition and lower rates.
- Larger precast elements are possible
- Less human fatigue and increased speed of erection.
- Enhanced freedom of design.

In certain circumstances designers may be searching for other qualities in lightweight concretes besides a low mass. These qualities could include:

- Thermal insulation in roof slabs, walls and floors of structures.
- Lower coefficient of thermal expansion.
- Acoustic insulation in sound sensitive situations.
- Fire protection.

There are however some difficulties associated with lightweight concretes. In most cases these concretes must be more than simply light. Perceived drawbacks of working with lightweight concretes are:

- In some cases specialised equipment and additives may be necessary.[7]
- Lightweight aggregates are sometimes more expensive than traditional aggregates.
- Mixes for lightweight concretes are usually cement rich.
- Shrinkage is greater in lightweight concretes than in conventional concretes.[2]
- Finish is often impaired.
- Protection against corrosion of reinforcing steel is inferior to normal concretes.[3]
- Greater care in design and manufacture is required.
- Difficulties in mixing due to the friability of lightweight aggregates and their flyaway nature.
- Some lightweight aggregates tend to float in the wet mix, particularly during vibration, leading to segregation and hence poor quality lightweight concretes.

DEVELOPMENT

Despite these concerns, lightweight concretes have been used with success in construction and precast applications. Two thousand years ago the Romans used Pumice, a naturally occurring aerated volcanic lava, as a lightweight aggregate in the construction of the Pantheon, the Coliseum, and many public baths. Pumice continued to be used in Europe during the middle ages, and more recently has found acceptance in the western parts of the United States, where this material is also mined.[8]

At the start of the 19th centaury, waste clinker was used as a lightweight aggregate for low density concrete in the construction of the British museum. But it was only in the early part of this century that the deliberate production of lightweight aggregates began in Britain, with the introduction of a sintering process for the expansion of shale.[9]

Reinforced lightweight concrete was used in the construction of ships and barges by the Emergency Shipbuilding Corp, during the First World War. Using the expanded shale process compressive strengths of 35 MPa were reached, at densities of 1760 kg/m^3. This feat was repeated during the Second World War, which saw the launching of lightweight concrete vessels such as the Lady Kathleen, 2460 tonnes launched 1943.[9]

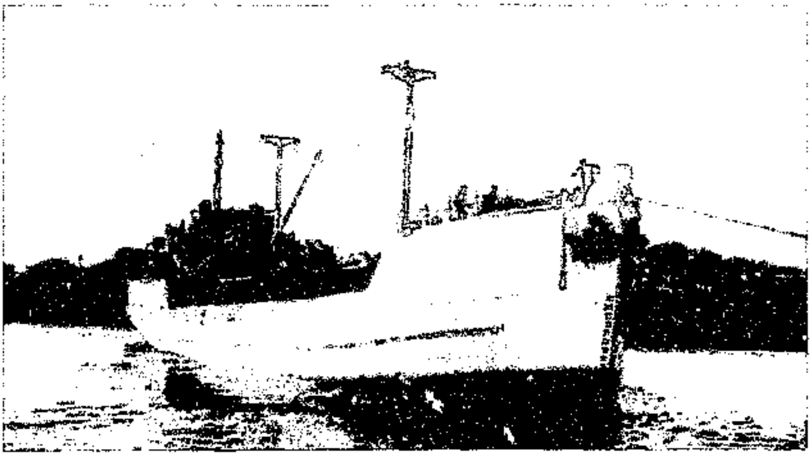

Figure 1
Lady Kathleen 2460 Tonnes 1943

Lightweight aggregates experienced increasing usage in the post war years including structural work in buildings and bridges. In 1979 the Parrots ferry road bridge in California, with spans of 200 m, was completed in lightweight aggregate concrete. Expanded shale was used as a lightweight aggregate in casting the 12 m wide by 9 m deep winged box girder. Total weight reductions of 20% were achieved at an estimated cost saving of 10%. Concrete strengths of up to 40 MPa were reached.[10]

Figure 2
Parrots ferry road bridge, California

ENGINEERING

Lightweight concretes are made with a wide range of densities from 400 kg/m³ up to the density of normal weight concretes, depending on the method of manufacture and the cement content. Strengths can range for the same reasons of mix design, as well as those of compaction and curing, from very low for insulating concretes, up to 60 MPa for structural grade lightweight concretes.[11]

Lightweight concretes are cured in the same way as normal concretes. Where porous aggregates absorb water, some of this water is released slowly during the hydration process, improving the ultimate strength of the concrete.

Lightweight concretes of up to 35 MPa have similar flexural strengths to normal weight concretes of equal compressive strength. Above this level lightweight concretes have lower flexural strengths.[2]

Poissons ratio, which is the ratio of lateral to longitudinal strain, remains approximately the same as for normal weight concretes. Modulus of elasticity of lightweight concretes is lower than that for normal weight concretes of equal strength. The higher the strength the higher the difference.[12]

Creep range of lightweight concretes is about the same as that for normal weight concretes. The average ultimate creep of lightweight concrete is generally slightly greater than that of normal weight concretes.[11]

Drying shrinkage is generally higher in lightweight concretes. The higher the strength the closer the shrinkage is to that of normal weight concretes.[13]

Thermal conductivity is directly related to the density, the lower the density the lower the conductivity, while the higher the density the higher the thermal conductivity.[13]

PRODUCTION

Lightweight concretes are produced in two principle ways:

- Formation of voids in the matrix.
- Inclusion of aggregates which are light.

FORMATION OF VOIDS IN THE MATRIX

Voids of air can be included in a concrete mix unwittingly through poor compaction. Fulton's Concrete Technology claims that "It cannot be too often stated that the presence of only 5% voids in the concrete mix reduces the strength of the cube by 30%".[14]

Voids may be included in the concrete matrix through the omission of the fine aggregate. Known simply as "no-fines" concrete, the cement and water form a paste which coats the particles of coarse aggregate, without filling the voids between them.

No fines concrete is cheaper due to the omission of the fine aggregate, and is principally used where its high permeability is an advantage, such as in drainage layers. No fines concrete has the appearance of severe honeycombing. Sawdust and wood wool concretes fall into this category.

Ice cubes, which melt during hydration, can be included in a mix. The water is then available to continue the hydration process, leaving voids behind. Low densities are achievable but at very low strengths due to the Fulton's void rule.

Air entrainment is the deliberate inclusion of tiny bubbles of air during mixing. This is achieved with admixtures, which have the effect of producing a foam of air bubbles which become dispersed throughout the matrix.

Bubbles should be between 0.05 mm and 0.50 mm and should not break down nor coalesce. Air entrainment has the effect of increasing the volume of the matrix by the percentage air content and thus the density is lowered by the same percentage. In concretes made with 19mm stone the recommended total air content is 6%.[15]

Entrained air improves workability, leading to decreasing water/cement ratios at constant cement content. Resultant strength gain is opposed by a decrease in strength due to the presence of voids. Nett strength loss can be up to 15% at the maximum permitted air content of 6% to 7%.[15]

Cellular concretes are a continuation of this idea, through a radical increase in the percentage of air voids in the matrix. Cellular, or aerated concretes are not concretes in the generally accepted sense, as aggregates are omitted. Air voids account for the bulk of the volume in a mix with the cement paste forming the walls of the bubble voids. Clearly the bubbles add nothing to the strength of such a concrete and it is the thickness, strength and physical relationships of the bubble walls that determine what loads can be resisted.

Cellular "gasbeton" was first developed during the second world war and has been used in Germany and most of Europe extensively. Gas concrete is so called, as air voids are formed by the chemical generation of tiny bubbles of gas while the concrete is still plastic. When Aluminium powder in added to the wet mix, the gas Hydrogen is generated, or when Zinc powder is added, Oxygen is formed.[16] The gas later escapes and is replaced by air. This material is primarily used for internal block walling, especially in colder climates, but has also been used for low intensity structural walling applications. Large blocks of "gasbeton" are usually cast, and are cut into smaller sizes after the initial set of the mix. These smaller blocks are then cured in an autoclave.

A simpler method for producing cellular concrete especially for in-situ applications is through the addition of a pref[illegible]ble foam, or the addition of a foaming agent at the time of mixing. The dens[illegible]ately varied by altering the amount of foam added to the cement slurry, [illegible]an be manipulated by increasing or decreasing the water/cement ra[illegible].

Cellular lightweight concrete is a[illegible]ea of [illegible]chnology receiving attention from researchers, with topics such as mix design and optimal void sizes under investigation.[17]

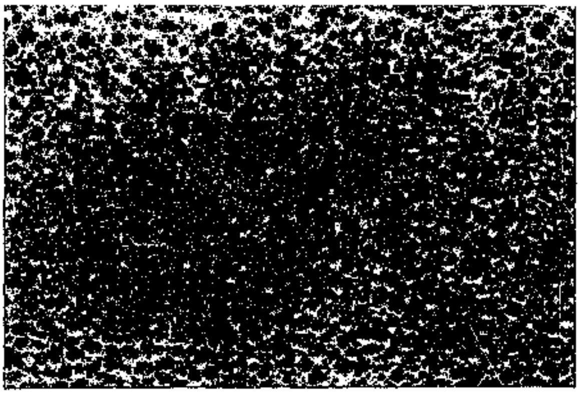

Figure 3
Cellular concrete

An organic protein or resin soap is added to water and mechanically agitated to form a foam. Cement and water, sometimes with sand, are mixed to form a slurry and both the foam and the slurry are mixed together, forming a cellular lightweight concrete. Cellular lightweight concretes are extensively used in South Africa.[18]

The entrapped air bubbles introduced yield a low density and have a strong plasticising effect. The foamed concrete can easily be pumped and requires no compaction. By varying the quantity of foam added to the cement slurry the density can be designed for an intended purpose.

Cellular lightweight concretes use air to replace stone. Compared to stone, air is always readily available when and where required.

INCLUSION OF AGGREGATES WHICH ARE LIGHT

Naturally occurring lightweight aggregates such as pumice, an aerated cellular lava, were used in lightweight concretes in Roman times. Naturally occurring aggregates require only crushing and screening to be suitable for use as lightweight aggregate. Pumice has a sponge like structure and occurs in commercially viable quantities in Europe and the USA. Scoria is also a cellular lava with an elliptical void structure. Scoria is red brown or black while pumice is greywhite, otherwise their qualities are similar.[19] Pumice and scoria are not available in South Africa.

Many lightweight aggregates are obtained from by-products of other industrial processes and consist of fuel ash or slag.

Furnace clinker should be obtained from high temperature furnaces with a minimum of combustible material remaining. Clinker is the hard remains of burnt coal which has fused into lumps. This material is used for precast walling blocks or bricks and can be used for low grade concrete work such as backfilling or roof screeds. Clinker is also known as "breeze", giving rise to the generic name "breeze blocks" for the rough building blocks made from clinker.

Foamed slag is produced by the rapid cooling of pig iron blast furnace slags so that steam is trapped in the molten mass to give a porous structure similar to natural pumice. Foamed slag has a good reputation for reliability in the United Kingdom, and may be used for structural lightweight concrete.[20]

Pelletised slag is a refinement on foamed slag where molten particles of foamed slag are mechanically rounded as they are cooled. The advantage of this extra step is that the resulting particles have smother surfaces and a rounder shape.

Pulverised fuel ash or Pfa is the collected flue gases of power stations and consists of minute spherical glass particles. The Pfa is mixed with coal slurry and peletised before being burned in a furnace at 1 200°C (sintering). This process forms a lightweight aggregate sold under the trade name of "Lytag" in the UK.[21]

Diatomaceous rock is made up of the fossil skeletons of minute marine life. The material is mined, crushed and calcined. It is naturally occurring and does not expand on heating as the burning process merely removes combustible material.

Certain minerals expand when heated due to the presence of water in the raw materials structure. Perlite is one of these minerals and will be dealt with in detail in Chapter Two.

Shale was the first material to be deliberately expanded on heating, specifically for use as a lightweight aggregate.[22] Clay can also be used in this process. Expanded shales and clays are marketed in the United Kingdom under many different trade names, but in South Africa, although there are reported cases of the manufacture and use of such materials, they are not readily available.[23]

Vermiculite is the geological name given to a group of laminated minerals resembling mica in appearance and consisting of silicates of one or more of the metals iron, aluminium, and magnesium. Vermiculite expands rapidly (exfoliates) when heated due to the formation of steam which forces the layers apart. Exfoliated vermiculite has a concertina like structure of layers, and is mined and processed in South Africa. Shrinkage is high in vermiculite, higher than in other lightweight aggregates, and has been quoted as much as 0.35%, or 3 mm in 900 mm.[24]

Figure 4
Expanded vermiculite

Finally, there is the artificially manufactured and expanded particles, known as polystyrene. Pellets of polystyrene contain an expanding agent and when heated in steam they swell into round beads, ranging from 3 mm to 5 mm in diameter.

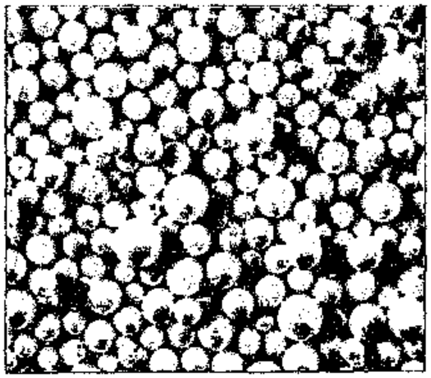

Figure 5
Polystyrene beads

The expanded polystyrene beads are coated with a chemical compound which is said to activate on contact with the wet mix. It is claimed by the manufacturer that the chemical coating enables the polystyrene beads to disperse evenly in the mix by causing them to repel one another. The coating is also said to enhance the bond between the individual beads and the cement paste.[25]

Polystyrene beads do not absorb water and do produce a reasonable quality concrete, however the single most profound difficulty in working with this material is the tendency of the beads to float, despite the chemical coating.

All lightweight aggregates with an effective relative density of less than 1 will tend to float, however some aggregates float more readily than others. This is a function of the porosity of the aggregate in question, and hence the absorption of water. As water is absorbed by the aggregate, the nearer the effective density of the aggregate tends to that of water. The closer the effective relative density of the aggregate to 1, the lower the buoyancy effect of the water on the aggregate, and hence less flotation.

Table 2 below, offers a summary of the qualities of lightweight aggregates in regular use in South Africa (excludes no-fines concretes). The loose bulk densities (LBD) do vary and the LBD figures quoted are typical averages only. The intention is simply to demonstrate the relationship between the LBD of the material used as an aggregate, and the probable resultant concrete density.

Table 2

Lightweight aggregates -Theoretical concrete densities.

Aggregate	Loose bulk Density [26] Kg/m^3	Predicted concrete Density Kg/m^3
Clinker	930	1 926
Foamed slag	610	1 542
Perlite	120	954
Vermiculite	100	930
Polystyrene	15	828

The above figures were computed for a concrete mix design based on a volume calculation.

Cement content was arbitrarily selected to be 450 kg/m^3 and the water content 360 litres (w/c ratio 0.8). The loose dry volume of aggregate is 1.2 m^3 per cubic metre or 120% of the required volume of lightweight concrete.[27]

The fresh concrete density is predicted by adding the individual masses of each component of the concrete. Using clinker aggregate from the above table as an example:

Cement		450 kg
Water		360 kg
Aggregates	(1.2 m^3 x 930 kg/m^3)	1112 kg
Total mass/m^3		1926 kg

CHAPTER TWO

PERLITE

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CHAPTER TWO

PERLITE

PERLITE

Perlite is a volcanic glass which, when heated, expands by up to 20 times the original volume, forming lightweight spherical beads. One cubic metre of ore will yield approximately twenty cubic metres of expanded perlite. This expansion is due to 2% to 6% combined water in the crude perlite rock. The water became entrapped into the amorphous material on instant cooling after a volcanic eruption. When quickly heated above 870°C the crude rock softens, the water vaporises, and the ore pops in a manner similar to popcorn. As the combined water vaporises, it creates countless tiny bubbles in the heat softened glassy particles. Each aggregate particle consists of a large number of individual, basically spherical glass bubbles joined by common cell walls. It is these tiny sealed glass bubbles which account for the light weight of expanded perlite.

Typical particle sizes range from below 75 μm, up to 6 mm, with a grading similar to that of crusher sand. Crusher sands have loose bulk densities in the region of 1 800 kg/m^3, while expanded perlite has a loose bulk density in the region of 120 kg/m^3.

Perlite is used as a filter aid for industrial liquids and edible products, as a filler for paints and explosives, as loose insulation, in fire proof and insulating plasters, and also as a lightweight aggregate for concrete.[28]

Perlite has proven itself when used as a lightweight, sound absorbing or thermally insulating material, and it is not the purpose of this project to revisit these properties. The primary focus of this research is to analyse the effect played by the grading of perlite aggregates on the resultant strength and density of lightweight concretes.

On the Witwatersrand there are two significant suppliers of perlite, viz.

Chemserve Perlite (Pty) Ltd
Pratley Manufacturing Company (Pty) Ltd

Chemserve obtain raw perlite ore by ship from European countries such as Greece, Turkey, and Italy. The ore is moved by rail to the Chemserve factory at Midrand, where it is crushed and screened to limit the maximum size of particle. Various grades are separated by cyclone prior to expansion. In some cases, additional milling is done to increase the quantity of finer material. Crushed ore is passed through a vertical furnace at a temperature of 900°C and leaves the furnace in the expanded state.

By far the bulk of the material is used as an aid in the filtration of products in the food and beverage production industries. The specific product for use in lightweight concretes and insulating plasters is known as "G..ulite C95", and is made up of unsorted expanded perlite. The particle size distribution (grading) is not engineered or manipulated, nor is the grading monitored on a regular basis. The consistency of the grading is simply a function of a constant crushing and milling process.

Pratley Manufacturing and Engineering Co Pty Ltd mine a local ore body in northern Natal. Substantial unexploited reserves also exist in the Maputo province of Mocambique. This ore body is described in a report by the company Mines Operation and Minerals Investigation Pty Ltd, in 1961, as "immense" and of "excellent quality".[29]

Local ores have somewhat different physical properties to imported ores and require a higher temperature (1200°C) for complete expansion.

The selling prices of the two products (per unit volume) are substantially different, with the imported product by Chemserve reaching the market in the region of 75% more expensive (1998), than the locally produced product.

Pratley also sell their perlite in a form in which the individual particles are coated with a chemical compound. The manufacturer claims that this "pre-treatment" seals the perlite beads, reducing absorption, increasing particle strength, and improving the bond with the cement paste.

The Chemserve perlite is not prepared or coated in any way after expansion. For the purposes of this research only the **non pretreated** perlite from Chemserve is used. This is an arbitrary selection, as either the Pratley pretreated ("Pratliperl") or non pretreated products could have been utilised, as long as the same material is used throughout.

Chemserve offer several very specific gradings of perlite for various applications. One grading, "Genulite C95", is marketed for use in lightweight concretes. Genulite C95 perlite has a broad grading profile similar to typical crusher sands, and a fineness modulus of 3.50. The meanings of grading terminology can be found in Chapter Three. In this research, lightweight concretes are produced using Genulite C95 perlite as the only aggregate and not in combination with any other aggregates.

Typical physical characteristics of expanded perlite obtained from Europe are compared with those of the locally mined perlite, in Table 3.

Table 3
European and South African perlite
Physical characteristics compared

Property	Typical EU [28] Values	Typical SA [30] Values
Colour (expanded)	White	Grey to White
Max free moisture	0.5%	0.5%
Ore softening point	870°C - 1093°C	1000°c - 1250°C
Fusion point	1260°C - 1343°C	1300°C - 1400°C
Expanded Loose bulk Density	95 - 120 kg/m³	+/- 100 kg/m³
Loss on ignition	1.9%	3.8%

Pratley claim that apart from the pretreatment of their perlite, the main difference between their product (Pratliperl), and that of Chemserve (Genulite C95) is that the Pratliperl particle is tougher, has a more sealed surface, and is more suited to lightweight concretes than the Chemserve product.

Chemserve claim that their product (Genulite C95) is chemically purer, it is whiter and lighter, and is more suited to use in filter aids. Genulite C95 expands at a lower temperature (900°C) than that of Pratley Pratliperl (1200°C).

Typical chemical characteristics of the perlite ores obtained from Europe are compared with those of the locally mined perlite, in Table 4.

Table 4
European and South African perlite
Chemical characteristics compared

Compound	Symbol	EU % [28]	SA % [31]
Silicon Oxide	SiO_2	76.2	73.6
Aluminium Oxide	Al_2O_3	12.1	12.7
Potassium Oxide	K_2O	4.9	5.0
Sodium Oxide	Na_2O_3	3.4	3.2
Iron Oxide	Fe_2O_3	0.7	0.7
Calcium Oxide	CaO	0.6	0.6

Chemical compounds existing in percentages of less than 0.25% are not stated.

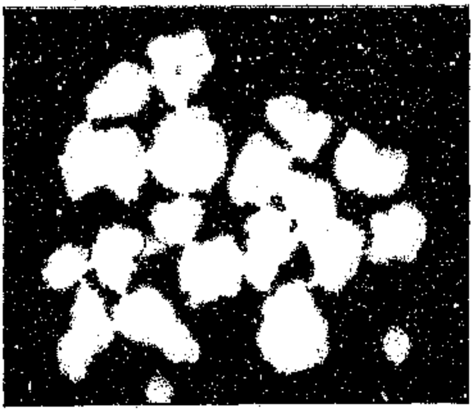

Figure 6
Perlite particles enlarged 5 X

Figure 7
Perlite particles enlarged 25 X

The American Concrete Institute (ACI) defines structural lightweight concretes as having a minimum compressive strength of 17 MPa and a maximum density of 1840 kg/m^3.

The Cement and Concrete Association, of the United Kingdom, report that perlite concretes can be made with densities from 400 kg/m^3 to 640 kg/m^3 and compressive strengths of up to 5 MPa.[32] The American Concrete Institute document "Guide to structural lightweight concrete" gives the density range as 250 kg/m^3 to 800 kg/m^3 and strengths of up to 7 MPa.[33] Pratley Manufacturing and Engineering claim that densities from 300 kg/m^3 to 1000 kg/m^3 and compressive strengths up to 23 MPa are possible.[30] Chemserve do not make any claims in this regard.

The spectrum below places Perlite in perspective in terms of a continuum of lightweight aggregate concretes when comparing compressive strengths and densities. Clearly Perlite is generally regarded as a lightweight aggregate more suited to very low strength insulating applications.

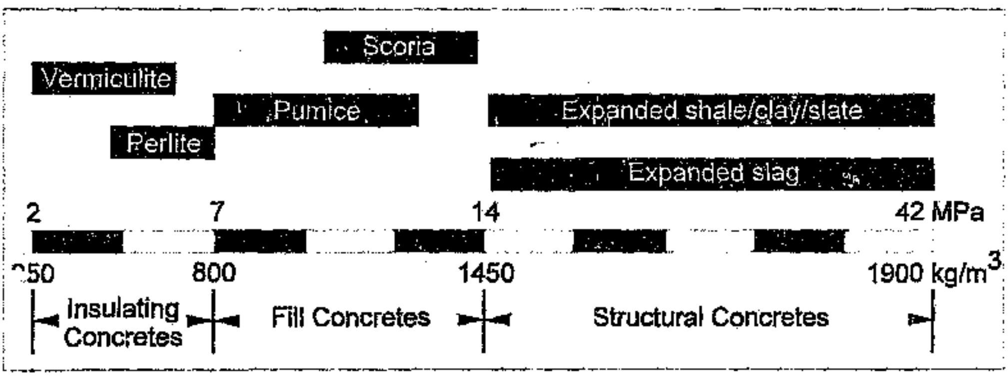

Figure 8
Continuum of lightweight aggregate concretes[33]

Chemserve perlite Genulite C95 is an acceptable aggregate in terms of both the American National Standards Institute specification ASTM C330-77 and South African Bureau of Standards specification SABS 794. A summary of the relevant points, taken from SABS 794 "Standard specification for aggregates of low density" follows :

- Lightweight aggregates covered by the specification include those prepared by expanding or sintering natural inorganic materials.
- Combined fine and coarse aggregates may not exceed a dry loose weight of 1040 kg/m^3. Successive shipments may not differ by more than 10% from an accepted sample.
- Inorganic impurities or staining materials are permitted within limits. Clay lumps not to exceed 2% by dry weight.
- Loss on ignition not to exceed 5%.

Chemserve perlite Genulite C95 is acceptable in all the above respects.

CHAPTER THREE

GRADING

GRADING

GRADING THEORY

The grading of aggregates refers to the distribution of particles of various sizes, and is determined by passing a representative sample through a series of standard sieves.

Standard sieve sizes are 4750, 2360, 1180, 600, 300, 150, and 75 microns for fine aggregate, as specified in SABS 1083 - 1976, "Aggregates from natural sources". The sizes of the openings in the consecutive sieves are approximately twice that of the next smaller size.

Fine aggregate particle shape and surface texture has a major effect on water demand. Grading has a minor effect on water demand but a major influence on workability, cohesion and bleeding properties of a mix in the plastic state.

Grading of an aggregate refers to the frequency of occurrence of particles of every size present. The characteristics of an individual particle are not of interest but rather the mean characteristics of a large number of particles.

In determining the grading profile of any particular aggregate, a sample is weighed and passed through a stack of standard nesting sieves. The sample is usually mechanically shaken for 5 minutes, or until not more than 1% of the total sample mass passes any one sieve during one minute of continuous sieving. The material retained on each sieve is then weighed and tabled. The individual weights are calculated as a percentage of the total sample. This is recorded as the percentage retained at that sieve size. Figures are calculated for the percentage of the total sample that would pass a given sieve, as a measure of how much of the total sample is larger or smaller than that size.

Authors Irani and Callis, in their book "Particle size - Measurement Interpretation and Application", state that a monodisperse system of particles is composed of the same sized particles whereas different sized particles are found in a polydisperse system. [34] Monodisperse systems are rarely encountered in nature. A monodisperse system will exhibit a large percentage of voids (in the loose dry state), as same sized particles do not interlock or "pack" well with one another. When blending two differently sized monodisperse systems, the void content (in the loose dry state) is found to decrease.

Weymouth's theory of particle interference calculated mathematically that the particles of each size group are distributed throughout the mix in such a way that the distance between them is equal to the mean diameter of particles of the next smaller size group plus the thickness of the cement films between them. This implies that for optimum gradings there always exists an optimum clear distance between adjacent particles of the same size as they lie in the placed concrete. The optimum distance is such that each particle size has sufficient space to move into the space between particles of the next larger size. To prevent harsh mixes, the closeness of packing in the concrete should be such that the average clear distance between particles of the same size should be not smaller than the average diameter of the next smaller size group.[35]

Sieve sizes taken from the Tyler series are therefore always half the preceding size.

Visualise the particles of an aggregate as the perfectly round spheres shown below, with their diameters given in micrometres.

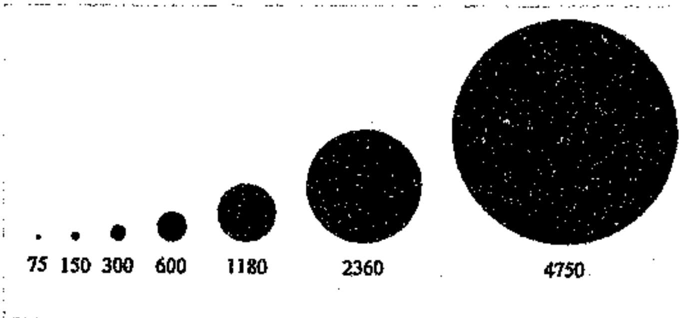

Figure 9
Relative proportions of particle sizes

Imagine that all the particles in a specific fraction are exactly the same size. The question is "What are the optimum proportions of each particle size for the ideal arrangement of particles leading to the best quality concrete?".

The problem with this visualisation is that the particles in a size fraction are not one size, but are distributed between that sieve size and the next larger sieve. The mean particle size within that fraction will lie somewhere between the maximum and the minimum, closer to the adjacent fraction which has a higher percentage retained. Assuming that the mean lies approximately in the middle of a fraction then the average particle size of the 600 micron fraction is 890 microns.

The parabolic curve of maximum density was first presented by Fuller and Thompson in 1907, as an attempt to describe the optimum grading of an aggregate in such a way that each particle fills the space between particles of the next larger size. This would result in the least number of voids and the least cement paste required to fill those voids. The so called "Fuller" gradings are only optimal within a narrow range of cement contents and limited maximum particle size.[36]

Parabolic curves, known as Fuller curves, are in fact percentage gradings, where the amount of material retained on each successive sieve is a fixed percentage of the quantity on the preceding (larger) sieve. These particle distributions are known as continuous gradings. Continuous, or smooth, gradings are those distributions in which there is a more or less even distribution of particle sizes, without a predominance or absence of any one size. An excess of 35% of one size as a percentage of the total is generally considered undesirable.[37]

Popovics writes in "Comparison of several methods of evaluating aggregate gradings" that absolute optimum gradings do not exist but that for given conditions of maximum particle size and cement content there is always a Fuller grading that will give a higher compressive strength than any other grading. That grading is known as the optimum grading.[38]

Although the Fuller curve has been modified by other researchers, mainly to allow for an increase in the percentage of fines, it has remained the basis for acceptance of continuous gradings.

Other authorities have disagreed, claiming that under certain circumstances gap gradings could be superior to continuous gradings. Gap gradings are particle distributions where one or more particle sizes are deficient or missing.

Feret M "Investigations upon the granulometric composition of sands"
Glanville W "The grading of aggregates and the workability of concrete"
Mercer L "The law of grading for concrete aggregates"

Feret, who was the first to develop the water/cement ratio law for concrete strengths before the turn of the century, claimed that gap gradings could be superior to continuous gradings.[39]

Glanville asserted that provided concrete is compacted to the point where air pockets are eliminated, then the compressive strength and other properties of the hardened concrete will be independent of the aggregate grading method and plasticity of the mix.[40]

Mercer stated that concrete mixes with aggregates having gap gradings can present superior placeability by comparison with those having continuous gradings, for the same water/cement, cement/aggregate, and sand/stone ratios.[41]

Fulton's concrete technology manual states that there is no optimal grading for fine aggregates, as determined from first principles. Rather, the percentages of an aggregate which occur in any one size, should fall within certain limits. The upper and lower limits are broadly defined for general purpose concretes and more narrowly defined for specialised concretes. Table 5 contains these limits.[42]

Table 5
Guide to fine aggregate grading - Fulton's limits.
Percentage passing

Size micrometre	Suggested outer limits	Preferred limits
4 750	85 - 100	90 - 100
2 360	60 - 100	75 - 100
1 180	40 - 100	60 - 90
600	30 - 75	40 - 60
300	15 - 45	20 - 40
150	5 - 20	10 - 20
75	0 - 12	3 - 6

Using an example to explain the meaning of Table 5, look at the limits for the 600 micron particle size. The table shows that as long as the percentage of a sample that will pass the 600 micron sieve is more than 30% and less than 75% of the total, the sand may be suitable for general purpose concrete. The preferred limits for specialist concrete work are more strictly defined, as more than 40% and less than 60% of the total sample by mass at the same sieve.

Figure 10 is a distribution plot of the "Fulton" limits of aggregate grading by percentage **retained** at each specific sieve size. This representation of grading indicates the actual percentage of a sample which falls between two sieve sizes and not the cumulative percentage of the sample passing any size.

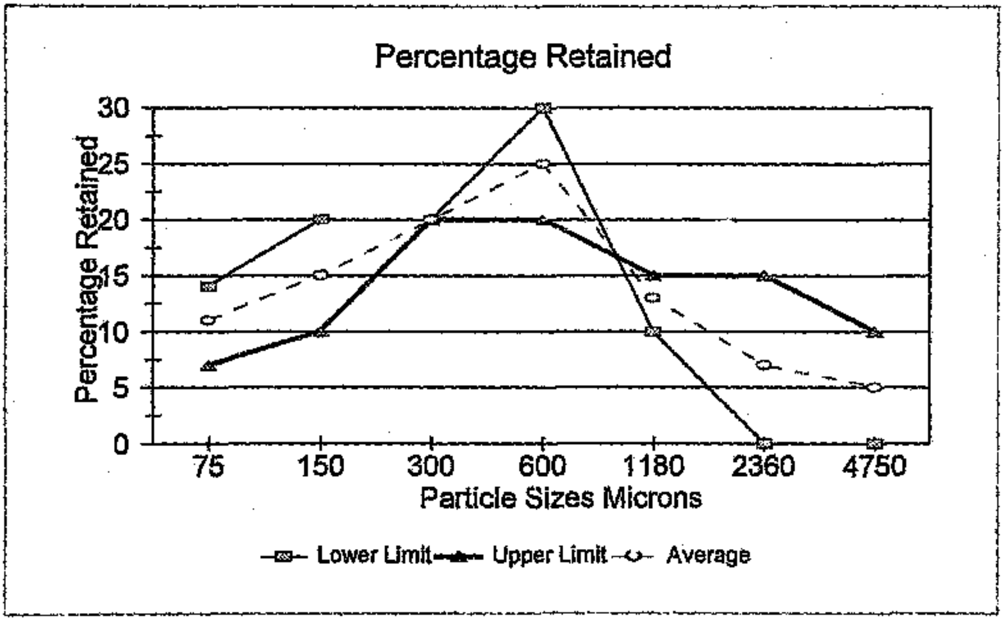

Figure 10
"Fulton" preferred limits by percentage retained

A grading is assumed to exist along the upper limit and another grading along the lower limit. The average is simply the upper and lower limits added and divided by two, and indicates that a normal distribution of particle sizes is desirable.

The fineness modulus (FM) of an aggregate is an index which describes the overall coarseness or fineness of a material. It is a measure of the average particle size and does not describe grading. Since an infinite number of gradings can be obtained that will give the same fineness modulus, and since these gradings can be continuous or not, the fineness modulus has fallen from favour as a method of designing concrete mixes. SABS 794 does not specify a fineness modulus for lightweight aggregates except to say that any one shipment may not differ by more than 7% from an agreed sample. Fulton's "suggested" lower and upper limits for concrete sands give FM's of 1.60 and 3.65 respectively, while the "preferred" lower and upper limits give FM's of 2.00 and 3.00.

The fineness modulus is calculated by simply adding up the figures for cumulative percentage retained at each sieve, excluding sub 150 micron, and dividing by 100. An example of this calculation, using Fulton's limits for concrete sands, is contained in Appendix Two.

Generally speaking, assuming constant loading conditions, the strength of a perfectly cured and compacted concrete depends on three things:

- The strength of the aggregate.
- The strength of the cement glue.
- The strength of the bond to the aggregate.

Because the compressive strength of commonly used aggregates far exceeds the concrete strengths sought, it is either the cement glue or the bond to the aggregates that is the limiting factor in a concrete strength.

Cement is usually the most expensive component of the material cost of a concrete. For this reason a designer will seek to minimise its use and still achieve the goal sought. For this reason the particles must pack together very closely minimising the spaces between particles.

In conventional concretes, the designer is also looking for a minimum surface area of all the aggregates added together, in order to reduce the amount of cement paste required to "wet" those surfaces. Seeking only to minimise the surface area leads to excessive interstices or voids between particles. "Optimum" gradings seek to minimise the interstices, while at the same time minimising the total surface area, thereby reducing both the volume of cement paste required to fill the voids between particles, and wet all the surfaces.

When designing lightweight concretes however, the weakest link is often no longer the cement paste, but rather the compressive strength of the aggregate. Lightweight aggregates usually have individual strengths far lower than the strength of the concrete sought. In some cases the lightweight aggregates can be said to add nothing to the strength. All the strength must come from the cement paste, as is the case in cellular concretes.

Lightweight aggregates provide a structure around which the cement paste forms. The aggregates define the thickness, slenderness, and positioning of the cement walls. All this is critical to the way in which a lightweight aggregate concrete performs the function of distribution of compressive loading.

This is the central concept that defines this research project. Is there another aggregate grading that will yield superior strength versus density performance in lightweight aggregate concretes?

A paper entitled "Influences of properties of gradation of lightweight aggregate on the Fg of a lightweight aggregate concrete" by How-Ji Chen (et al), presented at the International symposium on structural lightweight aggregate concrete held in Norway 1995, introduced the concept of a dividing strength (Fg) of a lightweight aggregate.[illegible]

Since the strength of a particle of lightweight aggregate is less than that of the mortar, a critical point, known as the dividing strength (Fg) exists. This dividing strength is the point in stress behaviour which occurs when the values of modulus of elasticity of the lightweight aggregate and the mortar are equal. Very often, processed lightweight aggregates such as Perlite, demonstrate increasing porosity and decreasing particle density with increasing size. The converse is also said to be true.

Experiments showed that achievable strengths of lightweight concretes increases with decreasing w/c ratio, a well understood concept in normal weight concretes. However after reaching a threshold compressive strength, the tendency to increase lessens.

This point is known as the dividing point (strength), and is a function of the physical characteristics of the lightweight aggregate used. Above the dividing point it is the failure of the aggregate and not the mortar which governs the compressive strength of the concrete. Up to the dividing point the cement content may be increased with the effect of raising the compressive strength, while above this point, increases in the cement content will be less effective.

The paper showed experimentally that as the maximum particle size increased, so the compressive strength at the dividing point decreased. The corollary is that as the particle size decreases so the compressive strength at the dividing point, and hence the achievable strength, increases. This concept plays a vital role in the selection of gradings for testing of the particle distribution theories.

South African standard SABS 794 Aggregates for low density concrete, and American standard ASTM C330-77 Lightweight aggregates for structural concrete have differing grading requirements. These are compared below, together with the Fulton's limits.

Table 6
Grading limits for lightweight aggregates
ASTM C330 - 77 and SABS 794 - Percentage passing

Size microns	SABS 794	C330-77	Fulton's preferred limits	Fulton's suggested limits
4 750	90 - 100	85 - 100	90 - 100	85 - 100
2 360			75 - 100	60 - 100
1 180		40 - 80	60 - 90	40 - 100
600			40 - 60	30 - 75
300		10 - 35	20 - 40	15 - 45
150	0 - 10	5 - 25	10 - 20	5 - 20
75			3 - 6	0 - 12

Comparing this information with the Fulton's preferred limits, it is clear that the grading requirements are not excessively strict, especially those of SABS 794. The figures do however indicate a preference towards coarser gradings.

CONTROL GRADING

In order to commence defining the perlite aggregate gradings for testing purposes the first step is to analyse a standard bag of Chemserve Perlite Genulite C95 as sold for lightweight concrete.

For this purpose three 100 litre bags were acquired. On opening it was found that the bagged product was insufficiently homogenous, in grading, for laboratory purposes. Six samples were then taken from various positions in one bag for grading analysis.

Table 7
Grading of six samples of Perlite C95 by percentage retained.

Size Micrometre	Top Left	Top Right	Centre	Bottom Left	Bottom Centre	Bottom Right
4 750	0.24	0.06	0.65	0.76	0.11	0.38
2 360	23.47	23.48	38.55	35.21	20.41	32.82
1 180	31.30	32.44	29.93	29.56	32.94	36.75
600	14.96	15.96	9.81	10.01	13.44	11.90
300	10.62	9.44	6.32	6.89	11.21	6.08
150	7.85	6.35	4.79	5.58	9.02	3.62
FM	3.18	3.21	3.63	3.48	3.06	3.65

Fineness modulus of the six samples range from 3.06 to 3.65 with an average of 3.36, which represents a variation of 20%. It is interesting to note that the fineness modulus does not necessarily decrease with distance from the top of the bag but that pockets of varying grading form within the bag.

Having decided that the grading of the bagged product was insufficiently constant, the entire 100 litre bag was sieved and analysed. The results appear in Table 8.

Table 8
Grading of Perlite C95 - entire 100 Litre bag

Size Micrometre	% Retained	∑ % Retained	% Passing
4 750	2.66	2.66	97.34
2 360	28.16	30.82	69.18
1 180	32.87	63.69	36.31
600	12.53	76.22	23.78
300	8.86	85.08	14.92
150	6.21	91.29	8.71

The control grading will be reconstituted for every control mix by measuring out the specific amount of each particle size required. In other words, the individual particle sizes are stored separately and are recombined in the desired proportions for each and every mix, as needed. The control grading varies slightly from that of the "entire 100 litre bag" grading, in order to facilitate the weighing process, but it is intended to represent the average grading of Genulite C95 as received from the supplier. Table 9 below compares the control grading with the "entire 100 litre bag" grading.

Table 9
Control grading and entire 100 Litre bag grading compared.

Size microns	100 Litre % Retained	Control % Retained	100 litre ∑% retained	Control ∑% Retained	Control % pass
4 750	2.66	2.00	2.66	2.00	98.00
2 360	28.16	28.00	30.82	30.00	70.00
1 180	32.87	32.00	63.69	62.00	38.00
600	12.53	14.00	76.22	76.00	24.00
300	8.86	8.00	85.08	84.00	16.00
150	6.21	6.00	91.29	90.00	10.00
FM			3.50	3.44	

Figure 11 below plots the Control grading distribution by percentage passing.

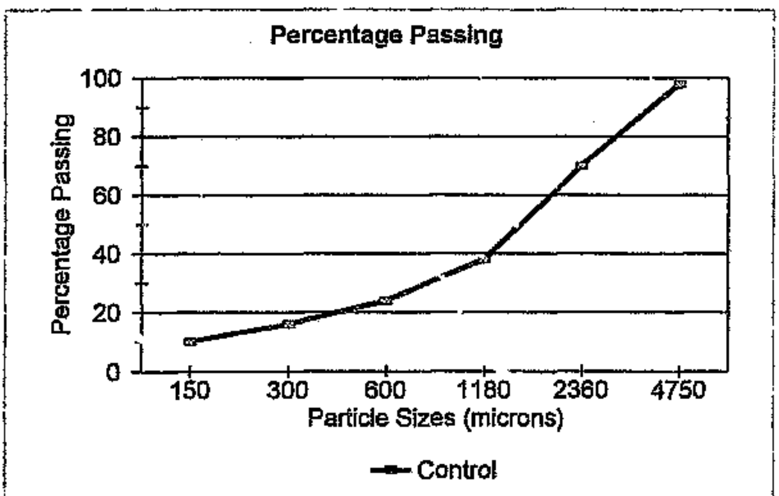

Figure 11
Control grading C 3.44
Percentage passing

Comparing the Control grading with the Fulton's "suggested" limits, and with the requirements of both the ASTM and SABS standards for lightweight aggregates it is found that this grading fails to fall within either of the two Fulton's set of limits and does not satisfy the requirements of ASTM C330-77. The grading does satisfy the requirements of SABS 794 : 1994 Aggregates of Low Density.

Table 10
Control grading C 3.44 - Percentage passing
Fulton and SABS 794, limits compared

Size micron	Control grading	Fulton's suggests		Fulton's prefers		ASTM		SABS	
4 750	98	85 - 100	ok	90 - 100	ok	85 -100	ok	90 - 100	ok
2 360	70	60 - 100	ok	75 - 100	no		ok		ok
1 180	38	40 - 100	no	60 - 90	no	40 - 80	no		ok
600	24	30 - 75	no	40 - 60	no		ok		ok
300	16	15 - 45	ok	20 - 40	no	10 - 35	ok		ok
150	10	5 - 20	ok	10 - 20	ok	5 - 25	ok	0 - 10	ok
75		0 - 12	ok	3 - 6	ok		ok		ok

FINENESS MODULUS BY VOLUME

American Concrete Institute document, "Standard practice for selecting proportions for structural lightweight concretes", suggests that when analysing the grading of a lightweight aggregate it becomes necessary to calculate the fineness modulus, not by weight retained, but by volume retained at each sieve. This is because the bulk density of each fraction generally increases as the particle size decreases. The volume occupied by each fraction determines the particle interaction and hence the void content.[44]

Loose bulk densities were measured for each specific fraction and are recorded in Table 11. In each case the loose bulk density was measured six times in order to best represent the condition of that fraction. The results are given in Table 11, to the nearest 5 kg/m^3.

It was anticipated that the loose bulk densities of the fractions would tend to increase with diminishing particle size. Measurement showed that loose bulk densities of the fractions varied, due to the presence of perlite ore particles which had not expanded on heating (see Figure 12).

Table 11
Loose bulk densities of all size fractions

Size microns	Loose bulk density grammes per litre
4 750	90.0
2 360	125.0
1 180	230.0
600	140.0
300	165.0
150	205.0
DUST	185.0

Carefully selecting only the lightest material in the 300 micron fraction, the loose bulk density was found to be 85 kg/m^3. Carefully selecting as much of the heavier unexpanded material as possible, the loose bulk density was found to be 445 kg/m^3. Taking six randomly selected samples, of the 300 micron material, the loose bulk density was found to be an average of 165 kg/m^3.

Figure 12 illustrates a particle of unexpanded Perlite ore surrounded by white expanded particles.

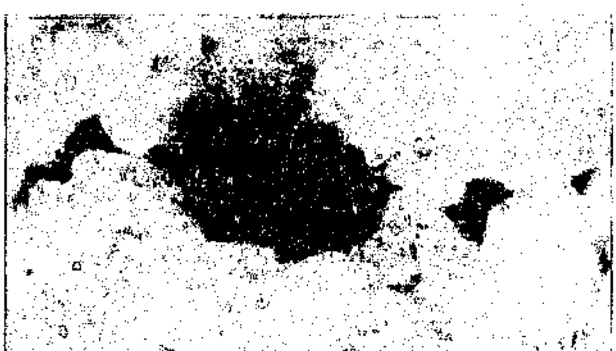

Figure 12
Unexpanded perlite ore particle

When calculating the fineness modulus, by volume, for the Control grading, assume a sample of 100 grammes. The percentage retained at each sieve is therefore the weight in grammes retained. The weight in grammes retained at each sieve is converted to a volume by dividing by the loose bulk density. Computing each volume retained, as a percentage of the total volume, the fineness modulus is derived from the cumulative percentage passing figures, given in Table 12 below.

Table 12
Calculating Fineness Modulus by Volume

Size microns	Percent retained by mass	L B D grammes per litre	Volume retained in litres	Percent retained by volume	∑ Percent retained by mass	∑ Percent retained by volume
4 750	2.0	90.0	0.0222	3.60	2.0	3.6
2 360	28.0	125.0	0.2240	36.29	30.0	39.9
1 180	32.0	230.0	0.1391	22.54	62.0	62.4
600	14.0	140.0	0.1000	16.20	76.0	78.6
300	8.0	165.0	0.0485	7.86	84.0	86.5
150	6.0	205.0	0.0293	4.75	90.0	91.2
75	10.0	185.0	0.0541	8.76		
FM					**3.44(m)**	**3.62(v)**

In our example using the control grading, the fineness modulus is higher when calculated by volume than when calculated by mass. This means that the grading is coarser than first thought. Fineness modulus figures will be differentiated by means of the suffix m (mass) or v (volume).

PURPOSE DESIGNED GRADINGS FOR TESTING

In order to test the theories of grading in lightweight applications, eight purpose designed grading blends will be reconstituted from individual fractions for comparison with the control.

A scalped grading being the control grading with particle sizes 2360 microns and above removed.

1. Scalped grading FM 2.77 "S 2.77" Table 13.

Three polydisperse gradings, each with an approximate normal distribution of increasing mean, and FM.

2. Polydisperse grading FM 2.0 "P 2.00" Table 14.
3. Polydisperse grading FM 3.0 "P 3.00" Table 15.
4. Polydisperse grading FM 4.0 "P 4.00" Table 16.

Four Monodisperse gradings each with all particles from only one fraction.

5. Monodisperse grading FM 1.0 "M 1.00" Table 17.
6. Monodisperse grading FM 2.0 "M 2.00" Table 18.
7. Monodisperse grading FM 3.0 "M 3.00" Table 19.
8. Monodisperse grading FM 4.0 "M 4.00" Table 20.

Table 13
Scalped grading S 2.77

Size microns	Percent retained by mass	∑ Percent retained by mass	Percent passing by mass	∑ Percent retained by volume
4 750	0	0	100	0
2 360	0	0	100	0
1 180	46	46	54	43
600	20	66	34	74
300	12	78	22	89
150	9	87	13	98
FM		**2.77(m)**		**3.04(v)**

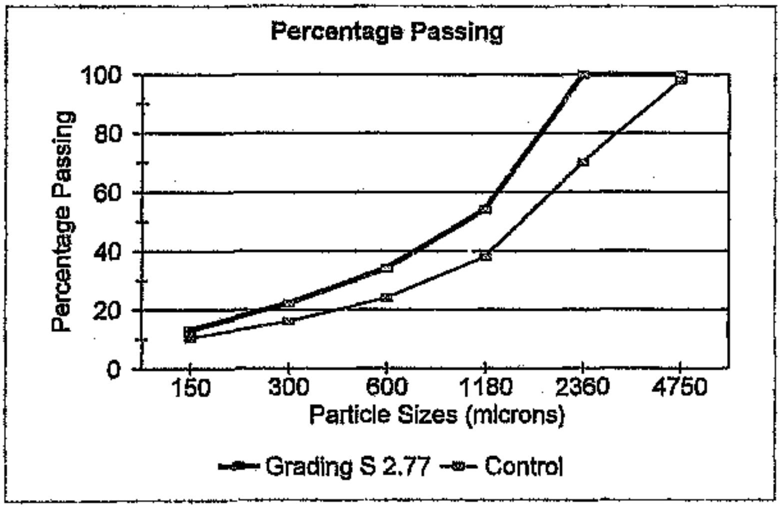

Figure 13
Scalped grading S 2.77
Percentage passing

Table 14
Polydisperse grading P 2.00

Size microns	Percent retained by mass	∑ Percent retained by mass	Percent passing by mass	∑ Percent retained by volume
4 750	0	0	100	0
2 360	0	0	100	0
1 180	10	10	90	7
600	20	30	70	32
300	40	70	30	74
150	20	90	10	91
FM		**2.00(m)**		**2.04(v)**

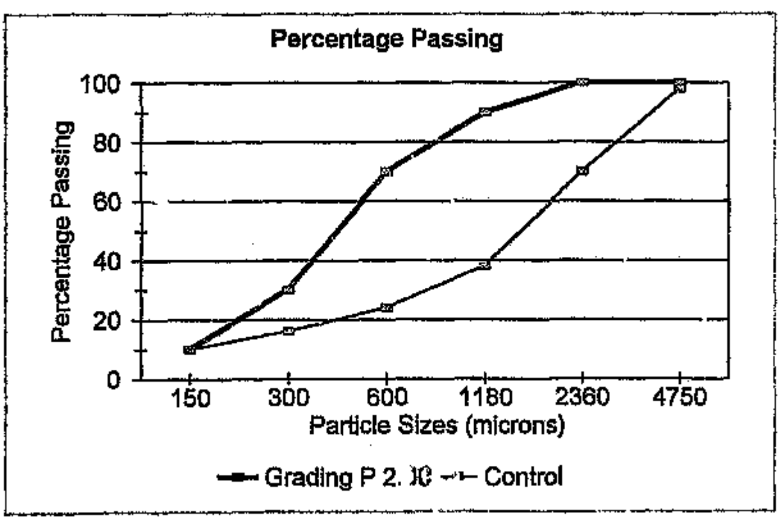

Figure 14
Polydisperse grading P 2.00
Percentages passing and retained

Table 15
Polydisperse grading P 3.00

Size microns	Percent retained by mass	∑ Percent retained by mass	Percent passing by mass	∑ Percent retained by volume
4 750	0	0	100	0
2 360	10	10	90	13
1 180	20	30	70	27
600	40	70	30	73
300	20	90	10	92
150	10	100	0	100
FM		**3.00(m)**		**3.05(v)**

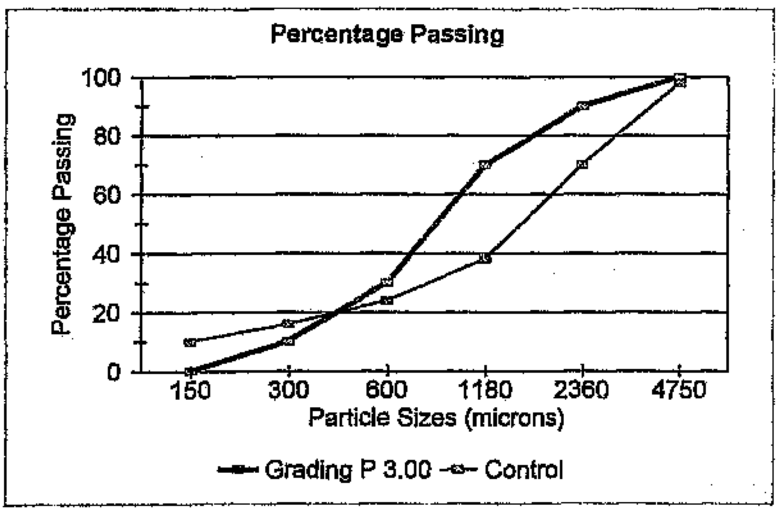

Figure 15
Polydisperse grading P 3.00
Percentage passing

Table 16
Polydisperse grading P 4.00

Size microns	Percent retained by mass	∑ Percent retained by mass	Percent passing by mass	∑ Percent retained by volume
4 750	10	10	90	17
2 360	20	30	70	42
1 180	40	70	30	69
600	20	90	10	91
300	10	100	0	100
150	0		0	100
FM		**4.00(m)**		**4.19(v)**

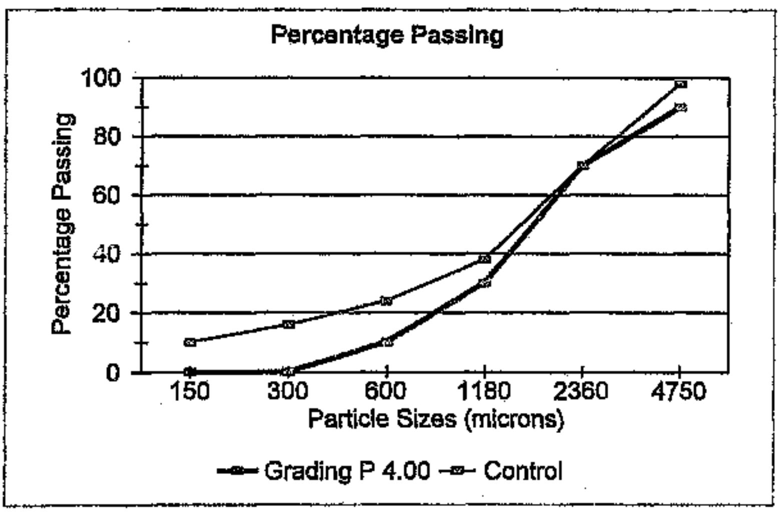

Figure 16
Polydisperse grading P 4.00
Percentage passing

Table 17
Monodisperse grading M 1.00

Size microns	Percent retained by mass	∑ Percent retained by mass	Percent passing by mass	∑ Percent retained by volume
4 750	0	0	100	0
2 360	0	0	100	0
1 180	0	0	100	0
600	0	0	100	0
300	0	0	100	0
150	100	100	0	100
FM		**1.00(m)**		**1.00(v)**

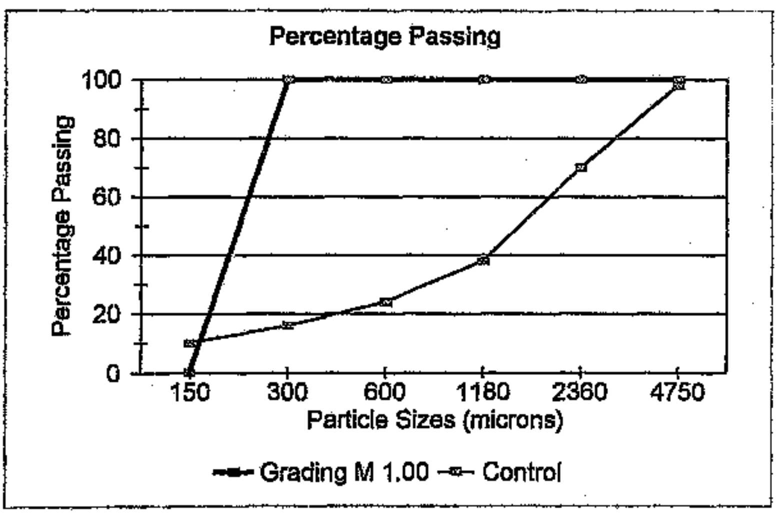

Figure 17
Monodisperse grading M 1.00
Percentage passing

Table 18
Monodisperse grading M 2.00

Size microns	Percent retained by mass	∑ Percent retained by mass	Percent passing by mass	∑ Percent retained by volume
4 750	0	0	100	0
2 360	0	0	100	0
1 180	0	0	100	0
600	0	0	100	0
300	100	100	0	100
150	0	100	0	100
FM		**2.00(m)**		**2.00(v)**

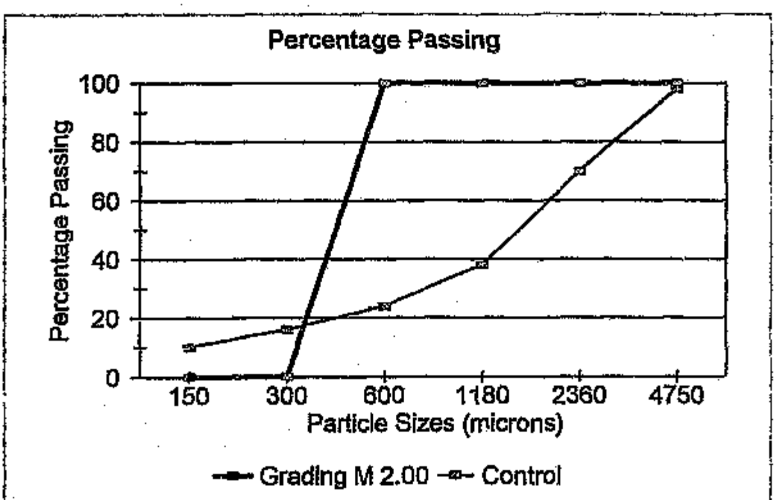

Figure 18
Monodisperse grading M 2.00
Percentage passing

Table 19
Monodisperse grading M 3.00

Size microns	Percent retained by mass	∑ Percent retained by mass	Percent passing by mass	∑ Percent retained by volume
4 750	0	0	100	0
2 360	0	0	100	0
1 180	0	0	100	0
600	100	100	0	100
300	0	100	0	100
150	0	100	0	100
FM		**3.00(m)**		**3.00(v)**

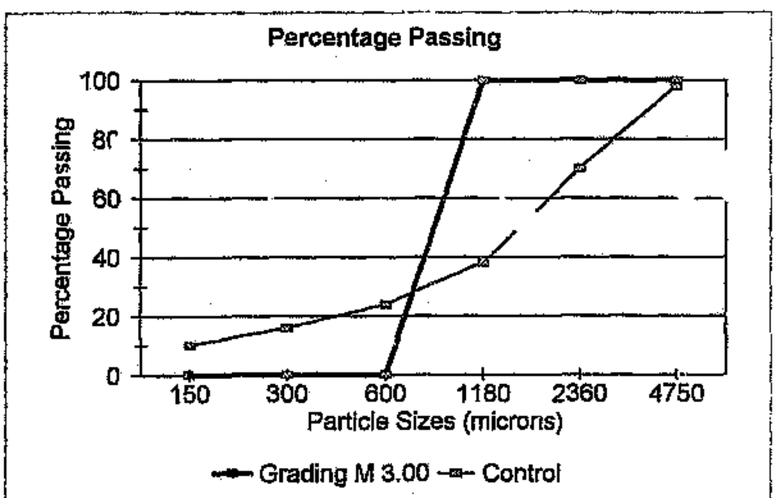

Figure 19
Monodisperse grading M 3.00
Percentage passing

Table 20
Monodisperse grading M 4.00

Size microns	Percent retained by mass	∑ Percent retained by mass	Percent passing by mass	∑ Percent retained by volume
4 750	0	0	100	0
2 360	0	0	100	0
1 180	100	100	0	100
600	0	100	0	100
300	0	100	0	100
150	0	100	0	100
FM		**4.00(m)**		**4.00(v)**

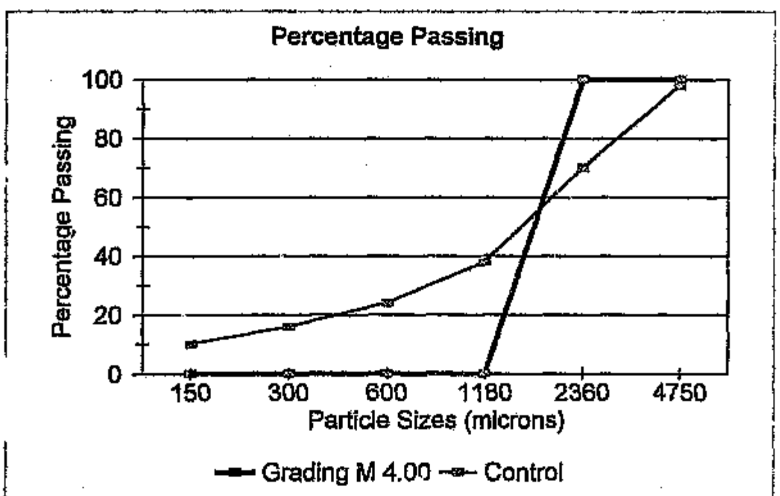

Figure 20
Monodisperse grading M 4.00
Percentage passing

The preceding tables are summarised in a quick comparison form in Table 21, containing the percentages retained and Table 22, containing the percentages passing.

Table 21
Comparison of all tested gradings
Percentage retained

Size microns	C 3.44	S 2.77	P 2.00	P 3.00	P 4.00	M 1.00	M 2.00	M 3.00	M 4.00
4 750	2	0	0	0	10	0	0	0	0
2 360	28	0	0	10	20	0	0	0	0
1 180	32	46	10	20	40	0	0	0	100
600	14	20	20	40	20	0	0	100	0
300	8	12	40	20	10	0	100	0	0
150	6	9	20	10	0	100	0	0	0
FM mass	**3.44**	**2.77**	**2.00**	**3.00**	**4.00**	**1.00**	**2.00**	**3.00**	**4.00**
FM volume	**3.62**	**3.04**	**2.04**	**3.05**	**4.19**	**1.00**	**2.00**	**3.00**	**4.00**

Table 22
Comparison of all tested gradings
Percentage passing

Size microns	C 3.44	S 2.77	P 2.00	P 3.00	P 4.00	M 1.00	M 2.00	M 3.00	M 4.00
4 750	98	100	100	100	90	100	100	100	100
2 360	70	100	100	90	70	100	100	100	100
1 180	38	54	90	70	30	100	100	100	0
600	24	34	70	30	10	100	100	0	0
300	16	22	30	10	0	100	0	0	0
150	10	13	10	0	0	0	0	0	0

All grading blends to be tested are defined and will be tested according to the testing procedures to be defined in Chapter Four.

CHAPTER FOUR

TEST METHODOLOGY

CHAPTER FOUR

TEST METHODOLOGY

TEST METHODOLOGY

LABORATORY

All laboratory testing was carried out at the concrete testing facilities of Pretoria Portland Cement (PPC) factory at Jupiter.

The laboratory has the responsibilities of routine quality control, customer services and research and development. The laboratory environment, the methods and procedures are ISO 9002 accredited.

The working environment is temperature controlled between 22°C and 25°C and the relative humidity is maintained between 55% to 70%.

Figure 21
Temperature and Humidity recorder

Grading of aggregates was carried out on a Ro-Tap mechanical sieve shaker, and analysed in terms of SABS method 829 1994 1st rev.

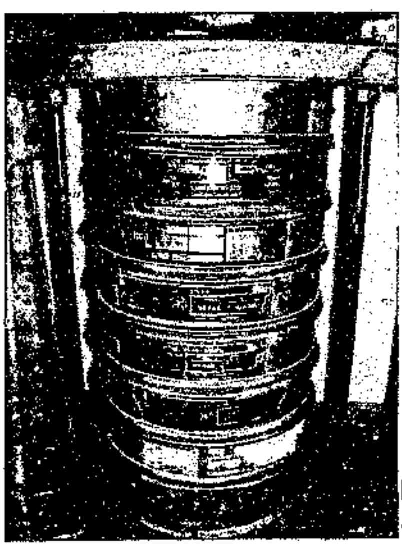

Figure 22
Stacking grading sieves

Portland cement used in all tests reported in this project was obtained from the lab silo (as required) and conforms to the SABS specification SABS ENV 197-1.1992.

All ingredients were measured out to a tenth of a gramme on Sartorius Excellence electronic balances. The contents of the mixing bowl was weighed immediately after mixing.

Mixing of all fresh mortar mixes took place using a Hobart automatic process controlled mixer, and according to a modified version of the standard procedure described in SABS EN 196 - 1: 1994. The reasons for the modification are detailed later in this chapter.

Figure 23
Hobart automatic mixer

In every case, the fresh mortar mix was tested for consistency using the Penetrometer test, according to the procedure described in test method SABS ENV 413 part 2. A plunger is dropped from a given height into a container of the fresh mortar mix. The depth of penetration is recorded. SABS ENV 413 part 1 defines standard penetration as 35 mm +/- 3 mm. Penetration results within a range of 6 mm are therefore deemed to indicate the equivalent degree of consistency.

The concept of standard consistency is intended as a means to establish a standard reference point when testing cements for strength. The amount of water required to bring a mortar to standard penetration is known as the water requirement of that mortar. Mortars at standard consistency can then be measured for other properties, such as air content, water retention, and workability (cohesivity). The principle of a standard mortar and standard laboratory procedures, is that all variables are eliminated leaving, only the qualities of the cement that are tested.

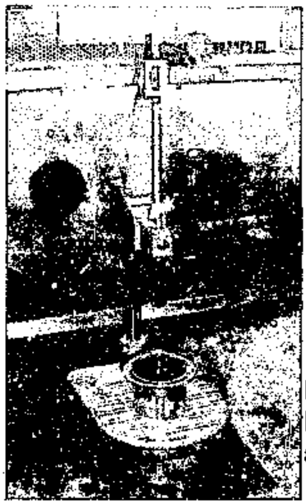

Figure 24
Penetrometer test apparatus

Three test specimens of 160 x 40 x 40 mm beams were cast from each mix. Beam moulds were filled on a vibrating table, set at a constant frequency of 3000 cycles per minute.

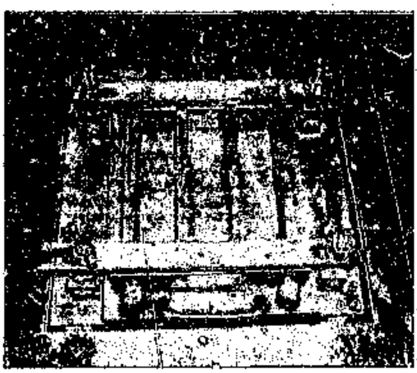

Figure 25
Beam mould and vibrating table

The beam mould and contents were immediately weighed and then marked for correct identification before being covered with a sheet of glass. Beams were stored in their moulds for the first 24 hours in a curing room at 22°C to 25°C and minimum 90% humidity.

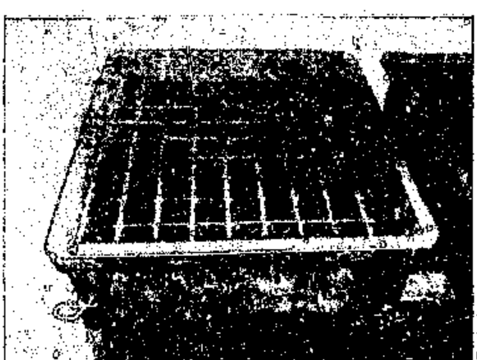

Figure 26
Curing tank

The following day the beams were individually weighed and then submerged in water at 22°C to 25°C for a further 27 days.

On completion of the curing duration of 28 days, the beams were wiped dry and weighed. Beams were then snapped in half on a Toni Technic transverse strength testing machine, and the loads at failure were recorded in Newtons. Beams were loaded at a constant loading rate of 3000 N/min.

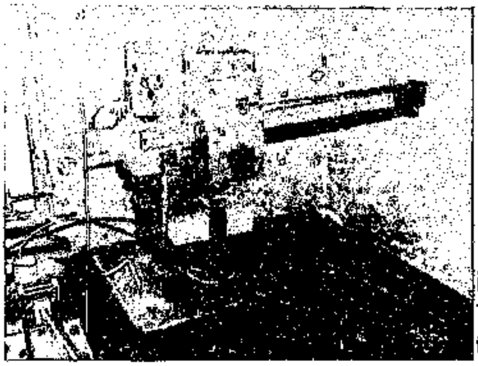

Figure 27
Toni Technic transverse strength test apparatus

Each half beam was then tested for compressive strength on a Denison crushing apparatus. Beams are loaded at a constant rate of 144 kN/min. The load at failure was recorded in kiloNewtons. This is converted to a strength in megaPascals by dividing the load by the area in compression, in square millimetres. Six sets of data were recorded for compressive strength and the mean was calculated.

Figure 28
Denison compressive strength test apparatus

The beam remains were dried in an oven at 60°C, until dry equilibrium was reached. Dry equilibrium is achieved when there is less than 1% change in weight over 24 hours. The oven dry weights were then recorded.

MIX DESIGN

Standard mix design theory of absolute volumes, developed using conventional materials, cannot be used for lightweight aggregate concretes. There are two principle reasons for this:

- The first reason is that when water is absorbed by the aggregates there is uncertainty regarding the water/cement ratio.
- The second reason is that when aggregates are porous there is uncertainty regarding the exact relative density. The mix design formula yields impossible solutions, such as 3300 litres of aggregate per cubic metre of concrete.

Mix design for conventional materials (fine aggregate only) by absolute volumes follows the following basic steps:

- Select an appropriate strength.
- Determine the water/cement ratio from precalculated graph.
- Predict water requirement for the necessary consistency.
- Calculate the cement content from the water requirement and the w/c ratio.
- Calculate the absolute volume of the aggregate by deducting the absolute volumes of water and cement from one cubic metre. Aggregate absolute volume is converted to mass by dividing by the relative density.

When designing lightweight concretes and applying the above steps, the following problems present themselves:

- Appropriate strengths may no longer be appropriate, given lower self weight.
- Water/cement ratio for appropriate strength is indeterminate.
- Water requirements are unknown.
- It follows that the cement content cannot be calculated.
- The absolute volume formula yields impossible solutions for volume of aggregate when loose bulk density is very low.

It is necessary to adopt another means of determining the correct proportions of constituents.

Commence with establishing the quantity of material required. Three beams of 160 x 40 x 40 mm occupy a volume of 768 ml. Allowing for 5% waste, the required volume of lightweight concrete is 800 ml. The principles of mix design using lightweight aggregates, as found in ACI document "Standard practice for selecting proportions for structural Lightweight concretes", suggests that the volume of aggregate should be up to 120% of the volume sought.[27] This volume of Perlite (120% of 800 ml) is 968 ml, and at a loose bulk density of 120 kg/m^3, weighs only 116 grammes.

Trials showed that 116 grammes of perlite yielded a totally inadequate volume to fill the three beam moulds. Mix design would therefore take place by trial and error.

The starting point was the requirement, of standard method SABS EN 196 - 1 : 1994, for a constant 450 grammes of cement per mix. Each mix would be tested across a range of water contents in order to later define the water content necessary for standard penetration and to select an appropriate constant water content for all mixes. The limits of water contents will be from "too dry" (unworkable), to too wet (particles float).

Trials indicated that 450 grammes of OPC, 225 grammes of perlite and 375 ml of water (w/c 0.83) yielded a wet mix of 1050 grammes. Three beams were cast, with an average wet weight of 337 grammes. The wet mix therefore contains 3.12 theoretical beam volumes, or 798 ml. This is only 30 ml more than required, or a waste of 3.9%, and is therefore acceptable.

MODIFICATION OF THE MIXING PROCEDURE

Mixing was carried out using the Hobart Automatic Mixer, initially according to the SABS EN 196 - 1 : 1994 process controlled procedure.

The procedure is as follows:

Weigh out all ingredients.
Add water to mixing bowl.
Add all cement.
Mix for 30 seconds at slow speed (140 rpm) before adding the aggregate.
Add aggregate steadily over the following 30 seconds, mixing at slow speed (140 rpm).
Change to fast speed (285 rpm) for a further 30 seconds.
STOP

Remove bowl and scrape sides and blade into the mixture for 1 minute and 30 seconds.
Replace and mix for 60 seconds at fast speed (285 rpm).
STOP

Initial trial mixes exhibited lower than expected yields. Over vigorous mixing may possibly have contributed to this.

A trial mix was carried out and wet screened. This involves washing the contents of each sieve, to remove all cement and water, leaving only the aggregate. The contents of the sieves are then dried and the grading re-analysed. Figure 29 illustrates the "before and after" curves, by percentage retained, for the control grading after mixing by the automatic process controller procedure. The fineness modulus was found to have reduced from 3.44 to 2.57, a reduction of 25%.

Note that particle sizes 4750, 2360, and 600 microns were all reduced in percentage retained, and that particle sizes 1180, 300, 150, and sub 150 microns were all increased. It is clear that the larger particle sizes were broken up into smaller sizes.

No specific weights are recorded below 150 microns as the sub 150 micron material is discarded together with the cement. This is because material this fine, forms a cake on the 75 micron screen and cannot be adequately washed. By subtracting the percentages retained at each sieve from the total sample it is possible to calculate the percentage of the total sample below 150 microns. It is this fraction that increased the most, indicating that a large portion of the particles are broken into much finer material during mixing.

The gradings are illustrated as percentage retained at each sieve in order to clearly demonstrate the changes in the amounts of material of that size in the sample.

Table 23
Comparison of before and after gradings.
Automatic process controlled procedure.

Size microns	Mass retained		% Retained		∑ % Retained		% Passing	
	Before	After	Before	After	Before	After	Before	After
4750	5	0	2	0	2	0	98	100
2360	63	23.6	28	10	30	10	70	90
1180	72	30.8	32	36	62	46	38	54
600	32	26.8	14	12	76	58	24	42
300	18	20.5	8	9	84	67	16	33
150	13	15.3	6	7	90	74	10	26
PAN	22	58.0	10	26	100	100	0	0
FM					**3.44(m)**	**2.57(m)**		

The fineness modulus decreased by of 25% from the "before mixing" grading to the resultant "after mixing" grading.

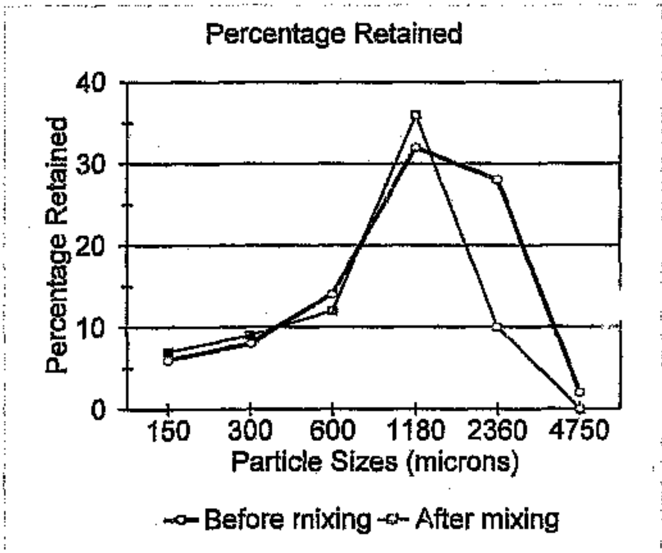

Figure 29
Before and after gradings - Percent retained
Automatic procedure

Two subsequent trial mixes of the control grading were carried out according to two other, less aggressive, mixing procedures. The results were then wet screened, dried and the grading reanalysed.

- Hand mixing according to a standard procedure.
- A semi automatic process using the Hobart mixer and mixing strictly in accordance with the time table but only at the slow (140 rpm) speed settings.

On plotting of the results it was found that the fineness modulus changed as follows:

Hand mixing	from 3.44 to 3.36, a change of 2.3%.
Semi automatic procedure	from 3.44 to 3.13, a change of 3%.

From the above the procedure it is clear that the hand mixing procedure is the least damaging to the aggregate. However, as this method is more susceptible to human error and is more time consuming, the decision was taken to use the semi automatic method and accept the increased change in fineness modulus.

Upon completion of the wet screening, oven drying and re-sieving, it was noted that the aggregates had changed in colour from pure white to light grey. The aggregate appeared to have absorbed water and cement. The loose bulk densities were rechecked and found to have increased by up to 92%.

Table 24
Change in Loose Bulk Densities (LBD)

Size microns	LBD "before"	Change	LBD "after"
2360	125	80%	225
1180	225	28%	288
600	143	92%	275
300	175	81%	316
150	250	61%	402

note: LBD measured in non standard cylinder of 100ml.

Figure 30 below illustrates the appearance of the perlite particles after wet sieving. Compare the photograph with Figure 6 and Figure 7 (Chapter Two). Penetration of cement into the particles is evident, through colour change, and damage to the particle surfaces is clearly visible.

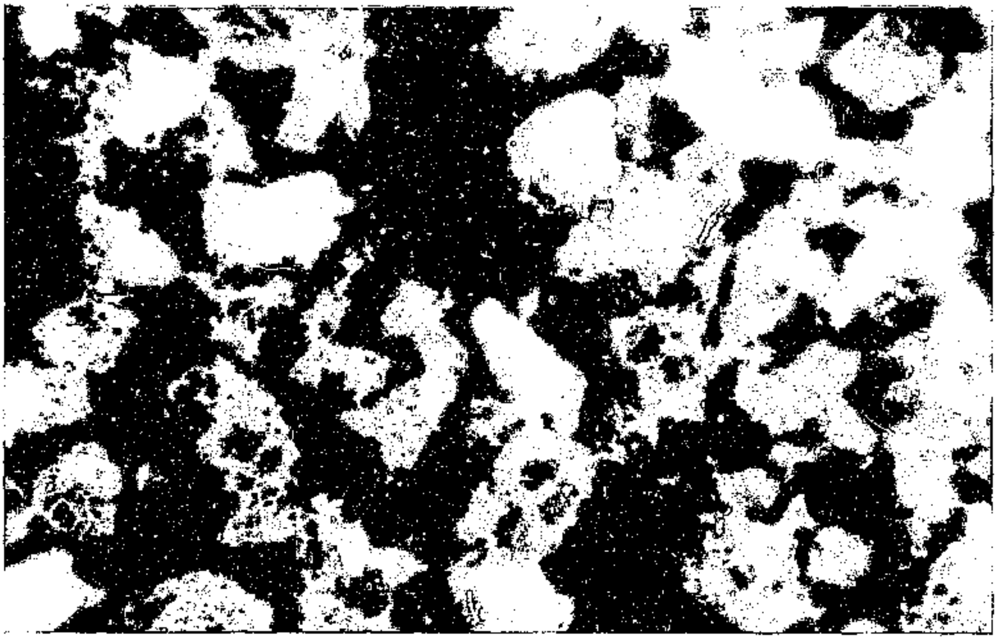

Figure 30
Used perlite after wet screening

APPROPRIATE SPECIFICATIONS

In all cases, tests performed were carried out in accordance with relevant specifications.

SABS 829 1994 - Sieve analysis, fines content and dust content of aggregates.
- Grading analysis.
  Tyler series sieves.

SABS 794 1973 - Standard specification for aggregates of low density.
- Loose bulk density measurements.

SABS EN 196 1994 - Methods of testing cement - Determination of strength.
- Cement content.
- Mixing as modified.
- Test specimens.
- Curing.
- Transverse and compressive strength tests.

SABS ENV 413 1994 - Masonry cement specification
- Consistency by penetration

SABS SM 861 1994 - Concrete tests - Making and curing of test specimens
- Casting and vibration.

CHAPTER FIVE

ESTABLISHING A CONTROL

ESTABLISHING A CONTROL

For the purposes of a control mix design, a number of points are restated:

1. Perlite and cement and water are the only materials to be used.
2. The cement content will remain the same for all mixes.
3. A perlite grading has been defined for use in all control mixes and will be tested across a range of water contents (w/c ratio).
4. The cement content is to remain relatively low, yielding low concrete strengths. This is in order that any effect of grading may be more clearly interpreted.

The function of a control is to establish a set of plastic state and hard state qualities against which the effect of variations in mix proportions and grading may be measured.

The grading utilised for the Control was titled the "Standardised" grading, as defined in Chapter Three "Grading". This grading was determined by sieving an entire 100 litre bag of "C95" perlite, as received from the supplier. For the simplicity of presentation and laboratory measurement, "percentages retained" have been rounded off to the nearest gramme.

Table 25
Control grading by mass retained. FM = 3.44(m)

Size microns	% Retained	Mass retained grammes	% Passing
4750	2	5	98
2360	28	63	70
1180	32	72	38
600	14	32	24
300	8	18	16
150	6	13	10
DUST	10	22	0
TOTAL	100	225	

The cement content was selected to be 450 grammes of OPC as this is consistent with the standard beam test for testing cement strength in SABS EN 196 - 1 : 1994.

Mixes were attempted across a range of water contents yielding concretes from "too dry" (insufficient compaction - unworkable) to "too wet" (segregated - particles floated).

Those results defined as" too dry" or "too wet" were discarded and only the remaining mixes are recorded.

On completion of the mixing process, the mixing tub and contents are weighed. This mass should equal the sum of all ingredient masses. This is intended as a check on the accuracy of the measurement and batching of individual ingredients. The penetration test is carried out and recorded. The beams are then cast and vibrated, and the mould and contents are weighed. Deducting the mould weight from the weight of the mould and contents, the average beam weight is calculated.

Dividing the tota' yield weight by the average beam weight, we find the number of beam volumes in the yield. Multiply the number of beam volumes in the yield by the beam volume and we find the actual volume yield of that mix.

Beams are 160 mm long, 40 mm wide, 40 mm high and have a volume of 256 ml.

Dividing the cement content of the mix in grammes by the volume yield in millilitres, and then multiplying by the beam volume, we find the actual cement content of the beams, as cast. The equivalent cement content per cubic metre is calculated by converting to kg per m^3.

This information, known as the Plastic State Data, is presented in Table 26. As an example, the first control mix performed was C 3.44/0.80.

Cement OPC	450 g
Graded Perlite "C"	225 g
Water H_2O	360 g

This mix is identified as C 3.44/0.80, where C is the grading code (C = Control), 3.44 is the fineness modulus, and 0.80 is the relevant w/c ratio.

Plastic State Data:

Water cement ratio	0.80
Penetration	10 mm
Actual mass yield	1032 g
Average wet beam mass	305 g

Volume yield in millilitres = Equivalent beam volumes x volume of beam

$$= \frac{\text{Mass yield}}{\text{Ave beam mass}} \times 256 \text{ ml}$$

$$= \frac{1032 \text{ g}}{305 \text{ g}} \times 256 \text{ ml}$$

$$= \underline{866 \text{ ml}}$$

Cement content of a beam in grammes per beam

$$= \frac{\text{Cement in mix}}{\text{Volume yield}} \times \text{vol of beam}$$

$$= \frac{450 \text{ g}}{866 \text{ ml}} \times 256 \text{ ml}$$

$$= \underline{133 \text{ g}}$$

Equivalent cement content per cubic metre

$$= \frac{\text{Cement in mix}}{\text{Volume yield}} \times 1000$$

$$= \frac{450\text{ g}}{866\text{ ml}} \times 1000\text{ l/m}^3$$

$$= \underline{520\ \text{kg/m}^3}$$

This information is presented in the following format:

Control Grading Mix "C 0.80"

W/C	Penetration mm	Predicted yield mass grammes	Actual yield mass grammes	Ave beam weight grammes	Volume yield millilitres	Cement content Kg / m³
0.8	10	1035	1032	305	866	520

Table 26

Control Mixes - Plastic State Data

W/C ratio	Penetration (mm)	Predicted mass (g)	Actual mass (g)	Ave beam weight (g)	Vol yield (ml)	Cement content
0.69	11	985	985	220	1146	395
0.70	9	990	989	253	1001	450
0.72	13	1000	1002	240	1070	420
0.80	10	1035	1032	305	866	520
0.83	35	1050	1050	337	798	565

Segregation commences at w/c 0.90.

Mixes below w/c of 0.67 were too dry to compact and those above w/c of 0.90 segregated with perlite floating. Figure 31 and Figure 32 illustrates these points.

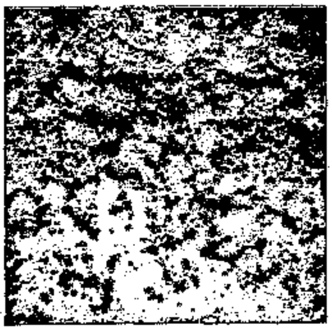

Figure 31
Mix C 3.44/0.67 - Too dry.

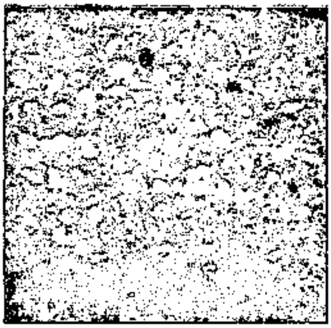

Figure 32
Mix C 3.44/0.90 - Too wet.

Interpreting the Plastic State data, presented in Table 26, we note the following trends:

1. Penetration increases with increasing water content.
2. Predicted mass and actual mass correlation indicates accurate measurement.
3. Average beam weights (wet) increase with increasing water content.
4. Volume yield decreases with increasing water content.
5. Equivalent cement content per m^3 increases with increasing water content.

Penetration increases with increasing water content.

Standard penetration is defined, in terms of SABS ENV 413 as 35 mm +/- 3 mm. All penetrations within a range of 6 mm are therefore considered to be the same degree of consistency. The first four mixes of the Control, w/c 0.69 to w/c 0.80, fall within 6 mm of one another, and hence can be said to be of similar consistency. Penetrations of 11 mm, [illegible] mm, 13 mm, and 10 mm are all within 6 mm of each other.

At some level of water cement ratio, above w/c 0.80, the wet mass of freshly mixed concrete goes "critical", and penetrations increase rapidly. Penetration at w/c 0.90 (omitted due to segregation) was 42 mm, indicating a continuing trend of increasing penetrations as the mix becomes more fluid.

Initially, penetrations at the dry end of the "wetness" spectrum commence slightly higher. Consolidation is very low and penetration is achieved by the compaction of cavities in the mix as the plunger drops.

Predicted mass and actual mass correlation indicates accurate measurement.

This is merely a cross check, intended to assist in avoiding confusion between different mixes and to ensure accurate recording of data.

Average beam weights (wet) increase with increasing water content.
Volume yield decreases with increasing water content.

Increasing the water content increases the amount of water available to coat the particles of the aggregate and cement. This has the effect of reducing friction between particles, leading to improved consolidation and fewer voids. The same quantity of material is concentrated into less volume. The wet weight of the freshly cast test beams therefore increases, and the volume yield decreases.

Equivalent cement content per m^3 increases with increasing water content.

Improved consolidation concentrates the available cement into the test beam. Less cement remains behind in the mixing bowl. The equivalent cement content per cubic metre increases together with the increase in beam cement content.

As the water cement ratio increases, two conflicting effects are anticipated.
- Decreasing compressive strength due to the water cement ratio rule.
- Increasing compressive strength due to concentration of cement in the beams.

Immediately upon casting, the beam moulds were marked for correct identification and were covered with a sheet of glass. Beams were stored in their moulds for the first 24 hours in a curing room at 22°C to 25°C and minimum 90% humidity. The following day the beams were removed from the moulds, individually weighed and then submerged in water at 22°C to 25°C for a further 27 days.

On completion of the curing duration of 28 days the beams were removed from the water, wiped dry and weighed.

Each beam was then snapped in half, testing the flexural strength. Both of the two halves were then crushed, testing the compressive strength. Loads at failure were recorded. Six sets of compressive strength data are obtained for each mix.

The remains were then oven dried at 60°C until there was less than 1% change in mass over 24 hours. This state is known as dry equilibrium. The beams were weighed again and the dry density was calculated.

This information is recorded, as the Hard State data, in the following format:

Mix C 3.44/0.80

Beams	Fresh mass grammes	Cured mass grammes	Dry mass grammes
A	303.0	320.1	218.4
B	305.8	323.9	219.6
C	303.1	321.7	217.8
	304.0	321.9	218.6
Density kg/m³ (Nearest kg)	1188	1257	854

	Transverse load at failure N	Compressive load at failure kN (6 halves)		Ave compressive load at failure kN
A	1150	14.1	14.3	14.2
B	1280	13.6	13.2	13.4
C	1150	14.3	12.4	13.4
	1190	14.0	13.3	13.7

The average transverse load at failure, in Newtons, is converted to tensile strength in megaPascals as follows:

$$\text{Tensile strength} = \frac{1.5 \times \text{load at failure (N)} \times \text{distance between supports (mm)}}{\text{Depth of beam cubed (mm}^3\text{)}}$$

$$\text{Tensile strength} = \frac{1.5 \times 1190\ \text{(N)} \times 100\ \text{(mm)}}{40 \times 40 \times 40\ \text{(mm}^3\text{)}}$$

Tensile strength = <u>2.8 MPa</u>

The average compressive load at failure, in kiloNewtons, is converted to compressive strength in megaPascals as follows :

$$\text{Compressive strength} = \frac{\text{load at failure N}}{\text{Area of beam/platen contact mm}^2}$$

$$\text{Compressive strength} = \frac{13700\ \text{N}}{1\,600\ \text{mm}^2}$$

$$\text{Comp}_{\text{i}}\text{essive strength} = \underline{8.6\ \text{MPa}}$$

POWER FACTOR

The power factor is the ratio of compressive strength to density (own terminology). The Power factor expresses the desire that lightweight concretes be more than simply light. Low density is often accompanied by lower compressive strengths, and therefore less inherent ability for a precast concrete to resist stresses induced during handling.

In the case of w/c 0.80 we have a compressive strength of 8.6 MPa and dry density of 854 kg/m^3.

$$\text{The power factor is} = \frac{\text{Compressive strength converted to pascals Pa}}{\text{Oven dry density kg/m}^3}$$

$$= \frac{8\,600\ \text{Pa}}{854\ \text{kg}}$$

$$= \underline{10.1\ \text{Pa/kg}}$$

If this mix were to have a higher compressive strength (say 10 MPa) at the same density (854 kg/m^3) then the power factor would improve (11.7 Pa/kg). Conversely, if this mix were to have a lower compressive strength (say 5 MPa) at the same density (854 kg/m^3) then the power factor would decline (5.9 Pa/kg).

Two concretes of differing density and compressive strengths could have the same power factor. For example, a typical construction concrete may have a dry density of 2450 kg/m^3 and a compressive strength of (say) 25 MPa. This concrete has a power factor of 10.2 Pa/kg. A lightweight concrete of density 854 kg/m^3 would have the same power factor, if the compressive strength were 9 MPa.

Analysis of the power factor will be the primary means of differentiation and adjudication between the various mixes, and is a more significant measure of performance than either compressive strength or density on their own.

The Hard State data for all control mixes are recorded in Table 27 (averages only).

Ave Beam Weights at 24 hours are cross checked against the Ave Wet Beam Weights in Table 26, to check for accuracy in recording.

Table 27
Control Mixes Hard State data

W/C	Ave beam weight 24HOURS	Fresh density kg/m³	Cured density kg/m³	Oven dry density kg/m³	Tensile strength MPa	Compressive strength MPa	Power Factor Pa/kg
0.69	218.4	853	1051	677	0.8	3.1	4.52
0.70	250.3	878	1064	726	2.1	4.7	6.46
0.72	239.0	934	1061	699	1.6	4.3	6.08
0.80	304.0	1188	1257	854	2.8	8.6	10.02
0.83	335.3	1360	1365	925	2.9	8.9	9.60

Segregation commences at w/c 0.90.

Interpreting the hard state data, presented in Table 27, we note the following trends, which are limited to the stated range of w/c ratios (explanation below):

1. As water content increases, the cured density and oven dry densities increase.
2. Compressive and transverse strengths increase with increasing w/c ratio.
3. Power factor increases to an optimum at w/c 0.80 and then decreases.

As water content increases the densities increase.

The volume of the freshly mixed mortar is inversely proportional to the water content. The higher the water cement ratio, the lower the volume of the freshly mixed mortar. As the amount of water available to coat the particles of the aggregate and cement increases, friction between particles is reduced, leading to improved consolidation and less voids. The same quantity of material is therefore concentrated into less space. Improved consolidation concentrates the heaviest component - cement - in the beams, thereby increasing the wet cured and oven dry densities.

Compressive and transverse strengths increase with increasing w/c ratio.

It was anticipated that strengths would tend to decrease with increasing water content, due to the w/c ratio rule. It was also anticipated that strengths would tend to increase in harmony with the simple increase in cement content of the beam. Strengths do not decrease in the range recorded. It is clear that the effect of the increased concentration of cement overpowers the strength decreasing effect of the w/c ratio rule.

Power factor increases to an optimum at w/c ratio 0.80 and then decreases.

Mixes of increasing w/c ratio exhibit increasing density. Compressive strengths show no decrease in the range recorded. However, the mix with the highest compressive strength is not optimal in terms of power factor. Power factors vary but are at an optimum at w/c ratio of 0.80. This is the mix with the highest compressive strength in megaPascals per unit weight. Above w/c ratio 0.80 increased densities are achieved but at decreasing improvements in strength. The power factor therefore decreases, as there is no additional benefit in the concrete density increasing beyond this threshold.

CHAPTER SIX

TEST RESULTS

TEST RESULTS

All tests were carried out in the identical manner as for the control.

Water cement ratio of 0.80, optimum in the control, was selected as a common starting point.

Increasing and decreasing water cement ratios were used and the limits of "too dry" and "too wet" were established.

"Too dry" occurs when the mix fails to consolidate sufficiently to remain in one single morph. The test for the "too dry" state was pegged at a minimum load at failure of 200 Newtons.

"Too wet" occurs when, during vibration of the beam moulds, the mix begins to segregate. As the perlite floats, a grey band of "Cement-Rich Perlite-Lean" matrix becomes visible. The test for the "too wet" state is therefore visual.

Mixes which were too dry or too wet were discarded.

In all cases, the water content required for standard penetration in terms of SABS ENV 413 (see Chapter Four) was identified.

Tables 28 to 42 hold all Plastic State data for all mixes. Tables 29 to 43 hold all Hardened State data for all mixes.

Table 28
Scalped Gradings S 2.77
Plastic State

W/C ratio	Penetration (mm)	Predicted mass (g)	Actual mass (g)	Ave beam weight (g)	Vol yield (ml)	Cement content
0.80	16	1035	1029	256	1027	440
0.85	12	1058	1056	307	881	510
0.90	9	1080	1077	317	870	520
0.95	10	1103	1099	300	939	480

Table 29
Scalped Gradings S 2.77
Hard State

W/C ratio	Ave beam weight 24HOURS	Fresh density kg/m³	Cured density kg/m³	Oven dry density kg/m³	Tensile strength MPa	Compressive strength MPa	Power factor Pa/kg
0.80	256	1000	1121	746	1.5	4.3	5.76
0.85	306	1195	1258	872	2.4	9.4	10.78
0.90	316	1234	1293	883	2.3	8.4	9.51
0.95	298	1164	1227	816	2.1	7.6	9.31

Segregation commences at w/c 1.04.

Table 30
Polydisperse Grading P 2.00
Plastic State

W/C ratio	Penetration (mm)	Predicted mass (g)	Actual mass (g)	Ave beam weight (g)	Vol yield (ml)	Cement content
0.75	14	1013	1011	196	1320	340
0.80	10	1035	1034	341	777	580
0.83	11	1050	1049	337	797	565
0.96	25	1105	1100	341	826	545
1.02	34	1135	1133	339	855	525

Table 31
Poly disperse Grading P 2.00
Hard State

W/C ratio	Ave beam weight 24HOURS	Fresh density kg/m³	Cured density kg/m³	Oven dry density kg/m³	Tensile strength MPa	Compressive strength MPa	Power factor Pa/kg
0.75	195	762	1168	590	0.7	1.8	3.05
0.80	340	1328	1394	982	2.5	10.2	10.39
0.83	334	1305	1367	957	2.6	9.8	10.24
0.96	340	1328	1394	900	2.3	8.1	9.00
1.02	339	1324	1367	875	2.0	7.9	9.03

Segregation commences at w/c 1.05.

Table 32
Polydisperse Grading P 3.00
Plastic State

W/C ratio	Penetration (mm)	Predicted mass (g)	Actual mass (g)	Ave beam weight (g)	Vol yield (ml)	Cement content
0.75	16	10[illegible]3	1010	189	1370	330
0.78	14	1025	1023	226	1161	390
0.80	12	1035	1036	316	840	535
0.82	12	1045	1044	314	850	530

Table 33
Polydisperse Grading P 3.00
Hard State

W/C ratio	Ave beam weight 24HOURS	Fresh density kg/m^3	Cured density kg/m^3	Oven dry density kg/m^3	Tensile strength MPa	Compressive strength MPa	Power factor Pa/kg
0.75	187	730	1070	539	0.7	2.1	3.90
0.78	224	875	1125	637	1.2	3.0	4.71
0.80	316	1234	1300	883	2.5	9.7	10.99
0.82	313	1223	1289	883	2.5	8.4	9.51

Segregation commences at w/c 1.00

Table 34
Polydisperse Grading P 4.00
Plastic State

W/C ratio	Penetration (mm)	Predicted mass (g)	Actual mass (g)	Ave beam weight (g)	Vol yield (ml)	Cement content
0.78	17	1025	1020	199	1310	345
0.80	19	1035	1033	310	856	530
0.82	20	1045	1048	310	867	520

Table 35
Polydisperse Grading P 4.00
Hard State

W/C ratio	Ave beam weight 24HOURS	Fresh density kg/m³	Cured density kg/m³	Oven dry density kg/m³	Tensile strength MPa	Compressive strength MPa	Power factor Pa/kg
0.78	200	781	973	593	0.9	2.7	4.55
0.80	307	1199	1270	873	2.6	9.5	10.88
0.82	309	1207	1270	883	2.5	8.8	9.97

Segregation commences at w/c 0.85

Table 36
Monodisperse Grading M 1.00
Plastic State

W/C ratio	Penetration (mm)	Predicted mass (g)	Actual mass (g)	Ave beam weight (g)	Vol yield (ml)	Cement content
0.83	8	1050	1047	248	1081	415
0.88	8	1070	1069	291	940	480
0.96	15	1105	1101	360	783	575
1.04	10	1145	1140	366	797	565

Table 37
Monodisperse Grading M 1.00
Hard State

W/C ratio	Ave beam weight 24HOURS	Fresh density kg/m³	Cured density kg/m³	Oven dry density kg/m³	Tensile strength MPa	Compressive strength MPa	Power factor Pa/kg
0.83	245	957	1133	679	0.7	1.6	2.36
0.88	289	1129	1320	801	0.8	1.9	2.37
0.96	359	1402	1453	943	2.3	8.1	8.59
1.04	365	1426	1457	927	1.9	6.4	6.90

Segregation commences at w/c 1.22

Table 38
Monodisperse Grading M 2.00
Plastic State

W/C ratio	Penetration (mm)	Predicted mass (g)	Actual mass (g)	Ave beam weight (g)	Vol yield (ml)	Cement content
0.80	8	1035	1038	307	866	520
0.83	10	1050	1048	329	815	550
0.87	10	1065	1063	325	837	535
1.00	26	1120	1120	335	856	525
1.07	29	1155	1154	335	882	510

Table 39
Monodisperse Grading M 2.00
Hard State

W/C ratio	Ave beam weight 24HOURS	Fresh density kg/m³	Cured density kg/m³	Oven dry density kg/m³	Tensile strength MPa	Compressive strength MPa	Power factor Pa/kg
0.80	303	1184	1270	855	1.8	7.6	8.89
0.83	329	1285	1348	930	2.6	9.6	10.32
0.87	322	1258	1320	906	2.5	8.4	9.27
1.00	333	1300	1356	864	2.3	7.1	8.22
1.07	332	1297	1340	847	2.2	6.7	7.91

Segregation commences at w/c 1.11

Table 40
Monodisperse Grading M 3.00
Plastic State

W/C ratio	Penetration (mm)	Predicted mass (g)	Actual mass (g)	Ave beam weight (g)	Vol yield (ml)	Cement content
0.80	9	1035	1036	314	845	530
0.83	14	1050	1048	318	844	535
0.86	9	1060	1058	309	877	515

Table 41
Monodisperse Grading M 3.00
Hard State

W/C ratio	Ave beam weight 24HOURS	Fresh density kg/m^3	Cured density kg/m^3	Oven dry density kg/m^3	Tensile strength MPa	Compressive strength MPa	Power factor Pa/kg
0.80	313	1223	1295	889	2.5	10.1	11.36
0.83	316	1234	1293	891	2.4	8.7	9.76
0.86	308	1203	1266	863	2.4	7.1	8.23

Segregation commences at w/c 1.00

Table 42
Monodisperse Grading M 4.00
Plastic State

W/C ratio	Penetration (mm)	Predicted mass (g)	Actual mass (g)	Ave beam weight (g)	Vol yield (ml)	Cement content
0.78	10	1025	1018	241	1080	415
0.80	35	1035	1034	325	814	555

Table 43
Monodisperse Grading M 4.00
Hard State

W/C ratio	Ave beam weight 24HOURS	Fresh density kg/m³	Cured density kg/m³	Oven dry density kg/m³	[illegible] strength MPa	Compressive strength MPa	Power factor Pa/kg
0.78	241	941	1055	715	1.6	5.8	8.11
0.80	324	1266	1320	922	2.6	10.0	10.85

Segregation commences at w/c 0.82.

The results of all tests were recorded, excluding those discarded as too wet or too dry. Trends identified are discussed in Chapter Seven.

CHAPTER SEVEN

DISCUSSION

CHAPTER SEVEN

DISCUSSION

DISCUSSION OF RESULTS

The following subjects are covered:

- Commencement of segregation and the width of the workability band.
- Performance at standard penetration.
  Defining a relevant standard penetration.
- Performance at standard water cement ratio.
  Defining a relevant water cement ratio.
- Compressive strength, Density and Power factor trends.
- Cement content factor.

Commencement of segregation and the width of the workability band

Perlite is extremely light. At certain levels of water content the perlite begins to float, forced up by the more dense cement and water slurry, which settles at the bottom of the beam mould. In some cases two horizons were visible, as the beam is filled and vibrated in two stages.

Table 44 lists the water contents at which segregation commences. The exact point of segregation is not identified, only the first observed point at which segregation is noted. All mixes which could definitely be said to have segregated are excluded from the strength density analysis.

Table 44
Commencement of Segregation

GRADING BLEND	M 1.00	M 2.00	P 2.00	S 2.77	M 3.00	P 3.00	C 3.44	M 4.00	P 4.00
FM	1.00	2.00	2.00	2.77	3.00	3.00	3.44	4.00	4.00
W/C	1.22	1.11	1.05	1.04	1.00	1.00	0.90	0.82	0.85
Penetration	36	34	40	30	27	37	42	36	26

The above table has been arranged, from left to right, in order of increasing fineness modulus.

Grading codes are given as "M" for monodisperse, "P" for polydisperse, "S" for scalped, and "C" for the control grading. Individual mixes are described by the grading code, the fineness modulus, and then the water cement ratio.

Figure 33 below, plots the w/c ratio at the commencement of segregation, against the fineness modulus of the grading used in a mix. The intention is to demonstrate that gradings of higher FM tend to segregate at lower w/c ratios, and that gradings of lower FM tend to segregate at higher w/c ratios, regardless of grading.

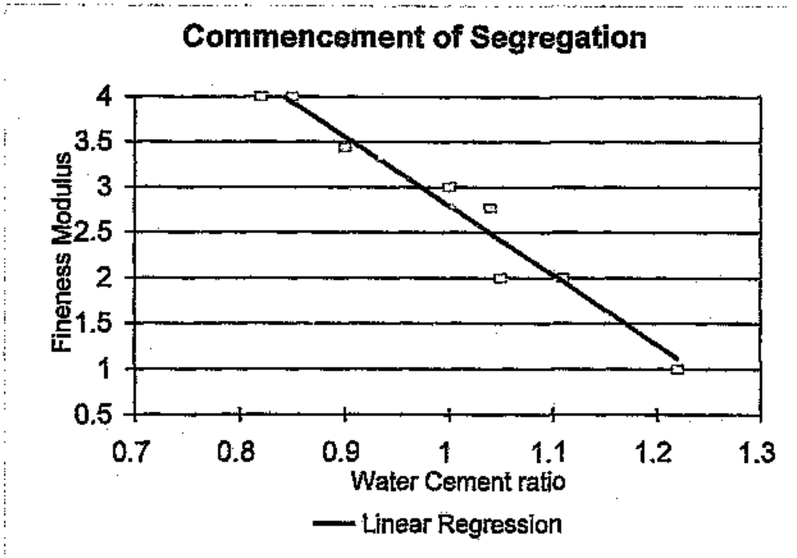

Figure 33
Commencement of segregation : FM versus W/C ratio

A linear regression has been fitted to the above data, indicating a correlation between FM and the level of w/c ratio at which segregation commences.

It must be borne in mind that no attempt has been made to extrapolate between the last w/c ratio, which did not segregate, and the first point at which segregation was noted. It is possible therefore that the actual point at which segregation commences is very much closer to the last known, non segregating point.

The test for segregation is a simple visual inspection of the broken beam, after transverse testing. A mix may be in an indefinite phase, in which it is difficult to say whether segregation has commenced, or not. Therefore, while the data presented regarding the commencement of segregation is not to be regarded as definitive, it is useful in indicating the predominant trend.

That trend is that for increasing FM, segregation commences at lower values of w/c ratio regardless of grading. The finer the material making up an aggregate, the greater the surface area of all the particles. All surfaces must be coated with water for a mix to become workable. The greater the surface area the greater the amount of water required to wet those surfaces and hence achieve workability or ultimately segregation.

Limits of acceptable workability are less subject to definition as it is even more difficult to say at which point a mix can be said to be "too dry". Mixes said to be too dry, are those which achieved tensile strengths of less than 0.5 MPa.

Table 45 records the approximate point of w/c ratio for "too dry" mixes and the distance between this point, and the point of commencement of segregation, as the band of acceptable workability. The workability band width is therefore measured in points of water/cement ratio. "Acceptable" is a term used loosely to describe mixes that are capable of consolidation by the defined procedure, and neither segregate nor refuse to consolidate.

Table 45
Limits of workability by W/C ratio

GRADING BLEND	M 1.00	M 2.00	P 2.00	S 2.77	M 3.00	P 3.00	C 3.44	M 4.00	P 4.00
FM	1.00	2.00	2.00	2.77	3.00	3.00	3.44	4.00	4.00
WET	1.22	1.11	1.05	1.04	1.00	1.00	0.90	0.82	0.85
DRY	0.80	0.78	0.73	0.78	0.78	0.73	0.68	0.75	0.75
BAND	0.42	0.33	0.32	0.26	0.22	0.27	0.25	0.07	0.10

The above table has been arranged from left to right in order of increasing Fineness Modulus.

The Workability band is described as width of w/c ratio, between the lowest point where mixes are said to be too dry, and the w/c ratio at which mixes are said to segregate. The greater the value, the wider the workability band.

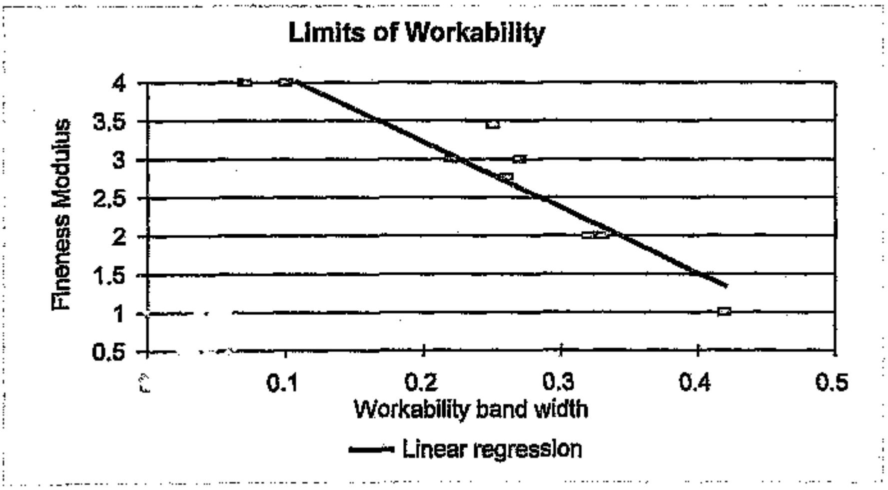

Figure 34
Workability band : FM versus Workability band width

A Linear regression has been fitted to the above data. The trend indicates that the lower the Fineness Modulus the broader the workability band, and the higher the Fineness modulus the narrower the band. The implications are that the higher the Fineness Modulus, the more susceptible a mix will be to errors in dosing of water.

Performance at standard penetration
Defining a relevant standard penetration

Standard penetration of 35 mm ± 3 mm as defined in SABS ENV 413 is inappropriate as a means of standardising the degree of consistency, for lightweight aggregate concretes manufactured with Perlite.

Three out of nine gradings segregated before standard penetration could be reached. Four out of nine gradings remained homogenous up to standard penetration but commenced segregation immediately thereafter. Only two gradings were stable at standard penetration, those being P 2.00 and C 3.44.

A relevant standard penetration should be selected as the optimal degree of fluidity in order to achieve the greatest degree of compaction with the least amount of water. As water is added, the degree of compaction increases. Increasing compaction will bring about higher cement contents, increasing the strength. A point will be reached, where after increasing water content will serve only to dilute the bonding power of the cement paste. The density will plateau, while the strength decreases. The power factor analysis will identify the optimum point.

The highest achieved power factor, for each grading, is recorded together with the relevant penetration for that mix, in Table 46.

Table 46
Power factor and penetration

GRADING BLEND	M 1.00	M 2.00	P 2.00	S 2.77	M 3.00	P 3.00	C 3.44	M 4.00	P 4.00
W/C	0.96	0.83	0.80	0.85	0.80	0.80	0.80	0.80	0.80
Power Factor Pa/kg	8.59	10.32	10.39	10.78	11.36	10.99	10.02	10.85	10.88
MPa	8.1	9.6	10.2	9.4	10.1	9.7	8.6	10.0	9.5
Penetration	15	10	10	12	9	12	10	35	19

Seven out of the nine gradings, tabled above, exhibit peak performance in a similar range between 9 mm and 15 mm penetration. The two exceptions are M 4.00 which performed best at penetration of 35 mm, and H 4.00 which performed best at a penetration of 19 mm. Both these gradings have a FM of 4.00.

For the purposes of this research, standard penetration is henceforth understood to be 12 mm plus or minus 3 mm. Thus the standard range of penetrations, from 9 mm to 15 mm, includes the optimal mixes for the majority of grading blends.

Having selected a standard penetration of 12 mm plus or minus 3 mm, it is found that grading blend M 3.00, a monodisperse grading of particles between 600 and 1180 microns, is the highest performer in this class.

Performance at standard water cement ratio

The standard SABS EN 196 test for cement strength calls for a standard water cement ratio of 0.50. This level of water content proved inappropriate for perlite aggregate, as mixes with this w/c ratio were found to be in the "too dry" category.

A relevant level of w/c ratio will be selected as a standard. Table 46 includes w/c ratio levels for the optimal mixes from each grading. Six out of nine gradings reached their optimal power factor at w/c 0.80, with a tendency towards higher w/c ratio's at optimal levels for gradings with lower fineness moduli. The top six performing mixes, are recorded in Table 47.

Table 47
Top SIX Power Factor results

Ranking	Grading Blend	W/C	Power Factor Pa/kg
1	M 3.00	0.80	11.36
2	P 3.00	0.80	10.99
3	P 4.00	0.80	10.88
4	M 4.00	0.80	10.85
5	S 2.88	0.85	10.78
6	P 2.00	0.80	10.39

Water cement ratio w/c 0.80, optimal in the Control, is optimal in five (83%) of the top six mixes. This level of water cement ratio is therefore selected as the standard.

Table 48 below records the results of all grading blends at the standard water cement ratio of w/c 0.80.

Table 48
Power factor and Compressive Strength in MPa at Standard W/C 0.80

GRADING BLEND	M 1.00	M 2.00	P 2.00	S 2.77	M 3.00	P 3.00	C 3.44	M 4.00	P 4.00
Power Factor Pa/kg	–	8.89	10.39	10.80	11.36	10.99	10.02	10.85	10.88
MPa	–	7.6	10.2	9.4	10.1	9.7	8.6	10.0	9.5

The highest performer in this class is grading blend M 3.00, a monodisperse grading of particles between 600 and 1180 microns.

Compressive strength, Density and Power Factor trends

Compressive strength and density are married in the power factor analysis. In terms of the defined method of adjudication of results, it is not enough to be lightweight without having adequate strength.

Figure 35 plots the density of every mix recorded, against the relevant compressive strength, in MPa.

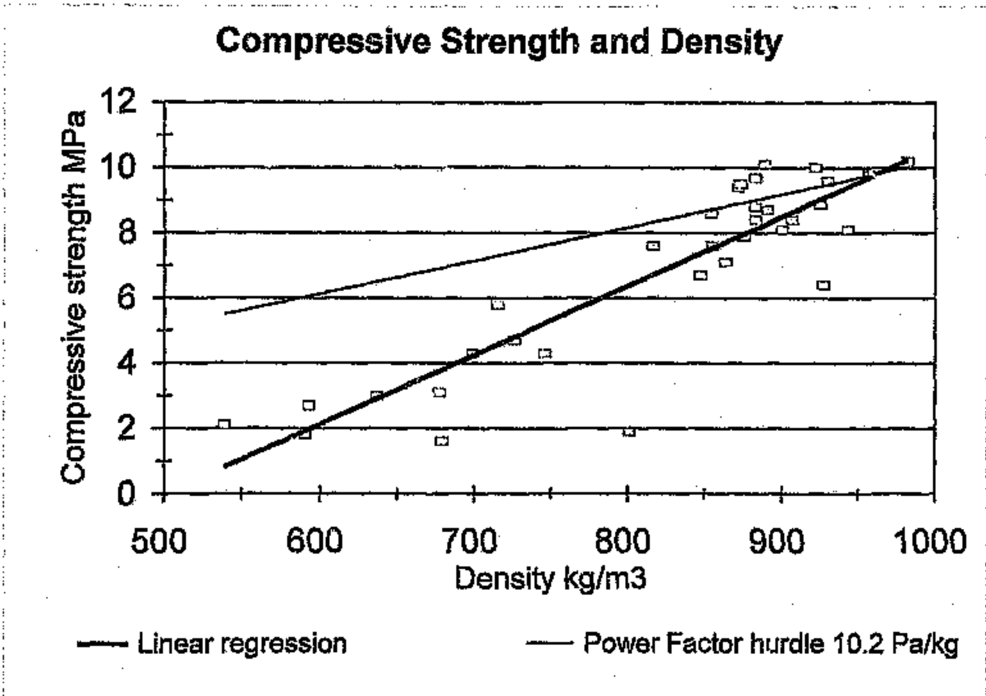

Figure 35
Compressive strength and Density

Figure 35 has a linear regression fitted, which clearly indicates that the relationship between strength and density is largely linear, and that generally higher strengths are accompanied by higher densities, regardless of grading.

The single most dense mix has also the highest recorded compressive strength in MPa. This mix is P 2.00/0.80, a polydisperse grading with a peak at 300 microns, and at a water cement ratio of 0.80.

Also plotted on the graph is a line of constant power factor, equivalent to a power factor of 10.2 Pa/kg, which is comparable to a typical construction concrete of density 2450 kg/m^3 and compressive strength 25 MPa. Those mixes which appear above the line are the "star" performers while those that fall below, are under-performers, as defined by the power factor.

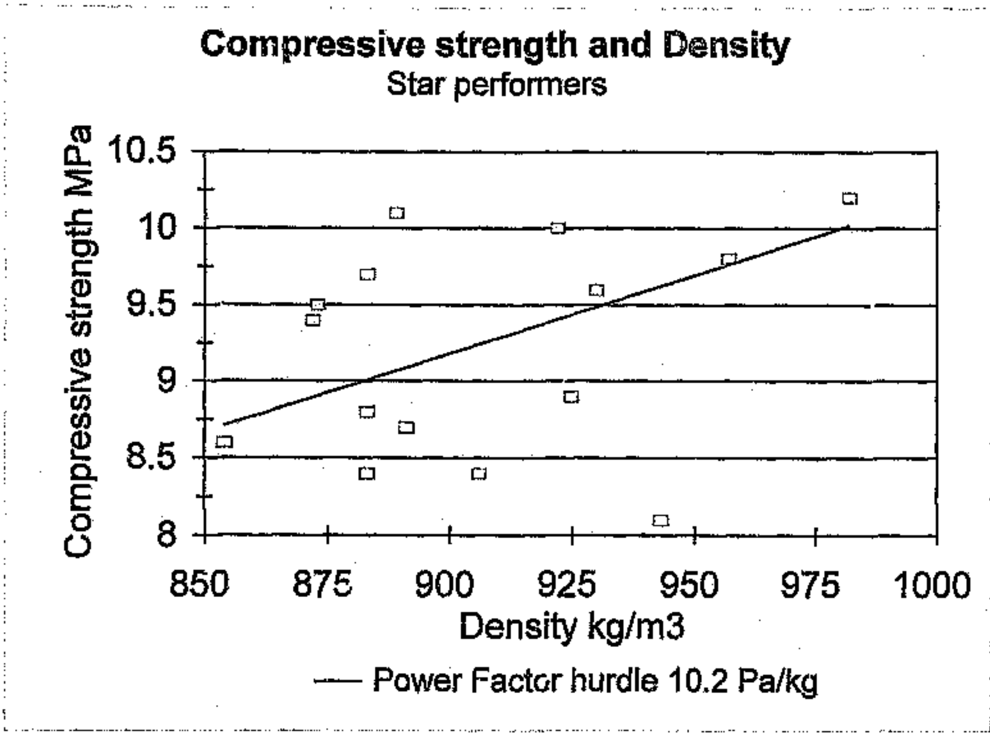

Figure 36
Compressive strength and Density

The above graph plots only the top performing mixes from Figure 35. A power factor (PF) hurdle of 10.2 Pa/kg divides the data. Those points below the line represent mixes which although dense, are weak and do not pass the PF hurdle. Those points above the line represent mixes which have achieved adequate strength for their densities.

Treat the eight points above the line in Figure 35 as having the same strength (9.4 to 10.2 MPa).

We have stated that higher strengths are generally accompanied by higher densities, regardless of grading. Why then do the densities of mixes of approximately equal compressive strength range in density from 872 kg/m³ to 982 kg/m³, a range of 12.6%?

To answer this question we must look at the cement content of each mix. Table 49 below repeats the cement contents (kg/m³) for each of the "Top Eight" mixes, above the line in Figure 36. The results are also ranked by Power Factor from left to right. The determination of cement content is explained in Chapter Five.

It is noteworthy that grading blend P 2.00 is represented twice while the control grading C 3.44 and monodisperse grading M 1.00 are not represented at all.

Table 49
Top Eight Performers - Cement content and Density

GRADING BLEND	M 3.00	P 3.00	P 4.00	M 4.00	S 2.77	P 2.00	M 2.00	P 2.00
W/C	0.80	0.80	0.80	0.80	0.85	0.80	0.83	0.83
POWER FACTOR	11.36	10.99	10.88	10.85	10.78	10.39	10.32	10.24
RANKING	1	2	3	4	5	6	7	8
DENSITY kg/m³	889	883	873	922	872	982	930	957
CEMENT CONTENT kg/m³	533	535	530	555	510	580	550	565

The cement contents are plotted against density in Figure 37.

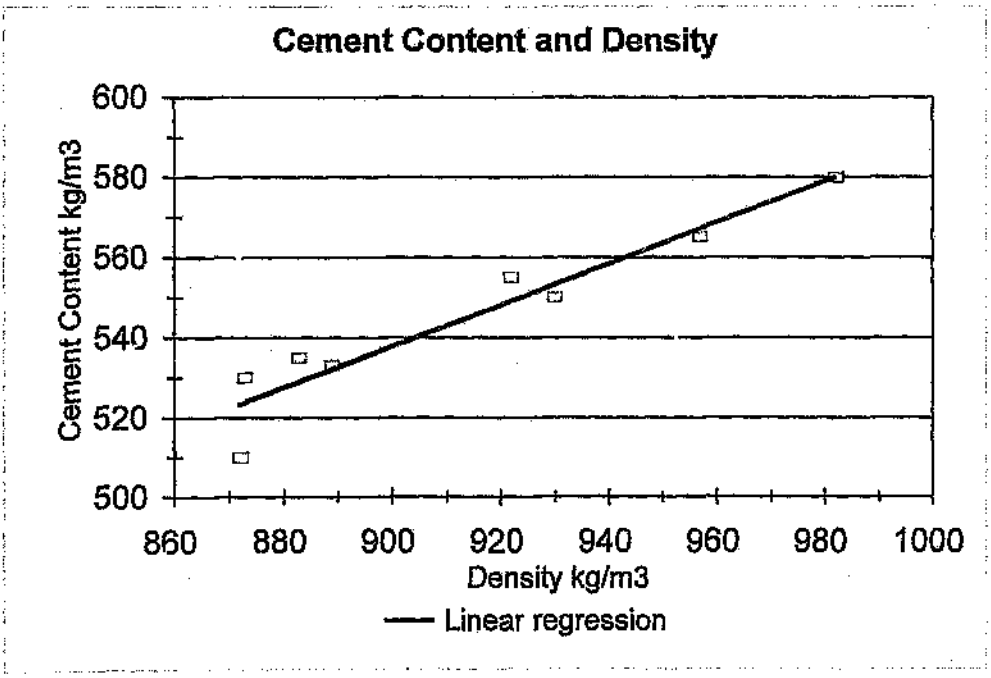

Figure 37
Cement Content and Density

A linear regression has been applied to the above data. The line indicates that a close relationship exists between the density of a mix and it's cement content.

We have seen that compressive strengths generally follow density, and that density is closely related to cement content. The final step therefore, in evaluating the test results, is to establish the relative performance of each mix in terms of a Cement Content Factor.

Cement Content Factor

A wide range of gradings were tested over a wide range of water contents. The resulting mixes vary in degree of consolidation. Mixes of greater consolidation concentrate the cement paste into the test specimens, thereby increasing the cement content of the mix relative to mixes of lower consolidation.

The Cement Content Factor is the ratio of Power Factor over cement content, and reflects the ability of a mix to yield compressive strength for each gramme of cement utilised, whilst still avoiding unnecessary weight. The use of this factor is an attempt to address the fact that mixes finish up with differing amounts of cement. In this way the results are rendered comparable.

For example, the optimum Control mix C 3.44/0.80 has a power factor (PF) of 10.02 Pa/kg and a cement content (CC) of 520 kg/m³. Dividing the PF by the CC and we obtain a Cement Content Factor of 19.27.

The Cement Content Factor is quoted without units. Higher Cement Content Factors are achieved by mixes that are strong for their mass and yet economical in their usage of cement.

The "Top Eight" performers from Table 49 all exhibit similar strengths, but at differing densities and cement contents. From Figure 37 it is evident that the density is closely related to the cement content of each mix. Having compared the strength and density trends through the use of the Power Factor we must now attempt to equate the cement contents.

Figure 38 plots the compressive strength of every mix against its cement content.

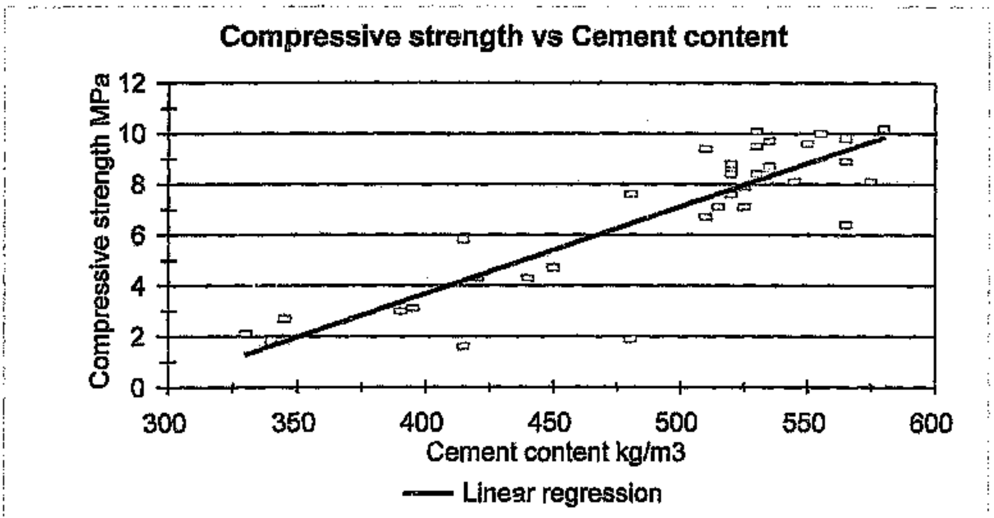

Figure 38
Compressive strength and Cement content

A linear regression has been applied to the above data. The curve indicates that a largely linear relationship exists between compressive strength and cement content, with higher cement contents exhibiting higher compressive strengths.

However, within this general trend, there are exceptions. These exceptions are analysed by means of the Cement Content Factor.

The "Top Eight" performers, in terms of compressive strength from Table 49, are tabled again in Table 50, recording the relevant power factor(PF), cement content (CC), cement content factor (CCF) and fineness modulus (calculated by volume). The data in the following table is ranked by cement content factor.

Table 50

Top Eight Performers - Cement Content Factor

Grading Blend	M 3.00	S 2.77	P 4.00	P 3.00	M 4.00	M 2.00	P 2.00	P 2.00
W/C	0.80	0.85	0.80	0.80	0.80	0.83	0.83	0.80
Power Factor	11.36	10.78	10.88	10.99	10.85	10.32	10.24	10.39
Cement Content	530	510	530	535	555	550	565	580
Cement Content Factor	21.4	21.1	20.5	20.5	19.5	18.8	18.1	17.9
Ranking	1	2	3	4	5	6	7	8
FM by VOLUME	3.00	3.04	4.19	3.05	4.00	2.00	2.04	2.04

In terms of this analysis, the two highest achievers are effectively the same.

The highest achiever remains the grading blend M 3.00, a monodisperse grading of particles, between 600 and 1180 microns.

This mix is neither the most dense nor the least, and the cement content is neither the richest nor the leanest. This mix does not have the greatest compressive strength. It is however the mix which is the most efficient in the usage of cement in attaining strength at the cost of weight.

It is the author's opinion that it is the superior structure of the matrix that is responsible for this performance. The Perlite particles add little or nothing to the strength of a lightweight concrete. The particles merely serve to define the characteristics of the cement walls that carry out the task of stress resistance. It is the thickness and length ("slenderness ratio") as well as the orientation anu distribution of the cement walls, relative to the principle stress, that are critical to the most efficient usage of cement in a lightweight concrete mix.

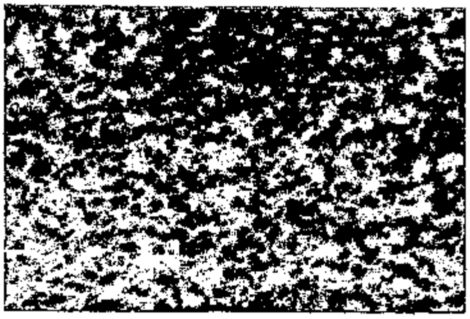

Figure 39
Top performing matrix M 3.00

Figure 39 portrays the uniform particle size and homogenous nature of the top performing matrix of grading blend M 3.00.

- **It is therefore the opinion of this research project that an optimal lightweight aggregate could be developed from a synthetic inert material, of relative density of 1, in tiny round spheres with a smooth surface texture and consisting of particles of between 600 and 1180 microns.**

Suitable materials could possibly include polyurethane, polyester resin, polystyrene, pretreated polypropylene, or ceramics and glass.

The relative density of 1 is suggested in order to avoid the segregation experienced when vibrating wet mixes. In some cases, the peak performances of gradings were achieved immediately before segregation commenced. The prevention of segregation could possibly expand the limits of optimal performance. The selection of the most appropriate RD is a matter for compromise between the necessity to prevent segregation by selecting a higher RD, and the desire for a lighter end result by selecting a lower RD.

Particle size should be uniform and lie between 600 and 1180 microns as this reflects the most successful grading tested, viz. Grading M 3.00.

The second highest performer in the Cement Content Factor analysis is the "scalped" grading S 2.77. This grading is simply the Control grading with all particles above 2360 microns screened out. The "scalped" grading ranked only fifth in the Power Factor race but improved into second position when the usage of cement was considered in the Cement Content Factor.

- **It is therefore the conclusion of this research project that the most practical step that can be taken in improving the performance of a lightweight aggregate is the screening out of all particles above 2360 microns.**

This is not practical or cost effective for end users, due to the fly away nature of the material, however it is feasible for producers to limit the maximum particle size, to 2360 microns, during production.

CHAPTER EIGHT

CONCLUSION

CONCLUSION

The use of lightweight concretes was reviewed.

The nature of Perlite was examined.

Theory of aggregate grading was discussed.

The details of the gradings intended for testing, and the means of such tests, were specified.

A control grading was established.

The results of the tests were tabulated followed by detailed discussion.

The conclusions based on the recorded data, and relevant to the variables tested, are as follows:

- Gradings of higher fineness modulus segregate at lower w/c ratios regardless of grading. Gradings of lower fineness modulus segregate at higher w/c ratios regardless of grading.
- Gradings of lower fineness modulus remain workable across a wider range of w/c ratio than gradings of higher fineness modulus.
- Power factor is the ratio of compressive strength to density and is a measure of the weight cost of every Pascal of compressive strength.
- Power Factor is used in this research report as a means to evaluate the performance of a lightweight concrete.
- Standard penetration, as a means of standardising consistency, is redefined to be 12 mm +- 3 mm for this set of data.
- At standard penetration, the highest performer observed was the grading M 3.00 a monodisperse grading of particle sizes between 600 and 1180 microns.
- Standard water cement ratio is redefined as w/c 0.80.
- At standard water cement ratio w/c 0.80, the highest performer observed was the grading M 3.00, a monodisperse grading of particle sizes between 600 and 1180 microns.
- A linear regression, applied to all mix results, indicates a general trend of increasing density with increasing compressive strength.

- Closer examination of the upper range of the strength density relationship reveals exceptions to the above rule. The most dense lightweight concretes are not the concretes with the highest Power Factor.

- Plotting cement content against density does demonstrate a clear proportional relationship.

- The highest performing lightweight concrete is that mix which is the most efficient in the use of cement, and not the mix with the most cement.

- The Cement Content Factor is the ratio of Power Factor to cement content, and is a measure of the efficiency of a lightweight concrete in achieving compressive strength at cement cost.

- As determined by the Cement Content Factor, the top two performing concretes can be said to have performed equally.

- It is a finding of this research project that the performance of perlite aggregates can be improved by screening out all particles above 2360 micron. This is demonstrated by the fact that the scalped grading outperforms the control grading in both Power Factor and Cement Content Factor. This is not practical for end users, due to the flyaway nature of the material, but it is feasible for producers to limit the maximum particle size during production.

- It is the opinion of this research project that the optimal lightweight aggregate, yet to be developed, is a synthetic inert material of hydrophobic nature and relative density of 1, produced in round particles, with a smooth surface texture, and consisting of particle sizes between 600 and 1180 microns.

Synthetic	Can be manufactured in a controlled environment to a constant standard and uniform quality.
Inert	Can be stored for long periods and will not react with the cement matrix or chemically breakdown in any way.
Hydrophobic	Will not absorb water or dissolve.
RD of One	This is a compromise between reducing the tendency to float in the cement paste (higher RD) and the necessity for a lightweight resulting concrete (lower RD).
Round	Improved consolidation due to less particle interlock.
Smooth	Reduced water required to wet all surfaces (lower water demand).
Sizes	Uniform particle size of between 600 and 1180 microns as this reflects the most successful grading tested, viz. Grading M 3.00.

APPENDICES

APPENDIX ONE
An example on conventional concrete mix design and predicted density calculation.

The mix design procedure used is taken directly from "Fulton's Concrete Technology",sixth edition, pages 594 to 601 (FCT) and is based on the theory of ABSOLUTE VOLUMES.

"The volume of compacted concrete produced by any combination of materials is equal to the sum of the absolute volumes of the cement and aggregates plus the volume of water and that of any entrapped air."

"The absolute volume of a material is the total volume os solid matter in all the particles, and is computed from the mass and relative density (RD)."

$$\text{Absolute volume of any material in Litres} = \frac{\text{Mass of the material (Kg)}}{\text{RD of that material}}$$

Conventional, wet cast concrete, mix design procedure:

- Select an appropriate strength for the use envisaged.
- Determine the water/cement ratio for the desired strength, from the precalculated curves found in FCT.
- Determine the water requirement of the aggregates with assistance from the precalculated tables found in FCT. The water requirement depends largely on the maximum stone size and the aggregate surface texture and shape. Adjust the water up or down to achieve the desired slump.
- Calculate the cement content in kilogrammes per m^3 by dividing the total estimated water content by the water/cement ratio.
- Determine the stone content in kilogrammes per m^3 using the predetermined schematic found in FCT.
- Calculate the sand content in kilogrammes per m^3 on the basis of the "absolute volume" formula, below:

Volume Concrete = Absolute volumes Cement, Sand, Stone and Water

$$1\ m^3\ \text{Concrete} = \frac{\text{Cement kg}}{\text{RD cement}} + \frac{\text{Sand kg}}{\text{RD sand}} + \frac{\text{Stone Kg}}{\text{RD stone}} + \frac{\text{Water kg}}{\text{RD water}}$$

$$\frac{\text{Sand kg/m}^3}{\text{RD sand}} = 1\ m^3\ \text{Concrete} - \frac{\text{Cement kg}}{\text{RD cement}} - \frac{\text{Stone kg}}{\text{RD stone}} - \frac{\text{Water kg}}{\text{RD water}}$$

$$\text{Sand kg/m}^3 = (\text{RD sand})\left(1000 - \frac{\text{Cement kg}}{\text{RD cement}} - \frac{\text{Stone kg}}{\text{RD stone}} - \frac{\text{Water kg}}{\text{RD water}}\right)$$

1 m^3 Concrete = 1000 litres

EXAMPLE :

Strength selected: 25 MPa at 28 days, batched by weight, slump 75mm, vibrated.

Water/cement ratio: 0.75

Water requirement: 215 l/m³ (a portion of this water is present in the aggregates)
Andesite crusher sand FM 3.2
No adjustment of slump necessary

Cement content: Ordinary Portland Cement
Content = Water content / w/c ratio
= 215 / 0.75
= 287 kg/m³

Coarse aggregate: Andesite 19mm stone.
1050 kg/m³ (from Fulton tables)

Sand content: Andesite crusher sand FM 3.2
Calculate the sand content in using the "absolute volume" formula.

Sand content kg/m³ $= (2.8)\left(1000 - \frac{287}{3.14} - \frac{1050}{2.80} - \frac{215}{1.00}\right)$

Sand content kg/m³ = (2.8) (1000 - 91.40 - 375 - 215)

Sand content kg/m³ = (2.8) (318.6)

Sand content kg/m³ = 892 kg

The predicted density of the above concrete is :

Cement	287 kg
Water	215 kg
Stone	1050 kg
Sand	892 kg
Total	2444 kg

See Table 1.
All predicted densities are based on the above formula of absolute volumes. The fine aggregate is of the same material as the coarse aggregate (FM's the same) and have assumed that the water requirement of the aggregates are the same.

APPENDIX TWO

Example of the calculation of Fineness Modulus from a sand grading.

Fineness Modulus is calculated for the Fulton's suggested upper and lower limits.[45]

Fulton's Suggested Upper Limit

Size Micrometre	Percentage passing	Cumulative Percent retained	Percentage retained at screen
4 750	85	15	15
2 360	60	40	25
1 180	40	60	20
600	30	70	10
300	15	85	15
150	5	95	10

The percentages passing are found in column one. The cumulative percentage of a sample retained is calculated by deducting the percent passing from 100%. The percentage retained by any one sieve is found by deducting the cumulative percentage retained at that sieve from that of the previous sieve.

The Fineness Modulus is calculated by adding the figures for cumulative percentage retained at each sieve, up to and including 150 micrometre, and then dividing by 100.

Thus the Fineness Modulus for the Fulton's suggested upper limit is 3.65.

Fulton's Suggested Lower Limit

Size Micrometre	Percentage passing	Cumulative Percentage retained	Percentage retained at screen
4 750	100	0	0
2 360	100	0	0
1 180	100	0	0
600	75	25	25
300	45	55	30
150	20	80	25

The Fineness Modulus for the Fulton's suggested lower limit is 1.60

BIBLIOGRAPHY

1. Chittendon, A.
"The properties, uses and economics of lightweight concretes"
BSc Research report, The University of the Witwatersrand, 1972, page 20.

2. Portland Cement Institute.
"Fulton's Concrete Technology"
Sixth edition, 1986, pages 824.

3. Portland Cement Institute.
"Fulton's Concrete Technology"
Sixth edition, 1986, pages 825.

4. Winston, M.
"The biology of the Honey Bee"
Harvard university press, Cambridge Massachusetts, 1987, pages 81 to 83.

5. Portland Cement Institute.
"Fulton's Concrete Technology"
Sixth edition, 1986, page 822.

6. Portland Cement Institute.
"Fulton's Concrete Technology"
Sixth edition, 1986, page 140.

7. Globert, C.
"An analysis of Neolite CSH and it's application in the construction industry"
BSc Research report, The University of the Witwatersrand, 1988, page 4.

8. American Concrete Institute.
"Guide for structural lightweight aggregate concrete"
Document ACI 213R - 87, 1987, page 2.

9. Cement and Concrete Association.
"An introduction to lightweight concrete"
Sixth edition, 1980, page 3.

10. The Concrete Society.
"A review of the International use of lightweight concrete in highway bridges"
Technical report No 20, 1981, page 3.

11. Portland Cement Association.
"Structural lightweight Concrete"
Structural bureau - Concrete information, 1962, page 3.

12. American Concrete Institute.
"Guide for structural lightweight aggregate concrete"
Document ACI 21[illegible] 1987, page 12.

13. Cement and Concrete Association.
"An introduction to lightweight concrete"
Sixth edition, 1980, page 8.

14. Portland Cement Institute.
"Fulton's Concrete Technology"
Sixth edition, 1986, page 759.

15. American Concrete Institute.
"Guide for use of admixtures in concrete"
Document ACI 211.1 - 91, 1991, page 22.

16. Portland Cement Institute.
"Fulton's Concrete Technology"
Sixth edition, 1986, page 823.

17. De Rose, L.
"Examination of the influence of mix design on the properties of micro cellular concrete"
MSc Dissertation, University of the Witwatersrand, 1998.

18. "Neopor cellular lightweight concrete - A lighter future"
Magazine advertorial appearing in - Housing in Southern Africa.
Unified communications, 1993, page16.

19. Akers, D. and Floyd, R.
"Pumice and Scoria evaluated as structural concrete aggregates"
Paper - ACI annual convention, 1984, page 3.

20. Cement and Concrete Association.
"An introduction to lightweight concrete"
Sixth edition, 1980, page 4.

21. Cement and Concrete Association.
"An introduction to lightweight concrete"
Sixth edition, 1980, page 5.

22. Portland Cement Association.
"Structural lightweight Concrete"
Structural bureau - Concrete information, 1962, page 1.

23. Council for Scientific and Industrial Research.
"Investigations into South African raw materials for manufacturing expanded lightweight aggregates for concrete"
Research report 217, NBRI bulletin 36, 1966, pages 17 to 19.

24. The building research bureau of New Zealand.
"Lightweight concrete - Artificial aggregates - Vermiculite"
Building information bulletin no 97, 1967.

25. Building Systems Technology SA Pty Ltd.
Producers technical manual
Part II Engineering data, page 1.

26. Portland Cement Institute.
"Fulton's Concrete Technology"
Sixth edition, 1986, pages 166 to 179.

27. American Concrete Institute.
"Standard practice for selecting proportions for structural lightweight concrete"
Document ACI 211.2 - 81, 1981, page 4.

28. Chemserve Perlite Pty Ltd.
Producers promotional material.
Midrand.

29. Edwards, T.
"Brief survey on the development in Southern Africa of an perlite expansion and acid lava export industry"
Mines operation and minerals investigation Pty Ltd, 1961, pages 6 and 7.

30. Pratley Pty Ltd.
Producers promotional material.
Krugersdorp.

31. Edwards, T.
"Brief survey on the development in Southern Africa of an perlite expansion and acid lava export industry"
Mines operation and minerals investigation Pty Ltd, 1961, page 5.

32. Cement and Concrete Association.
"An introduction to lightweight concrete"
Sixth edition, 1980, page 7.

33. American Concrete Institute.
"Guide for structural lightweight aggregate concrete"
Document ACI 213R - 87, 1987, page 3.

34. Irani, R and Callis, C.
"Particle size - Measurement, interpretation, and application"
John Wiley and sons, 1963, page 21.

35. Weymouth, C.
"A study of fine aggregate in freshly mixed mortars and concretes"
Proceedings ASTM, Vol 38, part II, 1938, page 354.

36. Fuller, W and Thompson, S.
"The laws of proportioning concrete"
Transactions American Society of Civil Engineers, Vol 59, 1907, page 67.

37. American Concrete Institute.
"The properties of concrete mixes"
Journal April 1940, page 462.

38. Popovics, S.
"Comparison of several methods of evaluating aggregate gradings"
Bulletin Rilem No 17, 1962, page 14.

39. Mercer, L.
"Gap gradings for concrete aggregates"
Paper - Journal of the American Concrete Institute,
Vol14, No 4, February 1943, page 309.

40. Department of Scientific and Industrial Research.
"The grading of aggregates and workability of concrete"
Road transport technical paper No 5, Second edition, 1947, page 1.

41. Mercer, L.
"The law of grading for concrete aggregates"
Melbourne technical college press, 1951, page 44.

42. Portland Cement Institute.
"Fulton's Concrete Technology"
Sixth edition, 1986, page 151.

43. Chen, H. Yen, T. and Ko, C.
"Influences of properties and gradation of lightweight aggregate on the Fg of lightweight aggregate concrete"
Paper - International symposium on structural lightweight aggregate concretes 1995, page 472.

44. American Concrete Institute.
"Standard practice for selecting proportions for structural lightweight concrete"
Document ACI 211.2 - 81, 1981, page 3.

45. Portland Cement Institute.
"Fulton's Concrete Technology"
Sixth edition, 1986, page 153.