MIRO - FINAL REPORT

Exploitation and Use of Quarry Fines

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SUMMARY

The purpose of this study was to ascertain the current state of knowledge concerning the exploitation of hard-rock quarry fines, and to present this information in an accessible form. To do this, the project partners carried out an extensive review of existing reports and papers, and undertook structured interviews with producers of quarry fines. This information has been used to produce this report and a relational database.

The proportion of fines produced from hard-rock (igneous/gritstone/limestone) quarrying has increased in response to factors that include changes in the design specifications for road pavements, and as a consequence of changes in crushing processes. The need to store quarry fines, at some sites, has increased as a result of the Aggregates Levy.

The definition of fines varies within the industry and will be constrained by the European Aggregates Standards, which specify fine aggregate for concrete and general use as passing 4 mm, for asphalt passing 2 mm, and filler passing 0.063 mm. In many quarry locations, the term ‘fines’ refers to undersized material from crushing plant that is given no further processing and accumulates over time, or material produced by bag-house installations. The maximum size of fines from crushing plant may be 6mm, and the proportion of size fractions below this varies greatly. Bag-house fines, which may become mixed with plant fines, are typically below 0.075mm. Construction products account for the greatest volume of quarried materials, and the position of fines within this market needs to be strengthened. Existing destinations include concrete/concrete products, asphalt-bound pavements, bound/unbound surfaces and earthworks/landscaping.

New research, mainly in the United States, is demonstrating the value of fine aggregates in improving the performance of concretes and asphalts. For these uses, adequate specifications for the aggregate appear not to exist currently, and are being developed, for example, by the International Center for Aggregate Research. Most importantly, grading, and concrete workability are key factors.

It appears that the ability of individual quarries to exploit construction applications for fines will depend on their ability to generate a product that meets specifications that are as yet at a research stage. The lack of clear guidance and considerable variability of fines as they exist in current stockpiles are obstacles to identifying new and relatively high value or high volume outlets within concrete and asphalt-bound products. For some applications, including use in bound and unbound layers, soil caps, infiltration layers and in general fill, improved knowledge of the characteristics of fines will help to maximise their potential for use in higher specification applications. Although fines are in competition with secondary aggregates which do not attract the Aggregates Levy for a number of uses, the relatively higher quality of quarry fines in terms of composition, physical properties and availability may still enable them to be competitive in the market place.

The widespread use of crushed rock in soil remineralization provides an outlet for quarry fines that may become increasingly important in view of its ability to meet new objectives relating to soil protection. There is a specialist market for quarry fines to

farmers, horticulturists and gardeners interested in alternative lifestyles. This appears to be well developed in North America and Australia, and is present in the UK. Although higher prices can be achieved than for low-grade construction uses, packaging and transport costs are high, and volumes are trivial compared to construction. Standards and specifications may be unfamiliar (and seem idiosyncratic) to the quarrying industry. However, the EU groundwater and Soil Directives that are currently being drafted are near completion and they will provide a driver for new markets in areas where soils are under pressure particularly from erosion.

As part of this study, a survey of producing companies has been undertaken in the form of structured interviews. The results of this survey are summarised, and provide a snap-shot view of the industry's current views concerning fines. This information has been gathered assuming confidentiality concerning specific locations and operations, and so is generic.

The review of existing published information has identified over 150 sources, including refereed journal papers, conference proceedings, relevant EU standards and web-sites. A brief summary of key points arising from the literature search is provided, together with full bibliographic references. To facilitate access to this information, a relational database has been produced that can be searched according to terms such as rock type, product type etc. The database is presented as a CD-ROM and is available on-line from Mineral Solutions Ltd (www.mineralsolutions.co.uk) and from the Quarry Products Association (www.qpa.org). The database has been produced using Microsoft Access™, and is intended to be developed further by users.

KEY FINDINGS

This study has generated the following key findings:

Generation of fines	
1	Fiscal changes, such as the introduction of the Aggregate Levy, may in some circumstances inhibit the exploitation of fines, creating additional problems for those responsible for their management.
2	Engineering design changes, including those linked to regulation, lead to changes in the portfolio of products derived from hard rock aggregate production, with consequent changes in fines production. In particular, increased use of high PSV aggregate in road surfaces increases the production of fines.
Marketing of fines	
3	Although some operations are able to deliver fines to responsive markets, others are either inappropriately located or unable for other reasons to do so.
4	Additional characterisation of fines may be needed as part of a marketing exercise, particularly to demonstrate consistency of product.
5	Additional processing of fines may be required to generate products suitable for specific markets.
6	New (or revised) specifications may be needed so that fines can map onto requirements for specific products and so achieve recognition as a quarry product.
Exploitation of fines	
7	Opportunities exist to increase the proportions of quarry fines used in construction products, provided specifications exist and can be met.
8	Opportunities exist to use fines in response to soil protection requirements, to compensate for soil erosion and to generate soil-substitutes.
9	A market-led approach is needed, which will require quarry producers to become familiar with the needs and practices of non-construction users of fines.

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1. INTRODUCTION: SCOPE OF STUDY

The production of aggregates from crushed rock generates a proportion of fines as a normal consequence of variable responses of the rock material to the crushing process. World wide, therefore, a number of strategies have been developed to make use of fines, in accordance with the needs of local markets, regulation and legislation (including fiscal controls). There is an opportunity to promulgate best practice in dealing with fines, but this can only be done if information concerning their use is gathered together and ordered in an accessible way.

The purpose of this study was to ascertain the current state of knowledge concerning the exploitation of hard-rock quarry fines, and to present that information in a form that would be accessible to the industry. To do this, the project partners carried out the following tasks:

1) structured interviews in person or by telephone with a cross-section of representatives from the quarrying industry (UK and mainland Europe)
2) visit to the International Center for Aggregates Research (Austin, Texas)
3) an extensive review of the available literature (in its broadest possible sense, thus including the Internet and non-reviewed publications).

An early finding was that the practical definition (although technically strict in terms of grading) and the generation of fines varies from operation to operation. A key part of the report addresses these issues.

To facilitate access to the results of the study, the review has been summarised in the form of a relational database (Microsoft Access™), in which interrogation can be made according to rock type, end use, or other criteria. A written summary of the material that has been consulted is reported, with full bibliographic and web sources.

Structure of report

To emphasise the key findings of the study, this report is structured as follows:

Part 1:
1) Introduction: scope of study
2) Fines as materials: survey of operators
3) Drivers and inhibitors for exploitation of fines
4) Conclusions and suggestions for further work

Part 2:
5) Methodologies
6) Previous reviews of uses of fines
7) Construction uses for fines
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Appendix 1: Types of rock crushers
Appendix 2: Use of the Access™ Quarry Fines Database

2. FINES AS MATERIALS

2.1. Definition of fines

(i) Definition of fines to European Standards

From the beginning of 2004 common European Standards for aggregates have been adopted (Quarry Products Association, 2003). One important change in the new standards is the terminology for fine aggregate, fines and filler.

Fine aggregate for use in asphalt is now defined as material passing the 2 mm sieve (BS EN 13043:2002, (BSI 2002b)) and fine aggregate for other uses, including concrete, is material passing the 4 mm sieve (BS EN 13043:2002, (BSI 2002a)). Thus, for all purposes (except asphalt) 4 mm replaces 5 mm as the break point between fine and coarse aggregate. From now on, quarry dust material intended for use as fine aggregate should be defined as material less than 4 mm in size, unless it is to be used in asphalt (<2 mm). New terminology will need to be adopted across the industry.

Under the new guidance quarry fines are defined as the fraction passing 0.063 mm (63 microns) and filler is material passing 0.063 mm that may be added to influence the properties of a mixture.

In this project the term 'quarry fines' refers to the finest quarry products from crushed rock aggregate production and which is colloquially known as 'dust'. Therefore, the term will include fine aggregate, fines and filler materials.

(ii) Quarry fines from crushing and screening

Crushed rock aggregate quarrying generates considerable volumes of quarry fines, often termed 'quarry dust'. This is a process-controlled 'sand-sized' residue from crushing and screening of coarser grades of aggregate products. Quarry fines, therefore, may vary depending on the particular process used.

The finer fraction of aggregate products (the 'quarry dust') is usually smaller than 5 mm in size, but some quarry operators separate the quarry dust on different sieve sizes. Interviews with quarry operators have shown that although most operators define their finest aggregate product as material less than 5 mm in size, others define quarry fines as material less than 3 mm in size, and some small producers may define their fines product as minus 6 mm material, depending on the individual company's markets for specific aggregate products.

Quarry fines consist of a graded mix of coarse sand, medium sand and fine sand sized particles, plus a clay/silt fraction (known as the 'filler' grade). The filler content is particularly important as it has a major impact on technical properties and, hence, on potential end use. Filler grade material is defined by the industry as material less than 0.075 mm (75 microns) in size. The filler grade content of the fines material may be reduced by washing with water or by other methods of separation to produce a clean, saleable 'sand' product. The very fine-grained filler residue is usually a 'waste' product.

(iii) Fines from bag filters

Very fine-grained quarry dust (filler grade material) is generated from dry processing plant operations (such as asphalt plants or secondary/tertiary crushing) and may be collected by bag filters, cyclones or electrostatic precipitators. This material is usually less than 0.075mm in size. Its properties will vary with rock type. Limestone filler is generally utilised (‘reclaimed filler’) in a range of applications but filler from both igneous rock and sandstone operations is usually treated as a waste, and disposed of within the quarry.

2.2. Generation of fines according to rock type

The volume of fines generated by quarries is generally unknown and there is a need to determine the magnitude of the problem of production, storage and use of fines in Britain. The exact levels of annual production are unknown; they are not specified in the ODPM AM (Aggregate Monitoring) surveys or in the Office of National Statistics AMRI (Annual Minerals Raised Inquiry) surveys.

The research carried out in this project indicates that, in general, limestone (including dolomite and chalk) quarrying typically produces around 20-25% fines, whereas sandstone/gritstone quarries produce up to 35% fines. Fines from sand and gravel pits vary enormously depending on the sand:gravel ratio and on the clay content, but are mostly between 5-15% of production. Igneous rocks are also variable lithologically, perhaps producing between 10% and 30% quarry fines. Assuming annual production of aggregates in Great Britain is around 238 million tonnes (British Geological Survey, 2003), then the total annual production of quarry fines in Britain is estimated to be of the order of 41 million tonnes (Table 1).

Table 1. Estimated production of quarry fines in Great Britain from different rock types

Rock type	Annual production (2002)	Typical % fines	Estimated fines production
Sandstone	12 million tonnes	30%	3.6 million tonnes
Limestone [1]	106 million tonnes	20%	21.2 million tonnes
Igneous rock	45 million tonnes	20%	9.0 million tonnes
Sand and gravel [2]	75 million tonnes	10%	7.5 million tonnes
Total			**41.3 million tonnes**

[1] including dolomite and chalk; [2] land-won

Some of this production, particularly the ‘sand sized’ fraction will be saleable, but filler-grade material (finer than 0.063 mm, in the new standards) is less saleable. The filler-grade content is variable, depending on rock type and the type and degree of quarry processing, but in general it accounts for between 10 and 20% of crushed rock aggregate fines (see below). National production of quarry filler-grade material is therefore estimated to be around 3.5 to 7 million tonnes from crushed rock sources and about 4 million tonnes from sand and gravel pits. Limestone filler is often sold as a filler in asphalt, or as aglime, but filler-grade products from other sources are generally not readily marketable and are stored on site.

2.3. Geographical distribution of fines

The distribution of quarry fines, the level of usage and current level of stocks of fines in Britain is unclear. The crushed rock aggregate industry maintains that the fines are not a waste material but are considered a product waiting for a market. Nevertheless, evidence collected during this survey suggests that usage is variable depending partly on fines character and quality, partly on local market opportunities and partly on the nature and structure of individual quarrying businesses. In addition, there is strong evidence suggesting that the Aggregates Levy has had a major effect on the utilisation of quarry fines in some areas. It is understood that until the introduction of the Levy most quarry fines were beneficially utilised. In the period since the introduction of the Levy, quarry fines have, in certain areas, become more difficult to market economically due to competition from cheaper alternative materials which are not subject to the Levy.

Anecdotal evidence suggests that stockpiles of quarry fines are increasing, although this situation does have marked geographical variations. In addition, the lack of construction of new roads in recent years has resulted in fines accumulating in quarries. However, short term construction contracts (such as the Birmingham northern-relief road) are opportunities to utilise local stocks of fines.

A number of general factors affect the geographical distribution of quarry fines:

- **Remote areas** – the markets for bulk materials are usually local to urban centres and hence quarries in remote areas have additional problems of finding markets for fines. This is further complicated if there are local sources of alternative materials (free of the Aggregates Levy) available to compete in the fines market. Examples include the availability of slate waste in North Wales and china clay sand in SW England.

- **High PSV quarries** – fines are a particular problem in quarries producing high PSV (>55) aggregates from sandstone/gritstone/greywacke rock types or from certain igneous rocks. There is, for example, a problem with fines arisings and excess stocks in Pennant Sandstone quarries in South Wales. The requirements are now for smaller sized chippings (10 and 14 mm) rather than 20 mm for road surfacing materials and hence a greater degree of crushing is required, generating more quarry fines. In addition, changing asphalt technology has resulted in reduced usage of quarry fines in the road surfacing materials. Also, the new thin surfacing materials result in higher consumption of high PSV aggregate, leading to increased production of quarry fines.

- **Markets** – the local market is very important. Some regions (such as limestone quarries in the Mendips or igneous rock quarries in Leicestershire) may be producing excess of fines owing to the large scale of quarrying operations and competition from many local sources. In other locations, however, there may be a local shortage of fines for a specific market (such as limestone fines for a block plant) and local quarries may optimise fines production by use of impact crushers. Alternatively, fines may be imported, where commercially viable, from other quarries/regions or a fines substitute may be used to meet a local demand.

- **Fines quality** – fines may accumulate if the material is of poor quality, particularly if it has a high filler content or is highly absorptive. Examples may include, certain Jurassic limestones and certain hardstone (sandstone and igneous rock) fines.

The quarrying industry currently uses the crusher fines wherever they can. Their aim is to maximise resource use, to increase profitability and reduce both wastes and environmental impact. Quarry fines are therefore not considered a waste material but are treated as a residue of the crushing and screening process, which can be sold into certain markets. The chief restrictions are specifications and costs. In general, most limestone quarry fines are utilised, but only some sandstone/gritstone or igneous rock fines are used. Sandstone and igneous rock fines are, however, usually stockpiled with the intention of sales, although some may be used locally on site in the construction of landscaping features or in site restoration.

2.4. Technical and other drivers governing fines production

All quarrying operations, including extraction, material handling and processing, will to a greater or lesser extent generate fines. However, most quarry fines are produced during the processing stage; which involves the crushing (Appendix 1), and size classification of quarried rock to produce ‘single-size’ aggregate (ranging from 20 to 6mm).

Crushing of quarried rock is carried out in stages, with the first stage known as primary, second stage, secondary and third stage, tertiary (with fourth & fifth stages less common). Different types of crusher will be used for different stages to reduce the size of the quarried rock from upwards of 1.5m blocks to successively smaller sizes, ultimately finer than 20mm. In general, the greater the number of crushing stages the higher the proportion of fines produced as a proportion of total plant throughput. Primary crushing is normally carried out by jaw or gyratory crushers and subsequent stages of crushing by cone or impact crushers (Appendix 1) (Hudson *et al.*, 1997).

Technical issues leading to fines production:

- Fine particles are produced by abrasion/ attrition of the rock as it comes into contact with other rock fragments; this is as a result of shear failure where projections from the rock surfaces are broken off as the particles smash past each other. As a result of this impact crushers tend to produce a more granular/ cubical particle shape but also a much higher proportion of fine material, 25-30% on average, than compressive crushers, 20-25% on average (Hudson *et al.*, 1997). In 2000, at Georgian Aggregate’s Duntroon Quarry (Toronto, Canada) the primary crusher was changed from an impact to a jaw crusher with the subsequent reduction in fines produced from 38% -5mm to 28%, equivalent to 100,000 tpa (Seberras, 2000). In 2003, Dufferin Aggregate replaced its vertical shaft impact crusher with a cone crusher which reduced its fines and increased its production of single-size aggregate from 40 to 50% of total plant throughput (Bateman, 2003).

- If an impact crusher is fed too fast the proportion of fines produced increases due to greater rock-on-rock interaction within the crushing chamber.

- The proportion of 'filler' grade material produced by an impact crusher ranges from 5 to 20%, with the proportion increasing with increasing operating speed (Ahn and Fowler, 2001)

- Scalping of the primary crushed material increases the capacity of the subsequent crushing stages and reduces the likelihood of material becoming wedged into the crushers (known as 'packing'). Packing could lead to excess fines being produced due to the greater rock-on-rock interaction.

- Impact crushing causes immediate fracturing of particles with no build-up of residual stress

2.5. Production of fines as a primary material

Manufactured sand is produced by the crushing of rock, typically in locations where there is a shortage of natural sand. It is also referred to as crushed rock sand, 'stone sand', 'crusher sand' and 'crushed fine aggregate'. Such manufactured sands are currently produced from hard rock quarries in several areas of Britain (in the Midlands from Triassic conglomeratic sandstones and in northern England and southern Scotland from Carboniferous sandstones) and also in other countries including Malaysia, Norway, the United States, Australia and South Africa. In these countries, as in the UK, crushed rock sand is generally blended with natural sands to produce the desired grading and workability. In the USA limestone and granite account for 86% of the rock used to make manufactured sand, with the remainder made from 'traprock' (basalt), dolomite, sandstone and quartzite (Ahn and Fowler, 2001).

Manufactured sand is increasingly becoming more accepted as an alternative to natural sand where the traditional sources are becoming less available due to resources being depleted, planning permissions for new deposits being harder to obtain and the need to make use of ever growing stockpiles of quarry fines.

Stress fractures, caused by compressive or impact crushing, will preferentially form along mineral grain boundaries and also across grain boundaries where internal weaknesses already exist. Therefore, sand tends to consist of more angular and irregularly shaped particles compared to natural sand, which tends to contain more rounded particles. This may make sand suitable for use in asphalt and concrete as angular particles give a better mechanical interlock. However, crushed sand products, particularly if they are to be used in concreting mixes must be consistent in quality and of acceptable grading. They preferably, therefore, need to be manufactured in a purpose-designed crushing and screening process, in contrast to crusher dusts from hard rock quarrying, produced as residues of coarse aggregate production.

2.6. Testing and quality of fines

The 'quality' (mineralogical, chemical and physical properties) of quarry fines broadly reflects the lithology of the worked material and the degree of processing it has undergone. To a large extent the 'quality' of most quarry fines produced in the UK is unknown with very little technical information available in published literature and limited access to known data due to commercial sensitivity.

In the late 1990s the British Geological Survey carried out a programme of quarry fines characterization as part of the EC-funded REFILL project (Mitchell *et al.*, 2001). Samples of fines from over 30 UK aggregate operations were analysed to determine their mineralogy, chemistry and particle-size distribution. A summary of the particle-size distribution and mineralogical composition of fines generated from different rock types is given in Table 2. Plant fines, which are produced from screening of crushed material, typically contain 50 to 60% sand and 15 to 50% silt/ clay. Filler fines, from dust collection systems, typically contain 5 to 20% sand and 80 to 95% silt/ clay. Limestone fines consist mainly of calcite (or dolomite); sandstone and sand & gravel fines are mainly quartz; and igneous rock fines are mainly quartz & feldspar.

This technical information provides a starting point for assessment of quarry fines suitability for use in mineral-based products. It was found that the properties of quarry fines could not be predicted due to the natural variability of the rock worked and the different crushing technologies employed. Laboratory testing must be carried out, even if the fines are produced from rock types and using technologies identical to plants with fines of known quality.

Table 2. Particle-size & mineralogy of quarry fines from UK quarries

Rock type	Particle-size distribution		Mineralogy
	SAND (wt% 2mm – 0.075 mm)	**SILT/ CLAY** (wt% <0.075 mm)	(not all minerals may be present)
Limestone			Mainly **calcite (or dolomite)** with a minor amount of quartz, mica, fluorite, barytes, kaolinite, pyrite & iron oxide.
- Plant fines	57.9	17.2	
- Filler fines	11.4	88.4	
Sandstone			Mainly **quartz**, with small amount of feldspar & calcite and a minor amount of mica, chlorite, rutile, dolomite & iron oxide
- Plant fines	55.9	19.3	
- Filler fines	18.4	80.2	
Igneous			Mainly **quartz** & **feldspar**, small amount pyroxene & amphibole, and a minor amount rutile, olivine, mica, chlorite & serpentine
- Plant fines	53.5	14.0	
- Filler fines	7.2	92.5	
Sand & Gravel			Mainly **quartz** and a minor amount of feldspar, calcite, mica, rutile & kaolinite
- Plant fines	49.7	48.4	

Data derived from analysis of quarry fines from 11 limestone quarries, 4 sandstone quarries, 7 igneous rock quarries and 9 sand & gravel processing plants.

3. DRIVERS AND INHIBITORS FOR EXPLOITATION OF FINES

Drivers (why should the producer want to shift fines):

- To minimise waste
- Need to generate revenue
- Volumes accumulating and taking up space in a quarry
- Need to reduce/remove costs of storage or disposal
- Customer demand for products for which fines are a by-product
- Need to avoid sterilising resources
- Need to avoid double handling of quarry products (efficiency)

Drivers (why should the market want to buy or use fines):

- High local demand for fines (e.g. nearby concrete block plant)
- Sustainability (whatever that might mean)
- Quality of raw materials (primary preferred to secondary)
- Opportunities for 'manufactured sand'
- Revision of specifications that permits increased fines to be used in concrete and asphalt
- Soil remineralisation
- Compensation for soil erosion
- Landscape restoration
- Production of composts from green waste (many sources)
- Other opportunities (e.g. drainage aggregates, sandbag fill, sports surfacings etc.)
- Opportunities to reduce extraction of sand and gravel for some applications
- DEFRA Soil Action Plan emphasises the need to properly manage soil resources, and to respond to stresses arising from climate change (www.defra.gov.uk/environment/landliability/soil/actionplan.htm)

Obstacles:

- Excess local production (e.g. Mendips, Charnwood) swamping local demand
- Inherent low value
- Aggregates tax on fines
- Transport costs to potential markets
- Lack of specifications for non-construction uses
- Current specifications may limit use in constructional applications
- Regulatory obstacles ('waste')
- Low and variable volumes/limited demand
- Need to treat fines as a product in the quarry (costs, training, space)
- Additional processing (screening) and associated higher costs
- Lack of understanding of non-construction uses/markets
- Customer ignorance
- Customer prejudice

4. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

The problem of what to do with fines that arise as a consequence of hard rock aggregate production has existed for several years and varies in its intensity from one location to another, internationally, nationally and regionally. In the USA, proportions of fines permitted in concrete products (for example) are less than that permitted in Europe, and so much effort has been spent on generating evidence for regulators to increase amounts that can be used.

The search of the literature and the internet has shown that a very wide range of applications has been considered and evaluated. We have found no ‘magic bullet’ solutions waiting to be exploited. Equally, we have found that it is not possible, in general, to map uses onto fines that are available, because the accumulation of fines within a quarry very often (usually) gives a stock pile of material that is below a nominal size (typically 3, 4, or 5 mm) but that has highly variable grading (particle size distribution). There is no doubt that this inhibits the exploitation of fines, largely restricting their use to relatively low value applications (fill, soil remineralization etc).

Clearly, construction uses are of greatest importance, and thus of the greatest interest, in terms of the volume of material that can (in principle) be accommodated by construction markets. The use of fines in concrete products is particularly demanding in terms of the specifications that need to be met (especially grading). However, improvements in the properties of concretes (including controlled low strength materials) produced using quarry fines (up to 17%) include:

- higher flexural strength,
- improved abrasion resistance,
- higher unit weight, and
- lower permeability (very important for reducing corrosion and/or leaching).

Increasing the proportion of fines also improves flow characteristics and workability, provided the fine aggregate is appropriately graded and shaped.

Similarly, improvements in the performance of asphalt surface materials have been observed through the incorporation of fines, again with carefully specified grading.

Outside construction, the only potentially significant alternative market that could accommodate large volumes would be in connection with soil management (to compensate for soil degradation through erosion or loss of fertility), but this is as yet poorly developed and unlikely to generate substantial revenue. There are however, some potential ‘niche’ uses for quarry fines which may not utilise a large volume of fines, but could still be a useful outlet.

There is a tendency for fines to be treated as a rejected material. Each quarry will produce fines with their own particular qualities, depending on the rock type and the crushing plant that is used. In some locations, stockpiles of fines may be mixed with other materials from within and outwith the quarry.

There is a clear need to develop specifications that can be applied to fine aggregates to make them acceptable to significant markets. The implementation of these specifications may require additional or more careful processing within the quarry, requiring a cost-benefit analysis.

New drivers that deserve to be developed include the Soil Action Plan (DEFRA). Here there is an opportunity to engage DEFRA in dialogue to assess the ‘market’ for fines in soil protection activities.

PART 2

5. METHODOLOGIES

The project has involved a review of published material, from a spectrum of sources including journals, non-peer reviewed articles and the internet. This has been supported by interviews with key individuals within the industry, who were asked to respond to a semi-structured questionnaire. A relational database has been produced using Microsoft Access™. This enables the information that has been collected in the literature search to be searched relatively quickly and easily.

5.1. Literature review

Bibliographic databases available through the Science Direct and Web of Science web-sites were searched for relevant peer-reviewed journal papers and conference proceedings. Searches on subject keywords such as 'fines' and 'waste' were used initially, followed by author searches once key researchers in the field had been identified. An extensive reference list of published work was compiled, together with a contact list of researchers in the field. Searches of research activity funded by UK Research Councils were also undertaken through their websites.

Broad internet searches for other materials including commercial literature were made using the search engine Google. Many search terms were used including, for example: "rock dust", "quarry", "fines", "waste", "innovation" and "recycle". Searches of internet message boards and discussion fora were made in an attempt to identify unusual or 'off-the-wall' uses of fines.

Additionally, searches were made of the British Standards database. These searches also used a wide variety of search terms, with a view to identifying existing and potential future uses for fines in products subject to Standards.

5.2 Stakeholder questionnaires

BGS, Mineral Solutions and the project partners were well placed to identify the most relevant stakeholders through their extensive network of government, industry, research organisation and NGO contacts in the quarrying sector. From this network a broad mixture of representative stakeholder individuals were identified and invited for consultation by interview.

All interviews were preceded by an explanation of the interview’s purpose (to investigate the generation, location, evaluation, development and utilisation of quarry fines) and were based on a semi-structured interview of general questions, but allowing flexibility so that other issues raised during the interview could be explored.

General questions included:
- How are fines defined?
- Are quarry fines a problem for your operations?

- How much is produced; are production data known and collated?
- What stockpiles exist and where?
- Does technical data exist on quarry fines and is testing regularly carried out?
- Are these data available?
- What markets/applications currently provide sales outlets for quarry fines?
- Have sales/markets changed in the past 10 or 15 years?
- What research is being undertaken into developments of markets for fines?
- Is it possible to reduce or optimise production of fines?

The following stakeholders from the quarrying industry were interviewed:

1. Gordon Lemon & John Lay, RMC Aggregates (UK) Ltd. (1/9/03)
2. Graham Goodhall, Francis Flowers, (5/9/03)
3. Graeme Richards, Aggregate Industries UK Ltd. (17/9/03)
4. John Bullock, Foster Yeoman Ltd. (23/9/03)
5. Steve Southam, Hanson Aggregates-North. (24/9/03)
6. Angus Kennedy, Maxwell and Son Ltd. (13/1/04)
7. Pat Lyons, Tarmac Northern Ltd. (13/1/04)
8. Stephen Robinson, Robinson and Sons Ltd. (14/1/04)
9. Bill Weir, Maxwell and Son Ltd. (14/1/04)
10. Peter Scoble, F.H.Gilman and Co. (30/1/04)
11. Rafael Fernandez Aller, Aridos (Spain) – by telephone (2/2/04)
12. Peter Huxtable, British Aggregates Association – by telephone (4/2/04)
13. Willie Brown, Brett Aggregates Ltd – by telephone (4/2/04)

5.3 Relational database

Information from the literature and web search has been used to develop a Microsoft Access™ relational database. The use of the database is described in Appendix 2, and the database can be downloaded from the Mineral Solutions website (www.mineralsolutions.co.uk) or from the Quarry Products Association website (www.qpa.org).

The data (over 150 records) collected in this study have been entered into Excel™ spreadsheets, which give the following details:

- Record number
- Source of information (bibliographic or internet reference)
- Date
- Quarry product
- Rock type
- Specific Use
- General area of use
- Specifications
- Relevant standards
- Notes and comments

The data tables can be augmented by the user, and the database can be modified to meet specific needs. The structure of the database allows searches to be made according to any of the categories listed above, permitting relatively rapid access to information collected during this study.

6. PREVIOUS REVIEWS OF USES FOR FINES

This study has drawn upon previous work concerning the identification of uses for crushed rock fines. In this section, a brief summary is made of key points from earlier studies.

6.1. Uses for fines derived from the Pennant sandstone

TRL Ltd. has undertaken a study of market applications for sand arising from production from the Pennant sandstone in South Wales (Lamb, 2003). The study investigates applications for sand, silt and clay-sized waste materials both combined and as separate components. Priority was given to applications using the untreated material. 44 potential applications were identified from a literature review; this list was refined on the basis of market research to 11 applications to be explored in laboratory trials. They are: surface courses for paths and minor roads; friction surfacing and micro-slurries; concrete applications; a cement extender; abrasives applications; horticultural grit and decorative chips; road sub-base; tile manufacture; synthetic soil; block manufacture; bedding sand for block paving.

6.2. Review of the Aggregate Industry in Wales

The Welsh Assembly commissioned a review of aggregate production in Wales (Arup, 2003), specifically to improve sustainability. Specific conclusions include:

1) china clay waste (from Cornwall) is suitable for substitution, at least in part, for a wide range of primary aggregate types;
2) waste from the extraction and processing of igneous rock and sandstone present a significant opportunity for greater aggregate use, but it may be more sustainable to use these materials for site restoration as less processing is required;
3) limestone and dolomite waste arisings, stockpiles, and usage proved impossible to quantify;
4) sand and gravel waste were deemed negligibly useful as an aggregate substitute because most of the material is of silt grade and recovering sand grade material is expensive, thus the main use is as backfill or sub-soil in site landscaping and restoration;
5) slate waste is currently used quite extensively as aggregate, and this could potentially be expanded.

6.3. ICAR: International Center for Aggregates Research, Texas

ICAR hold annual symposia where invited papers are given by representatives from the aggregates industry, relevant government departments and universities. Copies of papers from past symposia are available from ICAR (www.icar.utexas.edu, which also gives more information about ICAR).

ICAR has established 8 task forces, each of which has a mission and addresses key sectors of interest to the aggregates community:

1) uses for new product fines
2) superpave aggregate specifications and fine-aggregate properties and their influence on end-products
3) alkali-silica/alkali-carbonate reaction in portland cement concrete
4) criteria for use of recycled materials with natural aggregates in mixtures and unbound applications
5) pavement design
6) remineralization
7) frictional properties of aggregates used in pavement surfaces
8) communications

Of these (1) has produced significant outputs from the University of Texas at Austin, focussing on the use of fines in concrete. (2) is focused at Texas A&M University, in College Station. Substantial reports from this group are available on-line. (3) and (5) have produced results (again available on-line), but the remaining task forces have yet to do so in the form of ICAR Reports, although contributing to ICAR conference proceedings. The 'Remineralisation task force' (6) currently is dormant (2004), and has no chairperson.

Initial work on uses for new product fines is presented in the first report produced by ICAR (ICAR 101-1; 1995). This report, available only as a hard copy, describes a major effort undertaken to quantify and characterize fines (defined either as minus 3/8" or minus #200 (<75 mm)), their location, character, and sales. Uses identified include: ready-mix flowable fills, solid waste landfills, agricultural uses, pipe bedding, and mineral filler.

Following from the ICAR 101-1 project, a further project was set up specifically to examine the effects of increasing fines in Portland cement concrete. Progress was reported at the 1999 Symposium (Hudson, 1999). The project is a joint effort between ICAR, Vulcan Materials Company and Svedala Barmac. The project aims to determine an acceptable level of minus 200 mesh (<75 mm) material that will not diminish the overall quality of PCC. The project resulted in ICAR report 102-1F, published in 2001 (ICAR, 2001).

A paper was given at the 1995 ICAR symposium that examines the rationale for use of fines, lists potential end-use applications, and urges commitment from the industry (Wood, 1995). It was suggested that a predominant factor is the approach of the aggregate producer in regarding pond fines as a costly waste material and a "necessary evil" of aggregate production rather than adopting an attitude that the fines materials are potentially recoverable, usable and marketable by-products. Many uses for fines are listed by the author in the following categories: Asphalt concrete products, Portland cement concrete products, conventional crushed stone products, agricultural products, chemical products, industrial and precious minerals/metals, mineral coatings, fillers and pigments, environmental pollution control products, ceramics products, and anti-skid grits.

Also at the 1995 symposium, a call was made for specifications for specific construction products to permit greater use or greater volumes of quarry by-products, provided the performance of the resulting material is equal to or better than that of the material as currently specified (Wood and Marek, 1995).

Other meetings have been organized in the US for the discussion of utilization of fines, in addition to the symposia hosted by ICAR. For example, a seminar was organized by the Georgia Crushed Stone Association and the North Carolina Aggregates Association (Machemal, 1999). It was held to provide and share information and ideas on screenings and fines that others have marketed successfully.

6.4. Federal Highway Administration

This American web-site (www FHWA, 2004) outlines the material properties of quarry by-products and their potential uses. It is part of a user manual which presents the results of research conducted for the US Federal Highway Administration (FHWA) on guidance in the use of waste and byproduct materials in pavement construction. It includes a reference list. The rock types listed are: flint, trachyte, limestone, diabase, granite and quartzite. Uses specified are: embankment material, base or sub-base applications, mineral filler in asphalt paving, limestone screenings for agriculture. It is noted that pond fines require dewatering before use in these applications.

7. CONSTRUCTION USES FOR FINES

The 'conventional' uses for fines are predominantly in the construction industry, and demand depends strongly on road building and other construction activity. However, the full potential for use of alternative materials (i.e. not primary aggregate) in construction has not been reached due to factors including (i) uncertainty over their physical properties and how they will affect those of the construction product and (ii) the potential risk of environmental contamination (Hill *et al*., 2001). Hill et al. set out to show that alternative materials, such as quarry waste, can perform as well as or better than conventional aggregate used for road bases and bulk fill. As stated by Rockliff (1996), it is important that use of aggregates in construction is driven by end performance specifications that can be applied to a range of materials of different origins.

In these construction applications, the ability of an operation to sell fines will depend on local demands and competition from other quarries with access to the same market. These uses for fines are in applications with a high place value (Crouch, 1993), which means that those quarries distant from potential markets suffer economic disadvantages in addition (in the UK) to those arising from the Aggregate Levy. In these cases, alternative uses for fines that are worthwhile in reducing costs, if revenue generation is impossible, need to be considered. One possible application is in the development of soil-forming materials in restoration work, or in collaboration with local farmers, particularly in quarries in areas under landscape pressure.

The following sections in this report summarise key aspects of the source material that has been consulted. Initial comments address general and/or low specification uses for fines, followed by the use of fines in road surfaces, in concretes (including sections on test methods), and in artificial aggregates, blocks and tiles.

7.1. Competition with other materials

Expanding the markets for fines, perhaps by relaxing specifications and standards in the construction industry, will cut into the market for primary aggregate. Whilst this has environmental/sustainability benefits, it may not be an attractive prospect to aggregate producers. Other materials competing with fines in the construction sector are recycled materials such as construction and demolition waste. It is likely that quarry fines are of higher quality (in terms of acceptability and consistency in composition, physical properties and availability) than these wastes, and they therefore may meet stricter specifications.

7.2. Site remediation/landfill capping

Quarry site remediation is perhaps the most economically viable and well-established use for waste fines (e.g. Harrison, 2003). Fraser and McBride (2002) present a study of the case-specific geotechnical properties of fines when used as embankment material in a dolomite quarry. Pond fines were used to construct sloped embankments at the base of the vertical perimeter quarry walls. They found that increasing the dry bulk density by 0.1 gcm^{-3} over the mean density measured in situ did not improve the calculated factors of safety for slope stability enough to warrant increased mechanical compaction of the pond fines during embankment construction.

Huffman (2001) presented a case-study of the approach taken to solve the fines problem at the SRM Tarrant limestone quarry in Alabama The fines problem was especially acute for this quarry in a metropolitan area as it became “landlocked.” Valuable stone reserves became inaccessible until the pond fines were removed. Eight uses of pond fines were identified and in six of these cases, limestone pond fines from quarry were used on a commercial basis. Within 1.5 years, approximately 250,000 tons of pond fines were removed from the quarry and used primarily as special soil caps or infiltration layers at local landfills. Engineering properties of the limestone pond fines were found to be competitive with, and sometimes superior to, local soils used for general fill. Research indicates that limestone pond fines also show promise in acid mine drainage abatement and hydroseeding for erosion control purposes.

It was concluded from this case-study that economics, education and research were all important. Good communication and support were needed to allow convenient and satisfactory service to the customer, as pond fines are not a routinely marketed product. Being aware of the limitations of the fines (engineering properties, moisture, stability, and cost of handling and transportation) was critical. The need for many state and private geotechnical engineers to be educated about pond fines was reported.

Also in this category of ‘remediation’ can be included some rather specialist, but potentially important, uses for fines arising as mineral processing wastes:

Amaratunga (1991) describes how the agglomeration of fines can be achieved using a binder (e.g. cement, lime or ferrous blast furnace slag) in a disc or drum pelletizer. This process could be used to dispose of reactive, environmentally unsafe fines (copper-nickel tailings were used in the research). Possible alternative agglomeration techniques are pressure, briquetting, tableting, extrusion, rolling and compaction.

With similar motives, Marabini *et al*. (1998) describe a method for making glass-ceramics and glass- and rock-wool fibre from a combination of industrial, mining and quarry wastes (they use basalt and serpentine – the chemical composition is important for this application). The purpose of this work is to create new materials which can be used or disposed of without the environmental risk from heavy metals etc. present in some of the raw materials ('inertization of toxic elements'). Suggested uses of the ceramics are: paving, aggregate, radiant panels for stoves, ovens and radiators. Uses of rock wool are as a substitute for asbestos and in all fibre-reinforced products.

7.3. Unbound or loose fill uses: earthworks, road base and bedding

A widespread use for quarry fines is as unbound aggregate, typically used for road base, including haul roads within quarry sites. The wider use of quarry waste/ fines in unbound mixtures for road pavements has potentially been held back by inappropriate specifications (Rockliff, 1996).

A paper by Touahamia *et al*. (2002) shows that quarry fines can be substituted for primary aggregate used as coarse granular material for backfilling, highway construction, sub-bases for roads and railway tracks etc. In separate tests dry quarry waste, building debris and crushed concrete were compacted in layers separated using 'geogrid' reinforcement layers; their strengths were tested in comparison with crushed basalt, representing a 'traditionally used' aggregate. The quarry waste had a much smaller particle size distribution than the other materials (<5mm as opposed to <13mm). This study found that the presence of geosynthetic reinforcement greatly increased the shear strength (by up to 50%) and restrained deformation.

A 1996 ICAR symposium paper (Parker, 1996) reported a similar study investigating the advantages of crushed stone fines as engineered backfill for mechanically stabilized earth walls. Three materials, granite screenings, limestone pond fines and a natural pit run sand were tested for strength, permeability and chemical properties. A 12ft (4m) high geotextile fabric stabilized wall was designed using the measured properties, and it was found that crushed stone fines required less fabric reinforcement than natural sand, reducing costs.

Another study involved the construction of a test road from quarry waste (de Rezende and de Carvalho, 2003). An 80m long, 10m wide experimental road was constructed and tested over a 3-year period with low-volume usage. Quarry waste with a grain size of ≤ 100 mm was used to construct a 20cm thick base layer, which was covered by a 3cm-thick surface treatment. The results confirm that quarry waste can be used successfully as a base for low-volume road paving. A caveat is that the strength and durability properties of the paving are damaged by water.

Where soil erosion and land gradients are a problem for developers, fines can be an attractive alternative to soil backfill. Waste fines are more easily worked than clay-rich soils, benefiting the contractors. A test project was carried out in Georgia in 1988 by Vulcan Materials Company, consisting of backfill for the building of a large mall (Brown, 1996). Fines from Vulcan Materials Kennesaw quarry were tested and found to withstand the required bearing pressures (4000psf; approx 200 kPa). Moisture density, safety factor of bearing capacity, void ratio and angularity of the waste fines were also found to be suitable. The material allowed quick and economical construction of a large fill project in an urban area. Appendices to the paper contain the specifications of the material used.

Another 1996 ICAR symposium paper (Graves and Little, 1996) describes how unbound limestone fill can be strengthened by the addition of carbonate fines. Laboratory and field investigations were carried out in Florida and Texas. The fines create extra strength by a cementation process, which can be enhanced by adding calcium hydroxide to the mix. The amount of strength enhancement depends on the mineralogy of the limestone and fines used.

7.4. Other unbound applications– garden landscaping and recreation

There is a market for quarry fines to be used as a bedding or base material for drive ways, garden paths and patios taking the place of sand. Many examples of companies (based mainly in the USA, Australia and New Zealand) that sell quarry fines for landscaping and groundcover applications were found on the Internet. Some were quarries that directly market fines, whereas others were landscape suppliers that act as an intermediary between customers and quarries. Decorative aggregate is particularly saleable in dry areas where it is difficult to sustain lawn cover in gardens.

Examples include:

- The landscape supplies company Nuway sells crusher dust for filling and compacting material at AUS$39 per cubic metre (www Nuway, 2004).
- Canterbury Landscape Supplies (NZ) sells crusher dust at NZ$4.00 per 25 litres (www Canterbury, 2004).
- Centenary landscaping supplies, Australia, charges AUS$48.40 per cubic metre of 'crusher dust' (www Centenary, 2004).

Other uses for which quarry fines are sold directly, 'as-is', include track fines, path fines, and athletic infield material. An example can be found on the website of Graniterock (www Graniterock, 2004), a US quarry group company with direct marketing of their 'granite' (actually a hornblende gabbro) fines. The material is advertised as being: "*1/4 inch Minus, well graded to provide for excellent compaction and containing no large aggregate. Produced daily and stored in a covered bin so they are available dry year round. This aggregate is typically gray in color*."

7.5. Bound applications– Asphalt, bitumen, and other surfacing materials

Hill *et al*. (2001) point out that fine aggregate is less appropriate than coarse material for road aggregate because it is not as strong. However, it is appropriate for use in the manufacture of bitumen-based binders and other bound surfaces.

The mineral filler in hot mix asphalt is known to play an important role in stiffening the binder, whereas increases in toughness and fracture resistance due to the mineral filler are less well documented. A paper presented at the 1996 ICAR symposium (Anderson, 1996) suggested that the simple dry compacted voids (Rigden) test can be used to predict the effect of mineral fillers on the mechanical properties of hot mix asphalt.

A 1999 ICAR conference paper reported tests on the use of fines in asphalt (Collins, 1999). Re-blending aggregate to specific proportions can produce highly rut-resistant asphalt mixtures; test data are tabulated in the paper. One of the conclusions was that high frequency aggregate screening and innovative blending strategies can transform excess or waste quarried fine aggregates into high demand premium performance materials.

Effective test methods must be developed to allow better, more appropriate standards and specifications. ICAR report 201-1 (ICAR, 201-1) describes research into the properties and performance of asphalt mix designs with respect to the current specification for fine aggregate angularity, which contains restrictions. The results show that the restrictions in the specification are not needed to control gradation.

Also in the US, Luck Stone (www Luckstone, 2004) has developed and sells a variety of products for recreation surfaces that are made from fines, sand and binders. They include tennis and baseball court/field surfaces, footpath surfaces and golf bunker 'stabilizer'. The surfacing material is made from screenings/fines and binder in various colours with differing hardness, flexibility, friction and other properties.

The Utah Department of Transportation (UDOT) has strived to use performance-related acceptance tests for pavement materials (Anderson, 2003). This approach required a test that relates to the primary modes of failure in Utah. The most common failure mode has been moisture susceptibility or stripping and pavement rutting. It was found that the Asphalt Pavement Analyzer and the Hamburg Rut test machine provide test results that related to the field pavement performance. When combined with other hot mix asphalt mixture requirements, the specification is coming closer to ensuring a quality pavement without the use of a pavement warranty.

The Utah Pavement Council is a group with members from the industry sector as well as the regulatory sector working together to draft specifications that stress the performance or quality of the pavement materials. Better construction techniques and new technology are streamlined quickly into the process because of this effort.

7.6. Fines used as aggregate in concrete

In concrete applications, concrete blocks contain up to 40-50% fines and in some manufacturing locations may take all of the fines produced by local quarries. Ready-mix concrete typically contains 30% fine aggregate, made up of equal amounts of quarry (chiefly limestone) fines and sand. The amounts of sandstone and igneous rock fines used in this way are limited because of their high water demand, which generates drying shrinkage and other problems. These can be solved through the use of chemical additives, whose cost may in appropriate circumstances be offset by reduced haulage costs.

Both web and printed literature searches yielded many studies with quarry fines/waste used as aggregate in concrete, reflecting the large amount of academic and industrial research in this area. Researchers have studied ways to optimize various properties of concrete in which fines are used as well as characterizing the basic properties which may be enhanced or degraded relative to concrete made using ‘high-quality’ primary aggregate. Additional work has focused on the characterisation of fine aggregates to generate specifications that relate to their performance within concrete products. These include particle shape analysis as well as grading and mineralogical composition.

The following paragraphs summarize briefly key aspects of the consulted sources:

a) Testing and classification of fines for use in concrete

Over the years represented by the ICAR conferences (1994 to present), there has been an increase in research efforts into devising ways of characterizing, assessing and testing aggregate properties in order to predict the properties of concrete (or similar) made from it. Much of this research concerns the <75μm fraction.

Hudson (2003) states that it is nearly impossible to predict the performance of concrete sands from the common or traditional methods of characterizing these materials. The impacts and pitfalls of blending manufactured sands with existing natural sand sources needs to be fully understood so that the positive contributions of both types of sands can be maximized. He emphasizes that: "*the aggregate industry needs to understand how its own product works, if it is to have it used in concrete and to be remunerated for that product at a fair value*".

Effort has been made by ICAR to develop a framework for the classification procedure for use of aggregate fines in concrete (ICAR 101-2F). The focus of this project was to examine the methods and test procedures used in the past to characterize the properties of fines, and develop, on a preliminary basis, a framework to characterize and catalogue the properties of aggregate fines. Additionally, new methods and test procedures were proposed that will eventually complement a set of guidelines for the use of aggregate fines in Portland cement concrete. Possible applications of aggregate fines, such as in high-performance concrete, controlled low strength materials (CLSM), and insulated concrete forms are discussed as future directions of research.

The development of standards and classification for primary building/construction materials is an important area for appropriate research and legislation. Out-dated or superceded specifications must be changed to allow the use of so-called secondary materials where appropriate for reasons of sustainability. Inappropriate specifications and/or standards are a significant problem in the USA, and there are numerous ICAR symposium papers related to this issue. For example, a problem has arisen because specifications were written for the use of natural sands in concrete, and it is now common in many states for manufactured (crushed rock) sand to be used. In natural sands, the fines present tend to be clay minerals which will reduce concrete strength because they inhibit the bond between the aggregate and the cementitious mortar (Dukatz, 1995). From this arose the restriction on the percentage of fine material present. When manufactured sand is used, the fines are typically not clays. To show this, chemical analysis can be used to determine the clay mineral content (for example, the methylene blue titration).

Dumitru *et al*. (2001) reported the results of a study of alternative or complimentary methods for assessment of fine aggregates at the 2001 ICAR symposium. They concluded that mineralogical studies (such as X-ray diffraction analysis) should be used to ascertain compositions of secondary minerals and quantify amounts of those harmful in some applications (in particular amounts of clay minerals). Mineralogical studies should be a viable alternative to the methylene blue value method for quantifying the amount of clays in aggregate fines. It is then possible to differentiate quarry fines and remove the need to restrict the fraction of material under 75μm in good quality manufactured sands. They conclude additionally that the flow cone test method (ASTM C1252) should be modified in order to compensate for the shortfall in the method, where two material attributes are measured using one parameter. Also, in order to fill a gap between the physical and mechanical properties of fine aggregates and their actual performance in concrete, a mortar- based test is presented as a reliable and fast small-scale method for evaluating the suitability and relative performance of different fine aggregates to be used in concrete.

The approach taken by the state of Georgia to the issue of fines can be used as a case-study. In 1997, Georgia began allowing a higher percentage of crushed stone fines to be utilized in the production of Portland cement concrete (Watson, 1999). The relaxation in specifications for fines in concrete sand was adopted after a committee of industry, academic and civil servants set up by the Georgia Crushed Stone Association lobbied the Highway department (Machemal, 1997). Uses for fines were identified by the committee that are targeted to be relevant for Georgia aggregate producers. Similar committees may be useful elsewhere. Historically, natural sand was preferred because of its rounded particles which give better workability. In the North of Georgia there are no natural sand deposits and reduced haulage costs therefore made manufactured sand competitive, and the permitted proportion of fines was increased to improve workability. The gradation specifications are still unsatisfactory as a predictor of concrete quality, however. Other tests still need to be developed that can provide true performance-based specifications.

Prior to 1997, the quarries certified by the US Department of Transportation were required to maintain grading target values of 0-7% passing the #100 (150 μm) sieve and 0-2% passing the #200 (75 μm) sieve. Users had been adding fines to improve workability and finishability. This common specification for very low percentages of minus #200 (75 μm) fines in aggregate for asphalt and concrete mixes, and increased demand for manufactured concrete sand, have increased the rate of production of waste fines (Smith and Slaughter, 1996).

Specifications for concrete sand gradation have also been relaxed by the North Carolina Department of Transportation as a result of pressure from the aggregate industry (Saunders, 1995). On site test slabs were provided by the industry to finishers to compare performance with natural sand used in concrete for road construction.

b) use of image analysis to characterise fines

On-line image analysis as a method of characterising fines arising during production has been assessed in a number of papers.

Persson (1998) describes an image analysis technique for determining grain size and shape distributions of fine aggregate; this is a potentially useful method of classifying quarry products in order to determine their suitability for various grain-size-sensitive applications (including concrete). Another method to quantify particle shape, surface texture and grading is to measure the uncompacted voids as an indicator (Marek, 1995).

Masad (2001) presented a review of imaging techniques for characterizing the shape of aggregates used in asphalt mixes at the 2001 ICAR symposium. It is emphasized that the unique capabilities of image analysis techniques allow the development of low-cost automated systems for capturing the shape of large amounts of aggregates rapidly and accurately.

Kim *et al*. (2001) described a prototype laser scanner for characterizing size and shape parameters in aggregates at the 2001 ICAR symposium. The Laser-based Aggregate Scanning System (LASS) is being developed at The University of Texas at Austin to rapidly characterize various properties of construction aggregates. The LASS is expected to provide various other aggregate characteristics including angularity and particle texture as the research progresses. This ability to analyze multiple characteristics of aggregates automatically will enable aggregate producers to monitor various quality aspects of the products while they are being produced, so that instant process adjustments can be made to ensure better quality products.

Garboczi *et al*. (2001) describe how a combination of X-ray tomography, image analysis-type techniques, and spherical harmonic analysis can give a complete 3-D mathematical characterization of an aggregate particle. The derived mathematical form of the real particle also allows incorporation of the particle into various algorithms, allowing real particle shape to be used in models that before only were able to use simple shapes like spheres and ellipsoids. This method will also allow the rheology of a suspension of real particles to be simulated with good accuracy, which could result in a useful computational tool for concrete. Databases of 3-dimensional aggregate shape can be constructed, characterizing various aggregate sources.

Fletcher *et al*. (2002) describe the design and development of an aggregate imaging system for characterizing fine and coarse aggregate shape properties (AIMS). The system is developed to have the ability to capture images and analyze the shape of a wide range of aggregate size, which covers those used in asphalt mixes, Portland cement concrete and unbound layers of pavements.

c) properties of concretes using quarry fines as fine aggregate

Ahn *et al*. (2001) and Ahn and Fowler (2002) conducted a study into the effects of high fractions of fines in mortar and Portland cement concrete. A total of 50 sands were used in the mortar study, 10 of which were included in the concrete research. The following conclusions were drawn from the results of this study:

- Mortar compressive strength may decrease as the MBV (methylene blue value) increases. As the minus 75µm fines content increases, the compressive strength slightly decreased.
- Mortar drying shrinkage showed a similar trend for correlation among test results as compressive strength. The drying shrinkage increased as the MMBV (modified methylene blue value) increased. As the minus 75µm fines content increased the drying shrinkage may slightly increase. The drying shrinkage slightly increased as absorption capacity increased.
- Compared with concrete made of natural sand, high-fines concrete generally had:
    - higher flexural strength,
    - improved abrasion resistance,
    - higher unit weight, and
    - lower permeability (very important for reducing corrosion and/or leaching)

Very good quality concrete was made with manufactured fines contents of up to 17%. No admixtures were used in the study.

Crouch *et al*. (2003) investigated the effect of fine aggregate type on controlled low-strength material (CLSM; flowable fill). They developed a high-flow, rapid-set, non-excavatable controlled low-strength material for applications where time was critical.

It was found that this type of CLSM could be produced with a wide variety of Tennessee fine aggregate types. Fine aggregate properties such as gradation and angularity dictated the mixture proportions required to achieve flow, air content, and bleeding characteristics and therefore indirectly influenced the time of set and compressive strength development.

Derived from a major study of the use of fines in concrete, a summary of fine aggregate characteristics that affect the properties of mortar and concrete has been produced by ICAR, along with the correlations evaluated between these properties in a substantial study of the effects of high proportions of fines (ICAR 102-F).

Other projects undertaken by ICAR investigated the use of high-fines concrete in insulated concrete form construction (ICAR 103), and an extensive examination of tests used to measure concrete workability (ICAR 105-1).

A series of articles on fines was published in the American magazine ‘Pit and Quarry’ by Hudson (2001-2002) with the following rationale: "*Aggregates make up 80 percent of the volume of concrete, yet aggregates producers know very little about how aggregates influence their concrete clients' business - either positively or negatively. Only through understanding how aggregates work in concrete can producers start to gain fair value for aggregates products, and begin to use unwashed fines or other "marginal" material.*"

The use of quarry fines in concretes used as screeds and surfaces has been reported by a number of workers. For example, Ho et al. (2002) have tested self-compacting concrete made with quarry dust (granite, <0.250 mm) replacing limestone powder as a filler. The concrete mix may require a greater dose of superplasticizer if the quarry dust is used as supplied because the variability of particle size distribution affects flow properties adversely. Otherwise, the rheological properties of the quarry dust concrete compare favourably with traditional limestone powder concrete. Another study (Felekoglu and Baradan, 2003) looked at replacing cement in concrete with limestone powder to improve the self-levelling and self-compacting properties. A 10% replacement of cement with limestone powder was found to lead to the best performance.

Research by the Tennessee Technological University Department of Civil Engineering in collaboration with Rogers Group Inc., has shown that limestone screenings containing up to 21% finer than 75 micron can be used as aggregate to produce a flowable fill mix meeting National Ready-Mix Concrete Association performance recommendations (Crouch and Gamble, 1997). Flowable fill is also known as controlled low-strength material (CLSM). The proper air content (14-30%) in a well designed mix limited the strength, generated adequate flow, eliminated segregation, and greatly reduced bleeding by producing a cohesive homogeneous mixture. Flowable fill mixes containing limestone fines can be economically attractive where other aggregates are expensive – such as where river sand is expensive or difficult to obtain.

Topçu *et al*. (2003) report tests on properties of concrete made with mineral filler (limestone derived, <2mm grain size) partly replacing sand (composition unspecified, but presumably quartz). They found improvements in compressive and flexural strength. Permeability, absorption and porosity were decreased. These improvements were observed for up to 7-10% filler, in excess of this no changes or detrimental effects were observed. A similar study was undertaken by Çelik and Marar (1996); these authors used rock dust (limestone, <75 mm) to replace sand in concrete in proportions up to 30%, with all other ingredients and proportions constant. They then measured the following mechanical properties of the concrete when fresh and hardened: slump, air content, compressive strength, flexural strength, impact resistance, absorption, water permeability and drying shrinkage. The following conclusions were derived:

1) slump decreased as the percentage of dust increased;
2) air content of fresh concrete decreased as the percentage of dust content increased;
3) increasing the dust content up to 10% improved the compressive strength of the concrete. However, dust contents exceeding 10% were correlated with a gradual decrease in compressive strength;
4) increasing the dust content up to 10% improved the flexural strength of the concrete. However, dust contents exceeding 10% were correlated with a gradual decrease in flexural strength;
5) concrete made of up to 5% dust content had improved impact resistance. However, dust contents more than 5% reduced the impact resistance significantly;
6) the minimum value for absorption was obtained when the dust content was 15%. Dust contents higher than 15% increased the absorption of the concrete;
7) water permeability of concrete decreased as the dust content percentage increased;
8) increasing the dust content up to 10% increased the drying shrinkage. As the dust content exceeded the value of 10%, the drying shrinkage strain decreased. This has a relationship with compressive strength, the higher the strength of the concrete, the higher the drying shrinkage exhibited and maintained.

Similar experiments on the benefits of fines on concrete have been presented in several ICAR symposium papers, in which the emphasis is usually on concrete made from manufactured, and not natural, sand. All the studies conclude that more fines can be used in concrete than are typically permitted (in the US), however the actual percentage depends on end use and fines properties (Fowler, 1997). The percentages quoted range from 5% (Jackson and Brown, 1996) to 15% (Fowler and Constantino, 1997; Ahn and Fowler, 1999). Another study found that a 25% reduction in cement in concrete made using fines could be made while retaining the same 28-day strength (Fowler, 1995).

Singh and Majumdar (1981) investigated the strength properties of glass-reinforced concrete (grc) made with 40wt% quarry fines, as filler, and 5.45wt% glass fibre. The fines contained quartz, feldspar and clay minerals. The fines act as a diluent and so decrease the initial strength of the concrete, but over time the strength may not be different from standard grc – in fact the bending strength may be superior. Optimizing the cure conditions can improve the initial strength deficit.

Nataraja *et al.* (2001) devised and report a method of producing concrete of the required strength– by measuring the characteristic strength of the aggregate to be used (they used marble quarry waste) the necessary proportions of cement and water can be calculated to provide the required additional strength supplied by the cement mortar.

Evidence for commercial research and development of the use of fines in concrete and concrete-related products is less widely available; this may due to its economic sensitivity rather than it not being existent. An example of an innovative concrete-related product made from fines is a ballast made by the US aggregate producer Lafarge (Lafarge, 2004): "Ballast-Crete ® has fast become the preferred choice in ballasting for shipyards, naval architects and engineers around the world. Its superior performance under demanding conditions coupled with the expertise of Lafarge's technical staff have allowed us to find answers to just about any stability concern."

7.7. Fines used to make synthetic aggregate and lightweight aggregate

Issues which are readily apparent in the use of quarry fines include the effect of the particle size distribution and the very fineness of the particles. These problems can be addressed by binding the fines to make coarser and more uniform particles artificially. The procedure can be optimized for the production of light-weight aggregate, otherwise produced from relatively rare or scarce raw materials such as pumice.

For example, Wainwright *et al.* (2002) report how granite quarry fines were blended with paper sludge, clay, or a dredged harbour sediment and extruded then fired in a specially designed rotary kiln. Two of the aggregates produced in this way were tested in concrete, giving results that compared favourably with natural and other artificial lightweight aggregates. There are two trefoil rotary kilns at Leeds University, where this research was carried out, that may be used by businesses to conduct trials and feasibility studies (www Leeds, 2004), and experienced staff members are available for consultation. A bench-top kiln with a capacity of 2 to 3 litres enables small-scale feasibility studies to undertaken, whilst a laboratory-sized kiln with a capacity of 40 to 50 litres allows much larger-scale trials to be conducted. The aggregate produced by the laboratory kiln is in large enough volumes to be investigated for consistency and repeatability.

Another rotary kiln procedure for the production of lightweight aggregate is described by Weinecke and Faulkner (2002). Fly ash, bottom ash, waste fines, waste sludge etc. are mixed with a bentonite clay binder (2-3 wt%). The mixture is fired in a rotary kiln, and the product screened for size. The process of forming a lightweight aggregate relies on the ability of the material to 'bloat' when heated in the rotary kiln. So, the chemistry of the waste used must be appropriate for bloating to occur, or additives are needed. However, this paper (Weinecke and Faulkner, 2002) is not very specific about the type or chemistry of the material used.

Also, a United States patent exists (Frye, 1994) for a similar method of producing lightweight aggregate that could use quarry fines as a raw material (although this is not specified in the patent). The patent is for lightweight aggregate micropellets which can be used to replace sand in cement, concrete et al. Pellets are made by mixing ceramic clay, liquid and waste material (such as quarry fines) in a high-speed rotating pin mixer and firing at 2000°F (1100°C).

A US quarry claims on their website (www Rogers Group, 2004) to manufacture sand and 3/8” chips from its fines, but gives no details of the process. They mix the manufactured sand and chips with commercial base stone aggregate to make it less dusty and easier to handle, spread and compact while at the same time reducing their stockpile of fines.

7.8. Fines used as aggregate in brick and block making

An example of a business plan for a brick-making plant in India (where there is a very high demand for bricks) is published on a website (www India, 2004) linked to the Indian department of trade and industry. It is part of a government-sponsored development initiative. The bricks are made from a combination of quarry dust, lime and gypsum, and they are pressure moulded and air-cured. Full costings are given on the web page: crusher dust is costed at 50 Rs per tonne (<£1 per tonne).

Another example is given in an article about a South African quarry (South African Peak Quarry, 1998) – like in India, there is substantial demand for bricks and this quarry can sell all their waste fines as raw material to a nearby brick-making plant. "*Peak Quarry is the largest quarry of its type in Africa, mining 1.1 million tpy of materials to produce aggregates for building and construction materials, and dust for brick and block making. There is no longer a stockpile of fines, as the brick market continues to grow with construction in the region.*"

Bricks can be made without firing if curing can be caused by chemical reaction, forming so-called non-sinter chemical (NSC) bricks. These bricks can cut down on costs as the cost of heat for firing may be more than the cost of the chemicals. An example of a company that produces this type of brick is Goldwell (www Goldwell, 2004). The bricks are made from fines with a <5mm grain size range, and their specifications equal those of conventional bricks.

Another method of making bricks or blocks is by simultaneous vibration and compaction. A company called Resonant Shock Compaction, LLC, sells a machine for the manufacture of blocks from quarry fines (www Resonant Shock Compaction, 2004). A vigorous vibratory-compaction process is used in which a mix of granular materials and binders are placed in a mould and compacted for 2-5 seconds. The blocks can be used for: blocks and panels for building walls; light-weight aggregate (blocks are crushed to make aggregate); highway sound barrier walls, privacy walls and security walls; earth retaining walls and pond liners; paving blocks and roofing tiles. Research, development and demonstration facilities are located at the University of Denver, Environmental Materials Laboratory. Resonant Shock Compaction technology has been licensed for use in the United States, Japan and India.

A US patent (Weyland *et al*. 2000) is available that protects a method of making building blocks from waste particulate siliceous material such as rock mineral fines. The fines are combined with a calciferous additive and water and cured under the influence of controlled pressure and temperature for a pre-determined time. Shaped, high-strength building blocks of precise dimensions and desired properties are made.

At the 1998 ICAR conference, a paper was presented by a representative from AAB Building System Inc., a producer of insulating concrete forms (ICF). Joint research with ICAR at Texas A&M University on increasing the fines content in ICFs is reported (Sculthorpe, 1998). ICF technology is growing in use in residential construction in the USA, where ICF built homes can realize 44% savings for heating and 32% savings for cooling (totalling on average US$310 per house per year).

Wilding and Sayer (2002) describe how an aqueous granite powder suspension, consolidated with 5% cement and 5% coal fly-ash and cured for 90 days, was used to make artificial reef blocks. The blocks exceeded the strength requirement for commercial building blocks by five times and were tested for metal leaching– which was found to be significant but very low. They were deemed physically robust and environmentally safe, and are cheaper to produce compared with standard construction-grade blocks.

7.9. Tiles and artificial stone

Quarry tiles are a traditional product to make with waste fines. They can be marketed as ‘green’ or ‘environmentally friendly’. For example, tiles made by Quarry Tile Co. (USA; www Quarry Tile, 2004)) are advertised with the following statements: *"In general, Eco-Tile contains about 70% recycled solid waste, as defined by the EPA. Eco-Tile's recycled material is a combination of post-consumer recycled glass, post-industrial grinding paste from the computer industry, and post-industrial mining waste from the sand and gravel industry. About 25% is post-consumer waste and about 45% is post -industrial. All of the recycled waste products are within a 10-350 mile radius of our manufacturing plant and replace materials that previously were brought in from as far away as 2300 miles. Eco-Tile does not carry a premium price when compared to other Quarry Tile Co. products."*

"Like all of Quarry Tile Co.'s products, Eco-Tile meets or exceeds all of the requirements of ANSI 137.1 section 6.1 for Glazed Quarry Tile. It is available 50 plus colors, 5 field tile sizes and all of the key trim shapes needed for floors and walls."

Catarino *et al*. (2003) have published results of research into the properties of ceramic tiles made from slate waste fines (<100 mm). The tiles were made by uniaxially pressing the powders to shape and sintering in air in a muffle furnace at 1150°C. Properties of the tiles such as density, water absorption and bend strength were better than those of ceramic tiles made from clay (conventional building tiles).

In addition to tiles, artificial stone can be made from waste fines – as shown in research undertaken by Galetakis and Raka (2003) at the Technical University of Crete, Greece. Limestone dust and cement are mixed, humidified and compressed in a cylindrical mould (this was an experimental set-up and not at commercial scale) to form artificial stone. The stone has acceptable quality characteristics.

8. NON-CONSTRUCTION USES FOR FINES

Non-construction uses for fines include:
Agriculture
Horticulture
Leisure: gardening, model making, craft materials

Of these, agriculture and horticulture account for the greatest volumes of material.

8.1. Soil remineralization– fines as fertilizer

Many web pages propose the use of rock dust/quarry fines as a fertilizer or 'remineralizer' – an improver for poor soils for agriculture, horticulture and silviculture. Quarry fines are believed to improve soil quality by replenishing nutrients and by improving drainage and soil wettability. This use for rock dust seems to be especially prevalent in Australia, where there is a lack of glacially-generated fines enriching the soil.

The rock type is important, because the mineral content varies and, in general, igneous and metamorphic rocks will have more suitable chemistry than sedimentary rocks. Low P and K soils are most likely to benefit from 'remineralization'. It is also significant that this method conforms to organic farming regulations, unless fines are petrochemically contaminated due to the crushing method (www Acorn 2004). Another benefit to the farmer is that using fines does not normally require new technology as lime spreaders can be used. However, there exists a US patent for the manufacture of fertilizer pellets from a mixture of animal waste and rock fines (Glover, 1998). The formula is non-specific as it is intended that the fertilizer is tailored to the needs of specific types and areas of agriculture. For example, different rock types could be used to create different element/mineral concentrations where needed. In this patent, fines are defined at <0.297 mm. The animal waste and rock fines are heated to kill pathogens and de-water, and then formed into pellets for easy application.

The very extensive evidence of the value of ground igneous and metamorphic rock fertilisers in agriculture is reviewed by Harley and Gilkes (2000), who explain the geochemical background to rock nutrient sources. These authors conclude that powdered rock fertilizers are likely to be most effective where soils are dominated by minerals that are the products of extreme weathering (e.g. gibbsite, kaolinite) and where soil and its plant/microbiological communities can provide an adequate source of acidity for dissolution and to be a sink for dissolved ions. Nutrient cations must be released at a rate that supports plant growth.

Encouraging but inconclusive results have been obtained in some studies of the application of silicate rock as a fertilizer (see references cited in Harley and Gilkes). However, there are also studies published that report discouraging results (e.g. Bolland and Baker, 2000 and Bakken *et al*., 2000). Bolland and Baker concluded that fines from a granite quarry have no value as a fertilizer for wheat and clover. Bakken *et al*. trialled the use of nepheline, biotite and feldspar-rich tailings as K-fertilizers on grassland. They found that a substantial part of the K bound in biotite and/or nepheline in crushed carbonates, biotite concentrate and epidote schists is plant available whereas the K bound in K-feldspar seemed to be nearly unavailable for the grass plants. However, the biotite and nepheline weathered too slowly to replenish the native pool of plant-available K within a 3-year period with five harvests.

A report on field and container trials testing basalt dust and a glacial moraine dust as soil remineralizers at the University of Massachusetts was given at the 1998 ICAR symposium (Barker, 1998). Four crops were evaluated: lettuce, sweet corn, tomato and apples. Details of the amounts of rock dust and compost used in each trial are given as well as compositional analyses of the rock dusts. Basalt dust was round to have enriched soil fertility with respect to availability of some nutrients and it elevated the soil pH. These properties did not increase yields for lettuce; however, yields with compost and basalt dust were as good as those obtained with a complete organic fertilizer. Research with apple and sweet corn production indicated mineral fines had no effects on enhancing crop yields above those obtained with conventional practices. Container-grown tomatoes showed an early stimulation of vegetative growth with additions of mineral fines (see O'Brien *et al.*, 1999, for further details of the tomato experiments). In this study, glacial moraine fines had a lesser effect on available plant nutrients than basalt dusts.

Also in the USA, the Department of Agriculture, the National Aggregates Association, the National Stone Association and the U. S. Bureau of Mines co-sponsored a "Soil Remineralization and Sustainable Agriculture Forum" in May, 1994 (Able, 1995). Following this, a 3-year research programme involving urban and rural pilot test plots using granite, basalt and glacial fines was set up by the USDA.

In a related piece of work (Kramer, 1996), the US Bureau of Mines developed a GIS-based spatial analysis on using fines from aggregate operations to 'remineralize' agricultural and forest soils. The analysis is based on proximity of aggregate operations to agricultural and forest soils requiring replenishment of those minerals. The prototype focused on an area around Richmond, Virginia with a 75-mile radius.

Further examples of positive experiences of using rock fines as a soil improver can be found on the internet from a variety of sources:

Remineralization as a concept is promoted through an organization called 'Remineralize the Earth' (www Remineralize 2004), as well as some other agricultural organizations such as 'Men of the Trees', which is an international society of volunteers dedicated to tree planting for the protection of landscapes from desertification. Barrie Oldfield reported on field trials into using rock dust to improve soils in Men of the Trees plantations at a permaculture conference in 1996 (www Rosneath 2004). In a further example, 'Olives Australia' has carried out substantial trials on the use of basalt crusher dust for olive tree growth and health. The 'dust', which contains about 80% dust and 20% fine grit up to 4mm in size, is sold for use in gardens, landscaping, lawns, drive-ways and house slab foundations. All trials have resulted very positively in favour of adding crusher dust to the orchard site prior to planting. More detailed advantages and the method of use can be found on their web-page (www Olives 2004).

P. C. Madeley has published his (1999) BSc thesis on soil remineralization online (Madeley, 1999). In this study, two sets of experiments were carried out with lettuce and cress to establish the effectiveness of a 'mixed volcanic rock dust'. The lettuce was grown in perlite and compost whereas the cress experiments were grown in perlite alone. Growth of the lettuce in the dusted perlite medium showed a significant improvement over the control. The cress shoot height, root length and weight showed a significant improvement for the dusted cress over the control. Initial growth rates of all the plants were improved in the rock dust treated pots.

David Yarrow published an article in ‘Acres USA’ (www Acres 2004), a magazine covering eco-agriculture, which details anecdotes and experiments showing the effect of using Azomite rock powder (www Azomite 2004). Positive results were obtained using this pink clay (montmorillonite) powder from Utah for trials in tree- and tomato-growing.

Dr. Carl Rosen has written an article in ‘Greenbook 2000’ (Rosen, 2000), a publication by the Minnesota department of agriculture aimed at marketing sustainable agriculture. The article reports the methods and initial results of testing the use of basalt and granite fines on three farms. Slow release of nutrients from rock fines means that no crop response is seen in the first year.

An article by R. N. Lees in the news bulletin published by the Australian Institute of Geoscientists (Lees, 2003) discusses new uses for mine and quarry waste in agriculture. Basalt and granite fines with particle sizes <200µm are cited as examples of successful fertilizers in what is essentially a review article with a brief explanation of the theory behind their use. One aspect of the theory mentioned in this paper is the effect of paramagnetic minerals on plant growth. In simple terms, a paramagnetic material is one which when placed in a strong magnetic field, will become a magnet as long as the magnetic field is present. It has been suggested that paramagnetism is an important contributor to rock dust's effectiveness as a soil enhancer, and a pot trial by Dumitru *et al*. (1999) is cited as evidence. The trial involved four different basalt types; the basalt with the highest paramagnetism produced the most rapid plant growth.

Dumitru *et al*. (2001) presented further results of their soil remineralization experiments at the 2001 ICAR symposium. They conducted greenhouse trials using different types and application rates of basaltic quarry fines. The trials showed a beneficial impact on soil quality, plant health and growth. It is again claimed that basaltic quarry fines with higher levels of paramagnetic intensity have significantly improved plant growth when compared to basaltic quarry fines with lower levels of paramagnetic intensity. Attempts have been made to increase the rate of release of nutrients from quarry fines by adding microbial treatments, and this was achieved, resulting in an improvement of plant quality. The treatment has improved the soil water holding capacity and (in general) plant health and performance. Based on the success of greenhouse experiments, field trials have been carried out with good results. A specific emphasis has been placed in particular on golf courses and on the grass playing surfaces within high profile stadiums.

The theory that the paramagnetic properties of the minerals in soil are beneficial to plant growth is defined in a book aimed at the layman by Philip Callahan: “Paramagnetism: Rediscovering Nature's Secret Force of Growth”, published by Acres USA in 1995. There are some serious scientific errors in this book, which are outlined in a critique by Field Roebuck (www Froebuck 2004). Much misinformation about paramagnetism has propagated into the web-sites of companies selling rock dust for agriculture, and it remains unclear whether there is any basis in reality for the claim that paramagnetism enhances plant growth.

Other books on the subject of remineralization or rock dust as soil improver are available through the internet:

‘Rocks for Crops: Agrominerals of sub-Saharan Africa’, by P. van Straaten (2002) ICRAF, Nairobi, Kenya, 338pp (www Guelph 2004). This book is advertised as covering the subject of agrominerals used or of potential use in sub-Saharan Africa. Agrominerals are defined as rock-based products used to fertilize and/or improve soil. The book allegedly contains detailed information on the micronutrients required in agriculture, and what agrominerals are produced in the sub-Saharan countries.

‘Rock Dust and the Environment’, by D. J. Supkow, is a book which claims to be about the benefits of using rock dust in agriculture (www Energywave 2004). The potential wider benefits to the planet are highlighted by this author, who notes that weathering of silicate rock dust locks up and can therefore help control the levels of atmospheric CO_2. This idea, that the use of rock dust in agriculture has an ‘environmental remediation’ effect, is picked up in a web article promoting the activities of ‘Remineralize the Earth’ (www Globalideas 2004), which is notable for this quote: "*Robert Schindele is even more extreme. He eats gravel dust, two teaspoons a day, and markets it in parts of Europe as a 'mineral dietary supplement' under the name 'Superbiomin'– despite heavy opposition from the German and Austrian pharmaceutical industry. 'For years my hair was as white as snow,' he says, 'but since I have been taking gravel dust, it is almost black again. Chronic diseases, especially gout, disappeared.'* ".

Vendors of rock dust for agriculture include the following. This list is by no means exhaustive. Prices are not always given on-line.

http://www.minplus.com.au
The chemistry of the rock dust supplied to farmers is controlled by mixing different volcanic rock types. "Min Plus is 100% Natural, Multi-Mineral, Rock Dust. Min Plus instantly replenishes soil with minerals and nutrients found in volcanic rock. Min Plus Rock Dust activates the soil microbes and…" A report on this commercial product's use, written by researchers at James Cook University, is available from the website (PDF).

http://www.edkraemer.com/materials/index.asp
Dolomitic limestone quarry fines are marketed as "ag-lime" for soil improvement/ fertilizer. "Burnsville Quarry– this quarry produces high quality dolomitic limestone used in concrete, asphalt and road-base applications. Other specialized uses include agricultural application of quarry fines (ag-lime) for soil amendment, and the use of larger sizes (12" to 36") as erosion control materials along local lakes, streams and rivers."

http://www.acmewormfarm.com/soil.html
Glacial rock dust is sold at 10lbs for US$19 or 50lbs for US$49. "Using our Glacial Rock Powder in the garden insures that no trace elements will be missing. The soil

organism populations will explode. This is the star of our soil products. According to Rudolph Steiner, the father of biodynamic agriculture, this stuff works because of a spiritual connection to the cosmos. There is scientific evidence pointing to this, which we will be glad to forward to you."

http://www.agrowinn.com/rock.php
The rock dust supplied has a guaranteed analysis of Phosphoric Acid, Soluble Potash, Calcium, Magnesium and Iron. They also use paramagnetic properties as a selling point. "Agrowinn-Minerals is the finest rock dust on the market (also known as rock powder or stonemeal). Rock dust is environmentally friendly and will not leach into your ground water. It is also a slow release product; its super-fine particles will pass through a 2500 mesh screen with water agitation. It is also easily applied with boom-type sprayers with diaphragm pumps only."

www.howard.engr.siu.edu/mining/IMI/ad/MRD.htm: Mississippi Lime Co., Alton, Illinois, USA
"Mine rock dust (limestone) from an underground mine, eliminating all possibility of foreign contamination".

http://growingsolutions.com/home/gs1/page/29/4: AZOMITE® volcanic rock powders.
A typical analysis is available on the website. "The A to Z Of Minerals Including Trace Elements, AZOMITE, is a unique naturally mined mineral product from a volcanic deposit in Central Utah. This ultra-fine, odorless powder contains a broad spectrum of minerals and trace elements that support metabolic activity to enhance root growth, increase crop yield and improve soil health." US$19.95 for 44lbs.

www.motherearthorganics.com/pricing/pricing.htm: Mineral Rock Dust
A paramagnetic, 2300 mesh rock dust. "Mimics the actions of Mother Nature by replacing minerals once spread via glaciers, flooding and the wind. Over 70 trace elements feed soil microbes a feast which in turn feed the plants and promote soil and plant health. Mineral Rock Dust is PARAMAGNETIC. Experts (i.e.: Dr. Philip Callahan and others) teach that paramagnetic rock has a measurable energy signature in the infra-red range which has an incredible growth effect on plants." They recommend the use of 175-250 lbs /acre, with prices given as US$10.00-12.50 per 25lb bag.

http://www.nutri-tech.com.au/products/Nutri-Score.htm
'Nutri-Score Crushed Lava' is claimed to be highly paramagnetic and a typical analysis is available on the website. "Nutri-Score Crushed Lava contains good carbon levels, impressive re-mineralising potential and exceptional storage capacity. Nutri-Score has a water and nutrient holding capacity of 45%. It is a root zone wetter that increases drought resistance and improves nutrient retention. Nutri-Score reduces soil acidity and conditions all soils. Perhaps the most important benefit relates to the extremely high paramagnetism of the material. Nutri-Score has a paramagnetic score of 3500, which is twice that of rock mineral fertilisers."

8.2. Artificial soils

Quarry fines are valued as materials that resemble natural mineral-rich soils produced through mechanical rock weathering. With the addition of organic material a high-quality growing medium can be produced. Remineralize the Earth gives the guideline "*add 2-20 lb. of rock dust per cubic yard of compost, if one is doing pile or windrow composting*" (www Remineralize 2004) to the home gardener– or anyone else– interested in creating artificial topsoil.

The use of rock dust in agriculture appears to be gaining some support in the UK– a newspaper article published recently (Independent, 2004) tells of £95,000 funding granted by the Scottish executive to the Seer Centre for rock dust trials. This charitable trust was set up in 1997 by Cameron and Moira Thompson, in a move to test growing practices they had used in their six-acre garden. Adding volcanic rock dust, mixed with municipal compost, to the soil has enabled them to create a successful garden in an exposed, infertile glen near Pitlochry. Previously, erosion and leaching were so severe that nothing had been grown in the glen for almost 50 years.

Two examples of quarry companies that manufacture soils from quarry fines were found on the internet. Luck Stone Corporation adds compost to their quarry fines and sells the resulting 'high quality topsoil' (www Luckstone 2004; www Rockproducts 2004). The research and development work that created it was partly carried out by the Department of Soil and Environmental Science at Virginia Technical University (USA).

M. Collins and Sons Ltd are contractors who supply and deliver bulk landscaping, horticultural and quarry products (www Collins 2004). The products listed on their web-page are sourced or produced at M.Collins and Sons Woodgrand Quarry at Elderslie NSW (Australia). They produce a wide range of soil products, namely: Screened Topsoil, Turf Underlay, Topdressing or 80/20 Topdressing, Lawn Builder (topdressing), Organic Garden Mix (soil), Landscape Mix (soil), Rich Earth Compost, Native Mix (soil), Planter Mix (low density soil), Yellow Brick Sand or Red Brick Sand, Fill Sand or Red Fill Sand.

8.3. Other miscellaneous non-conventional uses

In comparison to construction and soil-forming materials, other applications for the use of fines are expected to demand relatively low volumes. Examples of specialist applications include abrasives and non-slip pedestrian surfaces, filtration and other applications where fines can substitute for sands. Additional applications, that may or may not be of general value, include ornamental and artistic uses and exploit the colour of the material (specialist paper filler; coloured fill for resin-casted sculptures; additives for pottery glazes).

The Great Northern Sand and Gravel company sells materials for model builders (www Ballast 2004). Fineness of dust and colour are critical for this application. Washed and sieved scale size sand, gravel, crushed stone and scenery materials are sold at CAN$2.49 for 7oz.

Harbor Gallery, Inc., (Oregon, USA) sells quarry fines as a modelling material for making ornaments called 'quarry critters' (www Harbor 2004). Similarly, it is possible to buy slate dust for modelling from Honister Slate Mine's online shop (www Honister 2004).

Rock fines are used in making traditional Japanese paper for the restoration of historical and antique paper doors. A web-page (www Jamco 2004) provides a synopsis of a documentary on this subject that was broadcast on Japanese TV. It featured a master paper maker who is the only living person with the traditional skills to make this type of paper. The rock type and amount of water are critical, but the resulting paper is heavy and durable.

A personal web-page was found that described the use of waste quarry fines as road bed for a garden railway (www Pacific 2004). They used 3 cubic yards of dust, but no details of the source are given.

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ICAR 101-2F: Framework for Development of a Classification Procedure for Use of Aggregate Fines in Concrete, (pp. 120).
ICAR 102-1F: An Experimental Study on the Guidelines for Using Higher Contents of Aggregate Microfines in Portland Cement Concrete, (pp 435).
ICAR 103: Use of High Fines Concrete (HFC) in Insulated Concrete Form (ICF) Construction, (pp. 126).
ICAR 105-1: Summary of Concrete Workability Test Methods, (pp. 92).
ICAR 201 Series: Superpave Aggregate Specifications:
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11. INTERNET SOURCES

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APPENDIX 1: TYPES OF ROCK CRUSHERS

(i) Types of crusher

Crushers work on different principles, as briefly outlined below:

- Jaw crushers consist of two heavy metal plates that open and shut like animal jaws (Wills, 1997). One plate moves back and forth against a fixed plate; the moving plate is usually pivoted at the top, which ensures that the receiving aperture (known as the 'gape') remains fixed. Quarried rock is fed into the top and is broken by the pressure of the two plates coming together. The rock is reduced in size and eventually passes out through the bottom of the jaws (the 'discharge' end); this has a variable aperture that can be adjusted to control the maximum size of the crushed material. The size of maximum opening is expressed as the 'open side setting' and the minimum opening as the 'closed side setting'. Jaw crushers have a tendency to produce a higher proportion of 'slabby' or 'flaky' crushed material. The crushed product typically has a D_{80} (size at which 80% of the particles are smaller) slightly less than that of the open-side setting of the crusher (McIntosh Engineering, 2003).

- A gyratory crusher consists of a steel cone (known as the 'head'), which is rotated eccentrically within a fixed outer mantle (known as a 'sleeve'). The gap between the mantle and cone decreases from the upper receiving end to the lower discharge end. The eccentric motion of the cone causes the gap to open and close at any one point (in cross section these are similar to the 'open' and 'closed' side settings of the jaw crusher).

- A modified form of gyratory crusher is known as a cone crusher, which has a shorter cone, a much greater crushing 'throw' (the apparent distance that rigid surfaces travel as they close together) and a greater operating speed. Cone crushers are often used in the secondary and other subsequent stages in conjunction with a primary jaw crusher as they produce a product with a more cubical shape. The discharged product from a gyratory crusher will have a particle-size approximately 55-60% of the closed side setting, whereas for a cone crusher it will be 70-80% (AusIMM, 2004).

- Impact crushers operate by applying sharp blows at high speed to free-falling rock.

- Hammer mills (or swing hammer mills) are a form of impact crusher, which have hammers (often known as 'beaters') that swing freely on a rotating shaft within a crushing chamber.

- The other main type is the fixed impeller crusher where the hammers (otherwise known as 'impeller blades') are fixed onto the rotating shaft which is either horizontal or vertical. The Barmac crusher, for example, is a vertical shaft impact crusher. The quarried rock is fed into the crushing chamber and is broken by impact with the beaters/ crusher lining or by attrition/ abrasion through contact with other rock particles.

(ii) Compression crushing

Crushers operate using two different crushing mechanisms, compression or impact. Compression crushing (as in jaw, gyratory & cone crushers) is where rock is broken apart by being compressed/ squeezed between two rigid surfaces.

Technical issues leading to fines production:

- Fracturing is induced as a result of tensile stress within the rock producing relatively coarse particles. Finer particles are produced as a result of compressive failure at the points of loading or by shearing of irregular projections from the rock surface. Limiting the area of loading can reduce the proportion of fines produced, for example using corrugated crushing surfaces/ plates (which can also reduce the amount of flaky material produced). Use of corrugated plates can reduce the capacity of the crusher.

- ‘Choked crushing’ refers to operating the crusher with a completely full crushing chamber (or where the volume of material received exceeds that discharged). This increases rock-on-rock interaction which reduces the production of ‘flaky’ particles but also results in excess fines production. If ‘choking’ is a problem, curved plates can be used especially at the discharge end.

- The ‘throw’ of a crusher varies from 1-7cm, it is usually highest for tough, plastic material and lowest for hard, brittle material. Large throws apparently result in excess fines production; this suggests that cone crushers produce proportionally more fines than gyratory crushers.

- Compressive crushing causes a build up of internal stresses in particles, which can lead to fracturing at later point, which is a potential source of fines.

(iii) Impact crushing

Impact crushing is where the rock is broken as a result of rapid loading (as in impact crushers), which generates very high internal stress and ultimately tensile failure (fracturing). Impact crushers are more effective for crushing of relatively plastic material (which would have a tendency to ‘pack’ in compressive crushers). Due to the high wear rate, caused by high particle velocities, impact crushers are mainly used for relatively non-abrasive materials such as coal, gypsum, limestone, phosphate and weathered shale. It is recommended that impact crushers should not be used on material containing over 15% free quartz (which is the main abrasive material encountered).

APPENDIX 2: USE OF THE ACCESS™ QUARRY FINES DATABASE

How to manipulate and query the database.

The Quarry Fines Database is a relational database, simply meaning that it is composed of a variety of related data tables rather than a single 'flat' data table like you would work with in Excel™. A schematic of the database architecture is given in Figure 1. To get the most out of the database it is useful to familiarize yourself with the data contained within in the tables and how the individual tables relate to each other. Understanding the data architecture helps when you come to query the database in order to find the information you want.

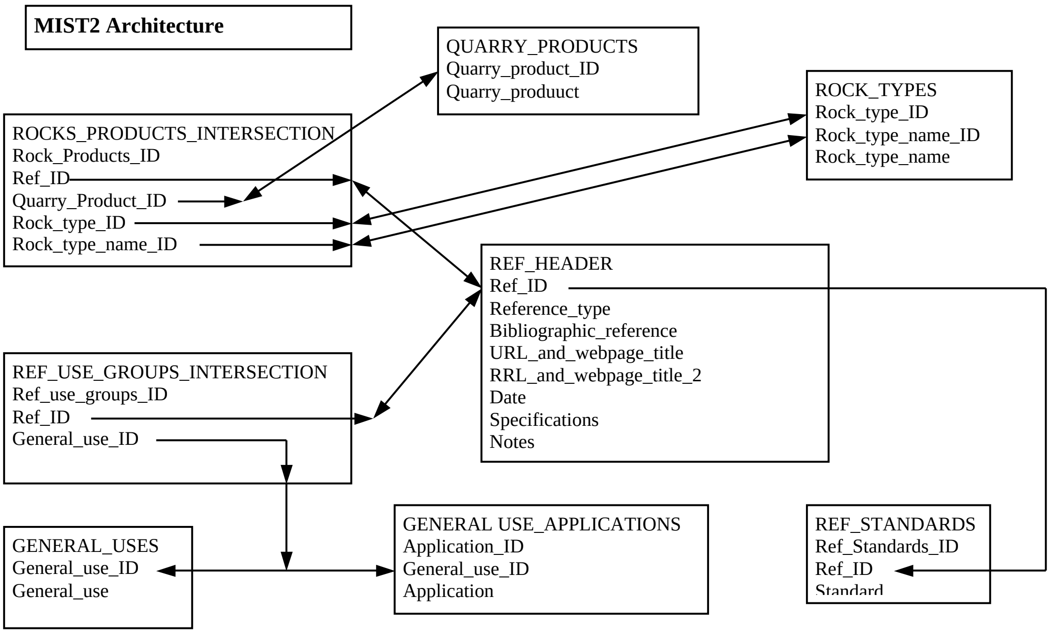


Figure 1. Schematic illustration of the Quarry Fines Database architecture.

Getting started - Introduction to Access

You open an Access database file much as you do any other Microsoft office application file. When Access starts it will open database window; a snap shot of the database window is shown in Figure 2. On the left hand side of this panel there is a list of objects; at present the Quarry Fines Database is only comprised of Tables and an example Query, therefore these are the only objects we need to worry about. The tables listed here make up the Quarry Fines Database and contain all the information you can Access. The schematic illustration of the Quarry Fines Database architecture shown inFigure 1 shows how these tables relate to one another. In the case of the Quarry

Fines Database the central component is provided by the Ref_Header table. The Quarry Fines Database is intended to act as a vehicle allowing you to investigate published data and also directs you to resources on the web from the URL fields contained in the Ref_Header table.

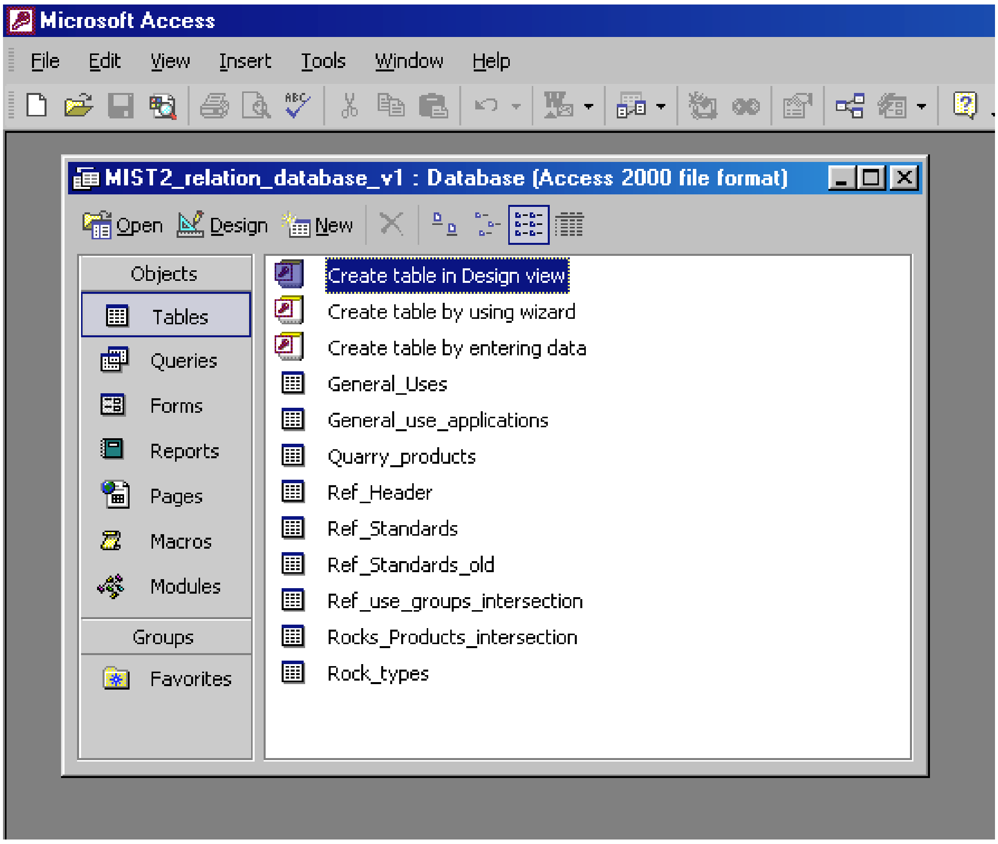


Figure 2. The Microsoft Access database window.

Building Queries

In order to view data held in the Quarry Fines Database you could simply open each table and search for the data you require; however, this can be tedious and inefficient work. One of the main advantages of using a database is that it allows you to ask questions using one or several fields from any of the tables which make up the relational database. In the Microsoft database environment this is done via 'Queries'. To start using queries simply click on the 'Queries' tab on the Microsoft Access database window. When you open the queries environment you will see a screen similar to that shown in Figure 3.

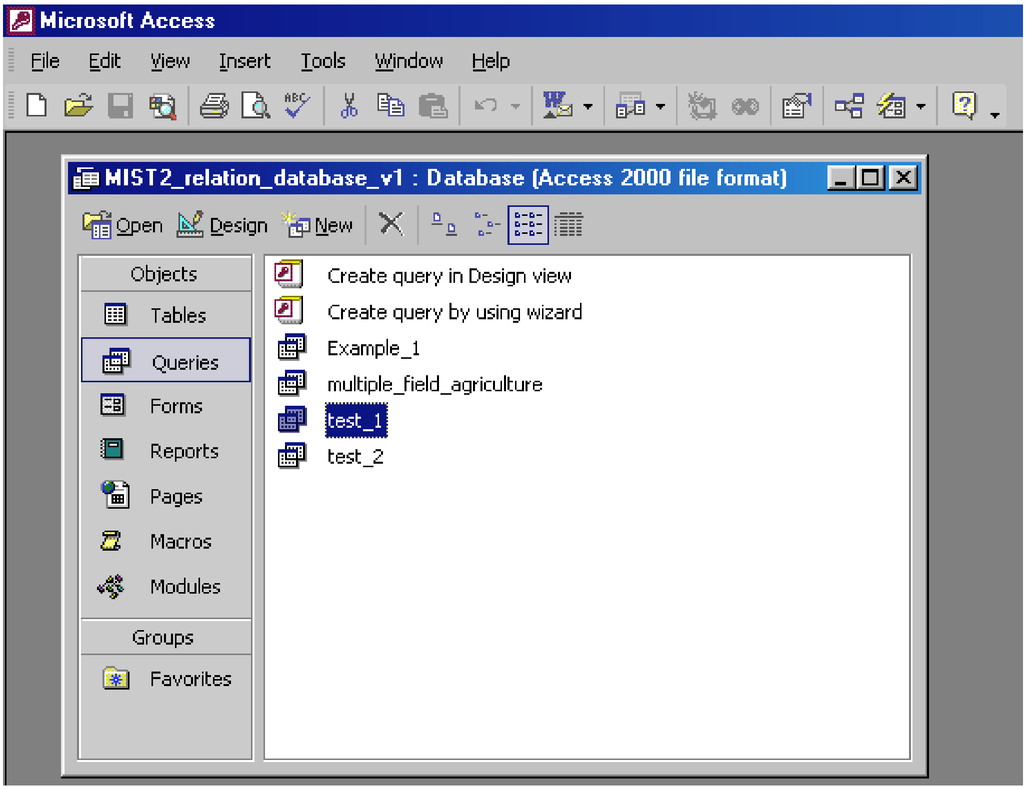


Figure 3. The Microsoft Access queries window.

The query window gives you two options:
1) Create query in Design view
2) Create query using wizard

Both are actually underlain by an SQL (*Structured Query Language*) statement which is essentially a high level database programming language. There are many types of query which are used for different database tasks such as viewing particular data based on specified criteria – known as a SELECT QUERY; other query types may be used to perform tasks such as updating, merging, or deleting tables or the data held in the tables which make up the database. Here we will concentrate on using SELECT QUERIES in the Design view in order to manipulate our database. To open the Design view simply double click it in the queries window. The Design view opens with 'Show table' box (see figure 4), which allows you to select the data tables from which you wish to view data or use to specify criteria upon which the query is based.

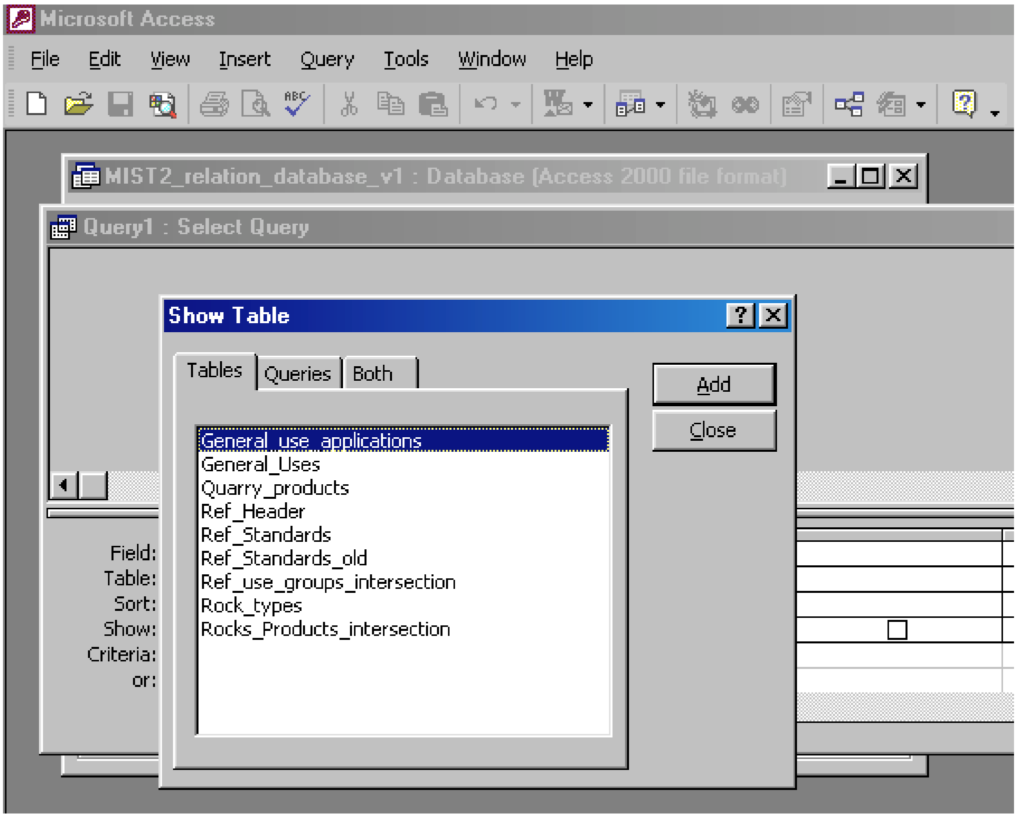
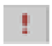


Figure 4. The 'Show Table' box used to select tables to be used in your query design in Microsoft Access queries window.

You select the tables you require simply by double clicking them, upon which they should appear in the top half of the Select Queries window behind the 'Show Table' box. Below this is a table grid called the query by example (QBE) grid in which you can visually construct the query. In order to select the fields you wish to view in your query you simply double click them in the table boxes and they should appear in the QBE grid. Figure 5 shows a query definition that joins Ref_Header to Ref_use_groups_intersection to General_uses based on criteria where the general use equals 'Concrete related'. A query is run by clicking the  icon on the query tool bar. Essentially this query is recovering all the references contained in the Ref_Header table that are concrete related.

Note on intersection tables:

The Quarry Fines Database contains two intersection tables – 'Ref_use_groups_intersection' and 'Rocks_Products_interesection'. These tables are used to restrict the amount of data repetition in the Ref_Header table thus reducing the size of the database. In a database you commonly have what are called one-to-many relationships, for example each single reference contained in Ref_Header may refer to multiple Use Groups, Rock types, Quarry Products etc. To circumvent having to have a reference entry relating to every Use Group mentioned, an intersection table allows this relationship to exist in the form of numerical Ids. This approach maintains the integrity of the relationships but reduces the size of the database and facilitates updating and changing the data.

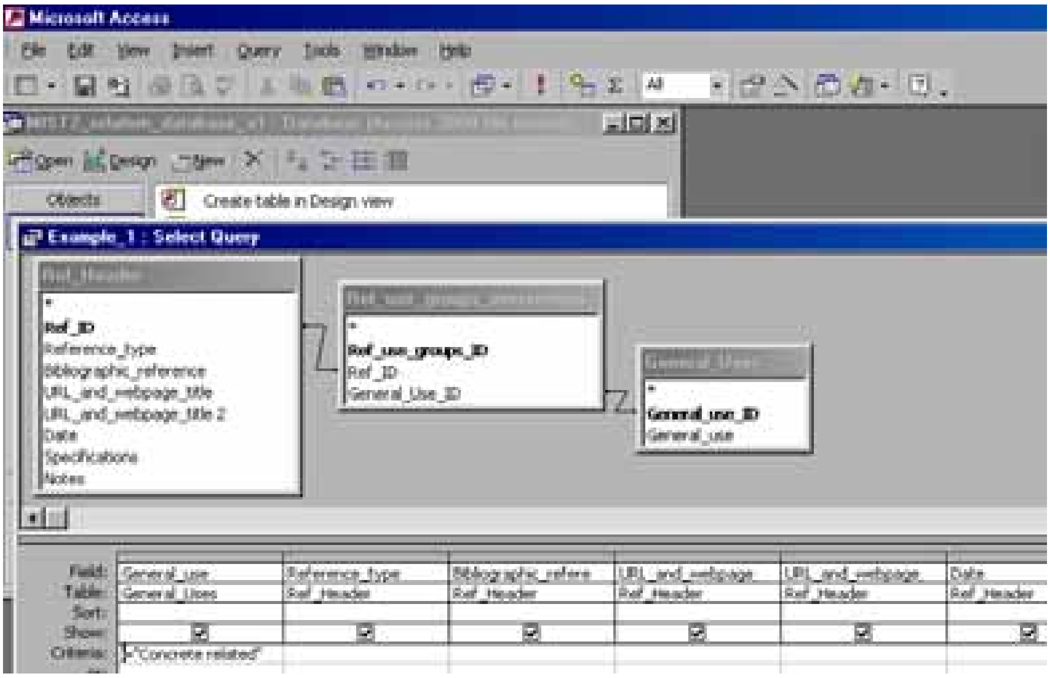


Figure 5. Query definition in the query design view.

The criteria field can be left blank and the query will simply return all the data which relates to the relationship you have specified. You can create queries using multiple criteria. However, it helps if you have a good understanding of the potential criteria relevant to the field(s) you wish to search on. For example if you enter 'oil and gas related' instead of 'Concrete related' the query wouldn't return any results. This is where being familiar with the database and its structure helps. Another way to do so enables you to view all the potential criteria for a particular field by using the filter option. If you run the query example_1 you will return the data table shown in Figure 6. To filter a query – i.e. to alter the query criteria click the filter by form icon . This will empty the table and leaving one blank row containing all the fields you selected to create your query structure. Each field will have a drop down box containing all the potential criteria upon which you can base your query – an example is shown in Figure 7. Once you have selected the criteria for your query simply click the filter icon and you will filter your specified fields. To return to the original data table just click the filter icon again.

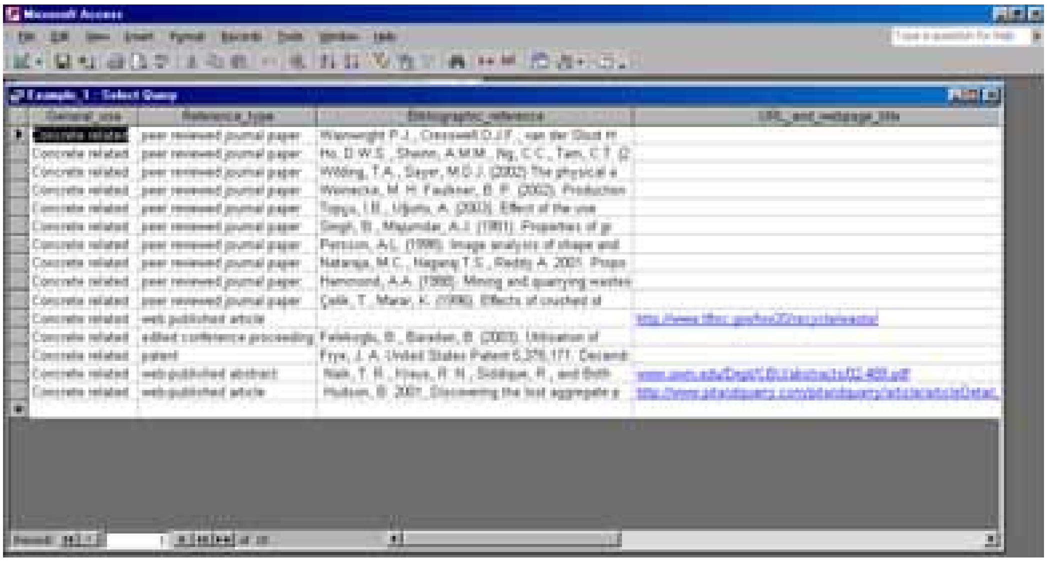


Figure 6. The data table returned from the 'Example_1' query.

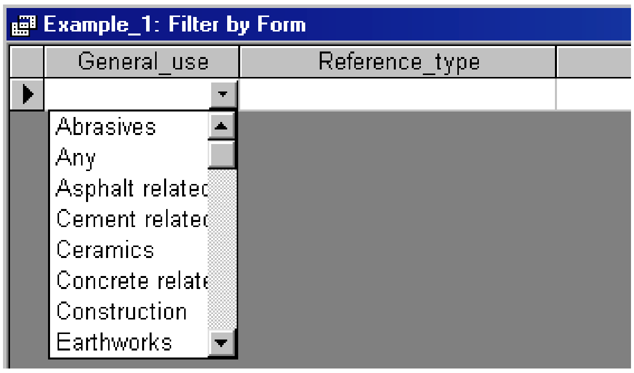


Figure 7. Example of a drop down box using the filter by form option in the 'Example_1' query.