DUST MOVEMENT FROM AND INTO QUARRIES

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ABSTRACT

This paper considers the use of depositional and flux dust monitoring at quarry and mineral processing plants with particular reference to a quarry in East Anglia.

The findings suggest that arable farming can be a major source of dust, reaching nuisance levels and at times significantly exceeding dust concentrations from properly managed quarry operations. Other adjacent activities including major roads and railways may also contribute considerable quantities of dust at the boundaries of operating sites. Conventional depositional monitoring methods fail to detect such dust movements unless very carefully correlated with meteorological information. Deposition rates should not be used as the basis of nuisance prosecutions.

The provenance of dust can be detected by flux monitoring and checked with a range of analytical methods and equipment to assess and fingerprint the chemistry and mineralogy of source materials. Examples of these methods are included.

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INTRODUCTION

Amongst many other environmental issues, quarry operators frequently need to have regard to dust on their site, but also dust that leaves their site. Such dust may lead to complaints from neighbours and even constitute nuisance resulting in action by local authorities and others. However scientists and engineers concerned with quarries understand that quarry settings are seldom the only source of dust in the vicinity of mineral operations. Quarries may lie near other industrial activities, landfill operations, roads and railways and arable agricultural land from all of which dust may also arise.

Dust conditions started to appear in some aggregate planning permissions in the late 1980s. The Environment Act 1995 subsequently placed Local Air Quality objectives on Local Authorities whilst the EU Air Quality Regulations 2000 embrace wide ranging aspects of air pollution including various categories of dust.

In 2000 the UK Government drafted guidance as an Annex to Mineral Planning Guidance II in addition to other annexes on water, noise, and blast vibration. Much of this work is now incorporated in Minerals Policy Statement 2 for England and Wales – Annex 1 (Anon., 2005), and the Scottish Executive Planning Advice Note 50 – Annex B (Scottish Office (1998).

Planning conditions usually phrase a condition as a limit to the mass of dust attributable to the site and deposited over a given area in a given time, typically 200-350 milligrams per square metre per day. Other sources can also be responsible for dust such as traffic, farming, other industrial activity including adjacent mineral operations and even rain washed continental atmospheric dust.

A number of issues therefore arise when considering the monitoring of dust at any quarry; including:

- Whose dust is it?
- How much dust is there?
- What is the composition of the dust?

This paper considers available methods of dust monitoring near quarries, the role of quarry operations and weather conditions in generating dust and the assessment of dust both leaving and entering quarries. Reference is made to the measurement of dust levels at a sand and gravel quarry in East Anglia belonging to Lafarge Aggregates. It also considers the relevance of deposited dust measurements still widely used at quarries in Britain and Ireland and compares them with directional dust data. Finally, it outlines some aspects of investigating the composition of dust in and around quarries.

METHODS OF DUST MONITORING

From the late 1970s various organisations became interested in trying to measure and fingerprint fugitive dust, especially the Opencast Executive of the then National Coal Board, in response to dust concerns around opencast coal sites (Merefield *et al.*, 1995). Ultimately various types of deposition gauges were developed and became useful if limited monitoring tools.

Historically the favoured method of monitoring around quarries has been deposition gauges such as Frisbee, Bergerhoff and the British Standard Deposit Gauge. These devices collect dust fall and report it as mg/m^2/day with a typical monitoring interval lasting for one month. The alternative method for monitoring dust in flux, that provides rough directionality, is the British Standard Directional Gauge (also known as the CERL-type gauge). This gauge collects dust that impacts with the inner wall of one of four vertical cylinders. The dust is washed into collection bottles and removed for analysis; dust levels are reported for each quadrant as a level of obscuration, or alternatively (but not as part of BS1747 Part 5) as mg/m^2/day. Some of these dust monitoring methods are shown in Figure 1. Other equipment is available including some expensive and sensitive instruments; the equipment considered here is inexpensive, robust and simple.

Hall *et al.* (1994) demonstrate that the relationship between dust in deposition and in flux is not straightforward. Limitations in the collection efficiencies of different sampling methods are discussed and the Frisbee-type is preferred for non-directional deposition monitoring due to its greater collection efficiency than the BS deposition gauge. The CERL gauge has generally good directional characteristics (limited to the 4 directions monitored) but variable, and generally poor, collection efficiency in relation to finer particle size dust and increasing wind speeds. Alternative and highly technical directional dust monitoring methods exist, but may be limited in availability in terms of siting or cost.

An increasingly popular directional monitoring method is the use of sticky pads or glass slides. These may be mounted on cylinders or boards with the surface exposed for a pre-determined period to collect dust as it impacts. The sticky pads are analysed using reflectometers to determine the loss in reflectance of the sticky surface (Beaman and Kingsbury, 1981; 1984). This is a measure of how dirty (dark) the surface has become and is often referred to as soiling units or Effective Area Coverage (EAC). These units are scaled from 0 – 100% and correspond directly to the percentage loss of reflectance.

Recent developments to the sticky pad system have allowed a greater degree of repeatability and scope for enhanced interpretation (Farnfield and Birch, 1997; Datson and Birch, 2007). The DustScan system referred to in this paper uses a standardised sticky pad, with pre-scored areas that can be revealed or retained. It has a cylindrical mount and attachment, and an orientated monitoring post (see Figure 1). The analysis of samples is conducted using optical scanners and specifically developed software; the results are stored in a database to generate reports and analyse data. Directional data is reported for every 15° around the instrument and provides a full 360° dust rose for the period of exposure.

Directional dust data is provided in a standard form showing AAC and EAC levels and the directions from which that dust has come. The measures are:

- AAC (Absolute Area Coverage %) – the presence of dust *irrespective* of colour
- EAC (Effective Area Coverage %) – the *darkness of potential* soiling by dust

It is recognised that AAC primarily identifies and ranks the significance of dust sources whereas EAC rates a nuisance potential that may be caused by the dust. Dust nuisance is not just restricted to specified high levels of EAC or AAC. The relationship of one to the other may vary. Sites with a typically pale dust may have a high nuisance potential due to one highly significant source and the associated quantity of dust, even though it may never

Figure 1. *Nuisance dust monitoring methods.* ***From left****: Bergerhoff deposition gauge; CERL directional deposition gauge; Frisbee deposition gauge with DustScan directional gauge.*

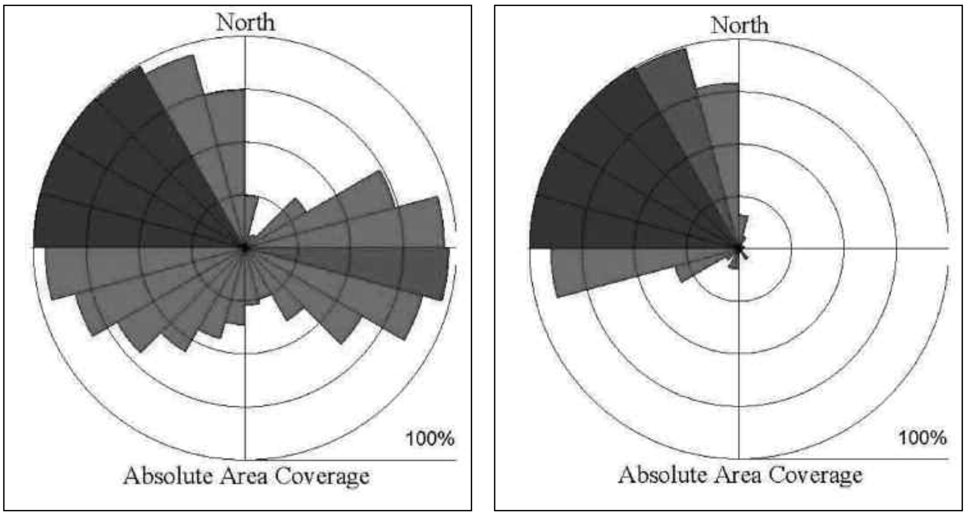

Figure 2.
Examples of Directional Dust Roses.

***Far Left** bi-directional dust source. This rose shows that there are two different sources of dust at the monitoring point. One from the north-west and one from the east. The darker coloured bars of the rose indicate higher AAC values, and therefore suggest that the source of dust from the north-west is more significant at this point.*

***Left**. AAC% Dust rose indicating a single dust source, from the north-west.*

reach critical EAC limits. In this situation it is possible, through a review of the data, to use source specific EAC trigger levels that more accurately represent thresholds of nuisance and recognises excessive dust build up.

As AAC is the more sensitive measure it is most appropriate to identify dust sources. A source is easily identified, visually, by the segment direction of the reported dust roses as shown in Figure 2. The radius of each 15° segment represents the magnitude of AAC from that direction; the greater the radius of the segment the more pronounced the source.

To attribute a level of significance to an identified source the following threshold values are used as indicated in Table 1. In addition, the angle of dust spread of AAC at saturation point (100%) can be used to further assess the significance of the source.

The potential for nuisance can be rated. AAC may reach 100% quite frequently. EAC is more widely and readily used to assess the likelihood of nuisance due to visual soiling effect *e.g.* how dark is the dust. The following general assessment criteria (Table 2) are based on complaint thresholds suggested by Beaman and Kingsbury (1981) and an uppermost limit suggested by Schwar (1994).

The soiling effect of dust measured as an EAC value depends on the type of dust and the colour and contrast of that dust, but it does not directly relate to the quantity of dust.

Source Significance		%AAC Value over 1 week
Very Low	0	<80%
Low	1	80% - 95%
Medium	2	95% - 99%
High	3	99% - 100%
Very High	4	100% for 45°

Table 1. *AAC Criteria.*

Nuisance Potential		%EAC Value over 1 week
Very Low	0	<2.5%
Low	1	2.5% - 5%
Medium	2	5% - 15%
High	3	15% - 25%
Very High	4	>25%

Table 2. *EAC Criteria.*

SITE DATA

Data on dust has been collected from the subject quarry in East Anglia for more than three years. The site lies within arable farmland with no other nearby industrial activities. Four sticky pad directional dust gauges (Nos. 1 to 4) have been installed, in order, around the site in the north-west, north-east, south-east and south-west corners of the quarry. Frisbee type deposit gauges (A to D) were also installed near each of the directional gauges *i.e.* gauge A is located near gauge 1, gauge B is adjacent to gauge 2 *etc*.

This study covers the period between August 2003 and September 2005 during which there were 52 monitoring periods, typically of two weeks duration. Monitoring has covered pre-operational, working and dormant phases in the quarry's life. The directional and deposit gauges were sampled concurrently over the same periods and with the same intervals. To assist in reviewing the findings of the study directional dust data was correlated with that for deposit gauges. Weather data based on information from three nearby weather stations and relating to wind speed, wind direction and rainfall, was also collected and assessed in the study. Figure 3 is a graphical example of the complexity of analysing directional dust data alongside wind and rain data. It may appear that a simpler plot might result from assessing deposited dust against the same weather information, but a study of the wind data indicates that wind may blow from different directions over a monitoring period and only rarely from a single direction.

Table 3 shows average AAC and EAC values for all 52 monitoring periods relating to dust samples taken at the four directional dust gauges at the corners of the site. The results are divided into dust arriving at the gauges from the direction of the site and dust coming into the site from offsite directions. It can be seen that gauges 1 and 4 show, in terms of AAC levels, that on average more dust is arriving at the monitors from offsite sources than from the site and that the reverse is the case for gauges 2 and 3. Hence it is immediately apparent that at the limits of a quarry situations exist where greater or lesser quantities of dust may be leaving or entering the site.

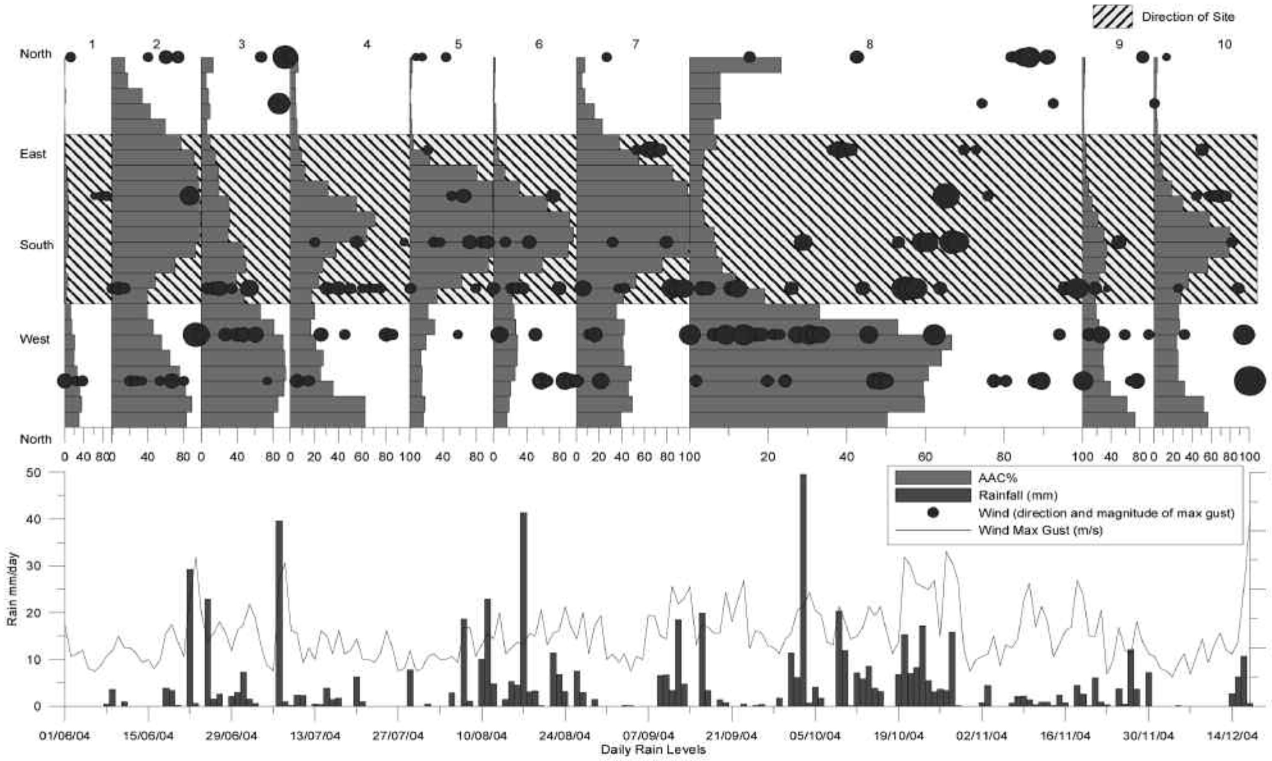

Figure 3. *Correlation of directional dust data and meteorological information.*

This information can only be obtained by directional monitoring although attempts are made to combine wind direction and wind speed information with deposited dust to assess in some fashion from which direction the dust may have come. The problems inherent with attempting to relate deposited dust and wind direction are discussed further below.

Table 4 summarises the Frisbee deposition data for the monitoring period. The dust mass at each point is the average mass of all its samples. Depositional data alone is non-directional, and simply shows what dust settled out of the air at that particular point. Gauges 1 and 3 received the most deposited dust, gauge 4 received just over half that of gauge 3. The average deposited dust mass of gauge 3, 69.4 mg as un-dissolved solids, would produce an inferred deposition rate of 122.4 mg/m^2/day using the Vallack (1995) method, and the standard 14 day exposure time in the calculation. Mineral planning permissions sometimes include a condition specifying that 200 mg/m^2/day of deposited dust should not be exceeded.

A correlation exercise was undertaken to investigate possible relationships between deposited dust levels and dust as measured using the sticky pad directional dust gauges. The directional gauge data used were EAC values for dust from all directions weighted to separate dust coming from onsite and from offsite directions. These average values were then compared with deposited dust values obtained from the Frisbee gauges. The findings of the correlation exercise are shown in Table 5 for each gauge and indicate that only moderate correlation factors can be achieved; factors are higher when the number of directions from which dust arrives at a gauge is reduced. Gauge 1 is such a case where dust appears to have arrived from a limited number of directions compared with that at gauge 2 where the

	AAC from Site	**AAC from Off-Site**
Monitoring Point 1 (north west)	46	54
Monitoring Point 2 (north east)	60	40
Monitoring Point 3 (south east)	61	39
Monitoring Point 4 (south west)	30	70
	EAC from Site	**EAC from Off-Site**
Monitoring Point 1	49	51
Monitoring Point 2	70	30
Monitoring Point 3	66	34
Monitoring Point 4	54	76

Table 3. *EAC and AAC Values for all 52 monitoring periods separated into dust coming from the site and from off-site.*

Table 4. *Average deposited dust mass (non-directional) during period from 26/08/03 to 28/09/05.*

	Dust Mass (mg)
Monitoring Point 1(north west)	67.8
Monitoring Point 2 (north east)	47.3
Monitoring Point 3 (south east)	69.4
Monitoring Point 4 (south west)	36.3

	All Data	**Site**	**Off-Site**
All points	0.70	0.63	0.64
1	0.83	0.75	0.81
2	0.59	0.54	0.53
3	0.70	0.70	0.66
4	0.68	0.46	0.67

Table 5. *Correlation factors between deposited dust and weighted EAC values for dust in flux for all 52 monitoring periods separated into dust coming from the site and from off-site.*

correlation factor is lower. The variability and level of correlation (generally low), both directionally and for all data, is thought to be related to the homogeneity of dust at each point. The correlation between the sub-divided directional information was never better than the correlation for the data as a whole implying that deposited dust can come from all directions. It is therefore appropriate to see what relationships, if any, exist between dust levels and wind speed and direction.

Another correlation exercise examined the relationship between rainfall and wind blow and directional soiling rates. Wind data was obtained from the Met Office and provided as daily mean wind speeds (m/s) and direction was reported as daily spot observations made at 09.00 hours with an accuracy of +/- 5°. The corresponding wind data was filtered using a spreadsheet to provide a list of daily wind speeds and directions for each monitoring period. This was further summarised as mean wind speed per period for each of the 15° segments.

Figure 4 shows the wind rose and wind speeds for the site. When considering deposited dust levels and wind speed and wind direction there was a high degree of variability from period to period with no general pattern distinguishable. It is inferred that other factors may be involved in determining dust levels. These include precipitation and other meteorological constraints noted below, topography and vegetation and dust generating activities including vehicle movements and materials handling.

Similar relationships were found when assessing both wind and rainfall and known directional dust values. Rainfall was examined on a period by period basis against the correlation in an attempt to explain the variability in the wind - v - dust correlation. There was little or no pattern when summarised graphically as shown in Figure 5. Other factors that may influence dust deposition including sporadic localised rainfall and wind gusts (not reported by the Meteorological Office data) none of which could be accommodated in the analysis.

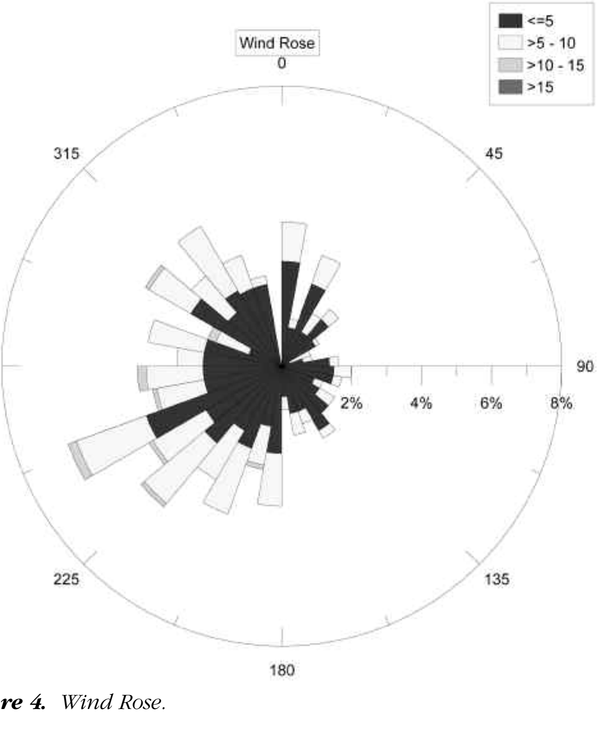

Figure 4. *Wind Rose.*

It is concluded that the evaluation of deposited dust data and meteorological information is not straight forward when attempting to use that data to assess where deposited dust has come from. Nevertheless meteorological data is very useful in assessing lag periods between rainfall, when there is little dust and the onset of conditions that may give rise to dust. This period varies from site to site and appears to depend in part on local soil and rock types.

THE COMPOSITION OF DUST

In addition to determining where dust comes from and at what levels, it is also possible to look at the composition of dust. As implied above examining the composition of dust from a Frisbee may be relatively meaningless unless the wind direction is uniform during the monitoring period. However with a sticky pad it is quite possible to explore the mineralogy and particularly the geochemistry of dust and to characterise specific dust sources.

This process is bound to be more successful when there are clear distinctions between a range of dust sources both from within a quarry and outside the quarry. It is possible to conceive of situations, especially with sand and gravel deposits, where the local soils reflect quite closely the characteristics of the mineral. In other situations where minerals are more deeply buried and have contributed less to the local soils *e.g.* under thick glacial cover, there may be significant differences with respect to minerals and chemistry between on-site dust sources and natural off-site dust sources. The situation at the East Anglian quarry referred to previously was investigated in a preliminary fashion by sampling local soils, sampling fines within the mineral deposit and sampling dust on sticky pads that appear to have emanated from the direction of the quarry and from the opposite direction. Figure 6 refers to samples taken at the site and from surrounding land where it can be seen that the weight proportion of fines is far higher in agricultural soils than for the as-dug minerals or the stock piles. However road surfaces both within and outside the site can have high levels of fines. Fines are the feedstock of dust.

Sub-samples of loose fines were examined under plane and cross-polarised light, but rapid identification is not straightforward. It was therefore considered that the best way of characterising the dust was by exploring the geochemistry rather than by direct mineralogical methods. A technique has been developed to employ standard ICP-AES techniques used in geochemistry. This can accommodate both loose samples of dust, but also sticky pad samples where blank corrections are undertaken. The accepted detection limit is 10 parts per billion; certain elements are not necessarily detected because of the limited mass of material being analysed as well as lack of abundance.

The weighted concentrations of major elements in agricultural soils, mineral fines and in two samples from different sticky pads from the boundary of the East Anglian quarry were determined (Figure 7). One sticky pad was of dust blowing into the site and the other from a monitor on the opposite side of the site collecting dust blowing out of the quarry. There are some interesting

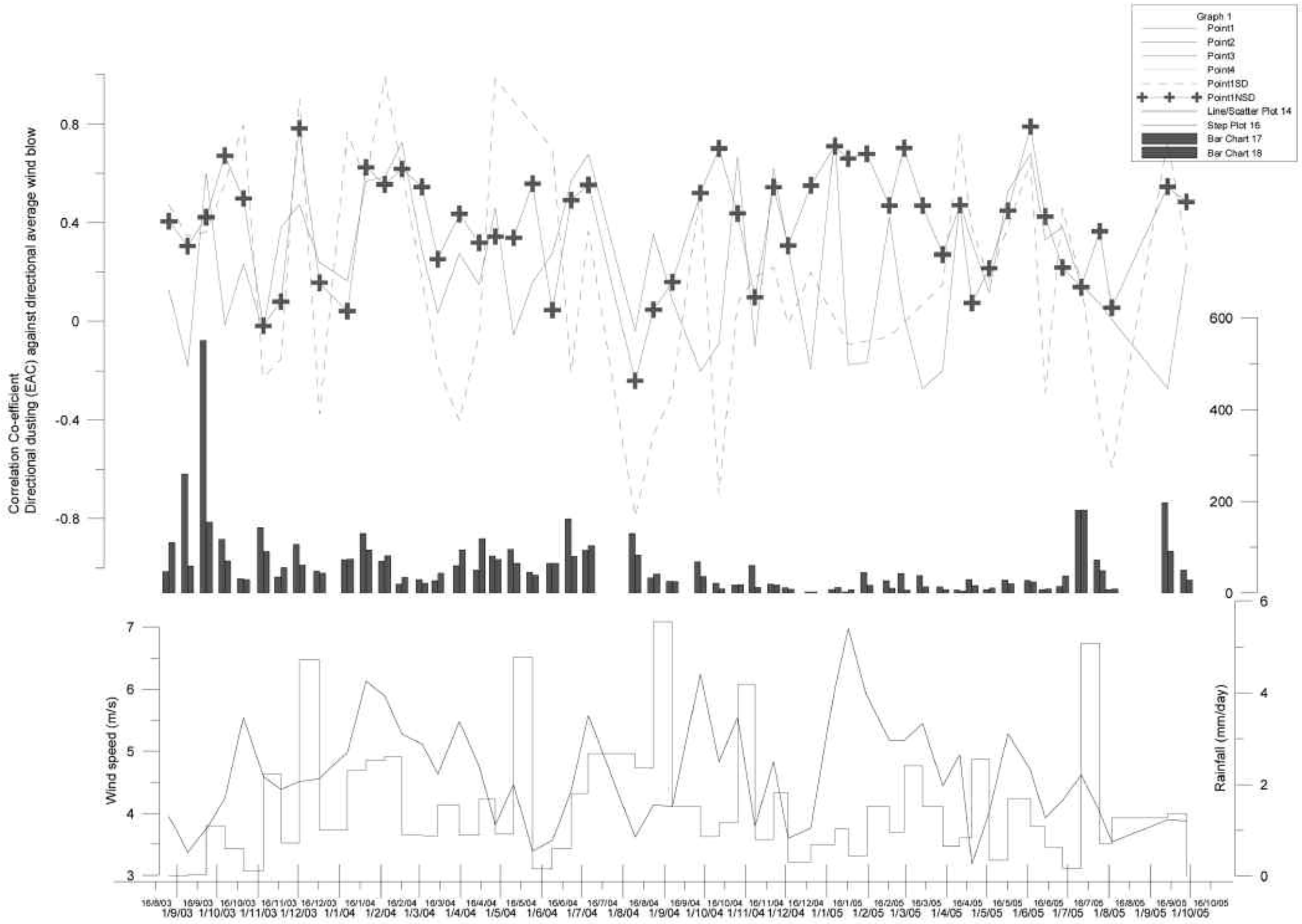

Figure 5. *Combined wind and rainfall plots.*

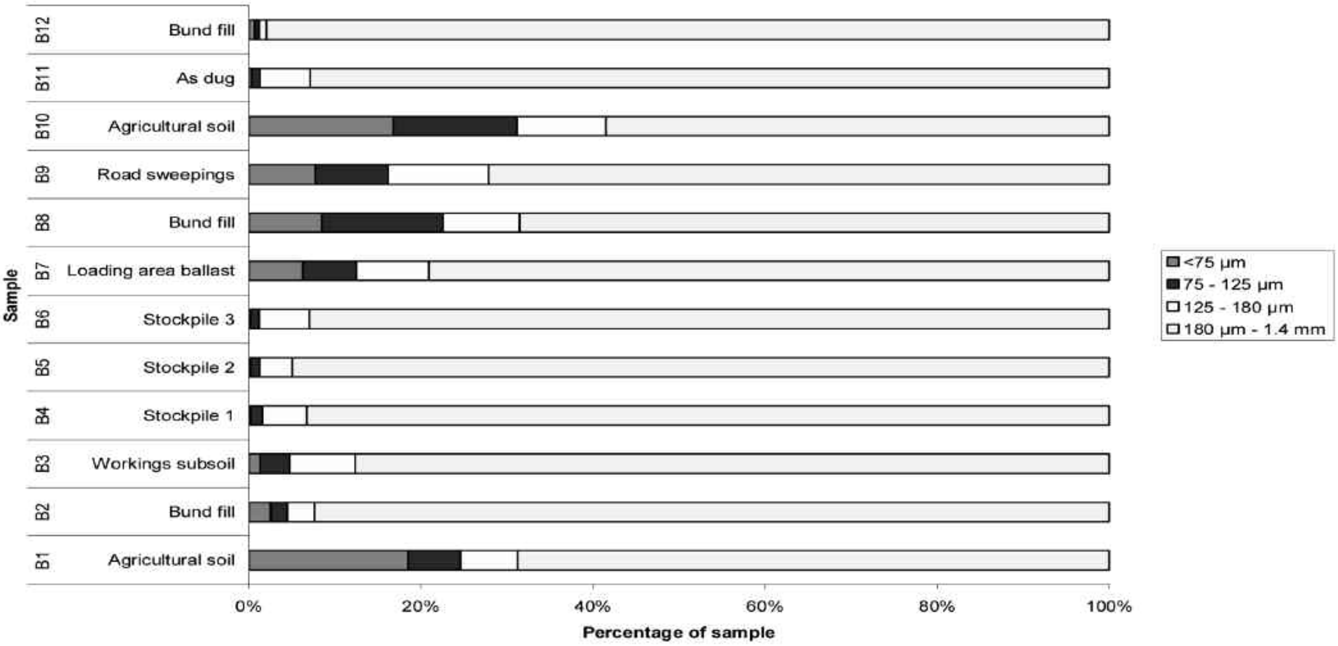

Figure 6. *Comparative particle size data for field samples collected in and around the site.*

conclusions from these analyses, *e.g.* inorganic fertilizer residues (Na, K) may be present at elevated levels in agricultural soils. These elements are at higher concentration in off-site dust than in on-site dust which may indicate that fines from adjacent farmland were in dust propagating towards the site. The relative proportions of Fe:Al are of particular interest. In "as dug" mineral the Fe:Al ratio is approximately 1:1 whereas in all other samples the proportions are approximately 1:1.5. This indicates that "as dug" mineral dust may not be the primary component of ambient dust at the site since off-site dust has a lower proportion of iron. The mineral has a higher proportion of iron. Minor changes in the concentrations of elements on opposite sides of the quarry can be accounted for in terms of gains or losses as wind blows into and across the quarry.

As indicated previously different sites may have different relationships between the geochemistry of the minerals and related materials (overburden, inter-burden *etc*,) and the soils within the vicinity. Similarly other industrial and agricultural activities as well as some internal quarrying activities can produce a characteristic change in the bulk chemistry of dust arising from those activities. The dust collected at different points moving away from a source will reflect changes due to attenuation in dust from that source and additional dusts arising from ground between that source and the monitoring point. Figure 8 shows different element concentrations within a series of dust samples moving away from an industrial dust source onto local uncontaminated soil. This technique of displaying the concentration of different elements uses Enrichment Factors where the concentration of individual elements is calculated in relation to the concentration of, in this case, aluminium.

Element	Agricultural soil	As dug mineral (fines)	Offsite dust	Site dust
Na	11.66	1.52	4.89	bdl
Mg	2.85	2.47	7.22	5.94
Al	29.90	40.51	32.64	33.74
K	26.44	10.75	10.49	8.60
Ca	4.06	1.50	28.71	26.84
Ti	4.60	1.90	2.60	2.36
V	0.06	0.09	bdl	bdl
Cr	0.04	0.06	bdl	bdl
Mn	0.40	0.34	0.65	0.74
Fe	20.00	40.86	12.79	21.80
Total	100%	100%	100%	100%

Figure 7. *Weighted concentrations of major elements.*

CONCLUSIONS

The quarry operator in East Anglia was quite justified in seeking to assess the contribution of off-site dust to dust levels at the margins of the quarry as shown in Table 3. Clearly the use of a standard mass of dust at a point being used as the criteria for the definition of nuisance is relatively meaningless unless the direction or directions from which that dust has come are fully understood.

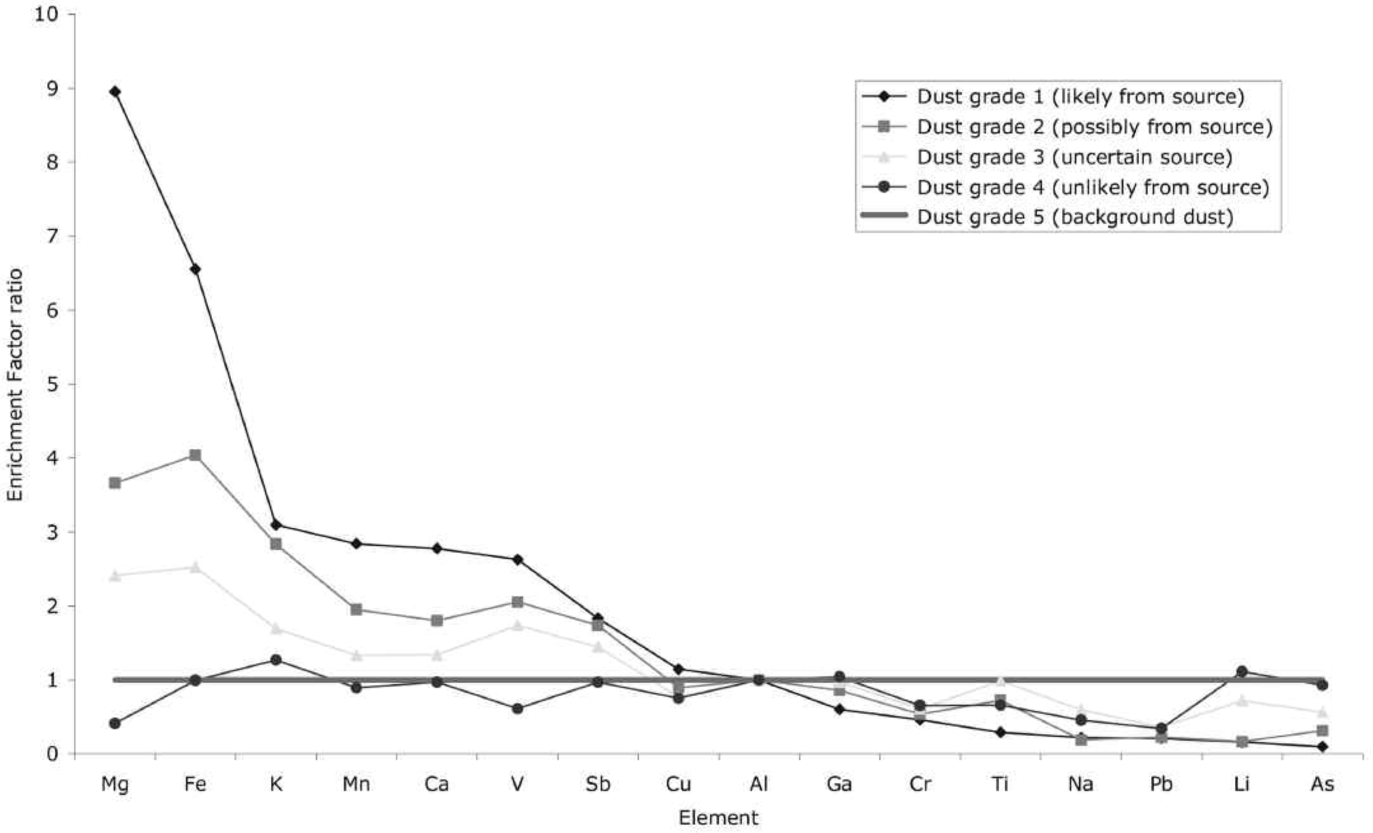

Figure 8. *Dust Characterisation – illustrating dust propagation and dispersion.*

There are no statutory dust limits, but mineral planning permissions commonly include a condition specifying a maximum deposition level *e.g.* 200mg/m^2/day. Such conditions should always be treated with caution when, as shown at the quarry concerned, 60-65% of the dust collected at the boundary of the operation came from off-site sources. Nevertheless some Local Authorities persist in imposing planning conditions with this inadequate method of dust monitoring.

There is no sound correlation between dust deposition and directional dust measurements. There are several reasons for this, reflecting potential differences in dust density and dust size from different sources.

Correlations with weather data can be difficult. Although generally there is a positive correlation between directional soiling rates and average wind blow there is a high degree of variability. This probably reflects the effect of antecedent rain inhibiting dust blow. It should be noted that dust arises not just from wind blow, but from generation at source. Directional sticky pad monitoring shows quite clearly where dust is coming from and this can match well with meteorological information although local activities can be equally instrumental in determining actual levels of dust generation and dispersion that occurs.

Quarries do, however, contribute to dust and monitoring is becoming an increasingly important requirement in respect of PPC regulations for plant installations including crushers and screens. It is important that future dust generation is related to the plant concerned and operators are not blamed for dust from out-of-quarry sources. Dust in quarries primarily comprises comminuted geological materials. Since these generally have a characteristic geochemistry this gives the potential for even greater confidence in attributing the source of dust, be it from the quarry or from elsewhere.

Dust monitoring should be capable of assessing dust contributions from specific quarrying processes. This is best achieved by directional methods.

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