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# UNDULATORY EXTINCTION OF QUARTZ IN BRITISH HARD ROCKS

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Undulatory extinction suggests a level of instability in quartz. The degree of undulosity has been used, for some time, to indicate the potential reactivity of the quartz in ASR. The method of routine measurement of the degree of undulosity has been found to be inaccurate. A new method for this routine measurement is proposed, in addition to the assessment of grain textures. The results indicate that it is possible to classify the stability of the quartz by texture and undulatory extinction.

## INTRODUCTION

The aims of this paper are three fold, to investigate;

1. The methods of measuring undulatory extinction and the results of measurements made on British hard rocks, and the implications of these results on ASR guide-lines.

2. Quartz grain textural characteristics and the implications of these to ASR.

3. Strained quartz in concrete showing signs of ASR.

Undulatory extinction in quartz is believed to result from strain within individual grains. The boundaries between different areas of strain are sometimes diffuse or can be relatively sharp; both are probable areas of high dislocation densities. This structural mismatch within original grains means that there is internal energy present, and means that the quartz is more chemically reactive. Hence, it is possible that such quartz could react with the alkalies in concrete to form the deleterious gel responsible for the expansion found in concrete structures.

Strained quartz is known from a number of different types of geological environment; granites and other quartz-bearing igneous rocks, sediments derived from such rocks and metaquartzites formed by metamorphism. This project has investigated the distribution of strained quartz-bearing rocks in Great Britain, with particular reference to those that are or might be used for concrete aggregates. This investigation has also assessed the current method for the measurement of undulatory extinction. The investigation is conducted in the light of suggestions made in the Concrete Society's Technical Report N$^{o}$. 30.(1).

The term 'undulatory extinction' refers to an optical characteristic of quartz, when seen in thin section (of 30$\mu$m thickness) and viewed in cross polarized light using a petrological microscope. Under these conditions, when the microscope stage is rotated the quartz grain is seen to exhibit non-uniform extinction, which can be identified by the sweeping motion of the zone of extinction across the grain, or as segmented extinction zones within a single grain boundary. The term `strained quartz' is often used when describing quartz showing undulatory extinction as these optical effects are the result of the strain within the crystal lattice of the quartz grain. The internal strain causes a displacement of the c-axes of the quartz thus producing undulatory extinction.

The inter-axial angles can be measured with a universal stage mounted on the normal microscope stage, this has been described in detail by Blatt and Christie (2). However, many studies, eg Dolar-Mantuani (3), have attempted to measure inter-axial angles using a flat stage method. The problem of measuring extinction angles without a universal stage lies in the fact that the c-axes of the strained parts of a quartz grain may lie in any orientation. "The relationship between true and apparent angles of undulosity in a quartz grain is a function of; (a) the angle between the plane containing the c-axes and the plane of the thin section, and (b) the pitch of the axes themselves within the optic plane" Paulitsch and Ambs (4).

Any true angle between the c-axes can give rise to an apparent angle, measured on a flat stage, which can vary from 0° to 180°, depending on; (a) the inclination of the plane containing the c-axes to the plane of the thin section, and, (b) the plunge of the axes within the plane.

In an example where the two c-axes lie in the same inclination plane, the variations in apparent extinction angle are shown here in graphical form, for a true angle of 20°, in Figure 1. The variation seen is a product of the variation in the inclination of the plane. Any other possible orientations of the c-axes where the axes are not in the same plane will produce apparent extinction angles that will plot between the two curves. Similar diagrams could be made for other true extinction angles; the form of each diagram will be similar, but with the true extinction angle varying on the right hand vertical axis.

When measuring undulatory extinction on a flat stage, Dolar-Mantuani (3) and others make the important point that, only grains with the highest possible birefringence should be measured; this indicates that the c-axes of the crystal are near to the plane of the thin section. However, the birefringence can only be a matter of judgement, not of measurement, unless the thickness of the thin section is also known. Inaccuracies can occur in the measurements if only one of the axes falls in the plane of the stage, as the angle being measured here is smaller than the true angle if both axes were in the plane of the stage.

We can see no merit in Dolar-Mantuani's (3) suggestion of measuring the first and last hazy extinctions. The size of this angle is probably a function of the angle of inclination of the optic-axial plane, and has limited relevance to the strain within the grain. The conclusion that can be drawn from this is that the only reliable optical method for obtaining the true angle of undulosity extinction is by use of a universal stage.

## A SURVEY OF BRITISH QUARTZ-BEARING HARD ROCK AGGREGATES

In order to assess the variability in the undulatory extinction angles a collection of granites, greywackes, meta-siltstones, vein quartz, quartzites, gneisses, and sandstones has been made. Thin sections were made and their detailed petrography determined using a petrological microscope.

From the literature it is clear that different workers have differing views of the best method for the measurement of undulatory extinction angles. As stated previously, the only accurate, and reproducible method of measuring the angular difference in the c-axes, is the universal stage method. In addition, four further methods were also used, two from the literature and two derived by the authors during the development of the project. The methods used are as follows:

1. Universal Stage Method.(TUEA)
2. DeHills/Corvalán Method.(DEHILLS)
3. Dolar-Mantuani Method.(DOLAR)

4. Extinction Point-Extinction Point on Universal Stage.(AUEA)
5. Extinction Point-Extinction Point on Flat Stage.(ROTA)

20 measurements of the undulosity of quartz, for each sample, using each method were obtained, where possible. Measurements of the undulosity were all made using crossed polars.

Universal Stage Method. (TUEA)

This method reorientates the c-axes so that they lie in the plane of the optic axis of the microscope. These measurements give the position of the c-axes as an inclination to the horizontal (plane of the flat stage) and as rotation of the stage. The data collected for each grain measured must then be plotted on a stereonet to enable the true angular difference between the two to be calculated.

DeHills/Corvalán Method. (DEHILLS)

DeHills and Corvalán (5), measured the flat stage rotation needed to rotate a given quartz grain from the point where "the first clear evidence of undulatory extinction appeared" through the point of maximum extinction to the point where the undulatory extinction disappeared from the grain. This rotation of the flat stage was recorded as the degree of undulosity.

Dolar-Mantuani Method. (DOLAR)

This method of measurement of undulatory extinction of quartz is described in detail in Dolar-Mantuani (3). The method is a development of the DeHills/Corvalán Method described previously. Dolar-Mantuani proposed that a more accurate way of measuring the sweep of the undulatory extinction was to measure the angular variation between the first appearance of extinction in the grain to the grain's last full extinction and that with the angular variation between the grain's first full extinction and the point of the extinction's last disappearance from the grain. Once again this method uses the flat stage of a standard petrological microscope.

Although not explicitly stated, it is the Dolar-Mantuani method that is referred to in Appendix 3 of the Concrete Society Technical Report N$^{o}$. 30.(1).

Extinction point-extinction point on the universal stage. (AUEA)

This method of measuring the angular difference between pairs of c-axes is a by-product of the universal stage method. The actual measurement is the rotation of the stage between the two points of maximum extinction. These measurements of AUEA (apparent undulatory extinction angle) measured on the universal stage are made on grains that show low birefringence,(when the c-axes are highly inclined, as near as possible to the optic axis of the microscope), one of the criteria for the universal stage method.

Extinction point-extinction point on the flat stage. (ROTA)

As in the AUEA method, the ROTA method is a measurement of the rotational angle between the two points of maximum extinction in the grain on the flat stage. It differs from the AUEA method in the fact that as part of the criteria for the Dolar-Mantuani method grains of high birefringence are selected for measurement, ie. grains in which the c-axes are as close as possible to the microscope's flat stage axis.

Results

49 of the original 72 samples were selected for detailed measurement following a preliminary optical investigation. The main criteria for the acceptance of certain samples was two fold, firstly on quartz actually being present in the sample, and secondly, on that of grain size. For the purposes of optical investigations the thin sections are required to be of a thickness of 30$\mu$m. Any sample exhibiting

a grain size of 30$\mu$m or greater was suitable for further detailed optical investigation as the grain measured could be guaranteed not to be exhibiting interference patterns from a grain lying below.

Figure 2 shows the distribution of points for TUEA values against DOLAR values. The values of DOLAR that lie within ±1° of the 25° line have a very wide range of corresponding TUEA values. Four points have been highlighted in Figure 2. to show this. Points (a) and (b) lie above the 25° line, therefore the samples from which they came are classified as containing highly strained quartz. When their equivalent TUEA values is measured they show a marked contrast in values, (a) having a value of about 3.5° where as (b) has a value of about 5°. The same is evident if DOLAR values less than 25° are taken, (c) and (d). The variations possible mean that only the TUEA values have any meaning.

Conclusions Of The Survey

At present the suitability of an aggregate for concrete, with relation to the possibility of ASR as a result of strained quartz, is governed by the criteria set out in the Concrete Society Technical Report N$^{o}$ 30. (1). Using these guide-lines and the data collected it is possible to identify samples that would fall into the `potentially reactive' category. Figure 3. shows the results for granites and gneisses. The points which fall in the `Potentially Reactive Zone' are those that would fail the criteria in the Concrete Society report. **Unfortunately these guide-lines are based on a method that we have shown to have very limited validity.**

## QUARTZ GRAIN TEXTURAL CHARACTERISTICS.

In addition to the optical methods of measuring the degree of stability of quartz grains, the general texture of the quartz grains in a sample is another method in assessing the stability of the grains. Features indicating stability or instability, presented in Smith and Dunham (6), range from, type of grain boundaries, grain size, grain shape.

Results

The textures found in quartz show a wide range of variation in the samples examined. The significance of the textural characteristics to potential alkali-silica reactivity is based on the assumptions that:

1. Grain boundaries (of all types) act as potential routes for the movement of alkaline fluids, and potential sites for reaction. The more complex the boundary the greater the surface area available for the reaction to take place upon.

2. Complex extinction may act in a similar fashion as grain boundaries, as they are an optical representation of the dislocation density within a grain. Dislocations are the equivalent of micro boundaries, therefore the same reasoning can be used as above.

3. Grain size once again affects the surface area available for the reaction to take place. The smaller the grains the greater surface area available, though against this, smaller grains tend to be more stable.

Using the textural characteristics results and comparing them with the TUEA values for the samples, it is possible to compare the relationship between the optical measurements and the physical appearance of the quartz grains. Histograms allow the relationship to be shown. Figures 4.a. and b. are the resultant histograms for the samples that are classed as stable and those that are classed as unstable.

Conclusions

The textural variation of the quartz grains observed in the samples give an extra line of evidence as to the stability of the samples, and therefore a possible clue to their potential for reaction in ASR.

The results of investigation only go as far as confirming the instability of quartz grains in a sample with a TUEA value of greater than 5° of undulosity.

## STRAINED QUARTZ IN CONCRETE SHOWING SIGNS OF ASR.

Some observations will now be made on the occurrence of quartz with undulatory extinction in aggregates in concrete, as seen during the examination of thin sections with the polarising microscope. The samples come from concrete in roads and highway structures in Great Britain, most being from a survey of 33 samples of concrete reported by West and Sibbick (7,8). Quartz with undulatory extinction can occur in both coarse and fine aggregate. In coarse aggregate (>2.36mm) the quartz is mainly present as a constituent mineral in rocks; and the rocks in which it is commonly observed are granites and metaquartzites, with some in orthoquartzites and sandstones. In fine aggregates (<2.36mm) the quartz is present as discrete detrital grains although in the coarser part of the fine aggregate recognizable fragments of quartz-bearing rocks can be seen. In those examples of concrete where alkali-silica reaction was detected (five), there were no instances seen in which quartz with undulatory extinction was the reactive aggregate or was involved in the reaction as a major constituent. In a number of instances microcracks can be seen to avoid quartz grains with undulatory extinction, but where very occasionally a microcrack does pass through such a grain there is no other evidence that the grain is the site of reaction. It should be noted, however that the number of cases of concrete suffering from alkali-silica reaction studied was small because of its rarity as a defect of road concrete. The observation that quartz with undulatory extinction is generally unreactive must be regarded as tentative for the present.

Since this work was published an example of ASR related to quartz with a high degree of undulatory extinction has been found Sibbick (pers. comm.). Test prisms using a aggregate, with highly strained quartz, investigated in this survey have shown reaction attributed to the strained quartz fraction of the aggregate Sibbick (pers. comm.). These results are to be presented by R.G.Sibbick in his paper at this conference. Such results now indicate that strained quartz should be assessed with the same amount of detail as are the other known reactive agents.

## AUTHORS' RECOMMENDATIONS.

It is suggested that the reactivity of quartz with undulatory extinction is a function of a number of features of the quartz grains, namely:

1. Undulatory Extinction Angle
2. Texture
3. Grain size

All three features are interconnected and are the result of the processes of rock formation and deformation. They depict a visual representation of the overall stability of the quartz.

As a result of the findings of this project and recent published works it is suggested that the following criteria be assessed before a quartz-bearing igneous or metamorphic aggregate be recommended for use in concrete:

1. The undulatory extinction angle value for quartz be measured using the universal stage method. Only aggregates that have a undulatory extinction angle value of ≥5° should be classified as being highly undulatory. Any value <5° but showing undulosity should be classified as undulatory, and any sample showing no undulosity at all should be classified as being non-undulatory. A value of ≥5°, alone, does not imply that the quartz is alkali-silica reactive.

2. Using the criteria set out in Smith and Dunham (7), quartz grains should be assessed, by their texture, for instability. Any rock type exhibiting unstable quartz textures should be classified as unstable. Any rock type exhibiting stable textures should be classified as stable.

3. If cases of ASR resulting from reaction with undulatory quartz are found, previous case histories of the aggregate should be examined (where possible), either in existing structures or in laboratory test prisms, to ascertain any past reactivity. Any rock type showing past reactivity should be investigated with a view to limiting or excluding its use in structures where there are potentially reactive environments.

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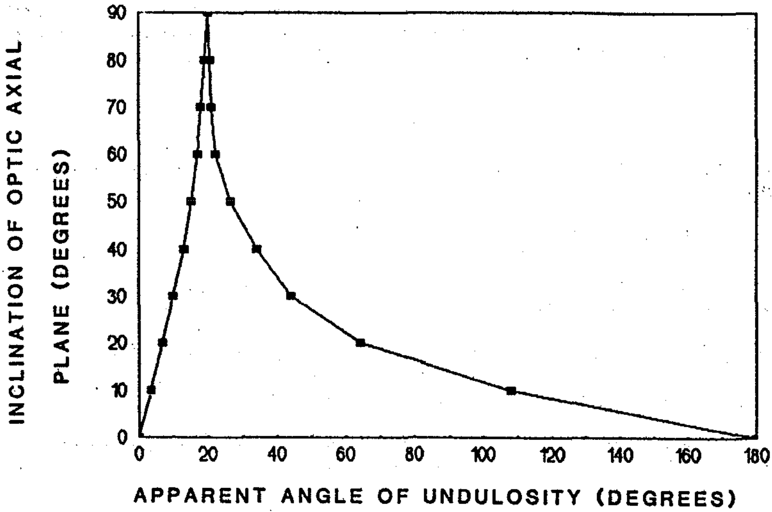


Figure 1. Graphical representation of the possible apparent extinction angles for a true extinction angle of 20°. Possible values plot on or below the curve.

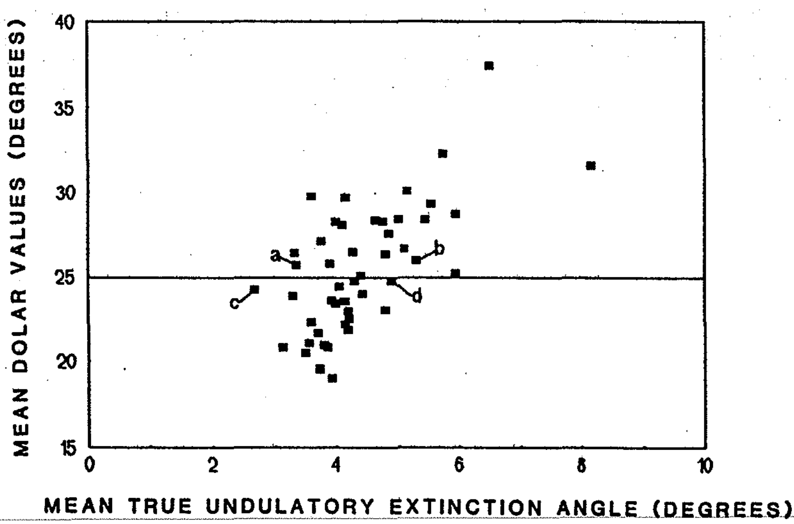


Figure 2. Graphical representation of the comparison between the values for the method prescribed in the guide-lines and the corresponding true angle of extinction.

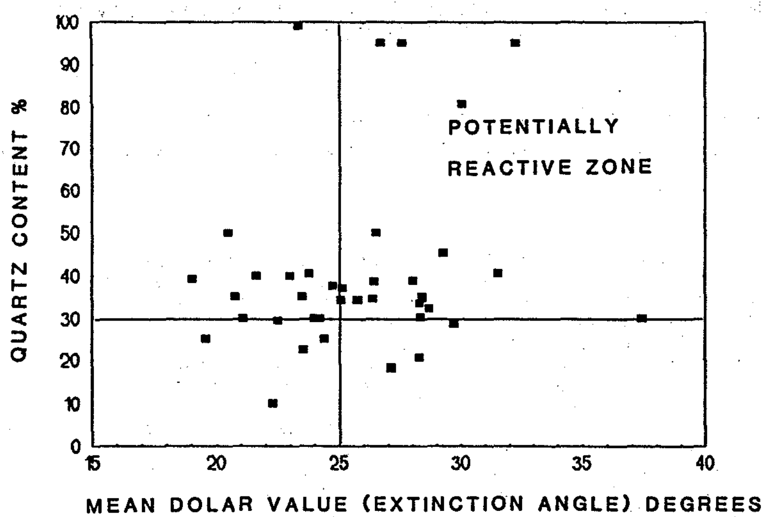


Figure 3. Graph showing the Concrete Society guide-line values for potentially reactive quartz and the distribution found in the examined samples.

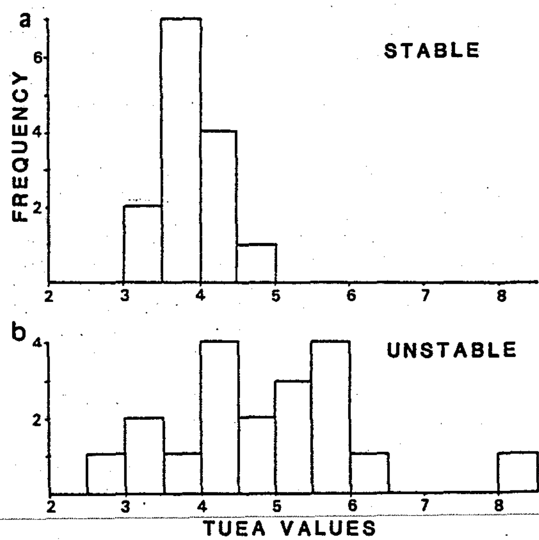


Figure 4a,b. Histograms showing the distribution of the true extinction angles when related to the textural stability of the quartz grains. a) stable textures, b) unstable textures.