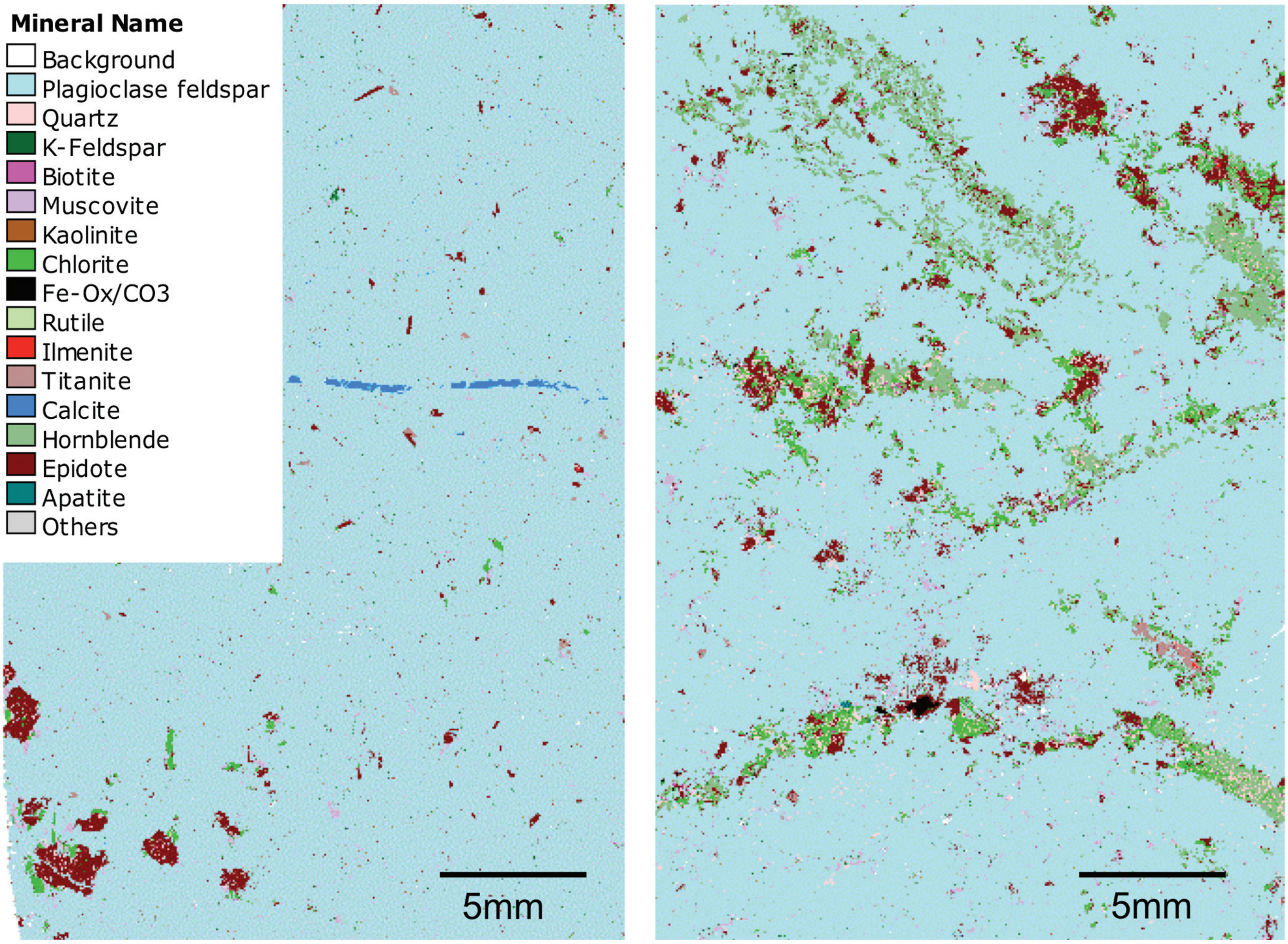

Figure 19. Anorthosite. Lingerbay, Harris, Outer Hebrides, Scotland *(sample 7/13 (left) and sample 9/13 (right)). (See Table 10). A medium- to coarse-grained crystalline rock with plagioclase as the major mineral along with patches and stringers of hornblende, epidote and chlorite in different proportions in the two samples. The interlocking mosaic nature of the plagioclase is not visible in the QEMSCAN® mode. The key shows all minerals, some of which are not visible at the scale of the images.*

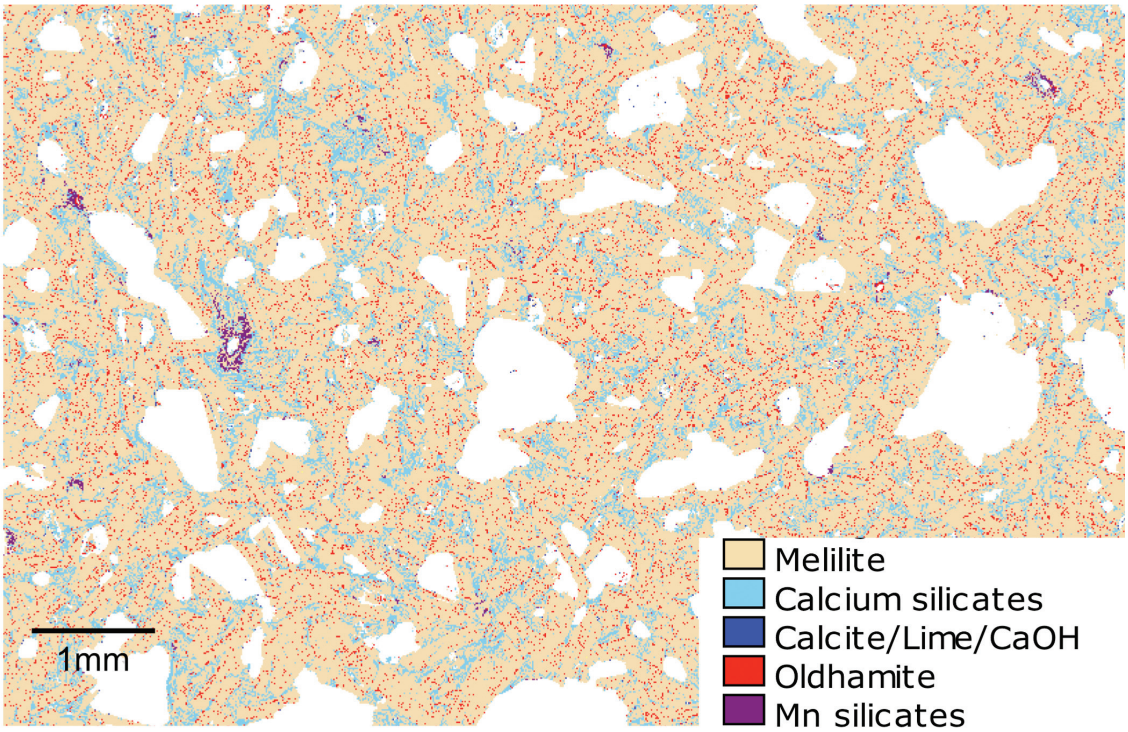

Figure 20. Blastfurnace slag. Scunthorpe, Lincolnshire *(sample 25/83). (See Table 11). A uniformly crystalline very porous material with an intergrowth of melilite and calcium silicates (probably merwinite and/or dicalcium silicate) with disseminated oldhamite (CaS) throughout. Isolated patches of an undetermined phase(s) of manganese silicate are present. The porosity is shown as white.*

Sample number	**Lingerbay, Harris, Outer Hebrides, Scotland** **Anorthosite**							
	7/13		8/13		9/13		10/13	
	%	Size µm	%	Size µm	%	Size µm	%	Size µm
Plagioclase feldspar	95.77	1051	93.90	960	85.82	544	78.05	285
Quartz	0.12	34	1.45	41	1.37	33	3.44	27
K-Feldspar	0.21	18	0.08	16	0.26	17	0.49	17
Biotite	0.01	17	0.02	16	0.08	22	0.16	17
Muscovite	1.19	29	0.59	28	1.44	30	1.54	25
Kaolinite	0.20	16	0.13	16	0.18	15	0.21	15
Chlorite	0.39	62	1.51	47	2.65	46	10.28	61
Fe-Ox/CO3	<0.01	48	0.01	28	0.09	67	0.01	23
Rutile	<0.01	20	0.02	38	0.01	21	0.01	16
Ilmenite	<0.01	81	<0.01	67	0.01	31	<0.01	23
Titanite	0.10	88	0.32	92	0.19	58	0.11	20
Calcite	0.36	110	<0.01	15	<0.01	15	0.75	34
Hornblende	0.03	16	0.44	38	4.19	88	0.29	16
Epidote	1.60	66	1.51	40	3.66	46	4.67	34
Apatite	<0.01	29	0.01	39	0.02	42	<0.01	18
Others	<0.01	<16	0.01	<22	<0.01	<17	0.01	<18

Notes: Fe-Ox/CO3; Iron oxides or carbonates

Table 10. *Modal composition and mean crystal sizes of anorthosite.*

Sample Number	**Scunthorpe, Lincolnshire** **Blastfurnace slag**	
	25/83	
	%	Size µm
Melilite	80.83	95
Calcium silicates	13.49	24
Calcite / portlandite	0.19	16
Oldhamite	5.07	17
Mn silicates	0.24	19
Ti phases	0.04	16
Others	0.15	17

Table 11. *Modal composition and mean crystal size for blastfurnace slag.*

DISCUSSION

The QEMSCAN® images provide a review of the petrography of several types of rock used in crushed rock aggregates in the UK. The images are different to photographs from a thin section using an optical microscope as they are directly related to the proportions of the different chemical elements present in the minerals and require interpretation to establish the mineral name. In effect they are chemical images of the mineralogy and are presented using false colours to show the texture. In addition, the vast amount of digital data collected from each sample (literally millions of X-ray spectra) enables the percentages of each of the minerals to be determined, and the crystal or grain-size and the relationship between the minerals to be established. The procedure is entirely objective. Subjective bias, that can be present in identifying, describing and quantifying mineralogy using an optical microscope and a point counter, is eliminated. However, representativeness remains a problem, as it does with optical microscopy. Multiple samples need to be examined to show petrographic variation in a product, particularly where an aggregate is made from an interbedded sequence of rocks or from a heterogeneous metamorphic complex. Even minor but significant variations can occur in aggregates from igneous rock quarries. The petrographic variation that can be found within some aggregates have been illustrated here (e.g. Hingston Down, Cornwall; Mountsorrel, Leicestershire; Harden, Northumberland; Middleton-in-Teesdale, Co. Durham; Roan Edge, Cumbria; Meldon, Devon). Although not occurring in the samples examined here, the presence and distribution of deleterious minerals in aggregates (e.g. significant amounts of sulphides) could also be easily established.

Further explanation of the grain size data is required as the values are likely to differ from measurements done by optical procedures. In the QEMSCAN® a 'grain' is measured as an individual mineral, and not a particle, which can be made up of one or more grains. There are some limitations because the data are taken from a two dimensional section and are known to underestimate true sizes (Pascoe et al. 2007, Sutherland, 2007). A similar underestimate would occur from optical measurements using a thin section. Further, the grain-size data are collected by recognising changes in the X-ray spectra in a linear mode. This can be skewed if the boundaries of particles are not distinguishable (e.g. quartz touching quartz gives a single grain) (see Figure 21). If a single different X-ray spectrum interrupts the linear sequence of the spectra from a single grain, two grains are identified even though the single different spectrum may be from a mineral inclusion within the grain. With an optical microscope, adjacent crystals would be recognised because of their different optical orientations and a minor inclusion of a different mineral would be ignored in a grain size measurement.

The general relationships between the rock type and physical properties of aggregates are well known and the data in Table 1 illustrate this well. Taking the PSV as an example, gritstones and greywackes are generally recognised as having superior PSVs (>60) compared with igneous rocks, which have lower PSVs (typically in the range 52-58) and differ from location to location and according to the rock type. Limestones polish and thus

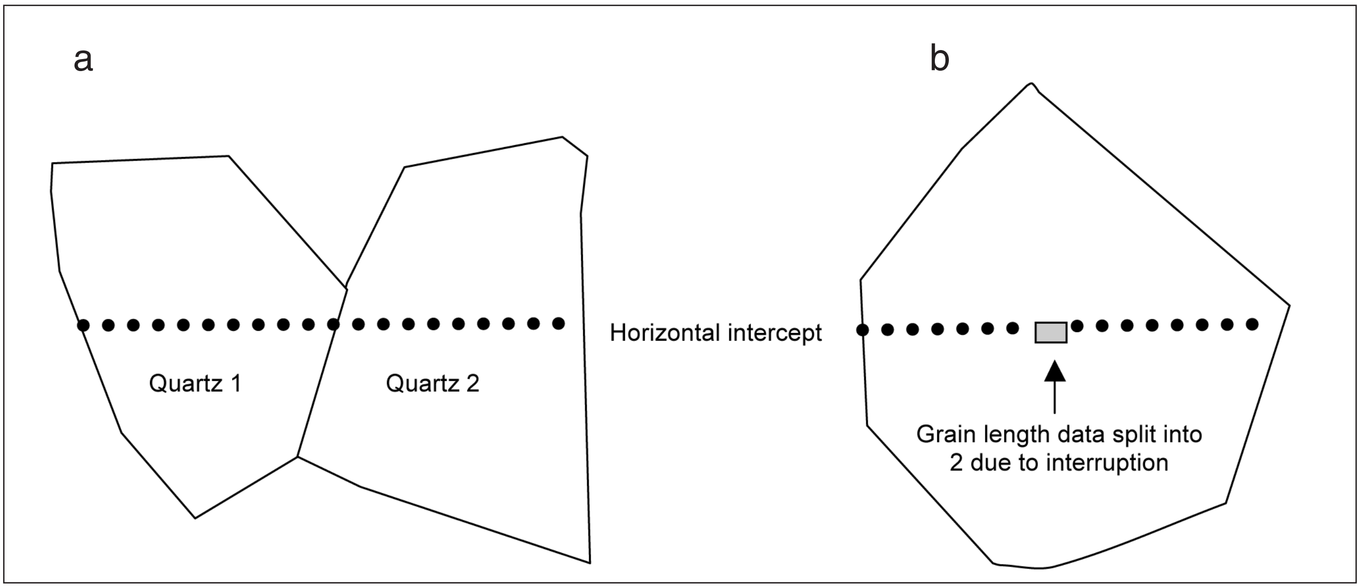

Figure 21. Interpretation of grain size data. *a. Touching grains of the same mineral; the technique is not able to determine the boundary thus identifies the grain as one grain and one length. b. An inclusion or rogue pixel in a grain causes the large grain to be split into two and identified as three different parts in the grain size data.*

generally have low PSVs (<40 to ca. 45), although some dolostones and impure limestones have higher PSVs.

The mineralogy and textures in the QEMSCAN® images enable some broad interpretations of the differences in the physical properties of some of the samples to be made. In general, the granites and granodiorites with their coarse grained texture have higher AIV, ACV and lower 10% fines, and hence slightly lower strengths, compared with the lavas and pyroclastics, basic igneous rocks, greywackes and gritstones that are finer grained.

The gritstones and greywackes, which have PSVs greater than 60, are indurated rocks made up dominantly of angular to subrounded quartz and feldspar grains, with a Moh's harnesses of 7 and 6 respectively, in a matrix dominated by softer micas and chlorite (Figures 5-17 and Table 9). These differences in hardness enable a continuously rough surface to be presented as the aggregate wears away during a polishing test and in use on a road. The granite and granodiorite samples in the present study, which have PSVs typically of around 52-55 and occasionally slightly higher, are dominated by larger quartz and feldspar crystals (not grains) with relatively lesser amounts of softer minerals such as micas and chlorite. A polished surface of granite and granodiorite, therefore, is dominated by hard minerals.

The presence of high amounts of soft chlorite, allied with a texture of rounded crystals of much harder quartz and feldspar could explain a PSV of 58-60 from Whitwick, Leicestershire, and likewise high amounts of chlorite and soft calcite in the sample from Greystone, Cornwall could explain a high PSV in the range 57-62 from this quarry, compared with many other igneous rocks.

The data in Table 1 show that for some quarries published PSVs from different sources are quite different, although in general the other physical properties do not show significant variations. For example, three published PSVs from Mountsorrel are 51, 53 and 58 (Table 1). These differences in PSV may relate to products from different parts of the quarry, perhaps as the quarry developed over time. Although the present samples are not directly related to the PSV measurements, the QEMSCAN® images and statistics of three samples from this quarry taken at different times show quite a wide variation in grain-size and in the proportions of the major minerals, particularly chlorite, that could explain the different PSVs reported. The mineralogical variations in the four samples from Lingerbay, Harris, Outer Hebrides (Figure 19 and Table 10), similarly indicate that there might have been a variable PSV of products from that quarry had it been developed.

Finally, the QEMSCAN® images of high purity limestones illustrate well the singular calcite mineralogy of these rocks, which polish to a smooth surface when subjected to abrasion irrespective of the allochemical constituents and their relationships to a sparry or micritic matrix. In contrast the impure limestone of Shierglas quarry, has minerals of widely contrasting hardnesses, such as hard quartz, feldspars, and zoisite with soft muscovite and calcite. This assemblage of minerals enables this rock to have a similar PSV (56) to that associated with many igneous rocks, albeit both the composition and the PSV are likely to vary within the quarry, as the rock is very heterogeneous.

CONCLUSIONS

Automated scanning electron microscopy (QEMSCAN®) has been used to determine and illustrate the mineralogy and petrography of a wide range of different crushed rock aggregates used in the United Kingdom. The technique enables the mineralogy to be quantified and size distribution and mineral association data to be obtained. The rock textures are illustrated using false colour imaging techniques related to the chemical composition of the minerals. The images can be used to interpret the differences in the physical properties between aggregates of different rock types. Although interpretation of the data requires a knowledge of the chemical composition of the minerals likely to be present in the samples, the technique is objective and avoids the subjectivity associated with recognising and identifying minerals in thin section, and quantifying them with a point counter. Multiple samples need to be examined in order to cover variations within an aggregate, as it does with optical microscopy. Automated scanning electron microscopy could be adopted as an objective procedure for companies formally to describe their aggregate products.

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