In the early fifties of the last century, Khirbet Qumran (the ruin of Qumran) was excavated together with another forty caves on the spur of the settlement and on the cliffs above. Fifty-one tombs (out of an estimated 1,100 graves) were also excavated. All three sections contained textiles. So far, Grace Crowfoot (Crowfoot 1953) has described 75 pieces, whereas Mireille Bélis (see her section and inventory in this volume) has given her opinion on 82 additional fragments of textiles found in Caves 8Q, 11Q, ‘small caves’ and ‘SPI’ of unknown provenance as well as in the famous Christmas cave (famous, because the late King Houssein himself was involved). The story of this last cave is told for the first time in this volume. Fragments from the Christmas cave are not included in the 80 samples described by Bélis. A map of all the forty caves is given in this volume.

At the outset, we wanted to know what were the materials used in the remains of textiles and other fibrous material found in Qumran. The type of fibre in ancient textiles is usually classified only by optical microscopy. Our first objective has been to unambiguously identify the type of fibres each sample consists of using techniques complementary to microscopy, such as x-ray fibre diffraction. Some of the textile samples were coloured or had coloured threads woven into them. This set our second objective, to identify these colorants, in particular whether they are mineral or vegetative, organic or inorganic crystalline pigments or non-crystalline dyes. Any one of these possibilities may be helpful in establishing whether the textiles sampled from Caves 8Q and 11 are similar to one another and consequently how they relate to the hapax, charred textile (QUM 503) from Locus 96 in the settlement and with QUM 524, the hapax sample from Tomb 1.

The purpose of definitive identification of fibre and colorant type is important in the context of views (Bélis in this Volume) suggesting that the textile fragments are not from the time period between 50BC - 68AD when the site was destroyed. It may be argued that identification of fibre type alone is not sufficient to exclude the possibility that Bedouin nomads may have left textile remains in the caves, in which case these samples have nothing in common with the occupants of the caves during the period in question. It is for this reason that comparison of the textiles from other locations with that found in Locus 96 and in the tomb is of particular interest.

In parallel with fibre analysis corroborating or refuting that not all the textiles are from the same epoch, we have submitted 18 samples to Groningen University for C-14 dating. The results are not yet in, but identification of fibre and colorant type can be obtained by diffraction irrespective of the age of the material. This report is primarily concerned with the first objective, identification of the nature of the fibres. Diffraction from non-fibrous material attached to some of the textiles is discussed but detailed analysis of the crystalline species present will be reported at a later stage.

**MATERIALS AND METHODS**

**Samples**

The fragments of fibres and textiles presented in this study are:

- QUM 502 from Cave 29.
- QUM 503 the only one from the settlement.
- QUM 524 the only piece from Tomb 1 in the South cemetery.
- QUM 504, 505 and 506 from Cave 8Q.
- QUM 510, 511, 512, 513, and 517 from Cave 11.
- QUM 518-523 and 525 from SPI.
- QUM 526, 527, 528 and 530 from Christmas Cave.

Fig. 1 shows some of the samples together with representative scanning electron micrographs and x-ray diffraction patterns from the intact samples.

**Experimental Details**

**Microscopy**

Visual examination of all the intact samples in the collection was first carried out with a stereo microscope at a magnification of x10-40. Further detailed examination was carried out by a textile expert, Penelope Rogers, using a polarising microscope and magnification of up to x400 (see annexe to this paper).
a  QUM 502, Cave 29 – Unprocessed bast fibre  SEM x720 bar 50 mm

b  QUM 503, KhQ, loc. 96 – Charred flax spun left-handed  SEM x400 bar 100 mm

c  QUM 504, Cave 8Q – Flax, spun left-handed  SEM x400 bar 100 mm

d  QUM 505, Cave 8Q – Flax, spun left-handed, dyed purple, soiled  SEM x4000 bar 10 mm

e  QUM 510, Cave 11 – Flax, spun left-handed, two threads dyed blue, soiled  SEM x400 bar 100 mm

f  QUM 511, Cave 11 – Flax, spun left-handed  SEM x300 bar 100 mm

g  QUM 512, Cave 11 – Cellulose fibre, spun left-handed type unidentified  SEM x300 bar 100 mm

h  QUM 513, Cave 11 – Unspun Cotton  SEM x730 bar 50 mm

No XRD data
Fig. 1 – Left column: digitised pictures of the textile samples referred to in the text. Middle column: scanning electron micrographs of single thread fragments or fibres extracted from the samples. Right column: diffraction patterns through the intact samples taken at the SRS with a beam footprint of 200 microns, exposure time 10 seconds.
Scanning Electron Microscopy

Single threads from each textile sample were extracted, mounted on aluminium stubs using conductive carbon cement and sputter-coated with gold. A Cambridge S90 scanning electron microscope was used at an accelerating voltage of 15 kV to image the fibres at a range of magnifications. Representative views for each sample are shown in Fig. 1.

X-ray Diffraction through the intact samples

Each textile sample was sandwiched between PVC washers and examined by x-ray diffraction in transmission geometry at station 9.6 of the Synchrotron Radiation Source (SRS), Daresbury Laboratory. The wavelength was 0.087 nm and the collimator defining the beam footprint had a cross-section of 200 mm. The data collection time was typically 10-60 sec using an ADSC Quantum-4 CCD detector at a distance of 150 mm. The active area of the detector is 2304 x 2304 pixels. The pixel size is 81.6 mm x 81.6 mm and the dynamical range is 16-bit. Calcite powder in a capillary was used as a calibrant. The data were further processed using locally developed software (Pantos unpublished) and the package FIT2D (Hammersley et al. 1996).

Micro-diffraction of single fibrils

The microfocus beamline ID13 at the European Synchrotron Radiation Facility (ESRF) was used to obtain micro-diffraction patterns from single fibres. The beam size was 2 mm as produced by a tapered glass capillary in combination with focusing by ellipsoidal mirror optics (Riekel 2000). The x-ray wavelength was 0.096 nm. Single fibrils of 3-6 mm length were extracted from the textile samples, glued on a metal frame, which was then mounted on a goniometer head, optically aligned with the aid of a video microscope and then translated into the x-ray beam. The microscope-beam distance (about 7 cm) was calibrated with an accuracy of better than 1 mm. The sample was then scanned through the beam with microscopic position resolution (better than 1 mm accuracy). In this way, position-dependent diffraction patterns could be collected. Two-dimensional diffraction patterns were recorded on a CCD detector (MAR Research, 2048 x 2048 pixels at a distance of 100 mm. The detector has a pixel size of 64.45 mm x 64.45 mm and 16-bit dynamical range.

Fig. 2 – S-spun (left-handed) thread from a) QUM510 and b) QUM512. Z-spun (right-handed) thread from c) QUM525 and d) the red-dyed thread of QUM530.
Calcite and corundum powder in capillaries were used as wavelength and sample-detector distance calibrants.

The single fibres from QUM 502, QUM 510, QUM 512, QUM 518 and QUM 525 were of a diameter around 10-20 mm. Fibres from modern reference materials (flax, cotton, ramie) were also examined. The Qumran fibres were much more inflexible and brittle compared to the modern fibres. In the case of sample QUM 524, extraction of a single fibre was impossible as the individual brittle fibres were strongly bonded together. A bundle of about 10 adjacent fibres was mounted on the metal frame.

These nine fibre samples were each scanned through the beam in 20 steps of 3 mm each. At every position, a two-dimensional pattern was acquired in 30 second exposure time. For further analysis of the data (e.g., averaging, azimuthal integration), the ESRF image processing software FIT2D was used (Hammersley et al (1996)).

**RESULTS AND DISCUSSION**

**MICROSCOPY OBSERVATIONS**

The twist of the threads was clearly seen at low magnification (Fig. 2), being S-spun (left-handed twist) for most of the woven fabrics with only two having a right-handed twist, QUM 525 and QUM 530. The latter contains red-dyed (right-handed twist) and undyed threads (left-handed twist). Samples QUM 502, QUM 513 and QUM 517 did not contain spun threads.

Details of the fibre characteristics and type identification are described by Rogers in the annexe to this paper. Bast fibres are fine and flexible cellulose fibres of almost circular cross section. Flax, hemp, jute and ramie are related bast fibres. Samples QUM 503, 504, 505, 510, 512, 518, 524 were diagnosed as flax (Linum usitatissimum L.) and QUM 502 as unprocessed plant-stem fibre. QUM 503 appears opaque black under the optical microscope but the silhouette showed diagnostic flax fibre features confirmed by SEM (Fig. 1-a,b).

Two of the samples, QUM 513 and QUM 525 are cotton, distinguished from bast fibre by the characteristic ribbon-like appearance while wool fibres in QUM 517, QUM 526, QUM 527, QUM 528 and QUM 530 were recognised by the scale pattern characteristic of animal fibres. Sample QUM 517 contained bundles of animal fur fibres (see Fig. 1-i).

**X-RAY DIFFRACTION OBSERVATIONS**

**200-micron beam footprint at the SRS station 9.6**

The diffraction patterns of all samples obtained at the SRS (Fig. 1) show a number of crystalline powder rings from particles attached to the fibres, in some cases incomplete and “speckly”, superimposed onto diffraction from the fibres themselves. The relatively much broader diffraction rings of plant fibres are partly due to the small cellulose crystal (microfibril) size, of the order of 3-7 nm, but more significantly, by the fact that the fibres illuminated by the 200-micron beam footprint at this station are not all oriented parallel to one another. This causes the rather large azimuthal broadening compared to the single fibre diffraction (see next section and Fig. 3). In the case of wool fibres, the misorientation of individual fibres is more pronounced as seen from the SEM images. The main advantage of performing diffraction measurements with the beam diffracting from an extended area of the sample is that a larger number of crystalline particles attached to the fabric diffract and, consequently, the diffraction rings are more complete and representative of all crystal orientations. This gives rise to a powder pattern which is considerably easier to interpret. Diffraction from the fibres themselves makes it possible to distinguish between plant (cellulose) and animal fibres. Wool is made of a fibrous protein, keratin, which is organised in coiled coil suprahelical ropes (McLachlan and Stewart (1975)) with microfibrils packed into macrofibrres. Diffraction from keratin macromolecules (Brika et al (1998)) varies for different species and different conditions of preparation, especially in the spacing of the equatorial reflections (approx. at 9.8Å and 4.7Å), and is quite distinct from that of cellulose microfibrils. The inherently wide azimuthal and radial extent of these equatorial reflections and misorientation of individual fibres results into a rather broad diffraction ring underlying the sharp crystalline reflections from the soil particles.

The measurements on the wool samples were taken primarily for identifying the diffracting minerals. Absence of a fibre pattern should be considered merely as negative evidence for the possible presence of wool fibre. Wool

<table>
<thead>
<tr>
<th>Sample</th>
<th>From 110(Å)</th>
<th>From 1-10(Å)</th>
<th>From 200(Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modern flax</td>
<td>43</td>
<td>36</td>
<td>47</td>
</tr>
<tr>
<td>Modern ramie</td>
<td>51</td>
<td>39</td>
<td>57</td>
</tr>
<tr>
<td>Modern cotton</td>
<td>–</td>
<td>–</td>
<td>61</td>
</tr>
<tr>
<td>QUM 510</td>
<td>54</td>
<td>47</td>
<td>59</td>
</tr>
<tr>
<td>QUM 512</td>
<td>51</td>
<td>41</td>
<td>56</td>
</tr>
<tr>
<td>QUM 518</td>
<td>45</td>
<td>48</td>
<td>56</td>
</tr>
<tr>
<td>QUM 524</td>
<td>48</td>
<td>35</td>
<td>44</td>
</tr>
<tr>
<td>QUM 525</td>
<td>–</td>
<td>–</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 1 – Crystallographic parameters (crystal sizes) of the samples investigated. The values are calculated from the widths of the three Bragg reflections.
fibres scatter much more weakly than bast fibre. This is evident in all samples identified as wool by OM and SEM. The flax and cotton samples on the other hand, scatter quite strongly and the fibres show a greater degree of preferred orientation compared to wool samples, as indeed seems to be the case in the SEM images. This is particularly noticeable for QUM 524 where fibres are seen to be joined laterally (Fig. 1-k).

The charred sample QUM 503 identified as flax on the basis of optical and scanning electron microscopy is an exception. Its corresponding diffraction pattern in shows no plant fibre diffraction features. This could be explained by loss of crystallinity due to heating, which although it has not destroyed the sample all together, it has been sufficient to perturb the crystalline order. This needs to be confirmed by control heat-denaturing experiments. As QUM 503 comes from KhQ, locus 96 an ‘open space’ south of settlement, other denaturing processes may also be involved.

On the basis of these, completely non-destructive, measurements at the SRS, we can classify the samples in the collection as follows, in agreement with OM and SEM:

![Fig. 4 – One-dimensional micro-diffraction diagram of QUM 510, obtained by azimuthal integration about the equator of the corresponding two-dimensional fibre diagram. a) Left: Data and least-squares fit. b) Right: Comparison with modern samples of flax and ramie.](image1)

![Fig. 5 – One-dimensional azimuthally integrated micro-diffraction patterns of QUM525 and modern cotton.](image2)

![Fig. 6 – One-dimensional, azimuthally integrated micro-diffraction pattern of QUM502 (cellulose IV) compared to flax (cellulose I). The insets on the left and the right show the fibre sample and the corresponding SEM image.](image3)
Bast fibre: QUM 502, 503, 505, 510, 511, 512, 518, 519, 524
Cotton: QUM 513, 525
Animal fibre: QUM 517, 526, 527, 528, 530.

The diffraction patterns from samples encrusted with soil particles (QUM 505, 510, 511 and 517) and those that are coloured or stained are discussed in the section on mineral identification below.

2-micron beam footprint at the ESRF beamline ID13

As alluded to above, accurate quantitative analysis from diffraction patterns of multiple fibres (threads or bundle of fibres in intact samples) is not possible for the following reasons: (i) The inner texture of cellulose fibres (orientation distribution of microfibrils inside the fibre) cannot be determined from fibre bundles where misalignment of the individual fibres leads to artefacts. (ii) Azimuthal integration of the diffraction diagrams may include intense crystalline, non-fibre, Bragg reflections superimposed on the broad cellulose reflections. These problems can be avoided by examining single fibres, the diffraction patterns of which are easier to interpret.

The textiles thought to be made from plant fibres on the basis of the microscopy diffraction of the intact fibre bundles at the SRS were investigated further with microdiffraction at ESRF. In the following, we classify the samples taking account of both the microscopy observations and the microdiffraction single fibre data.

Bast fibres (QUM 510, QUM 518, QUM 524)

The SEM images of samples QUM 510, QUM 518 and QUM 524 show fibres with a diameter around 10-20 mm. Some so-called “knee” defects that are characteristic of flax fibres (Turner (1949)) are visible for QUM 510 and QUM 518. Individual fibres are well separated and show hardly any defects along the fibre length. In QUM 524, some of the fibres appear laterally joined.

X-ray diffraction data were obtained from single, vertically oriented fibres. With regard to the internal structure, bast fibres are characterised by a very high orientation of the cellulose microfibrils along the direction of the fibre axis (Müller et al (2000)). The microdiffraction diagram of a single fibre of QUM 518 (Fig. 3a) demonstrates these orientational properties. The azimuthal arcing (broadening) of all Bragg reflections is very small, indicating an excellent internal orientation of the cellulose microfibrils leading to an almost perfect fibre diagram. Those of QUM 510 and QUM 524 are of similar quality.

The microfibril size is of great interest as it is specific for a given plant species. The three strongest cellulose reflections 1-10, 110 and 200 are found on the equator of the diagram (the horizontal symmetry axis in Fig. 3a). The radial width of these relatively broad reflections contains information about the cross section dimension of the cellulose microfibrils. To obtain these values, the fibre diagrams were azimuthally averaged in an angular region of approx. 20 degrees about the equator. The one-dimensional diffraction profiles thus obtained contain just the above mentioned three reflections in the scattering angle 2\(\Theta\) range 7° to 17°. The peak shape was assumed Lorentzian (Wada et al (1997)) and peak positions were calculated using cellulose lattice parameters (Woodcock and Sarko (1988)). The relevant lattice constants \(a\), \(b\) and \(\gamma\), reflection widths as well as a linear background were free parameters in a least-squares fit to the data. Data and fit for the bast fibre QUM 510 are shown in fig. 4a and are in excellent agreement.

The peak widths (in \(\Theta\)) were used to calculate apparent crystal sizes using the Scherrer equation (Azaroff (1968)) and are listed in table 1. The most reliable value is obtained from the width of the single 200 reflection that does not overlap with other peaks and can be regarded as the diagonal of the cellulose microfibril cross section. For QUM524, a diagonal of 4.4 nm is in good agreement with measurements on modern flax (4.7 nm).

In the case of QUM 510 and QUM 518, however, the crystal sizes are larger than those expected for flax. On the other hand, there is excellent agreement between the crystalite sizes determined from the least-squares fit for QUM 510 (5.9 nm) and that of ramie (5.7 nm). Furthermore the diffraction diagrams for QUM 510 and QUM 518 are a good match to those of ramie (fig. 4b). However, it must be considered that, though unlikely, it is possible that the increase in crystal cross section could be due to ageing effects such as annealing. Resolution of this ambiguity requires additional data collection and comparison with other ancient and modern fibres from various sources.

Cotton fibres (QUM 513, QUM 525)

SEM images for samples QUM 513 and QUM 525 show fibres with a ribbon-like shape and a diameter of approx. 25 mm (Fig. 1-h,l). This observation is characteristic of cotton in contrast to bast fibres which have a circular cross section. (Catling and Grayson (1982)).

Micro-diffraction data collected for sample QUM 525 are shown in Fig. 3b. The two-dimensional diffraction diagram is characteristic of cotton; there are four maxima on the azimuth at the radial position of the 200 reflection. This crossed appearance is indicative of a helical fibril structure. The azimuthally integrated data for QUM 525 exhibit similar characteristics to that of a modern cotton sample. A plot of the integrated intensity for QUM 525 and for modern cotton clearly illustrates this (fig. 5). A least-squares fit applied to the data yields a cross section diagonal of about 60 nm for both the Qumran and modern cotton as given in table 1.

Low-crystalline cellulose sample (QUM502)

The SEM image of QUM 502 is shown in the right inset of Fig. 6. The fibres are irregularly shaped, and the diameter varies along the individual fibres. Their surface is very rough. The two-dimensional diffraction diagram is of fibre symmetry with a relatively high degree of orientation, similar to bast fibres. Angle integrated one-dimensional data, however, indicate a very low crystallinity. Comparison with the diffraction profile of modern flax in fig. 6 shows up major differences: The 200 peak is found at lower 2Q, while 110 and 1-10 merge to a single broad peak. Cellulose of this kind is often classified as cellulose IV (Gardiner and Sarko (1985)) in contrast to the much more abundant form of native cellulose I. Cellulose IV occurs in primary plant cell walls, not in the dominant secondary walls of fibres of the kind used for textiles.
There are two possible explanations: (i) QUM 502 is a plant stem not used for textile making and just by chance found in the same place. (ii) The sample consists of highly degraded fibres. As all the other samples are in an excellent state of conservation, the latter seems less probable. Drying-twist tests of this sample by Rogers show features which have never been recorded in flax (see annexe).

**Unidentified cellulose fibre (QUM 512)**

On the basis of the data available currently, the bast fibre type in QUM 512 can not be identified securely. As is clearly seen in the SEM image in Fig. 1-g, the fibres have a diameter of 30-40 μm and a polygonal cross section unlike that seen in the other flax fibres. The micro-diffraction data indicates less well oriented cellulose than in bast fibres. When a least squares fit is applied to the one-dimensional integrated profile a crystal size of about 5.6 nm is obtained. Re-examination of this fibre by Rogers using ash analysis and OM of cross sections in transmitted and reflected light shows them to be flax (Linum usitatissimum L.) but with a rather unusual polygonal morphology (see appendix, section 2.). Thorough SEM re-examination of the same textile fragment examined by Rogers confirmed that there was no accidental mix-up of samples. Fig. 7 shows three micrographs from this sample at three different magnifications.

**Identification of Pigments or other crystalline material attached to the fibres**

As mentioned above, a complex diffraction pattern of crystalline powder origin is superimposed on the fibre pattern of several of the samples. It would be reasonable to expect that most of these diffraction rings are due to the soil particles the samples are encrusted with. Small crystals are clearly visible in the SEM images (see for instance QUM 505 and QUM 510 in fig. 1-c,e). Whether some of these diffraction rings are due to crystalline pigments the...
threads have been dyed with is difficult to establish at this point without ambiguity. Comparison of the patterns from QUM 505 (dyed purple) and QUM 510 (only two threads are dyed blue) in fig. 8 shows that all the crystalline powder reflections for both samples coincide indicating that they are due to soil particles, not crystallites of pigment.

Micro-diffraction from the blue-dyed and undyed fibres of QUM 510 show little difference. This would seem to indicate that the blue colorant is not in a crystalline state or at least not in sufficient quantity to give a distinct powder pattern. The diffuse or “speckly” nature of the diffraction rings (fig. 8 and fig. 9) indicates that we have a mixture of diffracting phases, at least one of which is composed of very fine particles. Preliminary analysis of the diffraction patterns of QUM 505, 510, 517, 526, 527, 528 and 530 show strong presence of quartz, an abundant component of clays and marls, calcite, typical of clays in the Levant, as well as at least one other phase which is also present in mud from the Dead Sea examined by conventional x-ray diffraction (fig. 8b). QUM 517 contains reflections not observed in the other samples. HPLC and Raman analysis of the dyes and phase analysis of the crystalline inclusions is in progress and will be reported elsewhere.

Sample QUM 524 is relatively unsoiled. The green particles attached to the fabric (fig. 10a) do not appear to originate from an intentional pigment colorant applied to individual threads. They look more likely to be corrosion products from a metal object the textile has been in con-

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**Fig. 8** – (a) Two halves of the diffraction patterns from the intact samples QUM505 (top half) and QUM 510 (bottom half) collected at the SRS with a beam footprint of 200 microns, wavelength 0.087 nm. The fibre is flax for both of them. Fine diffraction rings due to soil particles attached to the fabric appear at the same diffraction angle. (b) The integrated profiles compared with the diffraction profile of mud from the Dead Sea. The positions for quartz and calcite are indicated by arrows.

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**Fig. 10** – a) Optical micrograph showing the left-handed spun thread and the green polycrystalline particles attached to the fabric of QUM 524 which otherwise does not appear to have been dyed. b) Micro-diffraction pattern, collected at ID13 of the ESRF, from green particles protruding from a single fibre. The diffuse continuous rings indicate the presence of fine mineral particles.
tact with or other alteration products accumulated during burial. It was possible at ID13 to aim the beam at such particles protruding from the fibre they were attached to and obtain micro-diffraction data without superimposition of the fibre pattern (fig. 10b). We have not as yet identified the crystalline phase(s) these particles are composed of but it is clear from the rather broad and continuous nature of the diffraction rings that the crystals are very small as would be expected of corrosion products. High angular resolution diffraction is needed to determine crystal size and lattice parameters accurately.

Conclusions

Combined optical and scanning electron microscopy and synchrotron x-ray diffraction studies of textile fibres from Qumran have shown them to consist of three main types, bast fibres, cotton and wool. Micro-diffraction has allowed the determination of the internal organisation of single bast fibre from several of the samples, free of artefacts. Two of the samples are cotton one of which, QUM 525, is spun right-handed. All four samples from the Christmas Cave are wool, one of which, QUM 530, contains both left and right-handed threads. Diffraction from the wool samples was used primarily for identification of crystalline minerals attached to the fibres. Longer time exposures (a few minutes) of oriented fibres are needed to extract detailed information on the wool fibres themselves.

The charred textile (QUM 503) from Locus 96 in the settlement is spun left-handed and is judged to be of plant fibre on the basis of microscopy observations. The sample QUM524 from Tomb 1 consists of partially processed flax, also spun left-handed, the exact type of which has not been identified securely. Comparison of azimuthally integrated diffraction data of the ancient textile fibres with those of modern bast fibres indicate that there is scope for greater level of classification of fibre type based on precise determination of crystal lattice parameters rather than just morphological appearance under the microscope. In particular, the exact bast fibre type of QUM 512 remains rather unclear at present. Both SEM and diffraction data indicate a type different from that of “normal” flax.

Of the colorants and other crystalline particles attached to some of the fragments, only preliminary conclusions can be drawn. The heavily soiled samples QUM 505, 510 and 517 produce diffraction rings that correspond to quartz or calcite as well as another phase present in Dead Sea mud. These minerals are also found in the less soiled samples. In QUM 526, 527 and 530, coloured mostly red, and QUM 528, coloured green, the colorant would appear to be non-crystalline. Micro-techniques such as micro-Raman or micro-FTIR may reveal the nature of the dyes. The nature of the green particles attached to the fabric of sample QUM 524 has not as yet been identified securely.

It is clear, we hope, that the use of SR x-ray diffraction, has contributed information that can not be obtained from microscopy alone and has opened up new routes for further investigation. SR high resolution powder diffraction of the small crystallites attached to the fibres and detailed comparison with standards in mineralogical databases would help identify securely the diffraction phases.

Acknowledgements We wish to thank Dr John Peter Wild of the Archaeology Department, Manchester University, for advice and for samples of modern flax fibres. We are grateful to Dr Penelope Rogers of Textile Research in Archaeology, York, for the pre-examination of the textiles used in this work at very short notice and re-examination of the “problem” sample QUM 512, free of charge. The contribution of Dr Tim Wess of Sterling University and his students Graeme Cameron and Craig Laurie who collected preliminary diffraction data on single threads from some of the textiles on station 14.1 of the SRS is much appreciated. Finally, we wish to thank the staff of the Materials Science Lab and the management of SR Department, Daresbury Laboratory, for the provision of facilities and material encouragement of this project.

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METHOD OF IDENTIFICATION

Each specimen was examined at x10 magnification and a few fibres withdrawn. The fibres were mounted in water as whole-mount preparations, and viewed at x100 and x400 magnification, with a transmitted-light microscope fitted with a polarising analyser.

Cotton fibres were identified from the ribbon-like twisting of the fibre, the presence of rounded lacunae, and the fine spiral markings which became visible as the polariser was rotated.

Plant fibres were identified from their smooth profile, the fine central lumen, dislocations across the fibre and fine X and V markings. Flax, from *Linum usitatissimum* L., was identified by the ‘drying-twist test’, where wet fibres consistently rotated clockwise as they dried, and by other technical characteristics such as the shape of the cell ends and the character and density of the cross-markings. All samples of flax had been fully processed down to the finest possible filament, apart from the canvas-like fragment 524, where the fibres still lie in the fibre bundles in which they occur in the plant stem. It was not possible to see the internal structure of the carbonised sample, 503, as it was an opaque black, but the silhouette showed diagnostic features. Sample 502 has been described separately below.

Wool was identified by the presence of a cuticular scale pattern which was irregular mosaic, sometimes waved, with smooth near margins. Within the available time it was not possible to carry out a fleece-type analysis, but it was noted that coarse fibres and fibres with medullas (technically ‘hairs’) were rare. The fibres lacked pigmentation, indicating that they came from a white fleece (before dyeing). The animal tissue and fibre in sample 517 have been described separately below.

RESULTS

503: carbonised plant-stem fibre, probably flax
504: flax
505: flax
510: flax; plant seed present
511: flax
512: flax
513: cotton
518: flax [coarse white S-spun threads]
524: partially processed plant-stem fibre, flax or hemp (poorly preserved)
525: cotton; a single fine white animal fibre also in the sample
526: warp, red weft, black weft = wool; a single white feather fibre is also present
527: all yarns are wool
528: wool
530: red (Z) and light brown (S) both wool; light brown includes blue fibres

Sample 502

Sample 502 was labelled ‘unspun flax’. Microscopy revealed this to be the fibrous part of a plant stem or leaf, but the flax plant may be ruled out. The fibres rotate anticlockwise in the drying-twist test and individual cells are much shorter than in flax. In addition, there are chains of cluster crystals in chambered cells – features which have never been recorded in flax (Catling and Grayson (1982), p.16). The exact identity of this fibre is not known, although *Hibiscus cannabinus* L. (kenaf) and *H.sabdariffa* L. (roselle) are recorded as having similar characteristics (Catling and Grayson op.cit.). This would be best considered by a botanist.

Sample 517

This sample includes tufts of fur fibres with skin adhering at the base, and a fragment of fine bone or cartilage. This would appear to be the remains of a small mammal. There was not enough time available to investigate the species further.
COMMENT AND RECOMMENDATIONS

Flax and wool were widely available in the East Mediterranean world and are no surprise here. The cotton deserves further comment, however, as the early history of cotton in Israel is still unclear (Sheffer (1989)). The cotton plant was originally native to India, Abyssinia and Senegal, but there are sources which suggest that it was already being cultivated in Palestine by Talmudic times (Forbes (1964), ch. IV, p.49). Certainly, cotton bolls from plants growing in the ‘Holy Land’ were amongst the curios brought back to medieval Europe by Christian pilgrims. Cotton textiles were widely distributed in the Roman world, some being made in Roman Egypt, others more probably imported (Wild (1997), p.289). The only cotton textile so far identified at 1st-century Masada was thought, with good reason, to be a more recent, intrusive, textile (Sheffer and Granger-Taylor (1994), p.215); but there are a small number of more confidently dated examples from 1st-century Jerusalem, late Roman Nessana and ‘En Boqeq, and from the monastery of St John the Baptist near Jericho dated to AD c.800 (summarised in (Wild (1997), p.290).

The presence of cotton textiles is therefore of especial interest and the date and provenance of the collection of some importance. Further investigation of the fibres in these textiles should perhaps also include ‘fleece-type’ analysis of the wool specimens. This is a destructive technique, requiring one or two yarns (depending on thickness) from warp and weft. It would provide information on the quality of the fleeces from which the textiles were made. Further research of the cotton textiles should involve Dr J.P.Wild, who has a special interest in this subject.

SECTION 2: SAMPLE 512 FROM QUMRAN: FURTHER WORK

Sample 512 was identified as flax, from Linum usitatissimum L., in our report of 12 January 2001. Further work carried out at Daresbury suggested that this was not correct. The textile sample was therefore returned for re-examination.

RE-ANALYSIS

Three threads were removed from the weave, two from one system and one from the other, and separate sets of tests were carried out on each. All three proved to be the same. The results of these tests are summarised here.

Longitudinal mount, viewed by transmitted light at x400 magnification

These are long, fine fibres, with a smooth profile apart from occasional ‘dislocations’. The diameters range from 7 to 24 microns, but most are in the region of 11 microns. Cell ends are long and tapering. The fine lumina are clearly visible. There are occasional V and X cross-markings. No chambered cells or extraneous plant tissue is visible. Long diagonal cracks are visible and are assumed to indicate damage caused by preservation in an arid climate.

Cross-sections, viewed by transmitted light at x400 and incident light at x100 magnification

The fibres are polygonal with a fine central lumen. Each is separated from the next. The cracks visible in longitudinal view are also visible in cross-section.

Drying-twist test

All fibres consistently rotated clockwise.

Ashing

No crystals were visible in the ash.

IDENTIFICATION

These features are all consistent with the original identification as flax. Since three threads (four, counting the first sample) have now been separately analysed, and all have proved to be the same, it is unlikely that there is any variation within the textile sample.

COMMENT ON THE DARESBURY WORK

The fibres in the Scanning Electron Micrographs taken at Daresbury for Qumran #512 are quite different from those described here. They have a flattened appearance and, if the scale is accurate, they are in the region of 25-30 microns wide. The diagonal cracks visible in the textile sample cannot be seen in the micrographs. This suggests that there has been some confusion in the numbering of the samples or the images.

BIBLIOGRAPHY

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SHEFFER A., “Notes on cotton textiles found in Israel”, Archaeological Textiles Newsletter 9, p. 3 1989