PAVER LAYING COURSE MATERIALS : STATE OF THE ART

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Introduction

During the last 20 years, specifications for bedding sands (or laying course materials) have evolved world-wide. In the main, the specifications have been developed by parties with a background of concrete technology. As a consequence, these specifications adopt historic concrete manufacture specification criteria. In most instances, they have served the concrete block paving industry well, but in some heavily trafficked categories of highway pavements, failures have occurred even when national bedding sand specifications have been adhered to. Following several such failures in the US and the UK, the Author has investigated the nature of those sands which failed and has developed an alternative specification method which takes into account the geological origin and the microscopic structure of the smaller particles of the sand. This paper presents the outcome of the investigation and develops a bedding material classification system which has been used successfully in the most heavily trafficked highway pavements

The Nature of Sand

Sandy or arenaceous material occurs commonly in many parts of the world as either loose deposits or in cemented form as sedimentary rock. Silicates are the predominant minerals in both loose and cemented sands and many sands consist virtually entirely of them. Silicate sands are so common because silicates are the dominant minerals comprising the earth's crust. Feldspar is the most common silicate mineral on earth but it is less stable chemically than the other common silicate, quartz (silicon dioxide, $Si0_2$) so that by the time sand grains have been formed, quartz is the most common constituent mineral and the Feldspar has generally weathered to the clay mineral kaolinite.

Prior to forming sand, silicate minerals existed in the form of igneous or sedimentary rocks. Weathering and mechanical action dislodged crystals from these rocks and subsequent transport by wind or water created the deposits of sand and sandstone which are used commercially as laying course materials. In some beds, the sand is mixed with large pebbles to form sandy gravels, usually when a fast flowing river had sufficient energy to transport the larger pebbles. Rounded sand and gravel particles were originally angular and were rounded during transport.

Quartz is a very durable mineral and each grain may have a complex history of weathering, transport, deposition, further weathering and so on. Because of this, the shape of the sand grains can vary from being almost spherical to being angular. Quartz grains derived from granite are usually more angular than those derived from other minerals such as softer feldspars. In relation to laying course sands, the degree of angularity can be used as a basis for assessing grain hardness.

Many of today's loose sands, but not all, have previously existed in a lithified (cemented) state as sandstone. Some bedding course materials are manufactured by

crushing sandstone. Sandstone is formed by the compaction of deposited loose sand particles by overburden loading. When deposited, well graded sand particles are usually open textured, having up to 50% voids. Relatively low overburden loading reduces the voids to 25% as the grains reorientate and pack together. Often, fine material is deposited into these voids so that the void level reduces to 15%.

A common occurrence is for hydrostatic pore pressure to develop in these partly compacted deposits within the upper few metres of the deposit. If this pore pressure exceeds the overburden pressure, the sand becomes unstable and liquefies. The sand then flows and the grains reorientate themselves to form a solid mass with no voids. Subsequent cementing of the grains by the trace elements suspended in water then forms the sedimentary rock sandstone. When sandstone is subsequently crushed to be used as bedding material, there can be no guarantee that it will revert to the original grains from which it was formed. For this reason, crushed sandstone should be used only with care as a laying course material.

Loose sands, which usually comprise almost totally quartz are classified according to particle size distribution and angularity. Because of this, it is relatively easy to specify them for the laying course. Experience indicates that all such sands of appropriate grading are suitable for use as laying course material. Sandstones are more complex and may contain as little as 60% quartz. There are four common categories of sandstone in the UK and they are classified according to their chemical constituents as below.

Chemical Symbol	Mineral	% present in each type of sand			
		1	2	3	4
SiO_2	Quartz	96	66	75	63
Al_2O_3	Bauxite	1	8	10	14
Fe_2O_3	Hematite	0.3	4	2	1.5
FeO	Iron Oxide	0.2	1.4	0.8	5

1. Quartz arenites
2. Lithic arenites
3. Arkosic sandstones
4. Greywacke sandstones

1. Quartz arenites have a quartz context greater than 95% and contain very little fine grained matrix material. Typical UK examples comprise Hartshill Quartzite (central England), Holyhead Quartzite (North Wales), Eriboll Quartzite (North West Scotland), Penrith sandstone (North West England) and Ganister (Northern England). When fully crushed, these materials are suitable as laying course material. All of the beds have been recycled geologically, probably several times such that the softer materials have been lost.
2. Lithic arenites contain up to 75% quartz and have a clay matrix which may comprise 10% of the rock. Pennant sandstone is a typical example. They should be avoided as laying course materials.
3. Arkosic sandstones contain up to 80% quartz and may have up to 15% fine matrix material. Torridonian Arkose in north-west Scotland is an example. They should be avoided as laying course materials.
4. Greywacke sandstones are various shades of grey and comprise rock particles set

in a finer matrix. Examples include Feldspathic greywacke in North Wales and Silurian greywacke in southern Scotland. They should be avoided as laying course materials.

The scanning electron microscope (SEM) at the University of Newcastle upon Tyne has been used to examine various laying course materials. In particular, the character of the grains has been examined as follows. Two samples of sand, one known to perform well under heavy traffic and one recovered from a failed road trafficked principally by buses were photographed at various levels of magnification.

The SEM work on several sands has confirmed the importance of the shape and surface texture of the grains within a sample of sand. The SEM investigation is described in the Appendix. Essentially, those sands which exhibit premature degradation when used as bedding material can be seen to comprise many sub-crystals whereas stable bedding sands comprise independent crystals.

Another important factor in the nature of sands is the grading. For 20 years, UK practice has been to specify a good concreting sand i.e. a "sharp" well graded material. In this context, "sharp" usually refers both to the angularity and to the maximum size of the sand grains. Generally, this has been a sufficient specification. Only in conditions of heavy rain and channelised heavy traffic have some sands defined in this way failed. Because the term "well graded" feels correct intuitively, it had not been questioned prior to the investigation reported in this paper.

A statement in a standard geology text, first published in 1913 gives reason to question the assumption that "sharp" is necessarily a helpful adjective to use in specifying bedding sands. In "Petrology of the Sedimentary Rocks", J.T. Greensmith states :

> `In the top few metres of newly deposited, highly porous and well-stored sands, the pore pressure may build up to exceed the loading pressures until a point is reached when any type of small vibration triggers off mass movement. The sand then flows or liquefies'.

Greensmith is referring to the time when the sand was deposited naturally. However, the conditions which he describes are so close to those prevailing in laying course materials that the effect of "well-sorted" or well graded sands needs to be investigated. Should we be permitting sands which include fine material ?

Another reason for questioning the acceptance of fine material is the fact that water flowing through sand is capable of transporting sand grains. Siever, in his book "Sand" (Scientific American Library) shows that water velocity and particle size diameter which can be transported are related by the equation :

$$U = kd^2$$

where U = velocity of water (mm/sec)
k = constant
d = maximum grain diameter which can be transported

For smooth round grains, Siever gives a value of 8900 for k. This means that 75 micron diameter smooth round grains will begin to move when water travelling through laying course material attains a speed of 50 mm/sec and 25 micron smooth round diameter grains will move at 6mm/sec flow rate. From this, it can be concluded that the fine fractions within normally specified sand can be transported by water flowing through laying course materials at velocities which are easily attainable in practical situations.

Sand failure case history

The relevance of Greensmith and Sievers work to laying course materials can be understood by reference to a pavement failure in Seattle, Washington. Pine Street, Seattle was surfaced with rectangular granite pavers bedded in a crushed granite laying course material which contained 13% material passing a No. 200 (75 micron) sieve. The road was opened to traffic on 13 October 1988 and showed evidence of rutting during that day, which was characterised by continuous heavy rain. The laying course material had been installed over a 12 inch thick concrete roadbase and holes had been drilled through the concrete to encourage drainage of the bedding sand. During the first few days of operation, water travelling through the laying course material transported the fine fractions of the sand onto the surface of the underlying concrete slab and into the drain holes. The remaining larger sand grains became lubricated by the slurry formed by the suspension of the fine grains in water. As a result, the sand became unstable and in a matter of days, all of the sand in the vehicle wheel paths had been lost; the fine material having been taken away in suspension and the remaining laying course material having been pumped out of the paver joints onto the road surface.

During the summer of 1989, the road was reconstructed using an almost single sized quartz sand with no material smaller than 75 microns and with most particles within the range 500 microns to 3mm. The grains were cuboid and were very hard. The precompaction technique was used to install the sand and the finished pavement was treated with a polymer joint sealant in order to reduce the amount of water entering the laying course material. The repaired street has been in service for 4 years during which it is estimated that approximately 2,500,000 equivalent standard 8000kg axles have trafficked individual points in the pavement. There has been no movement in the road surface, even at the interface between pavers and adjoining concrete paving.

In the repair, the two agents leading to instability were eliminated - water and fine material. It is anticipated that the surface will remain in service with zero or minor intervention or 25 years, or 15,000,000 standard axles. It is interesting to note that both the original laying course material and the repair material were virtually identical mineralogically. The difference between the two materials was firstly in the grading and secondly in the angularity and surface texture of the sand grains. The material which failed had freshly formed angular round grains and the sand which remained stable had geologically abraded cubical grains.

World-wide Laying Course Sand Specification

In 1980, Shackel[3] gave the following minimum requirements for laying course sand. He stated that it should be non-plastic and that it should have the following grading limits.

Sieve Size (mm)	% Passing
4.75	95-100
2.36	80-100
1.18	50-95
600 micron	25-60

300 micron	10-30
150 micron	5-15
75 micron	0-10

The first authoritative UK laying course material specification was published in 1983 by the Cement and Concrete Association, the County Surveyors' Society and Interpave[4]. Clause 4.4.2 stated :

> 4.4.2 Laying course material
> Laying course material should be a naturally occurring sand or crushed rock fines which may be washed or unwashed. This granular material should be such that 90% passes the 5mm BS sieve. It should contain no more than 3% by weight of clay and silt and the materials should be free from deleterious salts or contaminants. The grading of economically available material may vary from locality to locality but the following grading has been found to give satisfactory results:

BS Sieve Size (mm)	% Passing
5	90-100
2.36	75-100
1.18	55-90
600 micron	35-59
300 micron	8-30
150 micron	0-10
75 micron (implied)	0-3

In some locations where a degree of rigidity is considered essential in the pavement surface, e.g. adjacent to drainage furniture, the incorporation of 5-6% by weight of OPC may be an advantage. In 1984, Garnett and Walsh[5] presented the laying course sand grading used by Kent County Council in their trials :

BS Sieve Size (mm)	% Passing
5	95-100
2.36	95-100
1.18	90-100
600 micron	80-100
300 micron	15-50
150 micron	0-15

In general, most sand specifications world-wide followed either Shackel's recommendation or the C & CA / CSS / Interpave specification. For example, the New Zealand concrete Masonry Association used Shackel's grading limits in their 1988 design guide[6] whereas the Australian Brick Development Research Institute Design Manual[7] adopted the UK values. BS6717 : Part 3 dealt with laying course sand in a similar manner to the C & CA / CSS / Interpave document except for the grading limits at the 600 micron and 300 micron sieve sizes where the limits were changed from 35-59 to 35-70 and 8-30 to 8-35 respectively.

The Blockley's Bedding Sand Guide[9] dealt with grading and geological origin. This guide states that laying course material should be naturally occurring alluvial silica sands from quaternary (i.e. geologically recent) beds. Four categories of sand are defined according to the pavement end use, viz :

Category 1	Severely channelised traffic
	Industrial pavements
	Bus stations
	Loading bays
Category 2	Adopted highways
	Petrol station forecourts
	Regular heavy traffic
	Aircraft pavements
Category 3	Occasional heavy traffic
	Car parks
	Driveways
	Overridden footpaths
Category 4	Footways

The grading limits for each of these four categories are as follows.

Category	% of sand passing 75 micron sieve	% of sand passing 600 micron sieve
1	Less than 0.1%	Less than 60%
2	0.1% to 1.0%	Less than 60%
3	1.0% to 3.0%	Less than 70%
4	3.0% and above	Less than 70%

Compared with previous specifications, this document placed greater emphasis on the nature of the sand particles and reduced the amount of material passing the 75 micron sieve for heavily trafficked pavements.

From the foregoing, it can be concluded that during the last 13 years, there has been a growing awareness of the importance of laying course sand. This is manifest in the reduction in material passing a 75 micron sieve. In 1980, it was reported that 10% of the sand could be finer than 75 micron whereas by 1991, this value had been reduced to 3% in the British Standard and to 1% for heavily trafficked pavements, reducing to 0.1% for bus stations and similar in the Blockleys Sand Guide. It is also reflected in the narrowing of the type of material permitted as laying course material. Only naturally occurring sands are now used commonly in the UK and even these are further confined to quaternary bed sands in one publication.

Other efforts to provide design guidance on laying course sands include work reported by Lilley an Dowson in 1988[10]. They described the phenomenon of "Elephant Footprints" as comprising elliptical shaped depressions in the surface of concrete block paving with a major axis in the direction of trafficking occurring in bus stations between 1 and 3 years after construction. These depressions were typically less than half a metre wide, up to one metre long and up to 50mm deep, i.e. the full

depth of the laying course material. The authors had developed the following hypothesis :

> "Sand grains of the laying course were breaking down (degrading) under a large number of repeated stresses, caused by the double-deck buses using the site. Degradation was such that a high percentage of the sand grains became as fine as silt which was then squeezed through the joints, in the form of a paste".

The hypothesis received support from an investigation which showed that sand recovered from elephant footprints was much finer than specified and contained a very high proportion of material finer than 75 micron. It is interesting to note that the sands developing depressions were naturally occurring Triassic materials, i.e. they would not be permissible, according to the Blockleys Sand Guide geological criteria. Lilley and Dowson sought to develop a test which would establish the suitability of a laying course material. They were of the opinion that grading and particle shape are of second order importance and the prime concern was to avoid the use of materials which could break down to sizes small enough to be able to be forced, under pressure, through joints between blocks or into the interstices of any underlying layer. A site investigation reinforced this view and led the authors to propose an abrasion test which simulated the degradation of sand and to place limits on the additional fine material which the test generated. They recommended that any pavement designed to carry more than 1.5 million equivalent 8000 kg standard axles should be subjected to the following grading and degradation limits:

Sieve size	Initial grading limits % passing	Grading limits after abrasion testing %
300 micron	8 - 35	8 - 50
150 micron	0 - 10	0 - 15
75 micron	0 - 3	0 - 5

The test machine comprised a ball-mill in which 200g of a sample of sand and two 25mm diameter steel ball bearing were rotated in a litre capacity porcelain jar at a speed of 50 rpm for six hours. For each test, the operation took place on 3 samples and precautions were taken to ensure that each sample was fully representative of the material being assessed.

Since 1988, this test has been in use and it is generally considered to eliminate poor sands. Recent experience of the use of the ball mill indicates that it is suitable as a basis for the elimination of those sands which initially have a low percentage of material passing a 75 micron sieve but which subsequently degrade to develop an unacceptably high proportion of such material. For this reason, it is considered to be a valuable tool in the avoidance of inappropriate bedding materials.

There is a question mark concerning the reproducibility of the results from the test and at least one authority has increased the speed of rotation of the ball mill in order to achieve a result sooner than 6 hr. It is recommended that the test regime should be exactly as Lilley & Dowson described[10] in order to allow their proposed limits to be applied generally.

From the foregoing, it is clear that the issue of laying course stability in areas of

severely channelised traffic, almost exclusively in bus stations, has become important within the last ten years and the traditional specification methods, which were based upon particle size grading are inadequate to deal with some paving situations.

Drainage of the Laying Course

Wherever difficulties have been experienced with laying course materials in heavily trafficked pavements, water has been a major factor. Whilst a little moisture enhances the stability of most laying course materials, experience indicates that many sands lose stability when a specific moisture content is attained. There is some discussion as to whether, and by how much, water penetrates the joints of concrete block paving.

Clark[11] undertook trials in which water was sprinkled onto untrafficked concrete block paving and in which surface runoff was weighed and expressed as a percentage of water applied (runoff coefficient). He described the application of between 20mm/hr and 55mm/hr and showed that pavements of slope 1% and 2.5% had runoff coefficients of between 70% and 90% in all cases. Further work by Smith[12] in which trafficked pavements of slopes 0.7% to 1.3% were subjected to simulated rainfall of intensities between 2mm/hr and 30mm/hr showed that as the intensity of rainfall diminishes, the runoff coefficient also diminishes. When rainfall is 5mm/hr or less, the runoff coefficient is around 50% or less so that several millimetres per hour of rain penetrate the pavement.

During his tests, Smith[12] observed that :

"Concrete block paving placed on a sand and gravel base, trafficked by automobiles, does not always have the joints fill over time with detritus (generating a high runoff coefficient). The sealing action of sediment and detritus in the joints may be negated or even reversed by sucking and pumping action of automobile tires on the concrete block paving."

From Clark and Smith's work, it is concluded that the concrete block pavement designer should anticipate the percolation of sufficient rainfall through the joints of pavers to reach a condition where the laying course material is affected adversely by moisture. It may be that trafficking will impede the ingress of moisture but there is insufficient data available to rely upon the "detritus sealing" hypothesis with any degree of confidence. As an example of the danger inherent in relying upon detritus sealing, consider Smith's conclusion in relation to a bus road. It is possible that the traffic may actually remove detritus, rather than deposit it. Therefore, there will always remain a possibility that such pavements may become well sealed between the wheel tracks and permeable in the wheel tracks which will have the effect of amplifying the volume of water entering the laying course in the wheel tracks.

Behaviour of inundated laying course material

In the extreme, liquefaction, as described in the previous section may occur and this has led to the collapse of a laying course in Seattle, and probably at several UK sites. The conditions which support liquefaction include vibration and hydrostatic

pressure. The replacement of a sand which did not permit water to flow with a single sized sand removed the opportunity for hydrostatic pressure to develop in Seattle and hence the pavement has remained stable for several years.

Of more relevance than the rare Seattle scenario are several other mechanisms which have led to unsatisfactory, although not necessarily sand collapse conditions. These mechanisms are :

(a) formation of slurry
(b) transportation of fine material
(c) loss of fine particles into underlying material
(d) entire pavement too flexible.

On several projects, a creamy slurry has been observed to spurt out of the paver joints close to a moving wheel load. A Scanning Electron Microscope examination of solids recovered from such a slurry at Wolverhampton Bus Station indicated that particles of size 1 micron to 10 micron, which have broken away from non-polished larger sand grains comprise the solid part of the slurry. When this type of material is formed in a heavily trafficked pavement, it forms a lubricant which leads to reduction in the strength of the remaining laying course material.

The transportation of fine material within the laying course has been observed on several projects. This has two adverse effects. Firstly, it forms voids in the laying course material such that subsequent rolling loads recompact the laying course, forming depressions or ruts. Usually this mechanism manifests itself as a collection of slight ruts and depressions in the paver surface.

The loss of fine particles into underlying material has occurred on several UK bus stations. Such projects usually have a lean concrete roadbase. Fine particles have been observed to wash into cracks and construction joints and to gradually prise the fissure into an ever widening gap. This has led to significant levels of local sand loss, i.e. "elephants footprints". Once a shallow footprint has been initiated, water stands in it and gradually percolates through the laying course material so that all of the sand in a specific location can be lost. A similar occurrence has been observed adjacent to inspection covers and gully gratings when fine material has entered the pipe network through a gap between the cover and its surrounding frame.

A pavement which is too flexible can lead to sand failure : indeed the symptoms associated with too much flexibility can be very similar to those associated with sand loss e.g. "unzipping" of the pavers. When a pavement deflects by 1mm or more, it has been found that the laying course material does not develop full strength and allows the pavers to move both horizontally and vertically.

The following factors have been found to ameliorate or eliminate all of the above mechanisms.

(1) use a single sized (or nearly so) laying course material
(2) use naturally occurring sands where each individual particle has been polished by the action of water or wind in geological time
(3) avoid surface drainage systems which concentrate runoff from large areas into small areas of paving

It is concluded that inundated (not necessarily saturated) sand is known to exhibit many characteristics which can affect the performance of concrete block paving adversely. The mechanics of inundated sand are complex and depend upon

several load related and material related properties.

A clear conclusion from considering the behaviour of inundated laying course material is that the fine particles, whether they be present in the original material or whether they were developed by the internal action of grain upon grain, should be eliminated or reduced to a controlled level. It is also clear that manufactured sands are far more likely to be affected by water than are naturally occurring materials with grain surfaces polished by geological weathering.

Pavement Design Factors Influencing Moisture in Laying Course

The following factors are frequently addressed :

(1) surface falls
(2) long and steep slopes
(3) paver joint sealing

For over 15 years, cross-falls of 1:40 and longitudinal falls of 1:80 have been specified commonly. Experience has indicated that such falls usually drain the surface adequately and provide a comfortable surface. Where falls of these values cannot be formed, lesser values have been used and a degree of surface ponding has been observed. It is considered that the above values have been operating satisfactorily and there is no reason to re-address this issue.

Long and steep slopes have been dealt with either by the provision of intermediate restraints at regular intervals, so dividing a long slope into a sequence of shorter ones or by ensuring that a pressure head of water cannot develop at the foot of the slope. It has been common to observe water draining out of the laying course and re-wetting the paver surface at the lower ends of slopes. A pressure head can be eliminated by creating positive drainage at the foot of a slope and intermittently along the slope, e.g. every 20m length of slope, depending upon steepness. However, there is little evidence to suggest that laying course material performs poorly on slopes. At the channel Tunnel Folkestone Terminal, ramps of length 40m and slope 1:12 have been paved.

Paver joint sealing has been specified regularly during the last few years, largely for one or more of the following reasons :

(1) to prevent jointing sand erosion by aircraft
(2) to prevent jointing sand being removed by vacuum road sweepers (town centre pedestrianisation)
(3) to avoid fuel contaminating underlying materials (petrol stations)
(4) to reduce moisture content of laying course material (bus stations and streets)

Whilst experience and laboratory evidence supports each of the above items, the additional cost of joint sealing is such that the operation should be undertaken only when there is a specific reason to do so. So far, two types of sealer have been used : a short term water based material and a long term polymer based material. By reducing the water content of the laying course, the potential for the sand to collapse is reduced. It is estimated that 10% of UK paving projects are sealed.

Assessment of Structural Integrity of Pavement

It has been found that the appearance of the surface of an area in which the sand has become unstable is very similar to the appearance when the whole structure of the road has failed. Indeed, there have been instances when a structural failure has been blamed on the sand. The replacement of the sand has then failed to resolve the difficulty. In order to determine whether an unacceptable pavement surface is a result of sand instability or inadequate pavement structure, it is recommended that a deflexion beam or Benkelman Beam survey be undertaken. The deflexion beam comprises a 12ft. long beam with a pivot 4ft from one end such that the longer end touches the pavement surface at the position being monitored. A gauge at the shorter end of the beam with its measurement point resting on a fixed point records a change in level of the other end of the beam. The monitoring end of the beam is positioned between the rear dual wheels of a vehicle having an axle load of 8000kg. The beam is aligned with the longitudinal axis of the vehicle. The vehicle is then moved slowly away from the measurement point and the pavement rises. Usually the vehicle needs to be moved by 3m before no further pavement recovery is measured. The dial gauge is read before and after movement of the vehicle and the following table can be used to interpret the measured vertical deflexion. Deflexions are conventionally measured in hundredths of a millimetre.

Pavement Deflexion (0.01mm)	Pavement Condition
0 - 15	Pavement in good condition
15 - 40	Pavement may be causing some loss of surface integrity
40 - 80	Pavement is too flexible for highway usage. Failure is occurring or imminent.
80+	Pavement has failed and should be rebuilt from subgrade upwards. Subgrade may need attention.

Usually, it will be necessary to undertake five measurements at any one location and skill is needed in reversing the vehicle to the exact locus each time. A group of five readings should be taken for every $500m^2$ of pavement being tested. Additionally, a set of readings should be taken either at or alternatively very close to any specific defect, e.g. "elephants footprint".

Conclusions

1 The occurrence of laying course instability is predominantly a UK bus station or bus road phenomenon but has also occurred on US bus roads. It has occurred on a relatively small proportion of paving projects and even in the case of UK bus stations, the great majority are performing well.

2. The following factors have always been present in failures :
   (a) crushed rock fine material containing 3% or more of fine material at the time of failure;
   (b) severely channelised traffic, usually buses
   (c) inundated laying course material

3. The following factors have not led to sand instability.
   (a) very heavy industrial vehicles
   (b) any particular paver shape, size or material
   (c) poorly graded materials above 150 micron sieve size
   (d) high speed (> 30 mph) traffic

4. In the case of relatively few types of paving, probably representing less than 1% of all pavers laid, present BS specification clauses are inadequate and the use of grading as the primary specification criterion needs to be re-addressed.

5. The ball-mill test developed by Lilley and Dowson is relevant in the case of pavements trafficked by conventional highway traffic and pavement trafficked by severely channelised traffic, principally bus stations. The following table is recommended for severely channelised heavily trafficked areas such as bus stations.

Sieve Size	Initial % Passing	% Passing after ball-mill testing
600 micron	Less than 60%	Less than 70%
300 micron	8 - 35%	8 - 50%
150 micron	Less than 10%	Less than 15%
75 micron	Less than 0.1%	Less than 1%

The following table originally proposed by Lilley & Dowson is recommended for adopted highways and other heavily trafficked areas where channelisation is no more severe than would be expected on a public highway.

Sieve Size	Initial % Passing	% Passing after abrasion testing
600 micron	Less than 60%	Less than 75%
300 micron	8 - 35%	8 - 55%
150 micron	Less than 10%	Less than 20%
75 micron	Less than 3%	Less than 5%

For all other categories of trafficked paving the provisions of BS 6717 : Part 3 are adequate and the ball mill test need not be undertaken.

6. In heavily channelised areas such as bus stations, the material used as laying course material should comprise quartz arenite and may be investigated with a Scanning Electron Microscope to ensure that the particles are similar in character to those shown in micrographs B and D. These micrographs show particles which have no fissures and which have the type of surface which will show very little abrasion. In contrast micrographs A and C illustrate the type of particles which should be avoided. They represent the type of particles which have resulted from recent crushing of cemented rock (including sandstone) and which are likely to become unstable, so forming slurry as shown by micrographs E.

7. In the case of heavily trafficked but not severely channelised traffic, the laying course material should comprise either material as described above or alternatively non-crushed quaternary beds alluvium deposits complying with the pre-abrasion and post-abrasion grading limits in 5 above.

8. For other purposes, laying course material complying with the requirements of BS 6717 : Part 3 is satisfactory. This permits the use of all naturally occurring well-graded sands with no more than 3% by weight passing the 75 micron sieve. There is no need to carry out the ball-mill test for such applications.

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APPENDIX

Investigation of laying course material using the Scanning Electron Microscope (SEM)

The Hitachi S-2400 Scanning Electron Microscope at the University of Newcastle upon Tyne has been used to examine three samples of laying course material, one which failed, one which performed well and third which was the fine residue recovered from the surface of a failed pavement. The purpose of the examination was to determine the structural difference between grains of sand in successful laying course materials and grains of sand in failed laying courses. The samples were as follows :

A. Crushed granite laying course material recovered from a failed pavement in Seattle, Washington.

The laying course developed pumping and instability within hours of opening to traffic on a rainy day. The material as laid had 13% material passing a 75 micron sieve and tests after failure indicated that it had between 14% and 15% of that material. A typical angular grain of characteristic size 3mm was selected for examination and micrographs are reproduced as follows :

Seattle Crushed Granite - 3mm grain

Magnification	Micrograph Reference
x 20	A1
x 2000	A5

Loose material had broken away from the original grains and this represented the additional fine material found after the failure. This fine material had formed a lubricating slurry and the whole laying course had collapsed.

B. Naturally occurring quartzite sand used as the repair to the Seattle failure.

This material had virtually no grains passing the 75 micron sieve and has been in service for over 4 years on a very heavily trafficked granite block street during many spells of continuous rain (45 inches per year). The road shows no rutting whatsoever,

even at the trafficked interface between the pavers and the surrounding concrete. The road is trafficked by a succession of three axle articulated buses with a central axle load of 13,000 kg i.e. 2000 kg more than is common in Europe.

A typical 2mm diameter almost spherical grain was selected for examination and micrographs are reproduced as follows :

Seattle quartzite sand - 2mm grain

Magnification	Micrograph reference
x 20	B15
x 2000	B19

In contrast to the crushed granite micrographs, this grain can be seen to have a smooth surface with relatively few surface particle of diameter one micron adhering to the surface. In this sand, the small particles represent a virtually unmeasurably small percentage of the weight of the 2mm grain.

C. Solids recovered from slurry pumped to surface during laying course failure at Wolverhampton Bus Station.
These samples were taken during February 1992 from a severely channelised bus route within the bus station. The laying course material had become unstable and the slurry was produced by the suspension of fine particles of laying course material. The laying course material comprised Triassic sandstone from the Birmingham area crushed to achieve the required grading. The following micrographs are reproduced.

Triassic crushed sandstone slurry particle from Birmingham

Magnification	Micrograph reference
x 20	E38
x 5000	E42

These two micrographs illustrate the nature of the solids pumped as a slurry to the surface of a pavement in a bus station in the rutted vehicle wheel tracks. By comparing them with the Seattle micrographs, it can be seen that the pumped material comprises the fine particles previously existing as a conglomerate in larger weakly cemented grains.

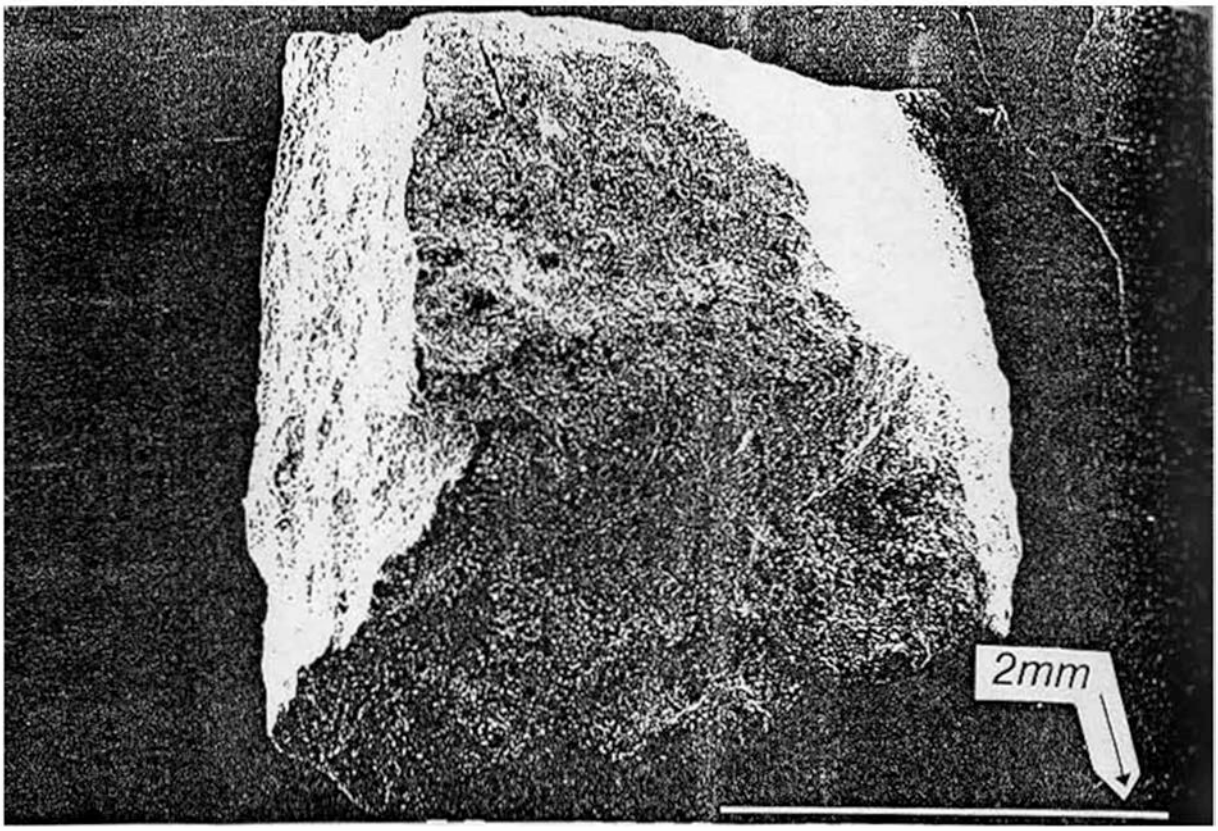
Summary of SEM examination

The information presented in this Appendix comprises part of a comprehensive SEM investigation into sands and crushed rock particles. All of the samples investigated showed a structure similar to one of the two presented. The SEM examination shows that there is a clear distinction between the structure of the grains of crushed rock fines and naturally occurring sand. It shows that crushed materials have a complex sub-particulate structure with a predominance of particles in the range one to ten microns. The solids recovered from slurry pumped from laying course materials suggests that particles abraded from weakly cemented multiple particle grains are responsible for the formation of slurry. From this, it can be concluded that laying course material instability in pavements trafficked by channelised traffic is caused by

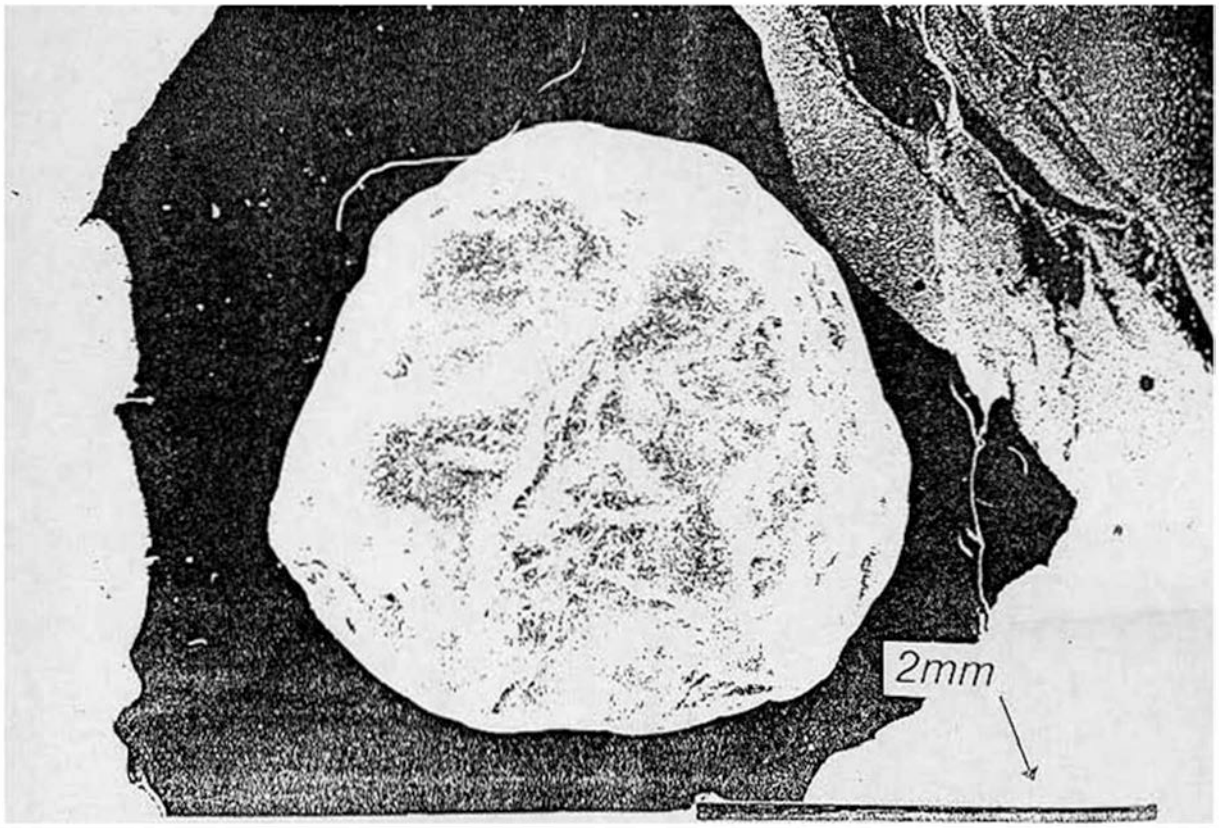
particles in the size range one micron to 10 micron forming a slurry. It is further concluded that the failure mechanism cannot occur if naturally occurring quartzite laying course material is used.

Costs of undertaking Scanning Electron Microscope Examination

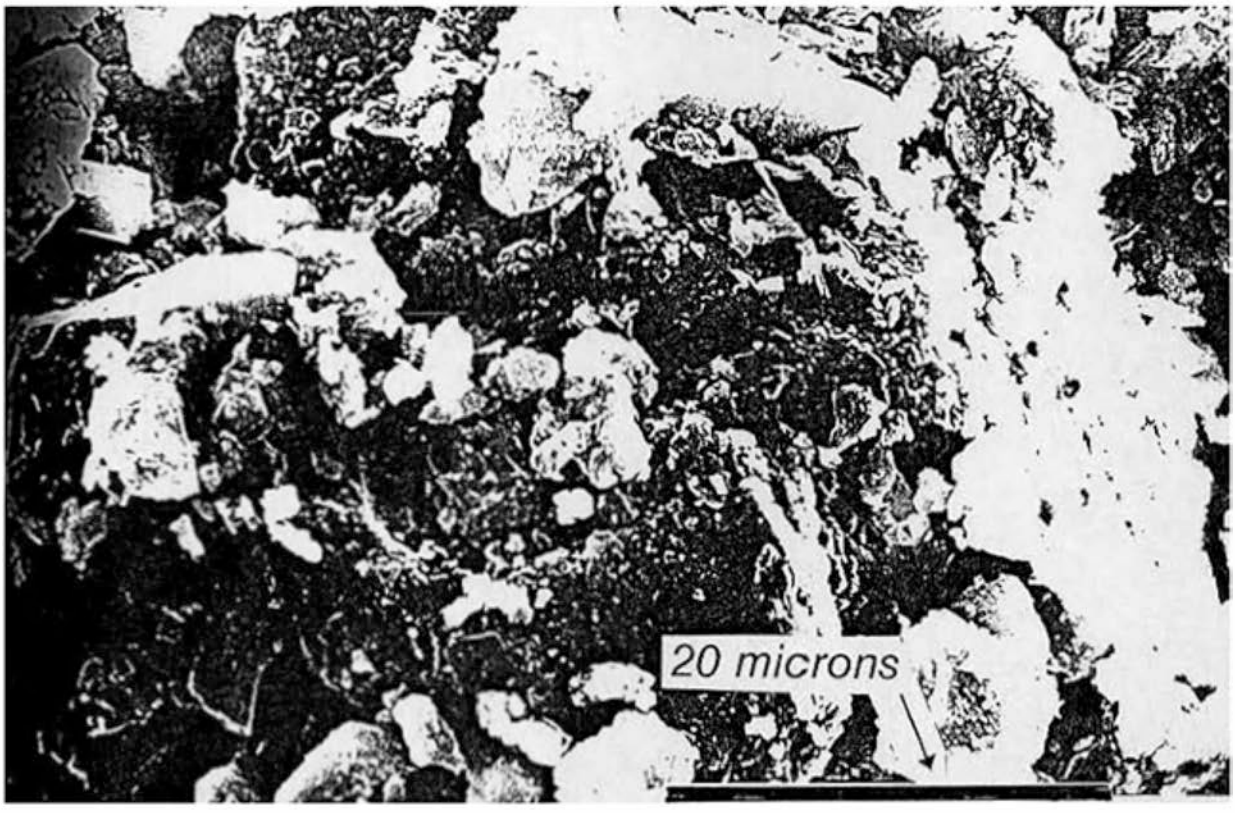
The use of the SEM in the examination of sands is of the same order of magnitude as more traditional testing. For example, the cost of a typical examination at the University of Newcastle upon Tyne is approximately £90 per sample in 1994. For this, a series of micrographs is produced at magnification of between X20 and X20000. Greater magnification is possible but this is of no benefit. In view of this, there is no reason to reject the SEM as a sand identification procedure on cost grounds.



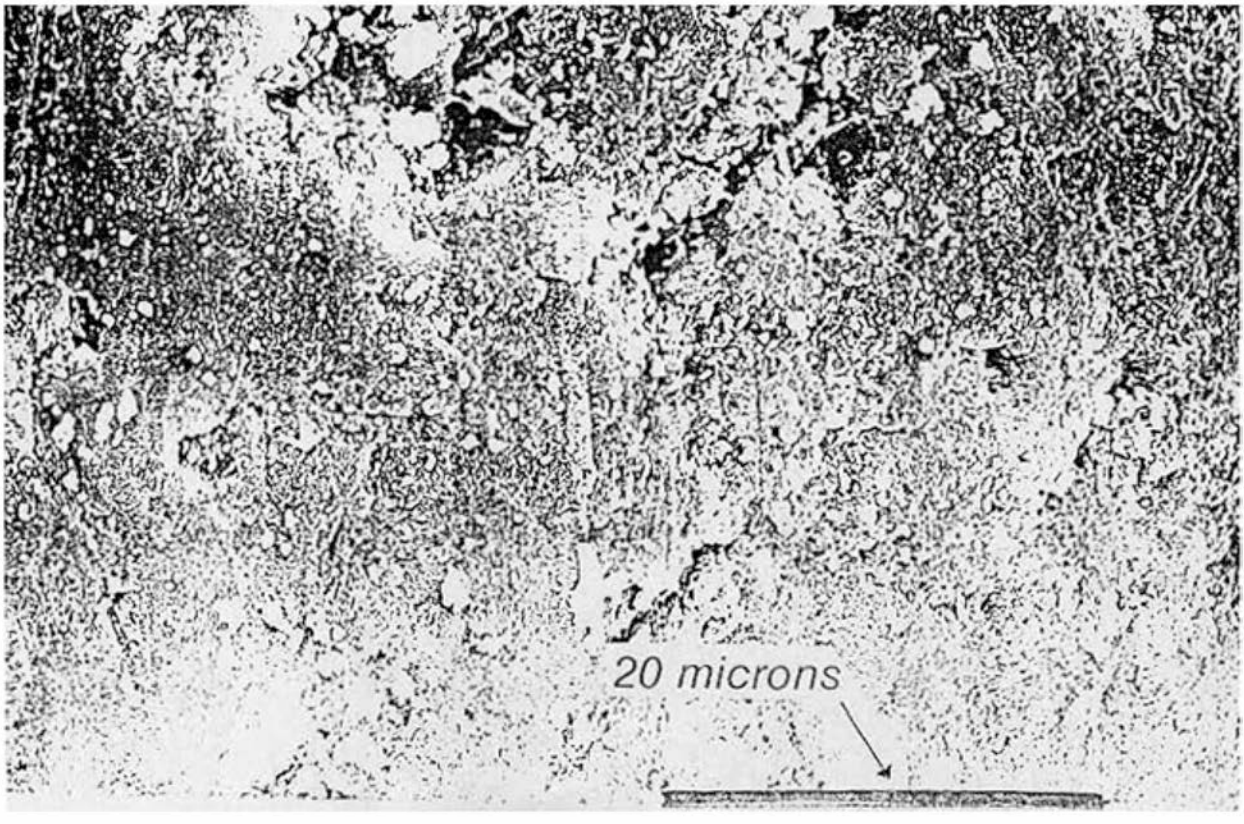
Typical 3mm sand grain recovered from failed Seattle pavement



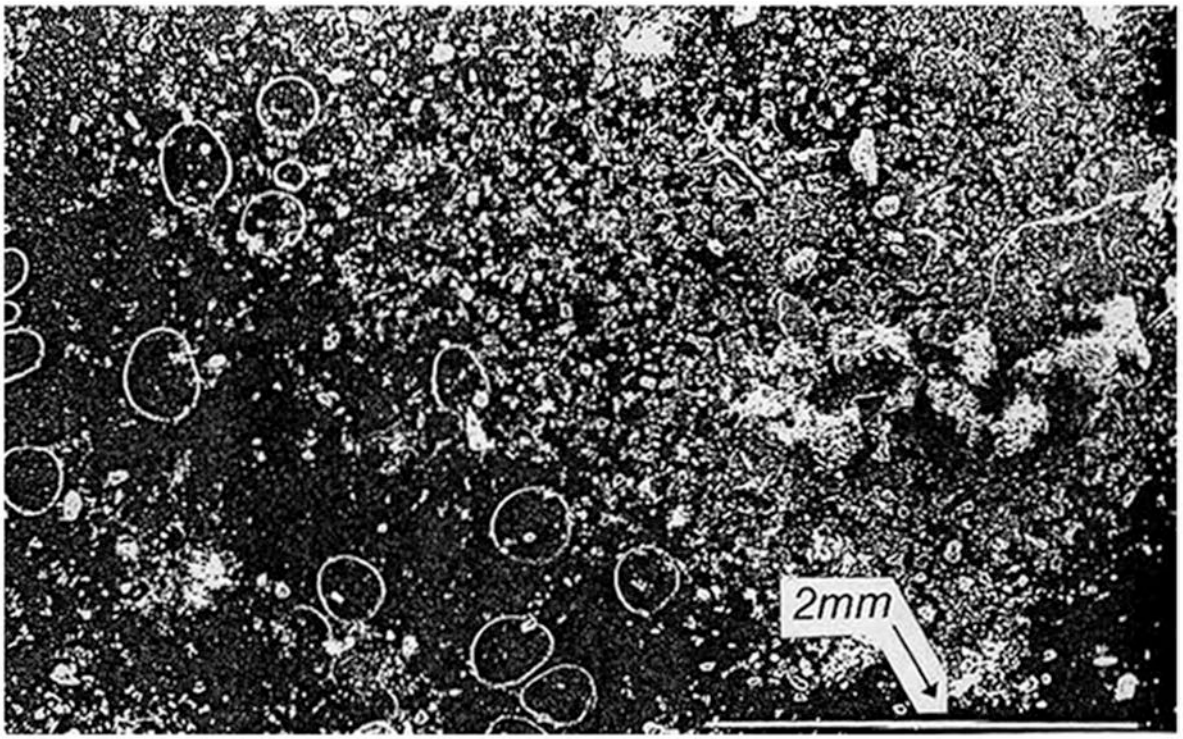
Typical 3mm sand grain used successfully in Seattle repair



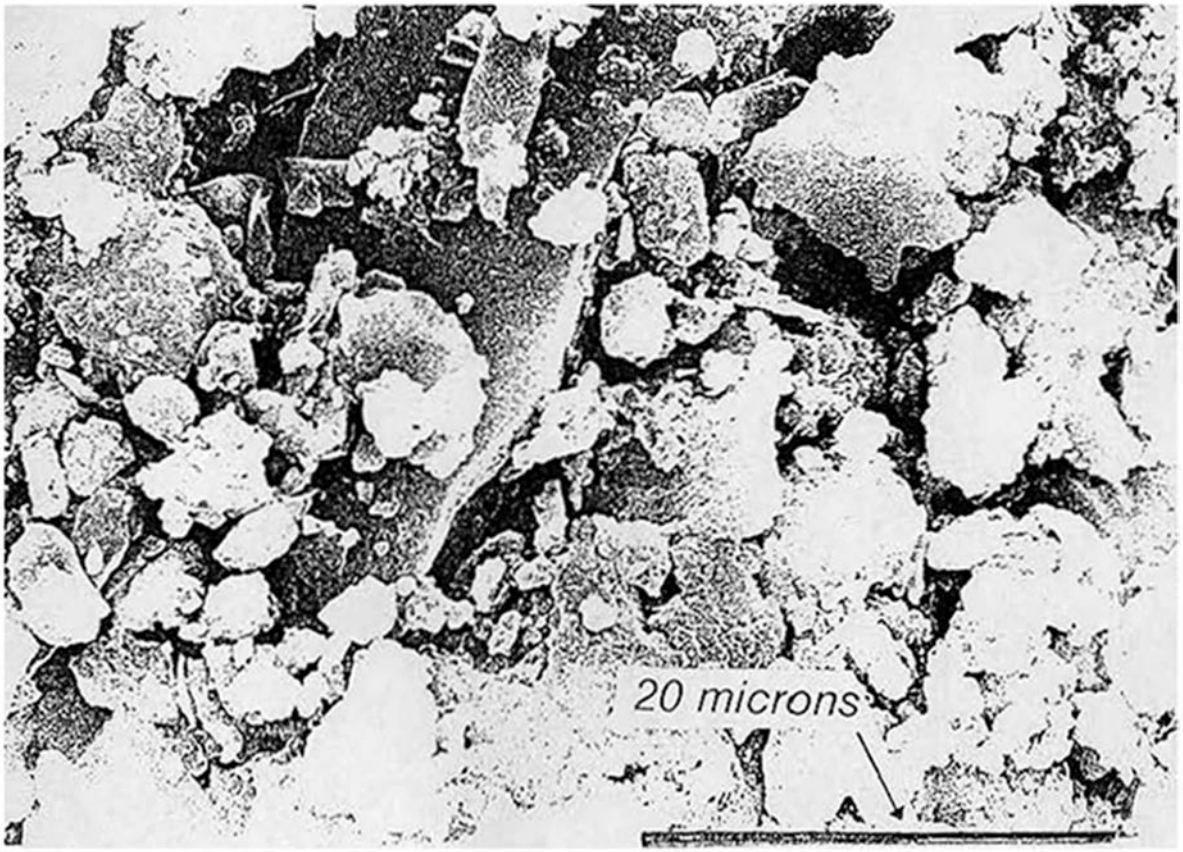
The face of failed sand grain at Seattle magnified X2000



The face of sand grain used in Seattle repair magnified X2000



Solids recovered from paste pumped from bedding sand



The nature of individual grains pumped from bedding sand