A TOTAL QUALITY APPROACH TO PAVEMENT SPECIFICATION

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ABSTRACT

The paper uses case studies in define ther reasons for pavements failing and identifies four principal causes of failure. These are firstly the failure of the joints to operate correctly, secondly, instability of bedding sands, thirdly, incorrect, or missing structural base and fourthly, inappropriate maintenance regime. A Total Quality Chart is presented which allows its user to identify the factors which need special attention and to ensure that the pavement is specified io avoid failure. Case studies are presented for seven areas which have underperformed and for two areas which have performed well. These case studies are used to define the factors which commonly lead to failure As well as the usual technical inputs to the specification procedure, the Total Quality Chart also includes an appraisal of any unusual environmental conditions which might prevaill. It also takes into account the public profile of the project and how visible the project is to the general public. By integrating these "soft" factors with the traditionally applied technical issues, the paper shows how a pavement can be guaranteed to perform to the client's requirements.

1 INTRODUCTION

During the last 25 years, the Authors have been involved in the design, specification, construction, development and usage of pavers both in the UK and elsewhere. They have observed the development of a body of knowledge which is sufficient to ensure that pavers can be used successfully to surface all categories of pavements. National and international standards have evolved for materials, installation procedures and design methods. Special attention has been paid to developing the technologies associated with heavily trafficked highway pavements' heavily loaded industrial areas[2], aircraft pavements[3] and pavements subjected to adverse environmental conditions such as vacuum sweeping flooding and extremes of climate[4]. Because of this, there is now sufficient information available to satisfy the needs of all potential paver specifiers. Yet, the incidence of pavements performing less well than the client expected has not diminished. This is often because the designer, specifier or installer has been unable to find a reference framework which will ensure that he focuses upon the germane issues. Rather, he has frequently been bombarded with a plethora of unconnected data some of which is in conflict and much of which has been driven by commercial interest rather than by a distillation of sound research and practice. As an example of this, there remain many regions where commercial interest dictates that pavers of proprietary shape are promoted as contributing structural enhancement to a pavement, when in fact research has shown the opposite to be true.

This Paper addresses the problem and presents a simple Total Quality Chart which will direct designers, specifiers and installers towards good practice and will lead them away from fruitless avenues which might otherwise distract them from giving their full attention to that good practice. The Chart does not seek to provide detailed solutions but refers to the sources of those details which have been proven through long term experience. This Paper explains how the Chart was derived by reference to case studies and industry/university based research. It gives examples of how several failures could have been avoided if the Chart had been available previously and shows how its use might change the way some pavements will be constructed in the future.

2 RECENT DEVELOPMENTS IN PAVER PAVEMENT TECHNOLOGY AND USAGE

Although there is some evidence that streets were surfaced with brick sized concrete blocks bedded on sand in Belgium in the 1930's, it is usually accepted that the modem paving stone era commenced in Rotterdam immediately after the second world war[5]. Traditionally, Dutch city streets were surfaced with brick but the shortage of coal throughout Northern Europe following the war led to a shortfall in the number of bricks needed for the more pressing need of house reconstruction. The Rotterdam city engineer used concrete pavers as a temporary substitute and this led to all Dutch authorities adopting concrete units such that by 1970, 15.000,000 m^2 of concrete pavers were being installed annually[6]. More recently , there has been a shift back to brick. The Dutch have adopted similar dimensions for both materials, which explains the term "Holland Stone" used in the US to describe rectangular concrete paving units.

The Dutch experience was paralleled tn West Germany through the 1950's and 1960's with the 1963 recession leading to many German building block manufacturers switching to paving units in order to keep their machines in production A fundamental difference between the developments in the two countries is that West German manufacturers prefered proprietary shapes which led to the establishment of shape-orientated promotional groups which have had a significant international impact. Essentially all other countries and regions adopt a mix of Dutch or German tradition, some favouring one strand and some integrating elements of both. Commonly, pavers are introduced to new regions by German industrial interests - shape licensors, paver plant manufacturers and installation equipment designers - but as markets mature, the more straightforward Dutch tradition frequently predominates. For example, pavers were introduced to the UK in the late 1960's and by 1973. all of the UK production comprised pavers of either West German origin or near copies, whereas by 1990, over 90% of UK pavers were rectangular and followed Dutch tradition.

Of course, many European city streets have been surfaced with small element systems for 200 years or more and indeed Roman Empire city streets were usually surfaced with stone units over 2000 years ago[8]. The essential ingredients in the modern resurgence of pavers are mass produced low cost units manufactured to accurate dimensions to facilitate cost effective installation. Also, modern pavers are engineered to allow their safe use by fast and heavy traffic, whilst at the same time being compatible with the needs of pedestrians in terms of slip, skid, abrasion and durability.

An interesting issue is whether mechanical installation will become commonplace during the next few years. So far, manual installation has proven cost effective and machines have been introduced when special factors militate against manual laying. For example, health & safety legislation has led to the introduction of installation systems in Rotterdam. Repetitive Strain Injury (RSI) is becoming recognised as an unacceptable consequence of long term employment in the manual installation of pavers. Mechanical laying has been introduced to Cyprus where young men prefer to find employment in tourism. Some proprietary German shapes are near impossible to place by hand and their promoters consider them to represent the forerunners of the next generation of pavers[9].

The Authors estimate that paver usage has risen from virtually nil fifty years ago to 0.7 billion square metres per annum by 2000. Germany remains the single largest market with upwards of 100 million square metres per annum. Other significant markets include 30 million square metres per annum in North America, 20 million square metres in the UK with many countries worldwide achieving figures of the order of 10 million. Figures are difficult to establish for developing countries but it is clear that on a per capita basis, African usage is close to European and parts of Asia, have significant industries. There has been a constant growth in Central and South America and China uses pavers commonly - the 460.000m^2 Hong Kong airport pavers were imported from China. In summary, for each person on Earth, 0.13 m^2 of pavers are installed annually and the Authors expect this figure to rise to 0.2m^2 by 2020. The increase will occur as a result of market penetration increasing year on year in western countries where population growth is often zero or sometimes negative and as a surge in developing countries which will outstrip population growth as the appropriateness of pavers becomes evident.

The size of the world-wide market has led to a massive body of information entering the public domain. Whereas the designer/specifier of the 1970's struggled to find any authoritative guidance, the difficulty can now be in coping with sometimes conflicting advice, which may relate to specific climates, materials, products or methods. A massive body of information is available through the series of international conferences and workshops, through trade groups, through national and international standards and through

experience which has evolved in companies and authorities involved with pavers. The next Section describes a series of landmark projects which have informed the body of knowledge and which together define the state of the art. By studying them, the Authors have developed the Total Quality Chart which is the focus of thus Paper.

3 LANDMARK PROJECTS IN DEVELOPING AN UNDERSTANDING OF PAVER PAVEMENTS

The case studies described here represent the waypoints which have guided the Authors towards their understanding of paver pavements. In each case, the project has failed in one or more respects or it includes an innovative element which has pointed the way towards a clearer understanding of the behaviour of a pavement surfaced with pavers. The Authors have learned that the following four issues need to be considered if the pavement is to satisfy the conflicting needs of all ot the parties involved in the development of a project.

Issue 1:- Environmental special external factors which affect performance.
Issue 2:- Visibility how many people will sec the project and from what distance.
Issue 3:- Traffic: nature, weight and frequency of loads.
Issue 4:- Public profile the contribution of the project to the enhancement of the physical world.

The case studies are described by reference to the four Issues and the way in which quantifying each Issue would have influenced the development of the project is explained. The critical factors in the nine case studies are summoned in Table 1 according to the four Issues which have been found to be relevant to pavement performance.

Case 1 - Bellevue Metro Interchange, Washington Slate, US.
Figure 1 shows the way in which areas of rigidly set buck pavers gradually deteriorated in this bus station The cement mortar bedding material failed to take into account the Environmental and Traffic Issues. There are many instances where similar failures have occurred and the Authors have found that rigidly bedded pavers cannot sustain heavy channelised traffic, particularly at bus stops.

Case 2 - Trench Lock Works. Telford, UK.
Figure 2 shows the condition of the road after 5,000,000 csa's. It is the access road to a brick manufacturer and is trafficked by heavy vehicles delivering the firm's products. It is important in that it is an early example of a paver road having regular heavy vehicles in an industrial context. The road remains serviceable as a result of its reinforced concrete base and the use of bedding and jointing sands which would fall into Category 2[10].

Case 3 - Bahrein Airport.
The area comprises an airport vehicle service and parking area Figure 3 shows how many of the pavers spalled as a result of the rectangular units having no spacers and being installed in a tightly packed manner. The problem was exacerbated by the absence of an adequate base. The problem would have been largely resolved by ensuring that jointing material was present and would have been fully resolved by so doing and providing a more rigid base. The design method for industrial pavements surfaced with pavers was developed at Newcastle University[2], initially as a Science Research Council project, then as a British Ports Authority contract and finally as a design method sponsored by British Precast Concrete Federation.

Case 4 - Leeds.
Figure 4 shows tire condition of pavers installed in a city centre street after very little use The pavers had been deliberately spaced to fit into previously constructed surrounds. This led to loss of interlock. Effectively, this is the opposite problem to the one described in Case Study 3 Together, they point to the importance oi installing the pavers "hand tight" so that the joint remains filled and generates interlock[11].

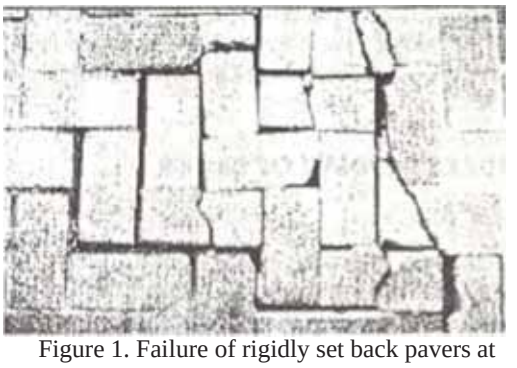


Figure 1. Failure of rigidly set back pavers at Bellevue Metro. Washington State, US.

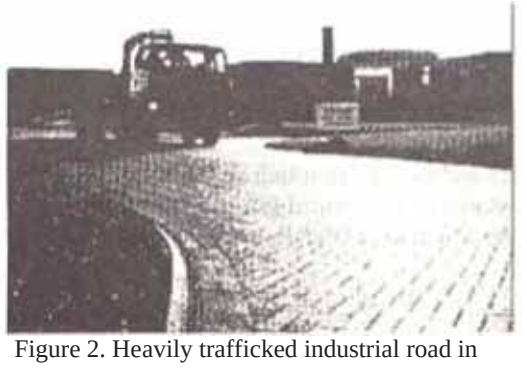


Figure 2. Heavily trafficked industrial road in Telford, UK.

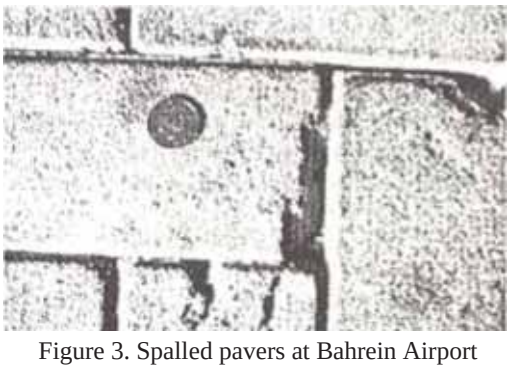


Figure 3. Spalled pavers at Bahrein Airport maintenance area.

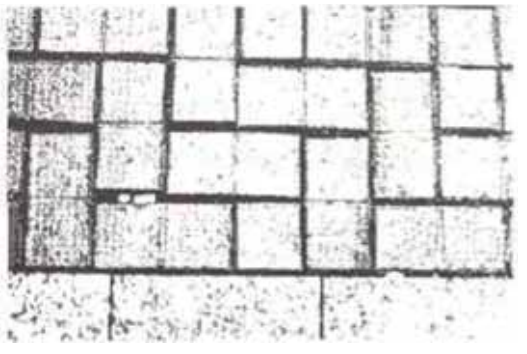


Figure 4. Jointing material has been lost from pavers at Leeds resulting in loss of interlock.

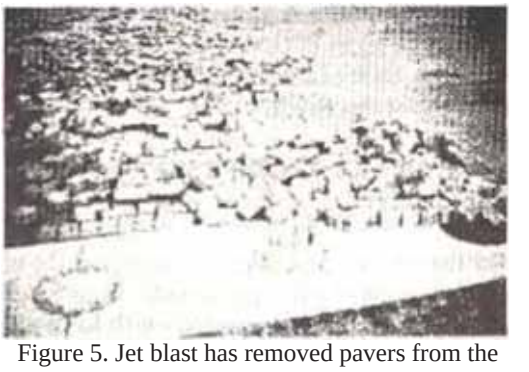


Figure 5. Jet blast has removed pavers from the Eastern Turning Circle at Luton Airport.



Figure 6. Victoria Road, Hartlepool, UK. showing high quality pavers on steel fibre reinforced concrete base.

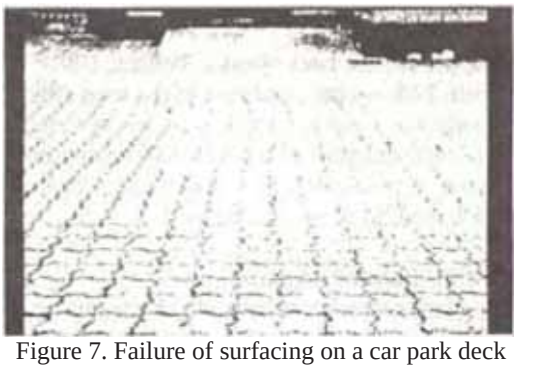


Figure 7. Failure of surfacing on a car park deck as a result of jointing sand being washed/vibrated into bedding course.



Figure 8. Pavers have been removed from a promenade at Paphos, Cyprus following a severe storm.

Case 5:- Luton Airport, UK.
Figure 5 shows pavers removed from the the Eastern Turning Circle at Luton Airport which occurred on a number of occasions, culminating in a significant failure which damaged an aircraft. A court hearing failed to establish the cause with any degree of certainty but adequate maintenance, drainage of the bedding material and loss of jointing material in an area subicct to regular jet blast were all points of discussion (one of the Authors represented one of the parties to the ensuing litigation). Other factors which may have contributed to the difficulties include the use of machines to install clusters and the need to undertake the work through the night with a morning deadline when the runway was back in service. Much of the development of the technology of pavers for aircraft pavements took place collaboratively by Luton Airport and Newcastle University. The work has been published by the Civil Aviation Authority in the UK[3] and by the Interlocking Concrete Pavement Institute with the approval of the Federal Aviation Administration in the US[12].

Case 6:- Pine Street. Seattle.
The project composed granite pavers installed over a bedding material which contained an abnormal proportion (>10%) finer than 75 microns (No 200 sieve size). It developed ruts during the first day's trafficking and was eventually reconstructed with a bedding sand with only 0 1% passing the 75 micron sieve. That was in 1989 and it has withstood heavy traffic for over 10 years with no significant maintenance being required. This project and several which showed similar traits in the UK led to the development of enhanced specifications for bedding materials. Research at Newcastle University has confirmed the need to restrict bedding materials in heavily trafficked projects to naturally occuring sands with limited amounts of material passing a 75 micron sieve.

Case 7:- Victoria Road, Hartlepool.
Figure 6 shows this heavily trafficked town centre street was constructed in 1993 and has withstood 7,000,000 csa's with no problems. This is as a result of the use of an enhanced specification sand and with the paver joints including a polymer stabilizer. The base comprised steel fibre reinforced concrete installed by a laser guided screeding machine to ensure accurate levels and therefore a consistently thick bedding layer. Research undertaken at Newcastle University has shown the suitability of steel fibre reinforced concrete for highway pavements".

Case 8:-- Parking Deck, Dublin.
Figure 7 shows details of the project in which proprietary shaped pavers were laid by machine over a coarse grit. The fine jointing sand was subsequently washed and/or vibrated into the bedding sand, so leaving the pavers in a non-interlocking state. The laying system whereby $0.5m^2$ clusters were installed without cross linking exacerbated the failure. Also, cluster laid systems develop a wider joint around the perimeter of each cluster, so diminishing interlock. This project highlights the need to ensure compatibility between jointing and bedding materials. It also illustrates that some proprietary shapes can prove more difficult to repair than would simple rectangular pavers.

Case 9:- Paphos Promenade.
Figure 8 show the condition of the promenade following a severe storm which flooded the pavement. Most of the pavers were washed into Paphos Harbour. The area should have been treated with a polymer joint stabilizer but the contractor has not followed the specification. Whether the area would have survived with the joints so treated is not certain but it would have endured the storm for a prolonged period. Research undertaken at Newcastle University into polymer stabilizers has demonstrated their ability to greatly reduce the permeability of paver joints[4].

The above case studies represent a small proportion of the projects with which the Authors have been involved. They have been chosen because they each led to a greater understanding of the way in which pavers behave and because they represent a class of problem which has occurred elsewhere with greater or lesser regularity.

Table 1. Factors and Issues relevant to the landmark projects.

Project Title	**Issue**			
	Environmental	Visibility	Traffic	Public Profile
Bellevue Transit	Bus stops Channelised	Public pedestrian area	10,000,000 csa	Feature paved area
Trench Lock Works	Tight turning 1500kg	Light pedestrian commercial project	5,000,000csa	Associated with landmark budding
Bahrein Airport	Hot/dry climate. Tight turning > 1500kg	Occasional pedestrian use	Heavy duty industrial	No public impact
Leeds	Vacuum sweeping	City centre public pedestrian area	Less than 10,000 csa	High profile civic project - principle material
Luton Airport	Maintenance access difficult. Tight turning >1500kg	Seen from distance	Aircraft	No public impact
Pine Street, Seattle	Cold wet climate	City centre public pedestrian area	10,000.000 csa	High profile civic project - principle material
Victoria Road, Hartlepool	Bus stop	Town centre public pedestrian area	7,000,000 csa	Civic project - principle material
Parking Deck, Dublin	Tight turning <1500kg	Occasional pedestrian use	Lightly loaded <1500kg	Associated with landmark bmldtng
Paphos Promenade	Flooding	Public pedestrian area	Pedestrian	Feature paved area

4 DISCUSSION OF COMMON THEMES IN PAVEMENT FAILURES

When the above projects are analysed collectively several unexpected conclusions can be drawn. The first is that whereas previous research has frequently focussed upon ensuring that the pavement components remain unstressed, in fact, failure rarely occurs as a result of straightforward overloading. A surprisingly common theme which correlates particularly well with performance and quality is the behaviour of the paver joints. Some of the most spectacular failures have occurred as a result of the paver joints ceasing to operate. The joints can be too wide, too narrow, unfilled or filled with inappropriate material. In any of these cases, the failure can be dramatic and sudden. The joints need to be considered in conjunction with the bedding material and care needs to taken to ensure that the jointing material does not drop into the bedding material.

Bedding sands have initiated failure when the material has been too fine to pemit the unimpeded flow of water. This has allowed hydrostatic pressure to develop in the bedding sand which has in turn reduced the shear strength of the sand. In the extreme case of Pine Street Seattle, a total collapse of the bedding sand occurred, resulting in quicksand conditions, in which the sand adopts the rheology of a zero-shear thud[10].

Although base failures are rare, this does not indicate that the level of attention given to the base can be relaxed. Rather, it suggests that designers have always been aware of the potential for failure in this area. This is not surprising bearing in mind that most projects are overseen by engineers with a background in structural mechanics. However, when other factors bring a pavement to a near failure condition, the provision of a strong base can be the lifeline

Maintenance has been observed to be a significant factor in pavement deterioration. Strangely the undertaking of excessive levels of maintenance has been as dangerous as underestimating maintenance. For example, the removal of jointing material by vacuum cleaning equipment has caused some difficulties[4]. However, a major conclusion to be drawn is that the client and the team responsible for providing the pavement need to define maintenance in an explicit way. Two extremes have been identified. On the one hand, it is common for completed pavements to be left to deteriorate. On the other hand some authorities have developed a Statement of Engineering Parameters, a legal document which sets out the anticipated

defects quantitatively year on year[14]. Intermediate levels of maintenance include repair on an as needed basis and repairing only those defects which render a pavement dangerous to its traffic.

From the above discussion, it can be concluded that the output from a total quality approach to pavement engineering should be information which defines:

1/ Paver joints
2/ Bedding material specifications
3/ Characteristics of base material
4/ Level of maintenance

Effectively, a means is required of allowing the four Issues of *Environment*, *Visibility*, *traffic* and *Public Profile* to define the appropriate levels for the above four outputs. The Total Quality Chart described in the next Section does so.

5 FORM FLATION OF TOTAL QUALITY CHART FROM CONSIDERATION OF FAILURE THEMES

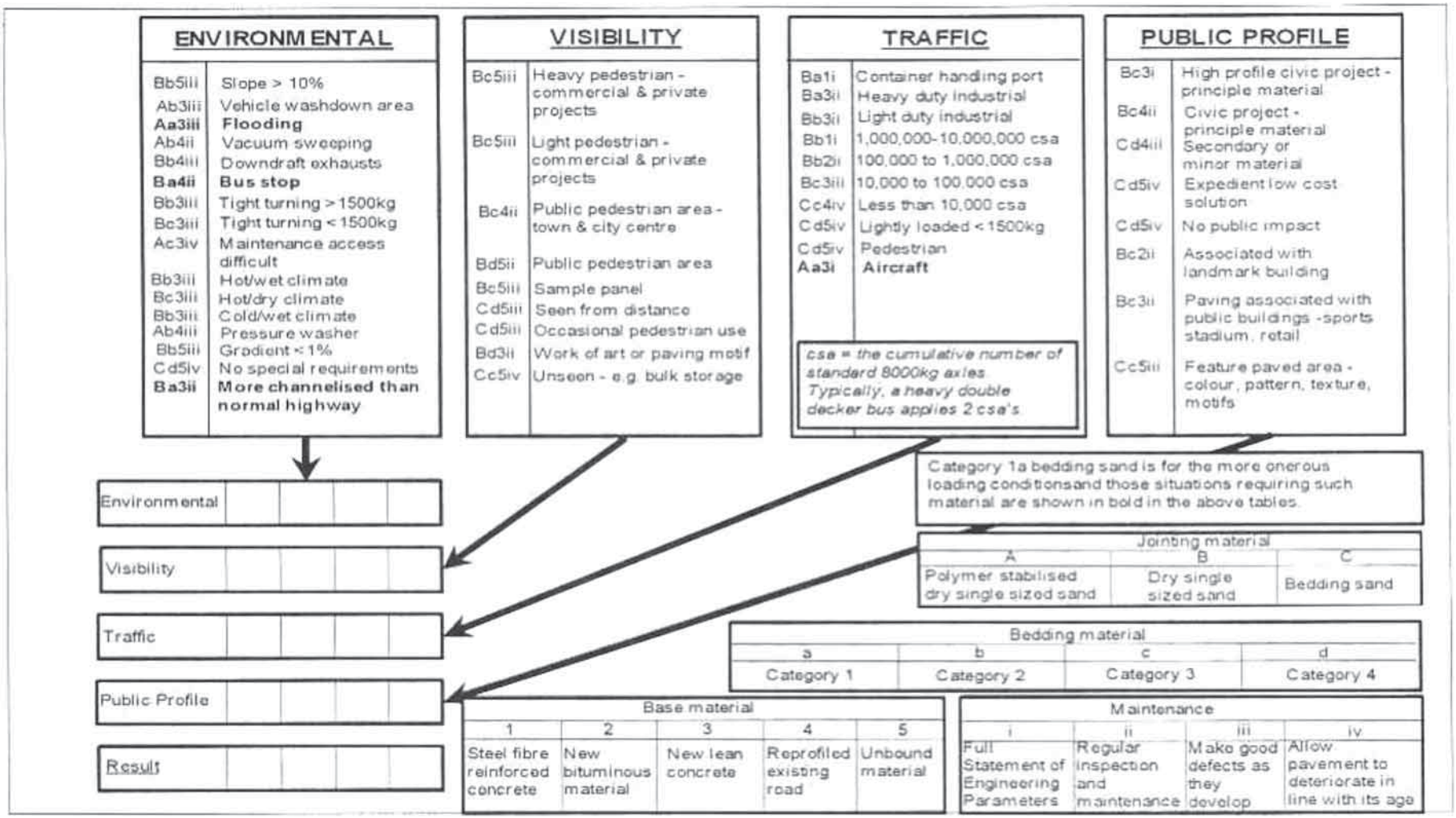
The Total Quality Chart is shown as Fig 9. Each of the four Issue categories includes a series of factors which fall within that Issue. The user can select those factors which apply to the project in hand. There may be more than one in each Issue box. Each factor has a four element code such as **Bc4ii**. In this code, the upper case letter, **B**, refers to one of three jointing materials. The lower case letter, **c**, refers to the category of bedding sand. The Arabic number, **4**, refers to the base material and the Roman numeral, **ii**, refers to the maintenance regime. For each of the four Issues, the user finds the code which is most onerous and transfers it to the appropriate box at the bottom left of the Chart. Once each of the four boxes is filled, the most adverse value of each element is transferred to the Result box. Hence the user can select the appropriate jointing material, bedding material, base material and maintenance regime. These four factors have been shown to be the crucial ones in long term pavement performance. Providing the data upon which the user bases his judgements is accurate, the Chart will ensure that the correct solution is produced. The user will then be able to focus upon developing the requisite specifications in detail.

6 EXAMPLES OF THE USE OF THE TOTAL QUALITY CHART

The Chart is now applied to the case studies already described by way of example. Table 2 summarises the codes developed from the Chart.

Table 2. Total Quality Cliart applied to Case Studies

Project Tille	**Total Quality Design Code**				
	Environmental	Visibility	Traffic	Public Profile	Result
Bellevue Transit	Ba3ii	Bc4ii	Bb1i	Cc5iii	Ba1i
Trench Lock Works	Bb3iii	Bc5iii	Bb1i	Bc2ii	Bb1i
Bahrein Airport	Bb3iii	Cd5iii	Ba3ii	Cd5iv	Ba3ii
Leeds	Ab4ii	Bc4ii	Cc4iv	Bc3i	Ab3i
Luton Airport	Ab3iii	Cd5iii	Aa3i	Cd5iv	Aa3i
Pine Street, Seattle	Bb3iii	Bc4ii	Bb1i	Bc3i	Bb1i
Victoria Road, Hartlepool	Ba4ii	Bc4ii	Bb1i	Bc4ii	Ba1i
Parking Deck, Dublin	Bc3iii	Cd5iii	Cd5iv	Bc2ii	Bc2ii
Paphos Promenade	Aa3iii	Bc4ii	Cd5iv	Cc5iii	Aa3ii


ENVIRONMENTAL
Bb5iii Slope > 10%
Ab3iii Vehicle washdown area
Aa3iii Flooding
Ab4ii Vacuum sweeping
Bb4iii Downdraft exhausts
Ba4ii Bus stop
Bb3iii Tight turning > 1500kg
Bc3iii Tight turning < 1500kg
Ac3iv Maintenance access difficult
Bb3iii Hot/wet climate
Bc3iii Hot/dry climate
Bb3iii Cold/wet climate
Ab4iii Pressure washer
Bb5iii Gradient < 1%
Cd5iv No special requirements
Ba3ii More channelised than normal highway
VISIBILITY
Bc5iii Heavy pedestrian - commercial & private projects
Bc5iii Light pedestrian - commercial & private projects
Bc4ii Public pedestrian area - town & city centre
Bd5ii Public pedestrian area
Bc5iii Sample panel
Cd5iii Seen from distance
Cd5iii Occasional pedestrian use
Bd3ii Work of art or paving motif
Cc5iv Unseen - e.g. bulk storage
TRAFFIC
Ba1i Container handling port
Ba3ii Heavy duty industrial
Bb3ii Light duty industrial
Bb1i 1,000,000-10,000,000 csa
Bb2ii 100,000 to 1,000,000 csa
Bc3iii 10,000 to 100,000 csa
Cc4iv Less than 10,000 csa
Cd5iv Lightly loaded < 1500kg
Cd5iv Pedestrian
Aa3i Aircraft
csa = the cumulative number of standard 8000kg axles. Typically, a heavy double decker bus applies 2 csa's
PUBLIC PROFILE
Bc3i High profile civic project - principle material
Bc4ii Civic project - principle material
Cd4iii Secondary or minor material
Cd5iv Expedient low cost solution
Cd5iv No public impact
Bc2ii Associated with landmark building
Bc3ii Paving associated with public buildings -sports stadium, retail
Cc5iii Feature paved area - colour, pattern, texture, motifs
Environmental
Visibility
Traffic
Public Profile
Result
Category 1a bedding sand is for the more onerous loading conditionsand those situations requiring such material are shown in bold in the above tables.
Jointing material
A Polymer stabilised dry single sized sand
B Dry single sized sand
C Bedding sand
Bedding material
a Category 1
b Category 2
c Category 3
d Category 4
Base material
1 Steel fibre reinforced concrete
2 New bituminous material
3 New lean concrete
4 Reprofiled existing road
5 Unbound material
Maintenance
i Full Statement of Engineering Parameters
ii Regular inspection and maintenance
iii Make good defects as they develop
iv Allow pavement to deteriorate in line with its age

By comparing the results from Table 2 with the codes which would apply to the case study projects, it becomes clear why some of the projects failed and others succeeded. For example, Bellevue Transit was constructed with inappropriate jointing and bedding material and should have been maintained according to a prescribed Statement of Engineering Parameters. The two protects which have performed well were constructed according to their code. The Bahrein Airport project included inappropriate jointing material and an incorrect base. Pine Street, Seattle had the wrong jointing and bedding material. The Dublin parking deck had the wrong bedding material. Luton Airport and the Paphos Promenade had the wrong jointing and bedding material.

The Total Quality Chart will inevitably fail to deal with all of the issues which will develop in the future and those interested are invited to suggest additions or amendments by e-mailing the Authors at john.knapton@ncl.ac.uk The Chart will grow in value as those with experience contribute that experience to the Chart. The Chart is available at web site:

www.ncl.ac.uk/-njk3/

7 CONCLUSIONS

1 To date, guidance relating to pavements surfaced with pavers has been fragmented with a bias towards ensuring that the paving units and the structural base are designed and specified accurately, whereas problems have usually been associated with the jointing and bedding sand.

2 The procedure described in this Paper can be used to produce an outline specification which will ensure that the resulting pavement will be appropriate for its function.

3 A pavement specification can be developed only when both technical and "soft" issues such as environment, visibility and public profile are taken into account. This applies to both initial construction and the maintenance regime.

4 A pavement cannot be considered to be fully specified until its maintenance regime has been developed. At one extreme, a Statement of Engineering Parameters can be developed which stales explicitly how the pavement will be managed through its prescribed life. At the other extreme, the pavement can be allowed to deteriorate progressively so it has zero value at the end of its design life.

5 There is now so much information available to the specifier that the main difficulty is in managing the data. Some of the data is in conflict and the specifier needs to understand the purpose of those organisations providing guidance. Some special interest groups have promoted solutions which are not scientifically proven.

6 The Total Quality Chart can be used to assist in the development of a new pavement, to upgrade an existing pavement (the upgrade might be in terms of enhancing the maintenance regime) or to understand why an existing pavement is underperforming.

7 The value of the Total Quality Chart will be enhanced if specifiers attempt to incorporate it into their work and report their experience to the Authors. It is hoped that the Chart will evolve as future paver projects feed into it.

8 Whilst the Chart is geared towards pavements surfaced with clay paviors, concrete blocks and stone products, it could be modified and applied to all pavement types.

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