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The use of RESIBLOCK *'22'* in Discrete Element Pavement Systems

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Executive Summary

This Report uses case studies to define the reasons for pavements failing and identifies those types of use where RESIBLOCK *'22'* will enhance the strength and durability of a pavement so avoiding failure. A Total Quality Chart is presented which allows its user to identify those applications where RESIBLOCK *'22'* should be specified to ensure that the pavement achieves maximum performance and avoids failure. Case studies are presented for seven areas which have underperformed and for two areas which have performed well. The Total Quality Chart includes an appraisal of any unusual environmental conditions which might prevail. 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 Report shows how a pavement can be guaranteed to perform to the client's requirements and how RESIBLOCK *'22'* can significantly contribute to this.

Introduction

During the last 25 years, the Author has been involved in the design, specification, construction, development and usage of pavers both in the UK and elsewhere. He has participated in 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, aircraft pavements and pavements subjected to adverse environmental conditions such as vacuum sweeping, flooding and extremes of climate. 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. An area where there is as yet no definitive guidance is in the application of paver joint specialist pre-polymer urethanes (SPPU's) such as RESIBLOCK *'22'*. This Report defines those applications and includes a simple to use chart which informs the user which pavement categories will be enhanced by the use of RESIBLOCK *'22'*.

Recent developments in paver pavement technology and markets

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 modern paving stone era commenced in Rotterdam immediately after the second world war. 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. More recently, there has been a shift back to brick. The Dutch have adopted similar dimensions for both concrete and brick, which explains the term "Holland Stone" used in the US to describe rectangular concrete paving units.

The Dutch experience was paralleled in 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 preferred 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. The essential factors 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.

The Author estimates 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, over 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 400,000m^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 Author expects 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.

Paver joint SPPU's such as RESIBLOCK *'22'* were developed in the mid-1980's, initially at Luton Airport, the world's first application of pavers for commercial aircraft pavements. Initially perceived as an aid to paver joints resisting jet blast and propeller wash, its uses extended through the late 1980's and the 1990's to many categories of pavements where air, gases, liquids, traffic and adverse weather conditions might remove jointing sand from pavements surfaced with pavers. It was also used to improve hygiene where contaminants would otherwise penetrate joints and has been proven to prevent the development of unsightly efflorescence on the surface of 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 block paving art and which demonstrate the value of paver joint SPPU stabilisers. By studying these case studies, the Author has developed the Total Quality Chart which is the focus of this Report (Figure 26). A major conclusion from the following is the high proportion of failures in which loss of jointing material has been a contributory, or initiating factor - failures which would have been avoided had RESIBLOCK *'22'* been applied in the first instance rather than as part of the repair. Together, they point to the need to consider joint stabilisation for a range of pavement categories.

Landmark projects in developing an understanding of paver pavements

The case studies described here represent the waypoints which have guided the Author towards his 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 following four issues need to be considered if the pavement is to satisfy the conflicting needs of all of 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 see 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 case studies are summarised in Table 1 according to the four Issues which have been found to be relevant to pavement performance.

Case 1 - Bellevue Metro Interchange, Washington State, US.

Figures 1 to 3 show the way in which areas of rigidly set brick 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 Author has found that rigidly bedded pavers cannot sustain heavy channelised traffic, particularly at bus stops. It is essential that flexibly bedded pavement systems are used - those pavements which were previously designed and constructed to act in a rigid fashion should now be treated as flexible pavements, usually with the application of RESIBLOCK *'22'*.

Case 2 - Trench Lock Works, Telford, UK.

Figures 4 to 6 show the condition of the road after 5,000,000 Cumulative Standard Axles (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. Several parts of this pavement have been treated successfully with joint stabilisation SPPU materials (materials identical in chemical composition to Resiblock, but predating it)

Case 3 - Bahrain Airport. (See Figures 7 to 9)

The area comprises an airport vehicle service and parking area. 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 RESIBLOCK *'22'*.

Case 4 - Leeds

Figures 10 to 12 show the 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 of installing the pavers "hand tight" so that the joint remains filled and generates interlock. The problem was resolved by the application of a joint stabilising SPPU.

Case 5 - Luton Airport

Figures 13 to 15 show the Eastern Turning Circle at Luton Airport which failed 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 subject to regular jet blast were all points of discussion (the Author 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 the Author. The work has been published by the Civil Aviation Authority in the UK and by the Interlocking Concrete Pavement Institute, with the approval of the Federal Aviation Administration, in the US. Effectively, joint stabilising SPPU's were "invented" at Luton in order to prevent the erosion of jointing and bedding sands by jet blast and propeller wash.

Case 6 - Pine Street, Seattle (Fig. 16).

The project comprised 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 since when 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 occurring sands with limited amounts of material passing a 75 micron sieve. The use of a joint stabilisation SPPU was the key element in the successful repair of Pine Street.

Case 7 - Victoria Road, Hartlepool (See Figs 17 to 19)

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 SPPU stabiliser. The base comprised steel fibre reinforced concrete installed by a laser guided screeding machine shown in Fig 18 to ensure accurate levels and therefore a consistently thick bedding layer

Case 8 - Parking Deck, Dublin.

Figs 20 to 22 show 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. The use of a SPPU joint stabiliser would have avoided this problem.

Case 9 - Paphos Promenade.

Figs. 23 to 25 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 SPPU joint stabiliser but the contractor had not followed the specification. Research undertaken at Newcastle University into SPPU stabilisers has demonstrated their ability to greatly reduce the permeability of paver joints.

The above case studies represent a small proportion of the projects with which the Author has 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 of 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	5,000,000 csa	Associated with landmark building
Bahrain 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 building
Paphos Promenade	Flooding	Public pedestrian area	Pedestrian	Feature paved area

Discussion of common themes in pavement failures

When the above projects are analysed collectively, several 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. RESIBLOCK *'22'* will ensure that the jointing material remains in place and would have eliminated all of the defects discussed in this Report.

Bedding sands have initiated failure when the material has been too fine to permit 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 fluid. Bedding sand failure can be prevented by the application of RESIBLOCK *'22'*.

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 untreated jointing material by vacuum cleaning equipment has caused some difficulties. 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. 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
5 Paver joint sealant material

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.

Formulation of Total Quality Chart from consideration of failure themes

The Total Quality Chart is shown as Fig. 26. 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.

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 Chart applied to Case Studies

Project Title	**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
Bahrain 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

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 projects which have performed well were constructed according to their code. The Bahrain 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.

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. The majority of those filed pavements which the Author has investigated would have worked had their joints been treated with RESIBLOCK *'22'*

2. The procedure described in this Report 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. The specification of Resiblock is driven environmental factors, visibility, public profile and traffic issues.

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 states 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. RESIBLOCK *'22'* will enhance the long term performance of paver pavements and will reduce the life cycle cost of a pavement. The reduction in future maintenance spending, even taking into account discount cash flow analysis will be greater than the initial application cost.

5. 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.