EFFECT OF SHAPE AND LAYING STRATEGIES ON GAP PERFORMANCE OF SEGMENTAL BLOCK PAVERS

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Summary
This paper discusses factors which affect the resultant gaps between segmental block pavers when these are laid in herringbone pattern over a large area as part of a civil engineering process to form a trafficable surface. The widths of the gaps are projected by a model which simulates the solution of the family of equations reflecting the physical characters of the blocks and the sequence and method of placement. Monte Carlo studies are used to show the patterns of gaps which develop and to investigate the impact of particular variables on gap performance, which is assessed in accordance with acceptance criteria specified for airport pavement works. The performance of rectangular and dentated block shapes is compared, and the differences between laying these in elbow bond with a single long face, and a 'patchwork' of small square areas are explored. The interplay of block design factors, manufacturing tolerances, and aspects of the block laying strategy is investigated for each scenario.

Introduction

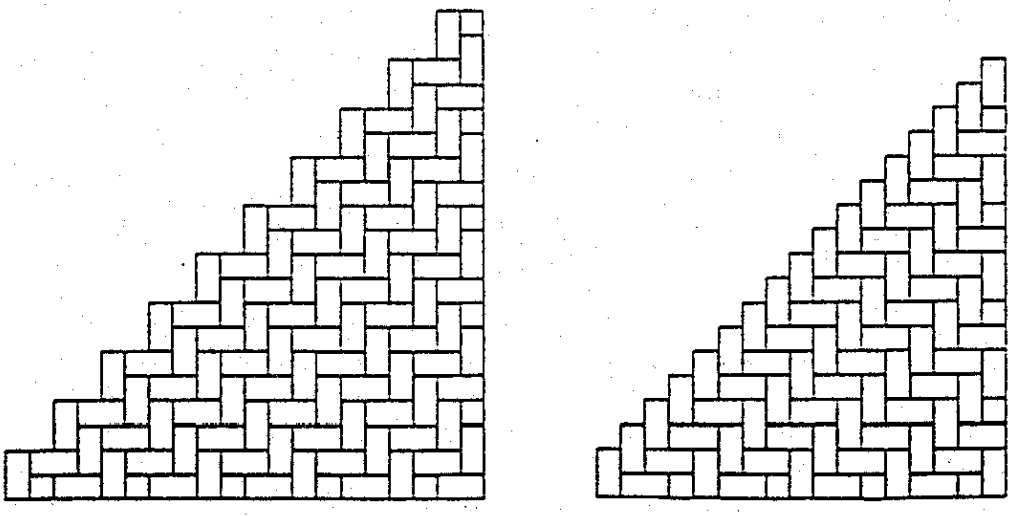
The modelling approach to investigating gap development between paving blocks as they are laid has been described by the authors in several previous publications [1, 2, 3]. Comparisons have been made between gap performance when rectangular and dentated blocks are laid in herringbone bond [2], and between herringbone and elbow bond for dentated blocks [3]. Aspects of the design, manufacture and laying of the blocks are input to the model under a statistically designed methodology in order to discover what parameter combinations allow optimal laying with respect to gap performance.

Some practical applications require very close control of gap sizes to maintain the integrity of the pavement [4,5], and while the theory of tiling with perfect blocks laid to perfectly sized gaps is well understood, the complex patterns of gaps arising from variations in actual block sizes, and the uncertainty in placing them, had not been investigated prior to the development of the model by the authors.

The development of gaps between adjacent blocks is modelled by a family of two-dimensional difference equations which reflect the physical characteristics of the blocks and the sequence in which they are placed together. Solutions of these equations show resultant

gap patterns for specific combinations of parameter values, and the impact of particular variables on gap performance. It has been found that many features of the simulated pavement are quite robust and reflect those observed in reality.

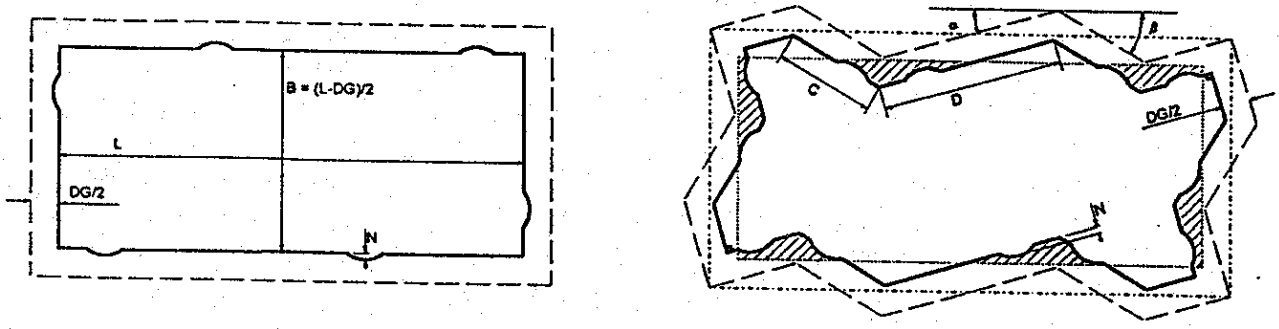
This paper will focus on laying blocks in elbow bond (EB) in a configuration bounded by two straight edge boundaries on the south and east edges of the pavement. This is illustrated in Figure 1. For comparison, an alternative laying sequence is also shown, referred to as herringbone bond (HB). Both sequences lead to a herringbone-pattern pavement but the operation of laying the blocks is different.



Elbow Bond Herringbone Bond

Figure 1

Two block shapes, rectangular and dentated, illustrated in Figure 2, are in common use in the industry, and as each shape has its champions, our studies have looked at both. The results presented show that an informed choice of block design parameters, laying method and manufacturing tolerances is essential in applications where gap size control is critical.



Rectangular block model Dentated block model

Figure 2

Acceptance criteria

Gaps between pavers (which are subsequently filled with sand or other stable material) are required to be not too small (otherwise the blocks may touch when the pavement deflects under load, causing spalling); nor too large (otherwise the structural integrity of the pavement may be lost) [5]. It is commonly required for airport paving that *all* gaps be between 1.5mm and 5mm, and that *in any selected area* (1m by 1m would be typical) there be not more than 5% of gaps over 4mm (these will be referred to as criterion 1 and criterion 2 in the following discussion). The aim of the model is to define and investigate the parameters which need to be controlled in the design, manufacture and placement of the blocks so that the herringbone pavement will satisfy these gap size criteria.

Although these permitted gap dimensions for an airport pavement appear extremely tight for a civil engineering application, and the number of gaps in a typical installation is extremely large, in practice 100% inspection for out-of-specification gaps is not at all difficult. This is normally done visually by experienced inspectors, and where there is doubt, cross-checks are made by gauges (see for example [4 p.112]). It is therefore essential that the model is similarly rigorous in reporting non-conformances.

The model records, for each simulated area of pavement, the presence or absence of gaps over 5mm (if any, the pavement fails under criterion 1), the presence or absence of specified areas where more than 5% of gaps are 4-5mm (criterion 2), and also the maximum gap size. The maximum gap size has been found to be a good indicator of overall gap performance, since the factors which cause criterion 1 or criterion 2 to be satisfied are also those which lead to the maximum gap size being, on average, below 4mm; and failure to satisfy these criteria is paralleled by an increase in the maximum gap size that is developed.

The Model

Modelling the development of a pavement requires first a model for the blocks being used, and second a model for the placement of the blocks in relation to each other. The important aspects of each of these submodels will be briefly described.

Modelling Physical Blocks

Designing Blocks Designing a physical block starts from a *module* (the external dashed line around the blocks in Figure 2) which would, if perfectly reproduced, cover the plane with no gaps present at all. The blocks under consideration are derived from rectangular modules in the proportion 1:2. The physical block is designed by cutting a strip of width DG/2 from the edge. If these blocks are then laid with gaps DG (the *design gap*) between them, they will again form a perfect herringbone pavement. Spacer nibs N units in dimension are supposed to be placed on certain faces: the rectangular blocks in the present study have six nibs and the dentated blocks 12 nibs, although other numbers are also in common use. The dentated block is defined by two angles, α and β as well as the length (L) and breadth (B) and DG. A set of hypothetical parameters, believed to be representative of blocks in use, was chosen to define the shape being investigated (L, B, α and β). These remain fixed through all the siulations, while variation in DG and N is investigated.

Manufacturing Blocks Block moulds are prone to distortion during the hardening process, subjected to considerable force during moulding, and progressively abraded by the concrete.

Distortion leads to variability in the blocks produced from that mould, and wear, together with changes from batch to batch of the input mix, the atmospheric and curing conditions, personnel and other imponderables cause the actual dimensions of the blocks to change unpredictably over the life of the mould. In large area pavements such as airports, blocks from lots made on different days and possibly even from different moulds will be used together. Perhaps in recognition of all these uncontrollable influences, current standards for allowable variation in manufactured block size permit a considerable range in the manufactured block dimensions.

Practices have been developed by the block laying trade in an attempt to overcome variability problems, such as mixing blocks from different lots on site so that the variation is evenly spread, or laying blocks in order of lot manufacture so that mould wear effects are incorporated gradually into the pavement. One of the key objectives and advantages of the modelling process which has been developed is its capability to reflect the effects of dimensional variability in the blocks. Accordingly, suitable random variables have been defined so that typical production variation can be simulated for each block shape.

For practical purposes it is desirable that the pavement can accommodate as much block variation as possible, since unnecessarily frequent replacement of expensive block moulds or use of other close-tolerance quality control techniques is undesirable. A small range of values for block standard deviations was therefore identified within which some, but not all, parameter combinations led to pavement compliance with criteria 1 and 2. These values are within a range that was observed in measurements of blocks which were used successfully to create a pavement satisfying these criteria, which indicates that the model's recommended level of variation appears to be attainable with current manufacturing technology. However, it is necessary to have the correct combination of levels of variation on each of the many parameters involved in order to achieve a satisfactory product.

Modelling Block Placement

As described above, this paper is concerned with pavement laid in elbow bond. For the purpose of simulation, the important feature of placing a block into a growing pavement is that the short side of each block adjoins the long side of a previously placed block, while the long side adjoins sides of two previously placed blocks, and if a single long face is laid, there are no trapped blocks.

The complex geometry of the dentated blocks means that the positions of the long and short sides cannot be adjusted independently of each other, as they can for rectangular blocks. An algorithm has been developed which computes an optimal position for a dentated block relative to the previously laid blocks, ensuring that any minimum gap constraints are met. Thus, a pavement consisting of a large number of variable blocks can be automatically simulated. In actual block laying, [6, p.205] says that blocks are placed in contact with previous blocks and allowed to fall into place. This is simulated by placing blocks in a position which is controlled by the dimension of the largest spacer nib involved.

As illustrated in Figure 1, the EB pavement develops with a long triangular face. At some point it is usual, and generally necessary, to finish off laying a square or rectangular region. An alternative laying strategy is that the area is covered by a series of small squares (or rectangles) in which case the requirement for laying a large pavement is that smaller square

areas interlock with the previous square(s). A pavement laid in such a manner will be referred to here as a *patchwork*, and the individual smaller areas of pavement as *patches*. The paper will investigate, through simulation, the differences between laying an area as a single square, or as a patchwork of patches. This study was in part prompted by the need to move toward modelling mechanical cluster laying of blocks, for which the patchwork is an approximation.

Simplifications
Some aspects of real blocklaying practice are simplified by this model. One row of blocks is placed at a time, according to predetermined algorithms, with no allowance for subsequently adjusting blocks. While this may appear to be a limitation, it is important to realise that the result obtained from the model show that discrepancies which may have an important subsequent effect on the pavement may not be discernable even to an expert eye, and that practical experience shows that attempts to fix up more than extremely small areas of pavement meet with little success. Further, the development of block/laying/gap specification paramenters which facilitate the laying of a large area of paving successfully in a single pass without revision would be commercially desirable.

In the modelling presented in this paper, the thickness of the blocks is ignored, so that only the plane pattern on the surface of the pavement is considered (or alternatively the blocks are assumed to have been laid on a perfectly plane substratum). Further modelling work is planned to address this additional variable, and also a more accurate representation of machine cluster laying.

Gap Performance Results

A sequence of factorial experiments has been carried out to identify those regions of the parameter space determined by design gap, nib dimensions, block and nib variance, block shape (rectangular or dentated) and single square or patchwork laying. The selected results presented here demonstrate some of the interesting features of the comparisons that varying all these parameters simultaneously affords.

Input Parameter Ranges
The results reported here examine blocks laid with nibs of nominal dimensions Nmm, N+0.2mm and N-0.2mm. The nib dimension is a random quantity with the nominal dimension as its average, and with standard deviation 0.08mm or 0.12mm, following the Beta probability law. The performance of the blocks was investigated for nominal design gaps DGmm and DG±0.6mm. Again, the actual size of the simulated blocks was a random quantity, with average length and breadth determined by subtracting the DG value from a nominal module size, determined so that the same number of rectangular as dentated blocks would be required to cover a given area. The allowable standard deviation values for blocks correspond to 99% of blocks being within ±0.35mm to ±0.88mm on the block dimension (Australian Standard specifies blocks to be within ±2mm of nominal dimension). Each combination of input parameters was used for two runs of the Monte Carlo simulation, to allow the differences resulting from different random number seeds to be incorporated in the results.

Output Gap Patterns

As well as numerical results relating to conformance with the acceptance criteria, it is interesting to see how the spatial pattern of gaps varies for different scenarios. Figure 3 shows oversize gap patterns developed with identical dimension input parameters, the left side with rectangular blocks and the right with dentated blocks. The rectangular blocks are clearly less sensitive to unfavourable parameter combinations. These results are samples of the pattern of oversize gaps typically found in simulated pavements. The striations, or tears, are a noticeable feature of the pavement, and the different directions of these striations are an interesting difference between the two block types.



Rectangular blocks Dentated blocks

Figure 3

Numerical Measures of Gap Performance

Figure 4 summarises one of the most significant results of numerous experimental runs of Monte Carlo simulation using all possible combinations of the input parameters (a full factorial experiment). On the left are displayed results for laying a single square region 5m by 5m, and on the right the same area laid in patches 0.8m by 0.8m. The upper pair of diagrams relate to interlocking blocks, and the lower pair are for rectangular blocks. The display shows the maximum gap size in the simulated pavements, each averaged over 12 repeats of the Monte Carlo simulation, with four different combinations of block and nib standard deviation involved in the averages.

Laying blocks in patchwork appears to magnify problems which can be generated in the single square strategy; the maximum gap size for each parameter combination being consistently larger for the patchworks. For all the four pavement types, the worst values for maximum gap occur when design gap is nominally DG+0.6, while there is relatively little difference between DG and DG-0.6 in any of the scenarios. It is not possible to make a similar statement about the influence of changing nib dimension N. For DG and DG-0.6, increasing the nib dimension tends to increase the maximum gap recorded. However, for DG+0.6 the maximum gap recorded is worst when the nominal nib is smallest.

Overall, the rectangular blocks perform better for the majority of parameter combinations. However, the dentated blocks in the combination of smallest design gap and smallest nib mean dimensions give the best performance for both single square and patchwork, and for the

single squares one half of the parameter combinations favour dentated blocks, the other favour rectangles.

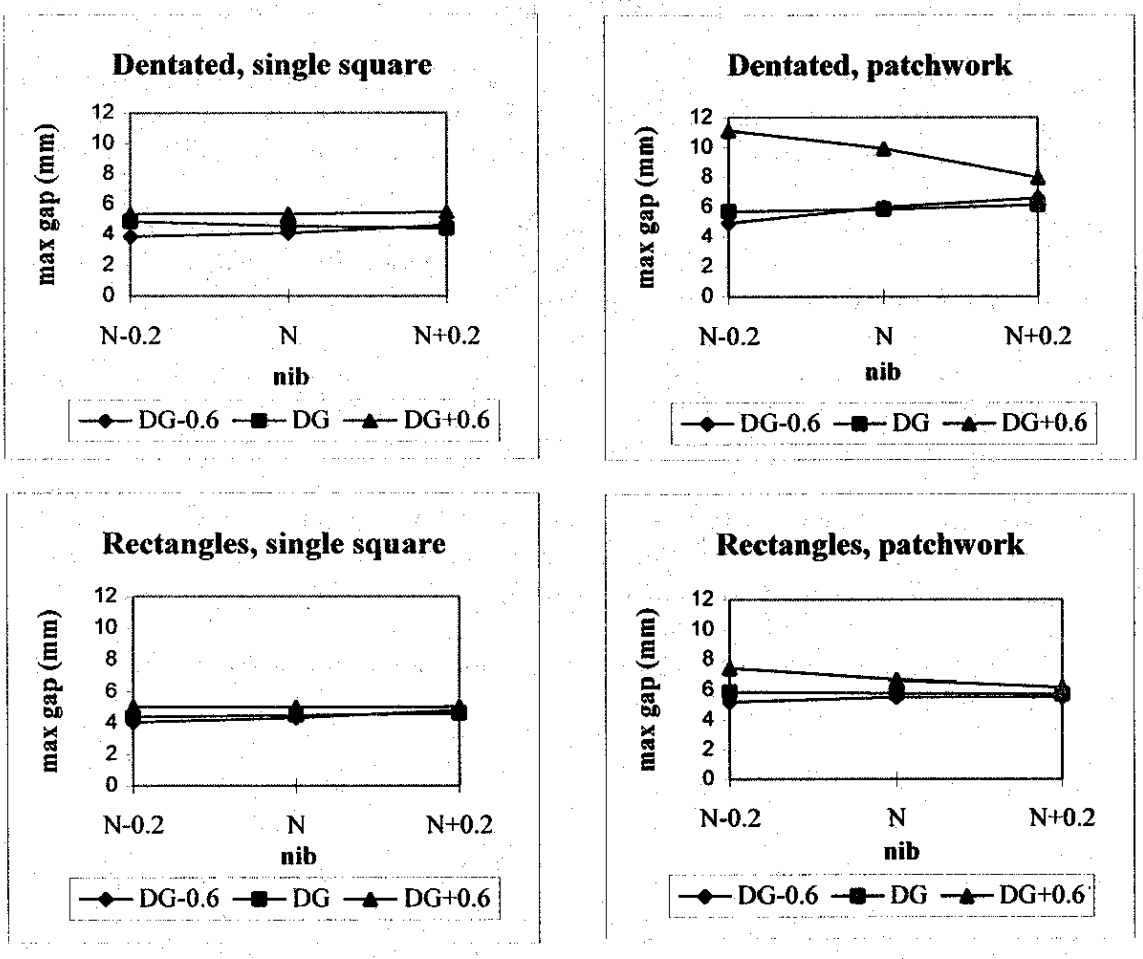


Figure 4

Other results, not displayed in a figure, show that increasing the amount of variation in the blocks makes a statistically significant increase in the maximum gap resulting (averaged over all the 36 combinations of other input parameters), and that this is a consistent result for all input parameter combinations in all four laying scenarios.

Conclusions

The factorial experimentation process has shown that there is interaction between the design features (the designer's selection of a value for block shape, design gap and nib dimension), manufacturing features (the standard deviation particularly of the block dimensions) and the laying strategy (patchwork or larger squares). Other studies have shown that the results for elbow bond reported here are not consistent with results for herringbone bond, and this is under investigation. These interactions must be understood for optimal performance.

It follows that it is essential for a block designer to determine desirable mean values for key dimensions, an achievable amount of variability for block and nib dimensions, block shape, and desirable proportions, given the particular gap size criteria being imposed and the proposed laying strategy.

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