MECHANISMS OF PAVER INTERLOCK

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SYNOPSIS

It has long been known that, both during construction and under traffic, pavers progressively wedge together and develop interlock. As a consequence, CBP surfaces behave like articulated slabs when distributing traffic loads. Whilst many measurements of the load spreading properties of paver surfaces have been reported there is still only an incomplete understanding of the mechanisms whereby pavers interact and share loads. This paper seeks to explore some of these mechanisms by both theoretical and experimental studies.

The paper begins by studying the interactions that can develop between adjacent pavers and between pavers and the bedding and jointing sands. The paper makes use of extensive profilometer data obtained in the field from a variety of CBP currently in service. Laboratory shear box and repeated triaxial load test measurements on a typical sand are then used to predict the forces that can assist load sharing between groups of pavers. It is demonstrated that these forces can be significant. Overall, the paper helps achieve a better understanding of the in-service behaviour of CBP and to understand the roles of factors such as paver shape, joint width and the choice of jointing sand.

1. MECHANISMS OF PAVER INTERLOCK

Even block pavements which are judged to be well layed typically exhibit small rotations of the pavers relative to one another. These rotations develop both during construction and under traffic. Such small movements are almost imperceptible to the naked eye but can be measured using profilometers to map the surface of the paving. Measurement shows the rotations are usually less than 10° and are associated with surface displacements typically less than 5 mm. Accordingly, the movements may appear to be of little practical import. However, because concrete pavers are manufactured to much higher and more consistent dimensional tolerances than any other form of segmental paving they tend to be laid so that the joints between the pavers are consistently narrow and relatively uniform in width. For example, in Australia, it is customary to require paving to consistently achieve joint widths within the range 2 to 4 mm and this proves relatively easy to attain in practice provided normal tolerances are maintained during paver manufacture. With such narrow and consistent joints rotation of a paver soon results in it wedging against its neighbours as shown schematically in the cross-section, Figure 1. As shown in this figure, the wedging action caused by rotation of paver B around a horizontal axis leads to the development of horizontal forces within the paving.

The wedging action illustrated in Figure 1 explains why it is commonly observed that paver surfaces can push over inadequate edge restraints and make the reinstatement of trenches difficult or impossible unless the surrounding paving is restrained from creeping inwards (Shackel, 1990). More importantly, it also explains why pavers act as a structural surfacing rather than merely providing a wearing course (Shackel, 1979, 1980 1990, 1999, 2001, Shackel et al , 1997, 2000). It is therefore of interest to examine the factors and forces contributing to the development of horizontal forces between pavers within concrete segmental paving. These factors include the paver shape and the laying pattern.

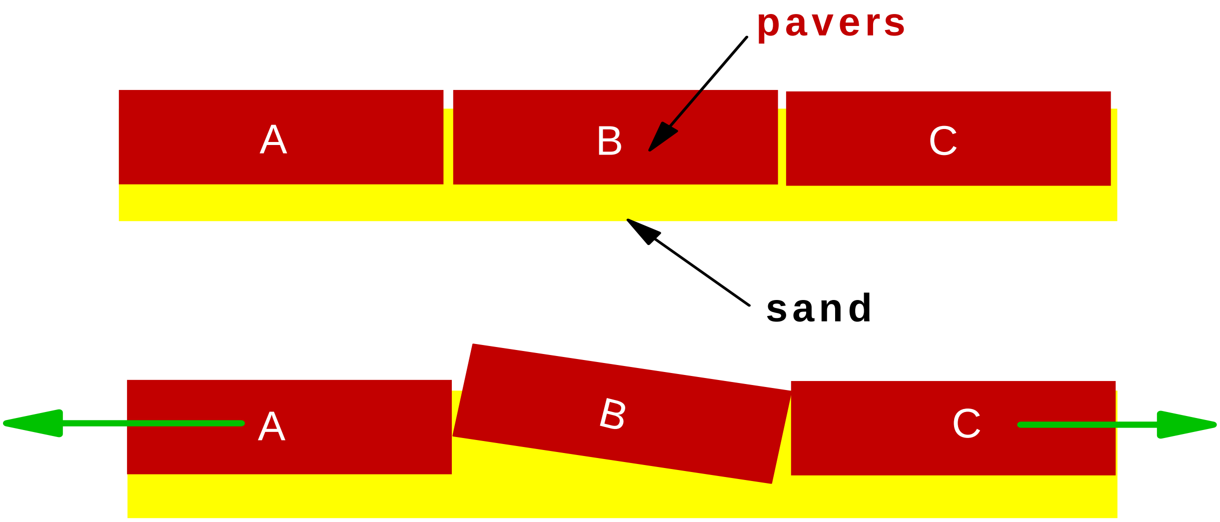

Figure 1. Rotation of paver B causing outward wedging of pavers A and B

The effects of paver shape can be understood by considering the effects of paver rotation upon the wedging together of the pavers. For the case of rectangular pavers this is illustrated schematically in Figure 2 Referring to this figure, if pavers B is subject to rotation about a horizontal axis through it's mid point then it is free to slide upon pavers A and C and will only push on pavers in line with the rotation such as paver D in Figure 2.   Wedging therefore occurs only in the direction shown by the arrows in Figure 2.

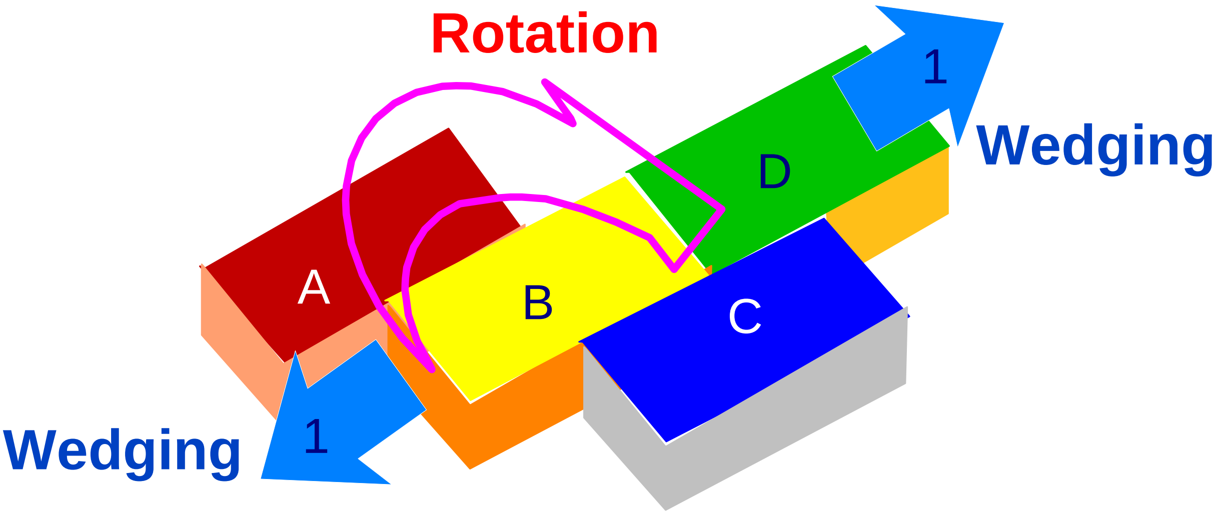

Figure 2. Effects of rotation on the wedging action of rectangular pavers.

By contrast, if the same rotation is applied to a shaped paver, then, as shown in Figure 3, paver B cannot rotate without pushing pavers A and B away. Consequently wedging now develops in the two directions shown by arrows 1 and 2 even though the applied rotation remains uni-directional. This provides a simple explanation why shaped pavers have been reported to exhibit higher moduli and better in-service performance than rectangular pavers (Shackel, 1979, 1980, 1990, Shackel et al, 1997).

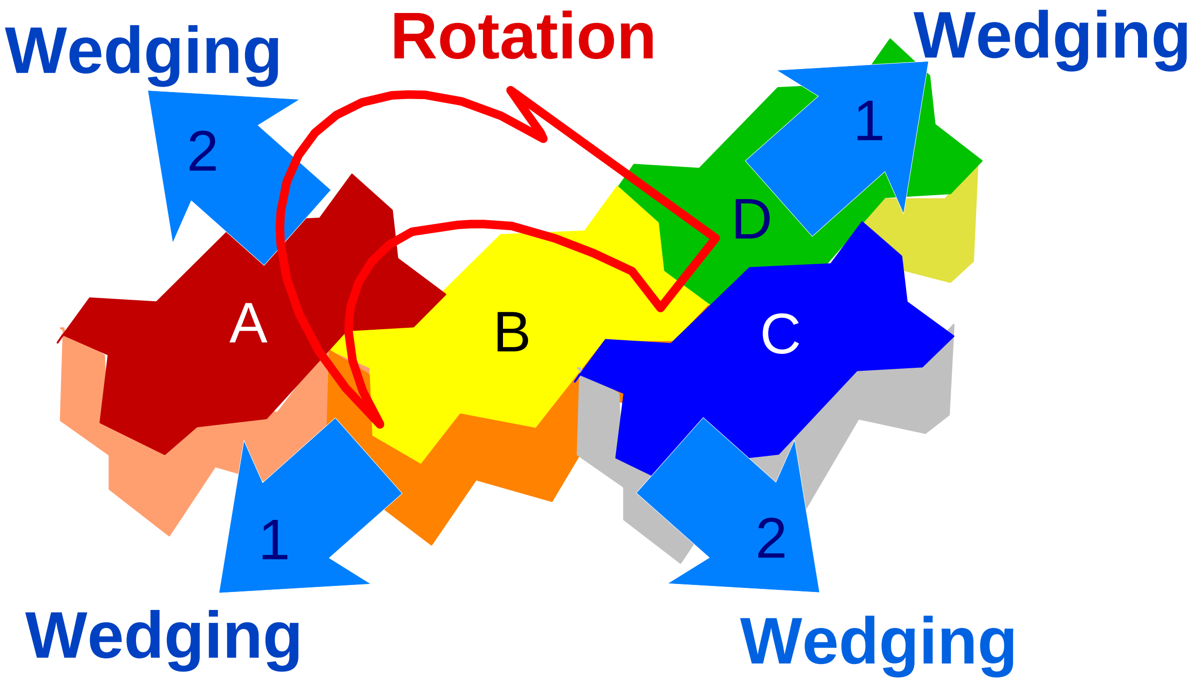

Figure 3. Effects of rotation on the wedging action of shaped pavers

On the basis of both tests and experience, engineers have long known that paving installed in herringbone patterns performs better than when laid in the stretcher pattern shown in Figure 2 and 3. Again, some explanation of this can be obtained by considering the effects of paver rotation. Figure 4 shows this for rectangular pavers.

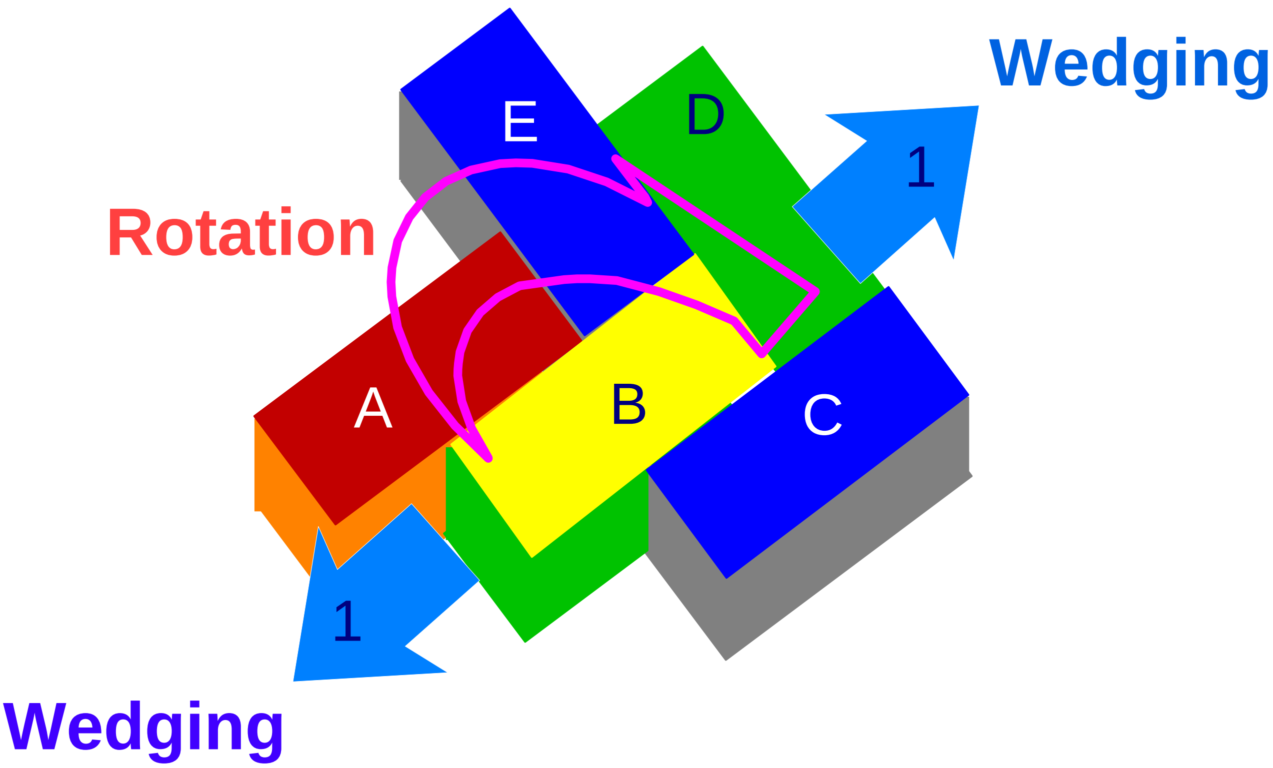

Figure 4. Effects of paver rotation on paving layed in herringbone bond.

From Figure 4 it may be seen that whilst, as in the case of stretcher bond, rotation of paver B can still occur without horizontally displacing pavers A and C, the movement of paver B about a horizontal axis will now induce some rotation of paver D around a vertical axis. This is in addition to developing horizontal wedging as shown by the arrows 1. This will tend to increase the wedging action throughout the paved surface and provides some explanation why herringbone patterns perform better than stretcher bond.

Some authorities have claimed that, once rectangular pavers are installed in herringbone pattern, they perform in a manner similar to shaped pavers. This is, however, contradicted by the results of both trafficking and laboratory load tests (Shackel, 1979, 1980, 1990). The most likely explanation for this is that, as shown in Figure 5, wedging in directions both along and across the axis of rotation remains the inevitable consequence of paver rotation irrespective of the laying pattern. Here the choice of herringbone bond merely adds additional wedging movements to the paving surface because of the induced rotations of the pavers about vertical axes.

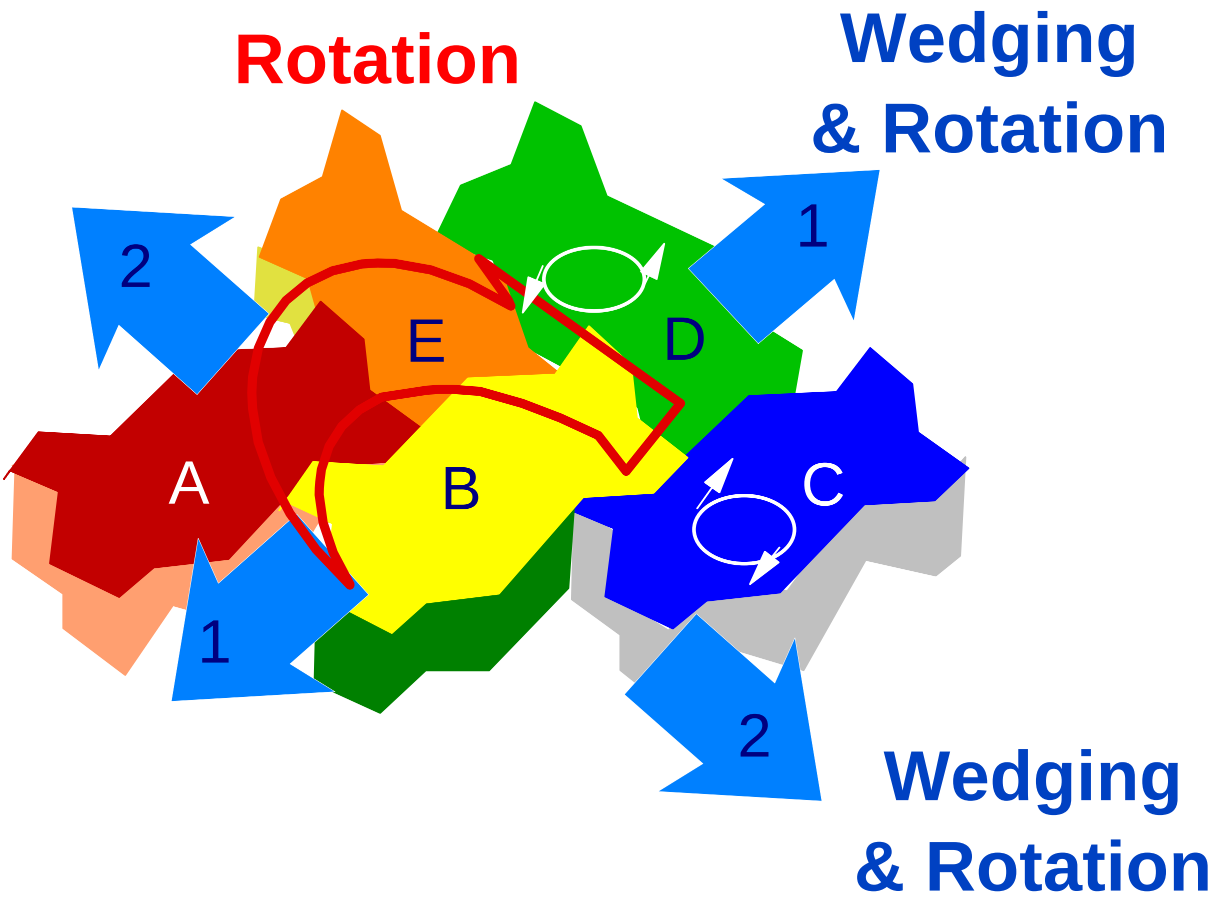

Figure 5. Effects of paver rotation on shaped pavers layed in herringbone bond.

The explanations of the effects of paver shape and laying pattern given above are simplistic because paver rotations are seldom confined to movements about just a single axis. Moreover, no account is taken of the joint width or the nature of the joint filling material. It might be argued that because most pavers are now fitted with spacer nibs the importance of the joint width and the joint filling material is minimal. However, it is usually found that the actual joint widths measured in pavements are bigger than the spacers. Moreover, tests of pavers fitted with spacers have shown that the pavers develop little or no structural strength when the joints are left empty (Shackel et al, 1996). In other words, the joints are crucial to segmental pavement performance. This is now considered in more detail.

2. THE ROLE OF THE JOINTS IN PAVEMENT INTERLOCK

In describing and modeling the behaviour of segmental paving many hypotheses have been advanced to explain the role of the joints. The movements that are likely to occur at the joints in segmental paving are shown schematically in Figure 6. These comprise movements caused by rotations and linear displacements of the pavers. In practice the movements shown as (a) and (d) in Figure 6 are less likely to occur than the other movements because they imply net elongation of the pavement. This will only occur when the pavement experiences rutting or heave i.e. some departure from the as-installed profile. In normal service the movements of pavers are likely to comprise combinations of both rotations and translations. In this respect it can be said, for example, that movement (c) in Figure 6 represents the combined effects of movements (b) and (f) or (a) and (e).

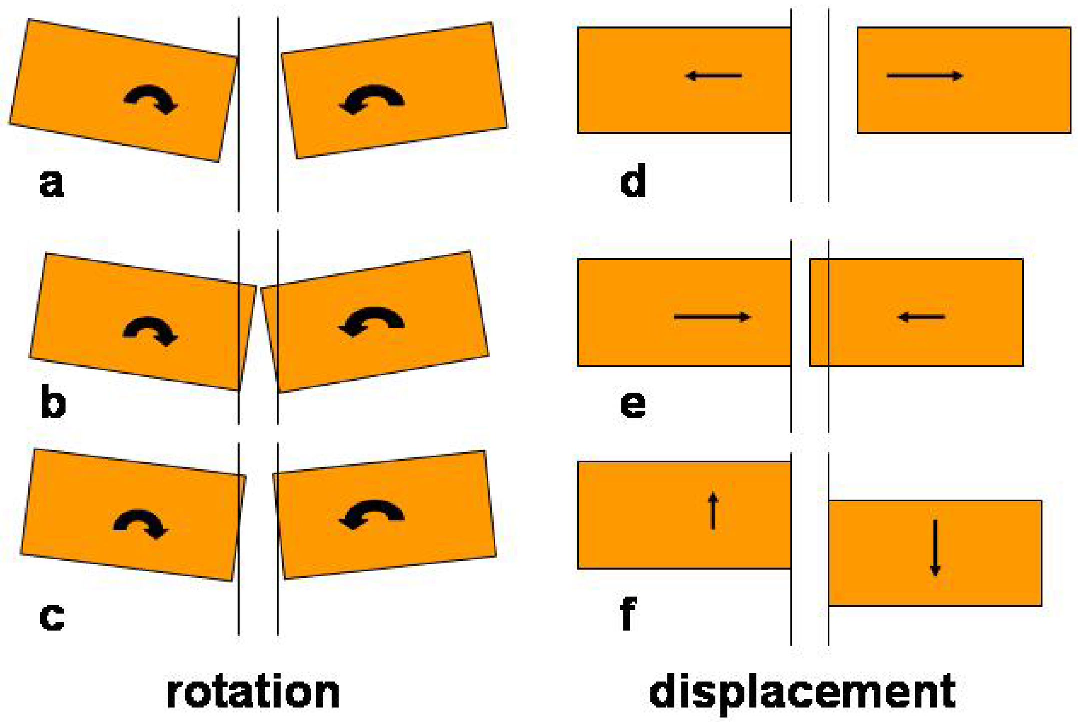

Figure 6. Movements at the Joints

Using profilometer studies it is possible to measure rotations between adjacent pavers and to measure lipping movement such shown as Figure 6(f). However, horizontal displacements such as those illustrated as Figure 6 (d) and (e) can only be measured directly and cannot be obtained from profilometer data. Nevertheless, some estimates of the strains in the jointing material can be obtained. Provided the stiffness of the jointing sand is known the strains can then be used to estimate the stresses in the material. Accordingly, to study the role of the jointing sand, measurements of typical jointing sand properties were combined with profilometer and joint width surveys of a range of concrete segmental pavements. The principal objective of this work was to estimate what magnitudes of force might be generated within the joints.

2.1 Sand Properties

For the purposes of this investigation a jointing sand widely used in the Sydney region was selected. This was studied by means of both simple shear and repeated triaxial loading tests conducted on both dry and saturated samples. The repeated loading triaxial tests followed AUSTROADS test procedures for characterizing unbound granular pavement materials. A summary of the sand properties measured by these tests is given in Table 1.

Table 1. Properties of the Jointing Sand

PROPERTY	CONDITION	
	Dry	Saturated
Angle Of Shearing Resistance	37°	35°
Cohesion (kPa)	1	2
Lower 10th Percentile Resilient Modulus (MPa)	71	54
Mean Resilient Modulus (MPa)	151	127
Upper 90th Percentile Resilient Modulus (MPa)	230	200

2.2 Profilometer Measurements

Surface profiles were already available for several concrete segmental pavements. These covered the conditions ruling immediately after the pavers were laid, following the first and second plate compactions (i.e. before and after filling the joints) and once the pavements had been under traffic for some time. All the pavements had been installed in herringbone bond using shaped pavers. The pavements had been laid flat without camber. The profiles were interpreted in terms of the vertical shearing displacement ("lipping") and the angular rotation of each paver relative to it's neighbours. These data are summarised in Tables 3 to 6.

2.2.1 Lipping

Lipping is the vertical movement along a joint between one paver and the next such as shown in Figure 6(f) i.e. a shear displacement. Lipping may be caused by many factors but, in these discussions, it the consequences of lipping that are important. It can be postulated that such shear movements of the joints may cause the jointing sand to dilate and, thereby, to increase the horizontal forces between pavers. Thus the measurement of lipping displacements may provide a means to estimate the forces in the jointing sand. Measurements of lipping from the profilometer data are summarised in Table 2 and Figure 7. From these it may be seen that lipping was greatest when the pavers were first installed but decreased during each stage of compaction. However, once the pavements were in service, lipping tended to increase under traffic.

Table 2. Summary of Lipping Measurements

Condition	50th percentile Lipping Displacement (mm)	80th percentile Lipping Displacement (mm)
Before compaction	0.8	1.0
After 1st compactiom	0.1	0.45
After 2nd compaction	0.0	0.33
After trafficking	0.56	1.21

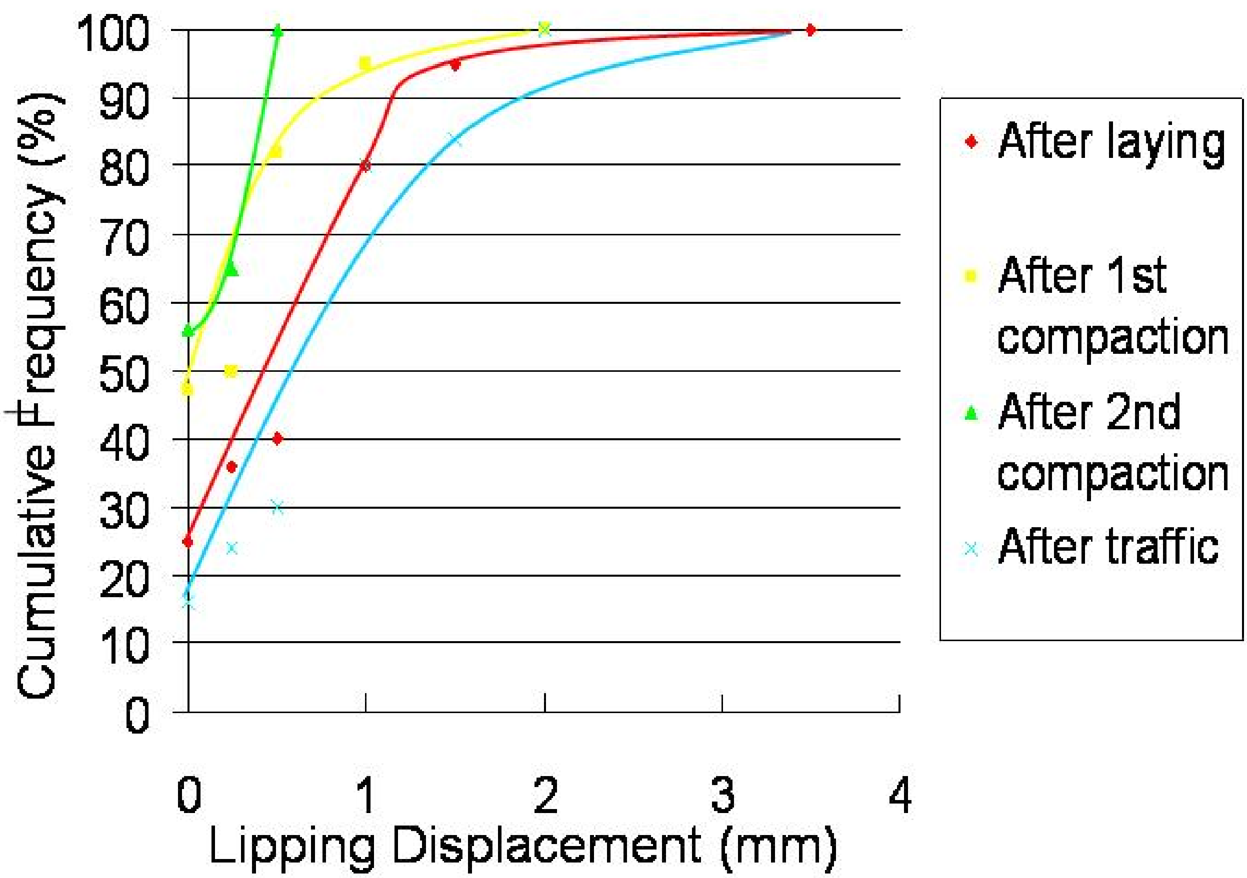

Figure 7. Lipping Displacement Measurements

The data summarised in Figure 7 and Table 2 showed that the lipping was generally not severe enough to cause a trip hazard or to visually impair the paving. Significantly, the magnitudes of the displacements within the jointing sand were much less than those needed to cause dilatancy in simple shear tests of the typical jointing material selected for study. Combining these data with the sand properties summarised in Table 1 led to an estimate of the average compressive stress in the sand caused by lipping displacements of no more than 5 to 6 MPa. It may therefore be concluded that shear in the jointing sand is probably not the major source of the horizontal forces that develop in concrete block pavements but, nevertheless, may make some contribution to these forces.

2.2.2 Paver Rotation

Superficially, it might be thought that only the rotation represented by Figure 6(b) could generate compressive force between pavers. However, it is important to recognise that a non-cohesive, frictional jointing sand can only transmit compressive forces. Accordingly, opening of the joints cannot generate stress in the jointing material where such stresses would be tensile. For this reason, all of the rotations shown in Figure 6 except (a) will result in some net compressive stress between adjacent pavers.

Large numbers of joint measurements over many segmental paving projects have shown that on average the mean joint width is usually about 3 mm for shaped pavers (Shackel, 1990). Moreover, at the time that the profilometer measurements were made, Australian paving specifications typically required the joint widths to be between 2 and 4mm after compaction. For the pavements for which the profilometer data had been collected the actual joint widths were not available. However, it would be reasonable to assume that the pavers were initially installed to achieve a mean joint width of 3 mm. This assumption made it possible to calculate the change in joint widths that would have occurred because of rotation of the pavers away from their initial profile. The frequency distributions of the changes in joint width could then be calculated. These are summarised in Figure 8 and 9 for the rotations shown schematically as Figure 6 (b) and (c).

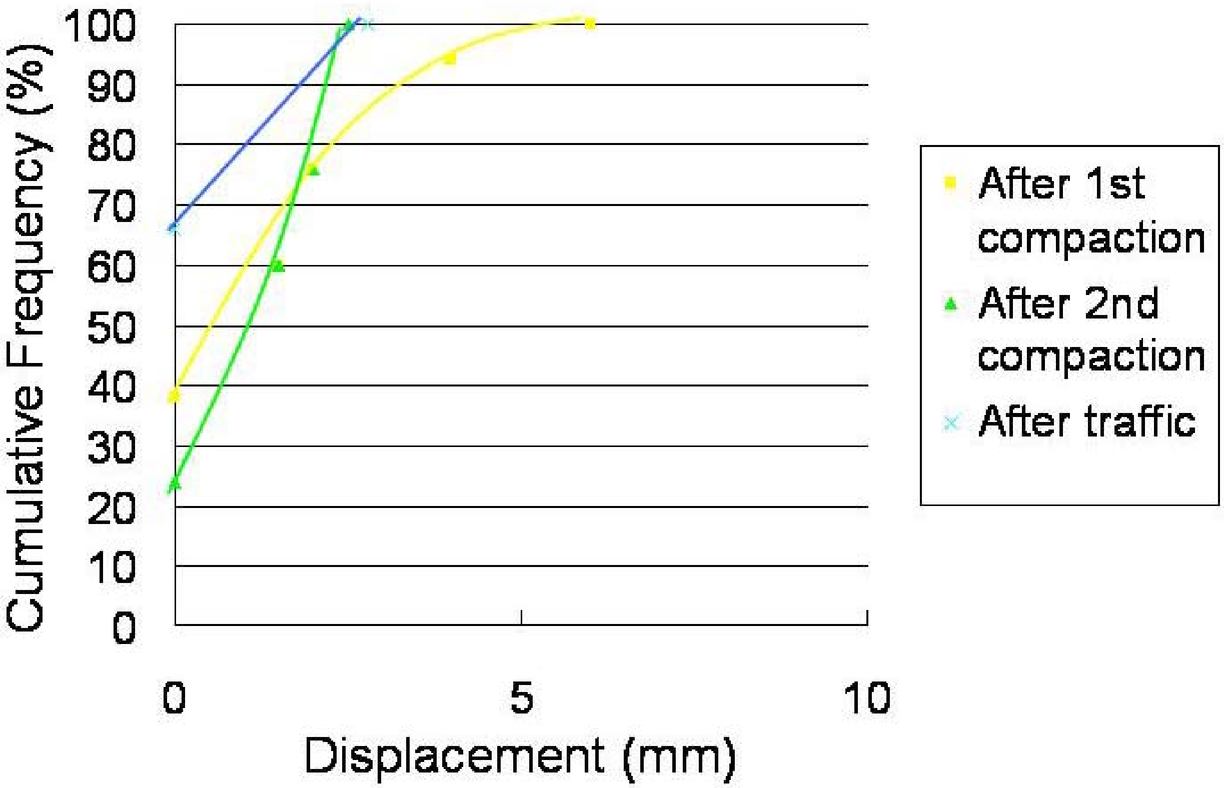

Figure 8. Distribution of displacement assuming pavers rotated about their tops

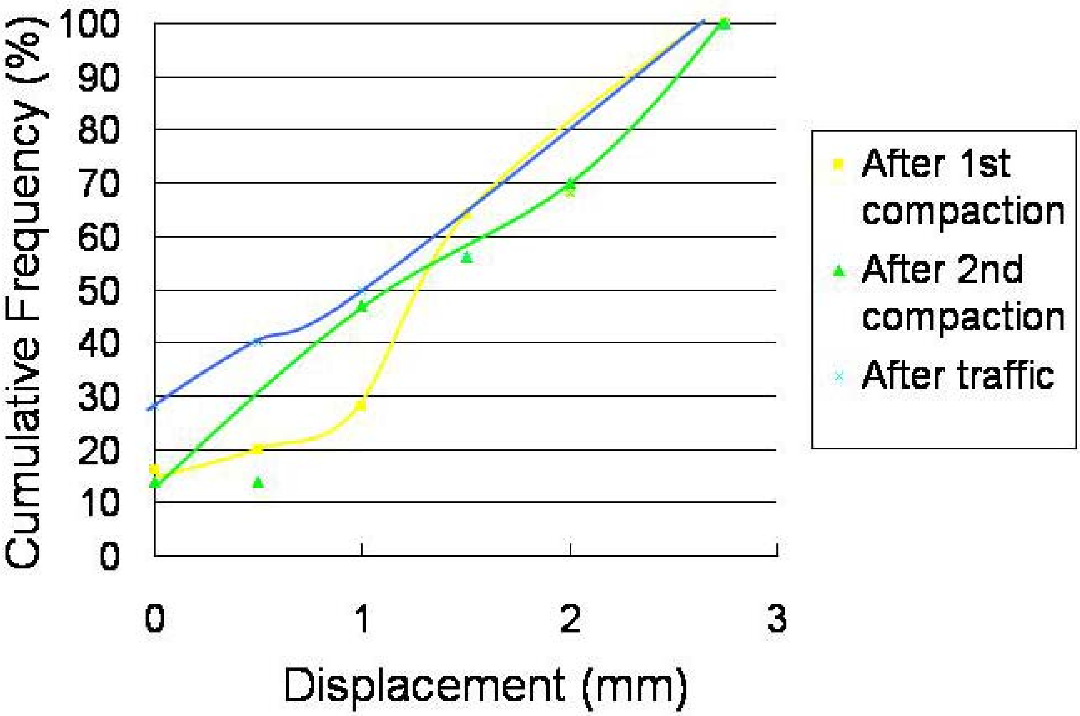

Figure 9. Distribution of displacement assuming pavers rotated about their mid points

Figure 8 is based on the assumption that the rotation was as represented schematically in Figure 6b. As noted above, this type of movement is associated with the pavement having departed from its design profile because of rutting or heaving. It will be seen that, as would be expected intuitively, the calculated displacements are much bigger than for the rotation illustrated as Figure 6c which assumes that the pavement remains close to its original profile (Figure 9). In this respect, Figure 8 shows that the joint displacements tended to decrease after each stage of compaction and decreased further under traffic. By contrast Figure 9 shows less evidence of compaction or traffic significantly reducing the displacements

By combining the calculated changes in joint width with the measured values of the resilient moduli of the jointing sand it was possible to estimate the range of compressive stresses that might theoretically develop within the jointing sand. It is important to note that, as for all granular materials, the resilient modulus of the jointing sand depended on the stresses in the sand (e.g. Shackel, 1973). Unless the magnitude of these stresses is known the resilient modulus cannot be accurately determined. The lowest value of confining stress used in the repeated loading triaxial test was 21 MPa. At this level of confining stress, resilient moduli between 60 and 90 MPa were measured depending on the degree of saturation. However, it was decided to use a more conservative estimate in computing the stresses in the sand and the resilient modulus was assumed to be just 50 MPa corresponding to the lower 10^{th} percentile of the measured values (Table 1). Combining this value with the computed displacements shown in Figure 8 gave average compressive stresses of up to 6 MPa between pavers based on the 50^{th} percentile displacements increasing to 20 MPa for the 80^{th} percentile displacements. For the data shown in Figure 9 the corresponding stresses ranged from 10 MPa for the 50^{th} percentile displacements up to 20 MPa for the 80^{th} percentile displacements.

3. CONCLUSIONS

This paper seeks to provide explanations of the mechanisms whereby pavers interact with one another to develop those unique load sharing structural characteristics that distinguish them from other forms of flexible pavement surface. This is sometimes termed interlock. The paper postulates that the mechanisms of interlock arise from the combined effects of paver rotations and shear movements (lipping) induced either during construction or which develop under traffic. In addition, lipping *per se* is sometimes used as a measure of the surface finish of CBP as it may indicate a trip hazard if not properly controlled.

From the analyses reported above it may be concluded that

1. Differences in the performance of segmental paving associated with paver shape or the choice of laying pattern can be explained, at least in part, by the wedging action that develops because of pavers rotating both during construction and under traffic.

2. For the pavements studied, lipping tended to decrease during construction only to subsequently increase under traffic.

3. The shear displacement or lipping that often develops between pavers is generally too small to mobilize significant dilatancy forces.

3. The forces developing between pavers due to lipping movements are calculated to be no more than 5 MPa to 6 MPa at most.

4. The average compressive stresses resulting from pavers rotating against each other can, at least in theory, achieve values from about 6 MPa up to 20 MPa.

The estimates of inter-paver stress given above are based on measurements made on real concrete segmental pavements. However, several simplifying assumptions were required in order to interpret these measurements. Despite this, the work reported here is useful in indicating that significant stresses can develop within the joints of segmental paving. This deserves much more experimental study so that the inter-paver forces can be properly quantified and modeled. This will help further define and quantify the mechanisms whereby CBP develops its structural strength.

4. BIBLIOGRAPHY

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