

Paving Design:

Is rigid-fix external stone paving the way to
go?

Introduction

Although paving is an important element in modern construction it was essential element in historical times for the movement of people and goods. In more-recent times paving is often ornamental, rounding off the design and complementing the construction, but even today some paving is meant to be functional as well as providing the high aesthetic value afforded by the use of natural stone.

Unlike the historical paving which was often somewhat boring and admittedly a bit rough (in more ways than one) modern processing techniques allow for a much greater range in the type of stone and in the dimensions of the stone paving. Furthermore there have been many significant advances in bonding media (adhesives, grout, and sealants) and protective coatings. Modern engineering test facilities are available to test stone and computers can be used to simulate load conditions. Yet there have been numerous significant paving failures in the last 20 years all over the world. Usually these failures have been due to a combination of contributing factors – not just a single factor 0- and some of the failures have been surprisingly elementary.

There are many key factors' that need to be considered in the design and successful construction of standard paving. For more-demanding paving, involving factors such as exposure to the elements and exposure to complex loadings, the analysis needs to be substantially more rigorous, Stone paving is not just a simple matter of sticking pavers to a prepared concrete bed or placing them onto compressed decomposed sand. Each major application is different and involves a combination of different factors. Expert advice needs to be sought on the stone to be used, how it is to be laid, by what pattern and on the maintenance of it. Short-cuts cannot be taken and in-house advice is inherently inadequate. Persuasive advertising, extended warranties, long associations with suppliers and that ever-pressing need to win contracts by those suppliers should not be determining issues.

Recent involvement in a number of paving applications has prompted me to examine and document some of the factors that can determine the success or failure of paving (assuming a high standard of workmanship) additionally, it has become clear that investigations into paving failures in Australia have failed to fully understand complexities and interplay of many of the factors.

There are basically three types of paving systems – adhesive fix, sand--bedded, and setts/cobblestones in a soft mortar. All three systems are being used in Australia but there is undoubtedly and overriding rigid fixing mentality. By fixing stone to a solid concrete base so that it cannot move is probably seen by the engineers and architects as the most straight-forward and most controllable solution. However, on analysis, it is a system that is subject to numerous potential lines of failure. Sand-bedding is a system that relies on a compressed graded sand or deco base upon which are placed smaller and thicker stone pavers in a particular patters,. Special sand is used between narrowly jointed pavers to lock the pavers into place; this is a system that is widely used in Europe and North America. Among the benefits are ready access to underground service, easy replacement in case of failure, and easy maintenance. The sett/cobblestone paving system utilizes small, usually square or cubic units varying in thickness from 30mm to at least 150mm. Their use tends to be restricted to areas of limited traffic and they can be laid in a variety of straight and radial patterns.

A paving project generally starts with a client's and/or architect's vision. The drawings then tend to go to and engineering section and progress to the budgeting section. None of these sections really know much about the performance of any stone and hope that they can get most of the information from a supplier (who hopes to make as much profit as possible, with the least amount of work and commitment, and with fingers crossed that everything will work out). But often the supplier does not know much about the stone (eg. Calling a marble a bluestone or calling a basalt a granite in not unusual) and because most of the stone is now being imported there is quite often a language problem between and Australian buyer and overseas supplier. Surprisingly, many overseas quarries do know what they are selling but this is not always conveyed to the purchaser in Australia. Unfortunately there are also some overseas suppliers who see Australia as a target for

dumping inferior material because of a perception that Australians have little expertise with respect to stone. This was confirmed recently by a European who claimed that Australians cannot tell s... from clay.

Assuming the client and architect have agreed on a colour and pattern for the stone and between them the engineers and budgeting section have agreed on a size and quantity they go to tender (unless there is a preferred supplier). Competition is fierce and potential suppliers will break their necks trying to get the contract. This usually means screwing the overseas supplier as much as they can get away with. And that is where quality is often compromised, not only in the stone quality but in the quarrying, processing and delivery.

Once the contract is let how much does the client really know about the quality of the stone that is to be delivered and how can he be assured that delivery will be of the standard expected from the conditions written into the contract. A financial stick is usually successfully applied to the Australian supplier but what happens when the overseas supplier encounters a change in the type of stone in quarry, gets into financial trouble, has machinery breakdowns, or demands more money for his product. Some of the human aspects cannot be controlled but at least the quarrying, production, quality control and shipping of the stone can, and must be organized before supply commences. An experienced stone scientist should be involved in every project dealing with a substantial amount of stone whether it be for paving or for any other application. This will ensure that the stone is available to be quarried, that the quarry has the capacity and expertise to quarry it, that it can be successfully processed in one or more designated factories, that quality control procedures are put in place and rigorously followed, and that testing of the stone will be carried out to Australian requirements. So for the small additional expense (in relation to the overall cost of the stone) the client can be assured that he gets delivered the stone at the time required and of the quality required.

(a) Factors that commonly assume a secondary role in paving integrity

1. Stone Composition

Most stone sold for paving compositionally sound provided that it is not placed in a chemically and physically demanding situation without undue stress. Once placed into an external environment the stone becomes subject to a variety of stresses. If mechanical loading is placed on that stone another set of stresses are added. This now requires a rigorous evaluation of the stone product to assess its suitability for that situation.

Although there are approximately 2,700 granitic rocks available on the world market and their compositions cover almost the entire spectrum of possible granite compositions on this earth they rarely consist of more than half a dozen minerals out of the dozen or so common minerals that make up the majority of common rocks. Quartz and the two varieties of feldspar (alkali and plagioclase) dominate most paving stone with small amounts of ferromagnesian minerals (biotite, amphibole, pyroxene), and traces of iron-titanium oxide competing the primary mineralogy. There are usually some secondary minerals in small amounts (eg. Clay, white mica, hydrated iron oxide, epidote, carbonate, and chlorite) and provided these remain as small amounts the stone is usually sound mineralogically. The basalts, dolerites and gabbros differ from granites in their mineralogy by having little or no quartz (hence softer), little or no alkali feldspar and minor amounts of biotite and amphibole. Instead, they contain abundant plagioclase feldspar and pyroxene (usually the calcic variety), lesser olivine, and variable but usually minor amounts of iron-titanium oxide. So, unless there are minerals and/or structures in a certain stone that might prove deleterious to its short- and long-term performance (such as reactive pyrite) the mineralogy of most dimension stone is innocuous and plays little part in paving failures.

Limestone and sandstone are also used as paving. However, because they tend to be more porous than the igneous and metamorphic rocks and are made of minerals that are either more susceptible to weathering (chemical and physical attack) or are held together by a variety of possible cements, they are recognized as being less resistant to environmental and mechanical stresses. Their use as paving tends to be dominated by non-commercial situations or in a form that takes into account the intrinsic properties.

2. Stone Strength

The texture of the stone, together with its mineralogy and structure play a major role in determining the strength of the stone. There are several ways of expressing the strength of stone depending on whether it is under compression or tension, in a dry state, or saturated. Early tests relied on compressive strengths but the

advances in processing the stone into slabs meant that there was a need to also test the stone in tension. The degree of saturation appears to have little influence on the strength of most dense crystalline rocks but the type of surface treatment given to stone can cause a serious reduction in strength (eg. Exfoliation). Tests have demonstrated that there can be a 30-40% reduction in the strength of certain granites due to the generation of thermal fractures.

Most granites exceed the compressive strength of 131MPa and 10.34 MPa modulus of rupture values recommended by the American society for Testing and materials (ASTM) but some do not because of features such as secondary veining, closed joints, systematic microfractures, hydraulic fracturing, thermal fracturing, hydrothermal alteration and weathering. Some of these features are not visible macroscopically and testing of all stone must involve petrographic examination.

Most common granites have compressive strengths over 150MPa and modulus of rupture values in excess of 14MPa. Fine-grained black granites tend to be at the high end with values around 250MPa and 25MPa, respectively. These values exceed by far the values for general commercial concrete which is required to have a compressive strengths of at least 32MPa. For comparison, the compressive strengths for a range of sandstones varies from around 40MPa to 75MPa and limestone from less than 20MPa to more than 120MPa.

In terms of choosing granite paving, absolute strengths above the recommended values play only a minor role in most applications, ie. There is little real difference in the performance of 160MPa granite compared to 190MPa granite. The most important aspect of stones strength is that it comfortably exceeds the minimum values. Granites not meeting these values are inherently weak and should not be used for exterior commercial paving.

3. Stone Colour

The colour of the stone is basically a function of its collective mineralogy. Light coloured granites contain an abundance of felsic minerals (quartz, plagioclase feldspar and alkali feldspar) whereas dark-coloured granites contain mafic minerals (calcic pyroxene, amphibole, biotite, olivine, orthopyroxene, and magnetite). Variations in the proportions of the minerals and occasionally certain textures, structure and type of finish can also influence the colour of stone. Because each minerals has its own diagnostic physical characteristics large abundances of certain minerals can influence the colour of a stone. However, there is usually a considerable overlap in the modal abundance of some of the minerals and often it is only a relatively small abundance of some minerals which determines the colour. The colour might also reflect the chemical and physical stability of the constituent minerals and provide some insight into the weatherability and/or durability of the stone. For example, brown is not a natural granite colour. There are no fresh, brown minerals that make up a granite. Brown indicated alteration and this can be effectively masking the true colour of the stone. With increasing depth (usually coinciding with a decrease in weathering) the brown colour may give way to fresh, green-and/or blue –coloured granite.

4. Imbibition coefficient

This is a measure of adsorption capacity of the stone. It is an indicator of stone quality and stone strength by providing a measure of the pore space and degree of fracturing. In stone that has been partly altered or weathered some of the water can also be taken up by extremely fine-grained clays and micas. The water absorption of granites typically varies from 0.10% (by weight) to around 0.45%. These values are recorded after full immersion for 48 hours. The maximum amount of water absorption recommended by ASTM is 0.4% (by weight). The dark, strong plutonic rocks are typically the most dense (least porous) and also the strongest. With increasing amount of felsic (light-coloured) minerals the degree of hydrothermal alteration, weathering, pore space and structural defects tend to be high. Felsic granites are often not as strong as mafic plutonic rocks.

The porosity of stone is often expressed visually and can become an aesthetic issue. A darkening of the stone along expansion joints, a patchy darkening and a greyish discolouration are signs that resident subsurface water is penetrating the stone from the base up. Very little water, if any, penetrates through the stone from the surface. Whilst it is subsurface (most in the screed, mortar bed or adhesive) the water is accumulating dissolved calcium and iron compounds. These substances (among others are then drawn through the stone by the thermal “engine” causing reaction and remobilisation of chemically susceptible and unstable minerals

en route to the surface where they precipitate. A high porosity will enhance this process and is one reason why beige granites appear to oxidise/dicolour more than dark-coloured granites.

It has been suggested that the absorptions capacity of certain granites can have a bearing on the setting/curing characteristics of mortar and/or adhesive. This is highly unlikely because most granitic stones would not be saturated at the time of laying nor would they have the capacity to draw large amounts of moisture out of grout before it has time to cure. The suggestion is true to an extent in the more porous limestone and sandstones which can suck up moisture or they can become substantially saturated after fixing.

5. Thermal conductivity

It has long been observed that dark-coloured stone appears to become quite hot at the surface when exposed in hot, sunny conditions and it has been suggested that the high conduction of heat through even 40mm thick black stone could be partly responsible for paving failure. The argument suggests that because of elevated surface temperatures there is a rapid conduction of heat through the stone thereby affecting the setting characteristics of the adhesive.

Scientifically, thermal conductivity is a measure of the quantity of heat Q transmitted through a unit thickness L in a direction normal to a surface of unit area A due to a unit temperature gradient ΔT and when the heat transfer is dependent only on the temperature gradient, ie. $I = Q \times L / (A \times \Delta T)$ and measured in watts per meter-kelvin $W/(m \cdot K)$. Although this is applicable to theoretical physics it is not strictly applicable to the changes of temperature from the top of a paver to the bottom.

Even the simpler concept of heat conduction (transmission of heat across matter) is not entirely applicable in the case of paving.

It was interesting recently to observe a situation where this argument was used against a failed 40mm thick stone, yet adjacent, identical 20mm stone (using identical adhesive) remains sound.

Another scientific fact is that with increasing silica content (as in light-coloured granite) there is an increase in the thermal conductivity compared to that of black granite but concomitantly there is a decrease in the thermal conductivity of stone as the temperature increases. This tends to have an evening effect between two apparent compositional extremes.

6. Heat retention of concrete base and stone

It has also been speculated that retention of heat by dark-coloured stone might adversely affect the bonding characteristics of the stone to concrete presumably due to a softening of the adhesive or causing it to become brittle. Thermal retention is essentially governed by three heat transfer mechanisms namely, conduction, convection and radiation and or a wide range of granites there is likely to be a little difference between their thermal retentivities principally for reasons outlined above.

Heating of the stone during the day is also likely to have a minor effect on the temperature of the concrete slab and therefore prolong the heat retention of the stone. Although unlikely to contribute to any degradation of the adhesive, elevated thermal conditions will slightly accelerate drying (and shrinkage) of the concrete base.

7. Thermal expansion

All natural stone and masonry materials expand as the temperature increase. In engineering terms it is known as the coefficient of linear thermal expansion and measured directly as $mm/mm/^\circ C$. Most stone falls within the range of 4×10^{-6} to 9×10^{-6} with slightly higher values for concrete over the same temperature range.

The thermal expansion of stone is one property that is usually understood by engineers who normally make adequate allowances for this property by the introduction of expansion/contraction joints at generous intervals.

Contrary to common beliefs there is no absolute relationship between the colour of a stone and its thermal expansion. A grey-coloured granite can expand more than a black granite even though the surface of the black stone might be hotter. Black stone often has a tight structure (few grain boundary imperfections, few microfractures) compared to say a mica-rich, partly altered grey or beige-coloured granite.

8. Stone Growth

Some porous stone such as a low-quality limestone, slate or sandstone have mineralogies and a structure which could be considered dimensionally unstable over time. Absorption of water into clay or mica-rich sedimentary rocks (especially with some dissolved chemicals and/or inorganic impurities), introduction of sulphates, and reactions between pollutants in the air with some minerals (eg. Gases of sulphur acting on carbonate) can gradually cause an increase in the overall dimensions of a susceptible stone. To achieve this, the stone must be at least moderately porous, must have an abundant supply of pollutants, is chemically reactive, and usually requires a long time. Most granites used for paving has a fairly dense and strong crystalline structure and does not all into the susceptible category.

Dimensional stability tests carried out in Australia have demonstrated a high degree of stability for granites compared with some porous sedimentary stone (albeit over a limited of time)

9. Climate

There is a perception that tropical climatic conditions impact on the performance of paving. This means generally elevated temperatures but with a restricted diurnal range, frequent rainfall during summer, heavy rainfall, extended periods of rain, and moderate to high humidity. Although these conditions could be considered uncomfortable and even difficult at times they are certainly not harsh or overtly detrimental to the performance of stone. For example, although temperatures can be in the low 30's (°C) and the number of sunlight hours/day quite high there is only a small diurnal range. Many places in say Perth, Adelaide and Sydney have similarly long daylight hours and significantly hotter daytime temperatures than in the tropics. They can also have somewhat high diurnal temperature range. This translates to greater stresses acting on the stone, adhesives and base than would be the case in the tropics. Moreover, the location of some paving is adjacent to the seafront and subject to persistent trade winds in winter and sea-breezes in summer. Huge areas of stone paving also grace many of the streets and footpaths of large cities, such as in Singapore, Hong Kong, Malaysia, Portugal, Saudi Arabia and the UAE.

A factor that is raised at times is the sudden quenching effect of relatively cool rainfall onto hot stone paving. Presumably the argument suggests that a rapid decrease in surface temperature will create stresses that can fracture the rock, cause a dramatic shortening of the stone surface which will affect the bonding with the mortar, concrete base or with the flexible construction joints, or which will in some way affect the adhesive. This argument has problems in three areas. First, there will be a large "inertia" within say 50mm thick pavers in that the thermal conductance is substantially slowed with prolonged wetting of the stone surface. In time, the heat transfer through the stone will equilibrate and should the stone surface cool to temperatures below the bottom of the stone, there will indeed be a reversal of heat transfer. It is important to realize that it only the top few millimetres of the granite paver that is substantially affected during the initial cooling period and not the entire paver. Because of the low temperatures involved in the "quenching", most igneous paving stone is capable of dealing with such stresses.

Second, to have any effect the cyclicity of these rapid cooling events needs to occur over decades. Failure of paving due to these climatic conditions is highly unlikely to occur within one or two years. And third, the "quenching" effect should be more severe on both stone and gout on thin (say 20mm) paving, a situation that has not been observed.

(b) Critical factors that can influence the integrity of rigid-fix paving

Having considered a large number of factors which might exert some influence on stonework in some places, in a variety of situations, using stone of wide compositional range and employing a system that does not follow strict the guidelines and standards, that are ostensibly followed in Australia it is necessary to examine a range of factors that are likely to play a significant role in the success or failure of rigid-fix stone paving.

1. Instability of the concrete base

Numerous investigations of paving failures in Europe have shown that the dominant cause of failure has been instability/failure in the supporting/underlying slab. Admittedly, northern Europe and other high latitude countries do face additional difficulties in concrete placement and durability due to sub-zero temperatures.

Nevertheless, there are many common factors, such as shrinkage, cracking, warping (curling) and reactive aggregate. Any dimensional instability in the concrete will affect the integrity of rigid-fix paving.

Below every concrete slab is a sub-base which also has to be effectively stabilized in order for the concrete slab to be stable. However, there are some situations that are challenging such as and-fills, steep slopes, unconsolidated material, old river channels, acid sulphate soils and mangrove flats and sometimes the in-house engineers don't get it right. Occasionally, problems do not present themselves in the first few years of service in these difficult locations because of changes in environmental conditions and usage, eg. unexpected vibrational effects. Furthermore, effective stabilization can be rather expensive especially where pilling to bedrock is required.

It is interesting that when paving falls on one of the first aspects to be investigated is the concrete base. A core is customarily taken, to confirm what – its thickness? Was this not being supervised during construction? And what will a small cylinder of concrete show in terms of overall slab stability?

2. Curing/shrinkage of the concrete slab

It has been observed that some thick concrete slabs are cured for only 7 days before paving commenced. This is contrary to general practice and the Australian Standard which requires a minimum of 28 days. However, adhesive manufacturers are providing assurances that their products are capable, indeed designed, to accommodate the shrinkage of the slab even during the early periods of maximum shrinkage.

It is widely recognized that 30% shrinkage will occur in the first 28 days, about 50-60% over the first 3-4 months, and the remainder over the remaining year. It is also recognized that thick slabs (180-300mm) take longer to cure (and longer to shrink) than thinner slabs. The amount of shrinkage is substantial with strongly reinforced concrete averaging around 1mm every 2 meters. This considerably exceeds thermal expansion of the stone. A strong grout between the pavers would ensure rigidity in the paving and there must be a possibility that shrinkage of concrete over 10meters (5mm) could stress the bonding of the adhesive, especially while thermal expansion is occurring in the granite.

As concrete cures and the volume of the slab decreases due to any or all of the four recognized shrinkage mechanisms (drying, autogenous, plastic and carbonation), tensile stresses are inevitable created in the slab and fractures develop. In the presence of seawater chloride ions will diffuse through the slab and cause corrosion of the steel. This is generally a longer-term factor of concrete instability.

3. Expansion joints

Expansion/contraction/construction joints are usually spaced as per standard requirements. Depending on the design, most joints are arranged in a square or squat rectangular pattern. Construction joints tend to be longer but little distinction is made from the more-common expansion joints. Curling of the concrete surface is commonly observed at construction joints due to differential shrinkage between the core and the top surface.

Most of the sealants used for these joints are two component polyurethane sealants with an expected life of around 10 years. But depending on the stability of the concrete surface, the adhesive used, the vehicle loading and the environmental chemistry, sealants not uncommonly show signs of deterioration after only a few years in service. An obvious compression of sealant at a joint might clearly demonstrate that the joint is working but also indicated that there are likely to be considerable stresses on the bonding of the adhesive.

Because these joints are rarely fully seated, especially in paving >30mm thick, they often serve as a source of water ingress and tracking. This permits the formation of subsurface resident water which causes many problems.

4. Size, Thickness and shape of the stone pavers

Large square paver sizes (600 x 600, 400 x 400) can be used for domestic use, shopping centres, and any other application where there is limited (if any) light vehicular traffic. The size is economical to produce and easy to lay but there is little variation possible in the paving pattern (stacker and stretcher). A 30-50mm thickness of that size reduces considerably the options of use and the most common applications for that size

are footpaths, sidewalks, garden paving, low level cladding and domestic driveways (i.e. where the traffic is light and infrequent)

A single 400 x 400 paver is sufficiently larger to accommodate an entire wheel loading even for wheels as large as a 40-seater bus. Provided that it is rigidly affixed to a stable, flat substrate without undulating or variation in thickness, trucks and buses could drive over granite paving with a low risk of failure because the compression and tensional loads are well within the capacity of most competent stones. However, any unevenness of the stone, unevenness in the concrete base, structurally inhomogeneous bedding / adhesive the presence of introduced material, or removal of any supporting material will cause point loading. Point loading can create pressures up to 20 times that of even loading and even 40mm thick granite and basalt cannot withstand this, particularly in the presence of dynamic (shock) loading. Shock loading is where there is a rapid impact on the stone paver (eg. From a rapidly moving/braking vehicle) akin to striking the stone.

Virtually all significant external paving projects in cities around the world use rectangular pavers. Sizes will vary according to the strength of the stone, texture and structures, the maximum weight of vehicles likely to drive onto them, the frequency of these vehicles, the type of sub-base, the type of base, the thickness of the paver and other considerations such as shipping, ease of production, ease of handling and ease of laying. Many different stone varieties are used for paving and considerable testing is done by ease of laying. Many different stone varieties are used for paving and considerable testing is done by most authorities/end users to establish the suitability of the stone in relation to its intended application.

In Europe, and to a lesser extent North America, there are arbitrary codes/categories for the use of stone paving and methods of laying. These categories recognize the engineering factors likely to have an effect on the durability of the stone paving. For example, bus stations are bracketed with airport landing zones in terms of the high dynamic loading of the pavement and, to ensure stability, small rectangular paving units with thicknesses up to 225mm are used. A more typical thickness specified for heavy vehicular traffic is between 80mm and 150mm. For lesser carriageways and roadways, rectangular paving units remain small but with thicknesses typically 70 to 80mm depending on the volume and weight of the traffic. The British standard BS6717 states that a minimum of 60mm is compliant for stone pavers for areas with vehicular access.

The most common application of square pavers is in the form of setts and cobblestones. La Mar Diamant. Located in Singapore has over 50 years of experience in laying pavers, having placed over 1 000 000 square meters in that time. For roadways, their typical unit is a cube of 100mm. Cobblestones can be 200 x 200 but with a thickness of at least 100mm. Even cubic setts in trafficable areas are arranged in circular and/or fan-shaped patterns that are not only aesthetically decorative but serve to deflect forces in a complex way.

In some designs a circular pattern is demanded with square pavers. The only way this can be achieved is by a progressive increase in the grout widths towards the outside circumference so that grout widths range from 20-30mm. The integrity of the paving is severely compromised because it is substantially reliant on the grout but which has a strength of only 20-25% of the stone. A breakdown of the grout (such as dynamic vehicle loadings on the pavers, chemical disintegration, salt attack) will lead to paving failure. Considerably greater strength and stability can be provided by supplying the stone pavers cut to a trapezoidal shape. The added strength of interlocking shapes in stone structures has been known for over 2000 years.

It must be emphasized that most of the thicker paving done in Europe, Canada and United States is not bonded to concrete but laid on a compressed grits/sand base. This is particularly useful in urban areas where there is a need to access services. Rather than requiring a jackhammer approach to remove/destroy firmly attached paving, the pavers laid on sand with a sand grout are simply removed and then replaced after the service work is completed. This approach has been demonstrated to dramatically reduce the cost of maintenance. The first section of the mall redevelopment in Perth (Hay St) has recently been completed using 75mm thick granite paving, laid on a compressed deco base. The remaining malls will be done the same way. The preferred Australian granites were tested in many configurations for strength but did not achieve the required rating. Even with the much stronger, imported granite many tests were undertaken to select the most appropriate, rectangular paver dimension.

I was astounded recently to witness an engineering requirement on the Gold Coast for an exfoliated finish to the underside of a brick-shaped granite paver in order to achieve less slip on a deco base.

5. Laying pattern of The Stone

It has been recognized that some paving patterns perform better than others. Tests and experience around the world have shown that the herringbone pattern is superior in many functions of paving (eg. Deflection, creep). However, this pattern performs best with rectangular units similar in shape to that of a household brick. In this pattern, static loads, dynamic loads and torsion are distributed over several paving stones with forces acting in different directions. The stacker pattern of paving is usually restricted to domestic use and internal use when there are no stresses or substantial loads. It is the most desirable and least effective pattern for external paving.

6. Adhesives

The effective bonding of stone paving to its base is essential in a rigid fix system. There are many ways of achieving this and the preferred method is by using an adhesive system. The traditional way of fixing stone to a cement screed in a wet slurry mix has generally been superseded for several reasons one of which has been long-term integrity.

Adhesives tend to be preferred because of the time constraints placed on projects, the likelihood of concrete base shrinkage, thermal expansion of pavers, and possible, prolonged saturation of the cementitious screed. Over other major financial consideration is the availability of adhesives which did not require lengthy curing times for the concrete base.

The adhesive market is very large and the competition among manufacturers to secure contracts is intense. Indeed, the choice of adhesives to fix tiles and pavers is very extensive and the decision making process for the choice of adhesive is difficult. This is especially so because of numerous advances in this industry in the last 10 years and frequent changes in formulations to remain competitive.

Because of the competitive nature of the industry the advertising commonly exceeds scientifically and technically proven specifications. Manufacturers can get away with this because in the large majority of cases the product serves its purpose (by keeping the tiles and pavers stuck to the floor) even if the quality of adhesion is poor. One method of securing a contract is to warranty the product for extended periods and even warranty the products for uses that are outside their own specifications. Careful examination of some of the warranties reveal ambiguities and conditions that enable the manufacturer to be absolved from blame in case of a failure. It must be remembered that there is no way that manufacturers of a wide range of products can adequately for conclusively research the efficacy of all their products in a very wide range of situations with an enormous range of natural and man-made paving materials.

There are several categories of adhesive system available for stone paving. One is a two-component system where a cementitious base is mixed with a polymer (synthetic rubber latex). Another is a flexible powdered adhesive containing fragments of rubber. A third uses a combination of thin but strong priming and bedding mortars. Epoxy adhesives could be added as another category. All have their strengths and weaknesses and it is essential to use the adhesive that is best suited for the intended application. Then it is important to choose an adhesive that is compatible with the working conditions. A hot, humid exposed environment can impose severely limiting conditions to the successful use of many adhesives. Open time, pot life and mixing time can be down to minutes in such environments. Where back-buttering is required in addition to the normal adhesive spread increased handling time and final positioning time is very limited when the weight of some pavers can be up to 20kg.

Adhesive with a substantial rubber component is widely regarded as suitable for domestic tile applications and possibly large areas of terrazzo and/or ceramic tiling in interior public places. In these conditions there is negligible dynamic loading and certainly negligible torsional loading. However, for external stone paving under severe and frequent loadings this type of rubber-based adhesive is totally unsuitable.

The thin, sandwich type of adhesive is used in Europe in an attempt to minimize the mismatch of strengths between the different elements in a composite paving structure and to direct the loadings through the stone and into the concrete base. For this to work effectively a high quality concrete base is required.

It is customary in Australia to present the stone product to a prospective adhesive manufacturer (along with a description/inscription of the project) for the formulation of specifications. The manufacturer then warrants the adhesive for whatever period is required. A critical analysis of the specifications shows that the descriptions

and requirements are often poorly worded, without a good understanding of the paving circumstances, and basically “marketing talk”. As noted earlier, the manufacturers of these products “hope” that the adhesives will perform satisfactorily as they have done in a number of other situations and circumstances.

Some manufacturers go further and require that all work carried out in the system recommendation must be carried out by a manufacturers approved specialist employing skilled personnel under the direction of an experienced supervisor.

7. Jointing widths and jointing material

Due to the regularity in size of stone paving (governed by standard tolerance requirements) the typical jointing widths in stone paving is somewhere between 3 and 5mm. However, it has been noticed that some designs call for a jointing width of 10-25mm on external stone paving. A jointing width of 10-12mm is typical for porcelain, terracotta and ceramic tiles in domestic situations but not for stone pavers affixed to a concrete base by adhesive. Interior stone tiling often demands narrow joints of 1-2mm which introduces some difficulties in grouting. Customary grouting practice is to sponge in the grout but this is poor practice because of the difficulties in getting the grout down the edge of the tile. Grout should have a bond with the bedding mortar or adhesive bed and the only way this can be done effectively is to butter the edge of the tiles prior to fixing (ie. More work). Butt-jointing stone tiles is another poor practice that frequently leads to failure.

Because of the contrasting physical behaviour and chemistry between stone and grout it is inevitable that fractures develop in grout, especially in a dynamic environment. Even though some grouts are fairly stiff with a compressive strength of about 40MPa (when freshly made) they are weak when compared with an average strength for stone pavers of around 160-200MPa. Increasing the jointing widths reduces the overall unit strength..

Two types of fractures develop – hairline partings along the stone and transverse fractures across the grout. Fractures clearly further reduce the paving unit strengths and allow easy ingress of water and chemicals. Grouts are also quite porous (3-5%) so can accommodate a range of dissolved substances such as salts and sulphates which can gradually lead to growth, efflorescence, and internal disintegration. A physical breakdown of the grout and its removal from the joints contributes to a loss of paving integrity.

8. Dynamic loading/torsional effect on pavers

Provided the grout remains intact in its original form a reasonable degree of rigidity could be expected even when flexible adhesive is used. However, because of its reduced strength compared to stone it is undoubtedly a weak link and differential compression of the grout by heavy and/or torsional (radial) loading (due to the angle of approach of vehicles) will inevitably lead to grout failure. Once the grout has been crushed or broken it is easily removed physically and the paver that was held in place by the grout is now less constrained. Any subsequent dynamic or torsional force on the unconstrained paver will lead to shearing along the adhesive/stone interface and impingement by the paver onto an adjacent paver or a flexible control joint. Once the stone paver adjacent to the flexible joint has sheared there is rapidly a progression of shear failure in the second line of pavers, and so on until the entire paving has failed.

A trafficable, paved slope presents a particularly demanding scenario in terms of a combination of different stresses. Roundabouts or bust terminals are rarely paved with stone fixed to a concrete base. Instead, because of the severe tangential deflection in such situations, setts, cobblestones or thick pavers are preferred, bedded on a compressed base. The frequency, spacing and thickness of the lateral restraints required for such situations need to be ascertained. Interestingly, in southern Europe many narrow winding roads are paved with stone setts and/or cobblestones and have remained trafficable for centuries.

9. Influence of salts

Salts and other chemicals (eg. Sulphates) have a physical property which can be very detrimental to some types of stone. Salts have a high crystallization strength, ie. When they come out of a saturated solution, they can exert considerable forces on the pores of some natural stone. Porous limestone and most sandstones are potentially susceptible to damage by the entry and subsequent crystallization of salts. The same stones are

also susceptible to damage through freeze-thaw action and appropriate tests need to be carried out to determine suitability for a certain application and/or determine the level of risk.

Although granites have very little pore space compared to the above sedimentary rocks, the grouts, mortars and adhesive have porosities and rates of water absorption similar to those of these sedimentary rocks. The location of a project immediately adjacent to the water-front means that there is an inevitability that some salt is carried from the sea to the stone paving. Because of its solubility, salt is carried in solution into the pores of the bonding media where it has the opportunity to build-up and concentrate. Although it is unlikely that in isolation it has had a significant impact on the strength and integrity of the mortars and adhesive it can contribute to an accelerated degradation of these bonding media once there is ready ingress of water through hairline fractures or failures in the stone. Chemically, salts are often not compatible with adhesives and react gradually to cause a weakening of the bonds in the adhesive.

10. Influence of water

In the absence of mechanical factors, water is generally the principal factor causing problems with natural materials, including stone. And thermal change is the driving mechanism that activated the water. The interaction between water and stone takes many forms. Some of these have already been mentioned previously. At first appearance, water could be ideally seen as simply falling onto the stone from rain and then being taken away by the drains. Upon drying, the effects of water appear to have disappeared. However, below the surface many reactions are occurring because of the residence and persistence of the water. Not only is the water the result of rain but nightly in many paved shopping/transport areas there is a cleaning regime in place which hoses down some of the paving, cleans windows and waters gardens. In other words, the grout, adhesive and concrete base are subject to water daily. Furthermore, it is not unusual for the paving design to allow water to freely track along construction joints where it can then move laterally away from those joints and be adsorbed by the grout and adhesive.

Prolonged contact with water can damage the bonding in the adhesive, particularly if there are dissolved chemicals such as salt, sulphates from vehicle exhausts, detergents and surfactants from the window and floor cleaning, phosphates from the planter beds, and hydrocarbons from vehicle leaks.

Water will also dissolve small amounts of calcium from the concrete base, grout, and cementitious adhesive especially at elevated temperatures (around 35-40°C) and precipitate the calcium at sites where the redox conditions are different and/or suitable. Iron is also mildly soluble in its hydrated forms and this can show as yellowish to light brownish stains on the stone, in contrast to the greyish stains of the calcium.

Apart from the chemical aspects of the interaction between water and cementitious products water can act as a powerful hydraulic medium. If a soft, absorbent or porous substance contains fluid, a strong compressive force will cause the water to be violently channelled away from the area of applied force. A large force acting on small amounts of free water in a porous/soft medium can create a hydraulic jetting effect that will rapidly break down the host medium, a multiple jetting effect caused by a series of bus or truck tyres can effectively remove the adhesive that is/was bonding the paver to the concrete. White blooms and stains appearing on the stone paving attest to the mechanical, physical and possibly chemical breakdown of the adhesive.

11. Sealers

The application of water-repellent substance to the surface of the stone might seem to be a saviour in a bottle that protects the stone from the effects of water and chemicals. This is far from the truth. Sealers can be detrimental to the performance of the stone as well as compromising the aesthetics. Salts, sulphates, calcium compounds and any other soluble chemical can be drawn up through the stone in response to the thermal engine noted previously. However, when the dissolved substances hit the sealer they can go no further. The "breathability" often referred to in advertising is applicable only to vapour, not liquid. Gradually enough pressure can build up to cause the surface and edges of the stone to crumble, fret and spoil. Before that, in granite that is porous, the soluble substances can accumulate under the surface of the sealer but then be remobilized to appear elsewhere in a different form if the substrate becomes saturated.

12. Workmanship

If any of the above factors have been overlooked in the planning and design, and there is a paving failure, there is always the intangible factor at the bottom of the pecking order which can be blamed – workmanship. Unfortunately this is all too common and the contractors are often in no position to argue the case against the architects, engineers and construction experts. Some contractors do follow the documentation to the letter and comply with all rules and regulations and the quality of workmanship is at least as good as most overseas projects in similar situations.

SUMMARY

There are many key factors that need to be considered in the design and successful construction of external paving. An understanding of the stone, particularly its behaviour in its intended application, is essential. Consisting of minerals that have come out of solution (igneous rocks), have recrystallised under elevated thermal conditions, pressure and stress (metamorphic rocks), or been the subject of erosion, attrition, sedimentation and then lithification (sedimentary rocks). Building stone is a complex natural material that has a range of physical characteristics, just like glass or steel framing. When placed under load or put into demanding situations these characteristics must be scientifically analysed to predict performance. Expert advice needs to be sought on the stone to be used, how it is to be laid, by what patterns, and on the maintenance of it. Short-cuts cannot be taken and in-house advice is often inadequate. The “she’ll be right” attitude is no longer acceptable.

When stone paving fails it generally fails due to a combination of factors and on analysis it is often the basic choice of paving type this is incorrect.

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