by **Peter Hartog**

out damn spot

(or not, as the case may be)....

The following article explains some recurring problems with limestone and other porous paving materials. It does not conclude that limestone is unsuitable for these purposes. Nevertheless, there is always a risk that it wil be misconstrued as a broad condemnation of limestone. The causes of the unsatisfactory results illustrated here are not inherent shortcomings in the paving materials themselves. These problems recur due to a failure to appreciate and make allowance for characteristic properties which differ from those of more familiar granites, dense marble, basalt, reconstituted stone and porcelain tiles. If appropriate precautions are taken in design and installation of paving and flooring of relatively porous stone, these problems can be avoided.

In this context, design deserves to be emphasized. It is simply unjust for architects and interior designers to hold suppliers and stone-fixers responsible for recognising and compensating for shortcomings in their specifications and construction details. When an architect specifies limestone paving with shallow drainage falls on a concrete slab without similar falls, provides no paths or concealed outlets for water to drain from saturated sand-cement bedding and omits a waterproof barrier between paving and abutting walls of porous split-face concrete bockwork exposed to rain, it is inequitable for the architect and its client to insist that the stonework contractor should alert them to the risks of lime-staining and efflorescence.

The defects in these examples flow from errors or omissions in design, not from flaws in materials or poor workmanship. The design professions' reliance on performance specifications has long been justified as necessary to encourage technically innovative and competitive tenders from specialist sub-contractors. When applied to the work of skill-based trades, such as tiling and stone-fixing, using a small range of specified materials, the current fashion for performance specifications is commonly little more than an evasive substitute for technical proficiency and diligent inquiry by the designer. How many designers specify expensive limestone flooring, paving and wall cladding but remain blissfully unaware of the handbooks and journals listed below? How many justify ignorance and laziness on the basis that their fee structures do not allow the time needed to study the properties and performance of the materals they select? If such arguments are valid, do they not apply equally to tradesmen operating on small margins?

The recent popularity of thin limestone slabs and tiles for flooring, paving and wall cladding seems to have generated a minor tidal wave of complaints from disappointed building owners and developers. Limestone is being widely used as a substitute for more familiar granites and marbles but without appreciation of characteristic differences in porosity, water absorption and alkalinity. Building Diagnostics Asia Pacific is currently investigating defective limestone installations in residential buildings, offices and luxury hotels in Australia, Singapore and Hong Kong. A common defect is staining which resembles damp bands and spots but which persists when all possible free moisture is extracted or driven off by heating. In picture- frame staining, such bands occur around the perimeters of porous tiles, slabs and pavers including those sealed before and after fixing. These phenomena are physically similar to damp staining. They are caused not by water itself but by materials deposited by transient dampness.

Simple discolouration is caused by the breakdown and diffusion of minerals with contrasting pigments such as iron oxides and hydrates (orange, brown and black) and sulphides (yellow and grey) or by run-off from rusting iron and oxidizing copper. Photograph 1 is almost self-explanatory; the base of a steel pail has deposited rust on reconstituted granite paving tiles and joint grout. The rust stains reflect light at the wavelength perceived as orange. Limestone walls at London's Canary Wharf display vivid green plumes below copper roofs and gutters. There are two components of reflected light; (a) that reflected directly at the surface, which is characteristic of the material's colour, and (b) that which is scattered, reflected and diffracted by fine-textured features of the surface. It is this scattered light which lightens the dry surface and dilutes the true colour of an object. What we mostly see in pigmented stains is light reflected directly from particles at the discoloured surface (*see* **Diagram 1**)

Transparent and translucent materials with no contrasting pigmentation cause a different form of staining which can be explained by considering wet spot optics, the behavior of light passing though a thin film of moisture or other clear coating on an otherwise opaque surface. Wet spot optics explains why moist spots on paper, fabric, stone or concrete almost always appear darker than surrounding dry surfaces.

When viewed in cross-section or glancing light under powerful microscopes, many surfaces which appear in everyday use to be smooth, such as polished stone, tile glazes, aluminium extrusions, plasterboard and plastics, are found to have rougher surface topography than the Bungle Bungles and the Himalayas. Some of these surface features have dimensions similar to the wavelengths of visible light. When such a surface is moistened, the fine structures which scatter light are coated with a thin film of water which forms an anti-reflection coating. By reducing the amount of light reflected from the surface towards the


PHOTOGRAPH 1

PHOTOGRAPH 1 *Rust staining on paving tiles. The wavelength of light reflected from the iron oxide at the surface is perceived as the characteristic orange colour of rust. The colour of the tiles and grout has been changed by an extraneous pigment.*

PHOTOGRAPH 2 *Rainwater flowing down the surface of these slate tiles has not introduced an extraneous pigment. The perceived darkening of the wet surfaces occurs because more light is scattered below the tops of microscopic surface features and less is reflected towards the observer. The thin film of water acts as an anti-reflection coating which accentuates the true colour of the stone, as does the clear anti-graffiti coating on the ground floor columns.*

viewer, the coating makes the object appear to be darker. The dark appearance is closer to the object's true colour when viewed in unscattered reflected light. For the same reasons, a smooth polished stone surface is typically darker than a honed surface, a wet polished stone surface is darker than a dry polished stone surface, electro-polished stainless steel is darker linished stainless steel, a glazed tile is darker than the same tile unglazed, wet hair is darker than dry hair and drops of water on cloth, paper stone, timber and concrete cause dark spots.

Moisture causes light to scatter more efficiently and deeper into the material. As a light beam penetrates further into a damp surface, it is intercepted by more surface features. A fraction of the light is absorbed and some is scattered, so a decreasing proportion is reflected at each successive surface. By the time the remaining light is reflected and refracted within the the object and back towards the observer, it has been further attenuated, i.e. its quantity has been significantly reduced. The observer perceives this lessened quantity of reflected light as relative darkness of the damp surface (*see* **Diagram 2** *and* **Photograph 2**).

The same phenomena occur (1) when microscopically thin coatings of clear or translucent dry calcium hydroxide and calcium carbonate have been deposited in the surface pores of limestone and marble and within near-surface grain boundaries of granite, and (2) when clear plasticisers, diluents and oils have migrated from elastomeric joint sealants, particularly silicones, into abutting stone. Thin sub-surface coatings of calcium compounds and sealant components have similar, but not necessarily identical, light-scattering and anti-reflection properties as thin films of moisture (**Diagrams 3 to 5**). Subtle differences can be detected (a) by comparing these stains with nearby surfaces made moist, for instance below a small piece of damp sponge, (b) by examining the relative depths of stain penetration through broken (not cut) surfaces, and (c) by comparing the relative rates of absorption of droplets of water on the surfaces.

Picture-frame staining (**Diagram 6** *and* **Photograph 3**) and other forms of dark staining which resemble surface dampness do not necessarily require the permanent or recurrent presence of moisture; they commonly occur in the aftermath of a single prolonged wetting. BDAP has been involved in a protracted dispute in which a contractor used radiators to warm stained white marble for three weeks before suspecting that seemingly damp stains were not caused by residual moisture. In another instance, marble and limestone tiles in hotel bathrooms were replaced twice before the actual causes of picture-frame staining were recognised.

We have encountered a few Yellow Pages building inspectors and dispute resolution consultants who rely on simple electronic moisture meters to demonstrate that picture-frame staining is due to the permanent presence of moisture. In reality, a surface impregnated by soluble calcium salts is made more dense and less porous. It offers less resistance to flow of current between the closely-spaced prongs of these rudimentary moisture meters. The reduced resistance can readily be misinterpreted as dampness. The same readings may occur after the sample stone has been dried for days in a soil laboratory oven. Opinions based on the use of mail-order moisture meters should be treated with caution. Some of these instruments give very different readings between different grades of gypsum plasterboard and different concrete blocks, all completely dry. They do not measure moisture content; they show relative levels of moisture (or resistance), often distinguished as red, yellow and green zones on a dial. They are useful for identifying approximate gradients of dampness across walls or floors of uniform materials, but high readings alone do not prove the presence of moisture.

A final caution: staining from deposition of calcium salts, sealant plasticisers and the like cannot be removed by treating affected surfaces with acids and solvents. If anyone believes otherwise, please let us know and send samples for testing. We will publish the results.

diagrams

Diagrammatic representations of reflection of light from a dry surface and wet spot optics, i.e. dark "damp" discolouration from deposition of clear and translucent materials in pores close to the surface of natural stone and ceramic tiles.

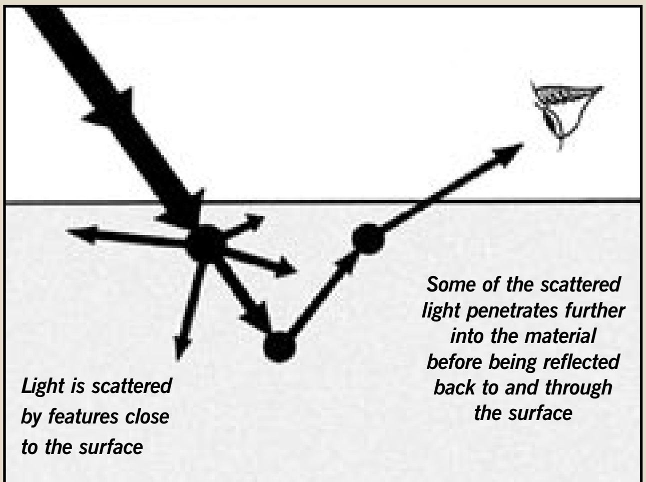

DIAGRAM 1

There are two components of reflected light; (a) that reflected directly at the surface, which is characteristic of the material's colour, and (b) that which is scattered, reflected and diffracted by textural features of the surface. It is the scattered light which lightens the dry surface and dilutes the true colour of the object. In the diagram below, light passing into a rough dry surface is immediately scattered. Some component of the incident light is reflected and re-reflected back to the surface, then refracted towards the viewer.

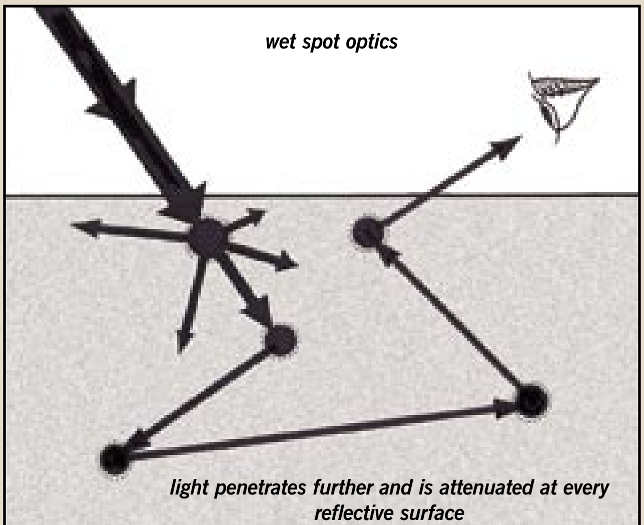

DIAGRAM 2

When the surface is moistened, the structures which scatter light are coated with a thin layer of water. By reducing the amount of light reflected from the surface towards the viewer, the thin coating of water makes the object appear darker. The dark appearance is closer to the object's true colour when viewed in unscattered reflected light. For the same reasons, a smooth polished stone surface is typically darker than a honed surface, a wet polished stone surface is darker than a dry polished stone surface, electro-polished stainless steel is darker than linished stainless steel, a glazed tile is darker than the same tile unglazed and a drop of water on cloth or paper creates a dark spot. In the diagram below, the film of water in a damp surface forms an anti-reflection coating on the textural features that scatter light. A smaller proportion of light is reflected at each interface.

It is scattered more efficiently and deeper into the material. As it penetrates further, the light beam is intercepted by more surface features. A fraction of the light is absorbed at each feature. By the time the remaining light is reflected and refracted from the object to the observer, it has been further attenuated, i.e. reduced in quantity. The same phenomenon occurs (1) when microscopically thin coatings of clear or translucent calcium hydroxide and calcium carbonate are deposited in the surface pores of limestone and within the grain boundaries of granite, and (2) unstable clear plasticisers, diluents and oils migrate from elastomeric joint sealants into abutting stone. Picture-frame staining and other forms of dark staining which resemble surface dampness do not necessarily require the permanent presence of moisture; they may occur in the aftermath of wetting.

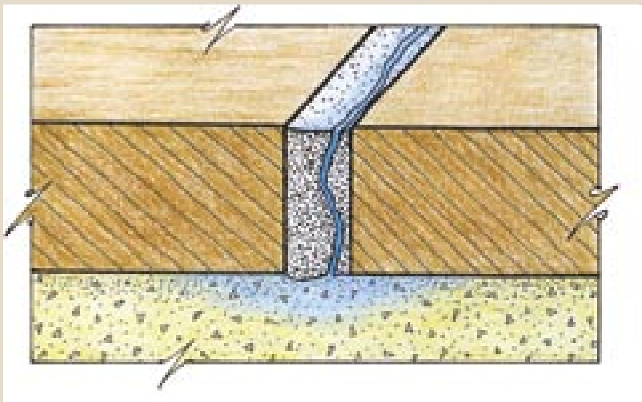

DIAGRAM 3

Rainwater and irrigation water seep downward through fine fissures in grouted joints and gaps in butt-joints. The water flows into sand-cement mortar bedding where it dissolves the calcium hydroxide which occurs in excess in hydrated Portland cement.

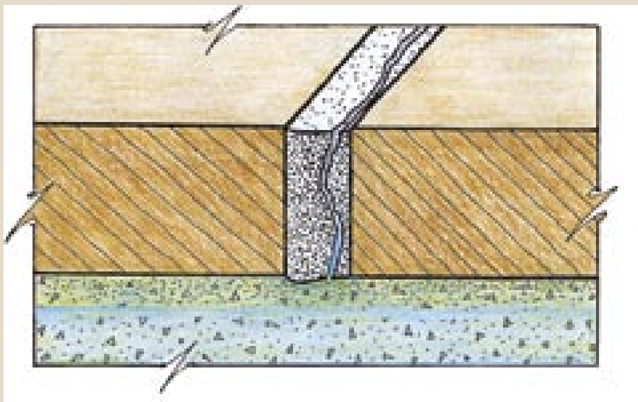

DIAGRAM 4

If the water does not drain efficiently from the bedding, the cement-rich mortar may become saturated. Fresh water flowing under the paving will then mix with and displace water tainted by dissolved calcium salts, also known as free lime. The solution rises back to the surface where it evaporates and reacts with carbon dioxide gas in the air.

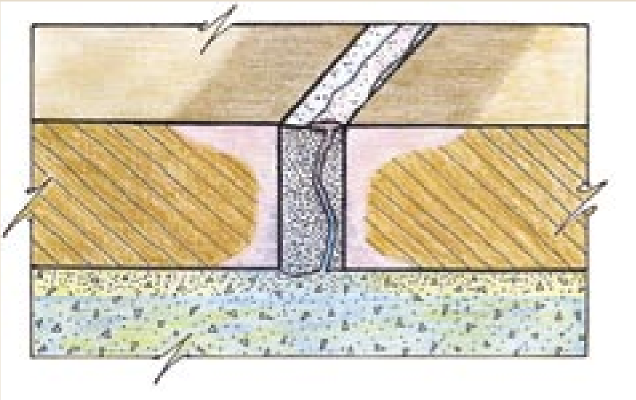

DIAGRAM 5

The last stage of picture-frame staining in porous natural stone and unglazed ceramic tiles. Solid crystalline calcium carbonate, from the reaction between atmospheric CO_2 and calcium hydroxide in solution, temporarily plugs up fissures near the surface. The highly alkaline solution below is forced into the joint grout and through nearby surrounding porous stone. Lime-tainted water from the bedding may also spread across and be absorbed at the surface. Pure calcium carbonate is white. When it precipitates in sub-surface pores in light-coloured limestone and marble, it alters the absorption, refraction and reflection of light in a way that causes the dark staining and wet appearance. The stains characteristically remain even when stone tiles are removed and completely dried in a soil laboratory oven.

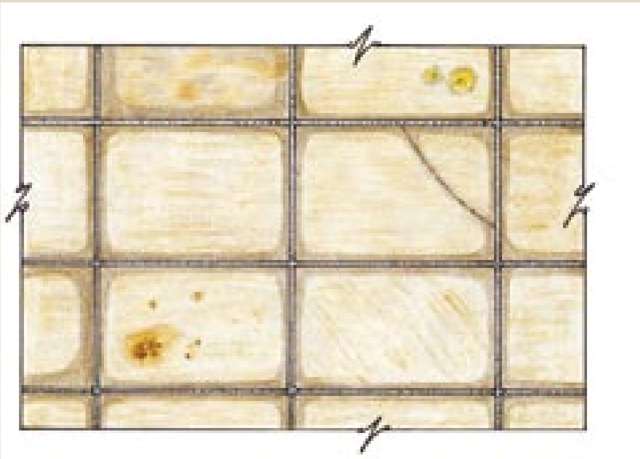

DIAGRAM 6

So-called picture-frame staining in porous limestone flooring and paving. Dark bands without differential pigmentation occur along grouted joints and butt-joints. Moisture meter measurements may show no significant differences in the moisture content between dark perimeter bands and unstained centres of tiles. Wetting of the stone from rainwater and moisture trapped in the bedding dissolves, transports and diffuses soluble iron minerals, notably orange and brown oxides and hydrates (concentrated at A and diffuse at B) and yellow and grey sulphides (in blooms at C). Picture-frame staining also occurs along some natural veins and flaws (D) which are more porous than the parent stone. These forms of staining also occur in some granites, marbles and other popular paving stones, in terracotta paving tiles and reconstituted stone. The fault is not in the paving material but in the methods of bedding and fixing.

PHOTOGRAPH 3

PHOTOGRAPH 3 *Picture-frame staining in paving of a porous Italian limestone, here photographed as the stone dried in sunlight after rain. Bands of dark stains along joints and natural fissures did not disappear when moisture meter readings confirmed that the surface of the stone was uniformly dry. In other words, the stains were not due to the presence of moisture at or below the surface. They were caused by deposition of water-soluble materials transported upwards from the bedding and through the tight grouted joints.*

PHOTOGRAPH 4

PHOTOGRAPH 4

A close view of very fine gaps between abutting limestone paving tiles and a narrow cement-based grouted joint. The scale of the macrophotograph is close to 2:1. The joints are about 1.75 mm wide. Narrow gaps along the sides of such joints are common in paving but are not readily visible from a normal standing position. They allow rainwater to flow into porous sand-cement mortar bedding. Unless the water drains from the bedding faster than it is replenished, the bedding may become saturated. Water and dissolved constituents of the bedding will then rise to the surface through joints and fissures in the stone.

PHOTOGRAPH 5

PHOTOGRAPH 5

A close view of water percolating upwards through joints after the surface of the limestone paving dried in sunlight. The heat of the sun has caused moisture trapped under the paving and in the joints to convert to water vapour and expand. The vapour pressure forces water in fine gaps (see Photograph 2) to flow back to the surface. The water carries dissolved calcium hydroxide from Portland cement in the bedding. The hydroxide reacts with carbon dioxide in the air and is precipitated along the joints and natural fissures as dense white encrustations of calcium carbonate, a compound which is insoluble in hot water. The purple colour on the swab at the centre of the photograph is phenolphthalein indicator dye which changes from clear to magenta at a pH of about 10. The dye has been used here to confirm that water along the joints is highly alkaline, i.e. it is not fresh rainwater but water which has carried dissolved calcium hydroxide from Portland cement in the bedding layer.