# *HOW NOT TO LEARN FROM MISTAKES:* RECURRENT AND FORTHCOMING DEFECTS IN INSTALLATION OF CERAMIC TILES

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## INTRODUCTION

Since 1982 most of my erratic career in architecture and building diagnostics has in some way involved investigation of defects in design, construction and performance of high-rise and wide-span buildings. The effects of such defects have included catastrophic collapses of structures such as an eight-storey hotel, two factories and a shopping centre. More commonly, I deal with mundane defects that are not life-threatening; cracks, leaks, corrosion and staining, premature deterioration of seals, poor performance of glazing, coatings and finishes. The term building diagnostics was coined in North America in the 1980s. It conveys a wider meaning which includes integrating knowledge gained from investigation of defects and failures into the design process, so that the risk of their recurrence can be reduced or eliminated. It is a discipline with a high level of frustration, for in retrospect almost all construction defects seem to have been easily avoidable.

Building diagnosticians, forensic engineers and failure analysts in the construction industry tend to apply their resources to fields in which recurrent problems generate a predictable stream of engagements and income. In this sense, events over which we have little control influence our fields of interest. We have an unusual incentive to spot trends in the use and abuse of materials in order to scramble up the appropriate learning curve. In Australia in the 1980s, problems of concrete durability, flat roof waterproofing and lightweight curtain walls were endemic. A small army of consultants, litigators and support personnel soon took to the field. In the Yellow Pages phone book, the number of entries under the heading Building Consultants and Dispute Resolution Specialists increased exponentially. One architect in Sydney marketed his services as a Building Pathologist.

During this time, ceramic tiling barely featured in dispatches from the front. Between 1980 and 1990, I was involved in only three or four investigations of tiling failures, all in some way related to mislocation or faulty installation of movement joints in public area flooring and paving. I did not regard ceramic tiling generally as a problematic material or as a subject warranting much attention. There seemed to be no future in tiling failures. I was impressionable and easily misled.

There is, however, some circumstantial evidence that my naivete corresponded to that of the architectural profession and building industry as a whole. In 1951 and 1958 the Commonwealth Scientific and Industrial Research Organisation (CSIRO) published a short report titled Failures of Wall and Floor Tiling: Their Causes and Prevention. In 1973 it published a useful four-page digest on defects in internal ceramic tiling. Not much had changed over 20 years except the introduction of "the American method" of tile fixing, organic adhesives and high-strength concrete. A paragraph on bowing failures in wall tiling did not even consider the contribution of creep, shrinkage and elastic shortening of structural concrete. The CSIRO's note was republished in 1987 without significant changes. In 1979 the Australian Government's Department of Housing and Construction circulated the results of a national survey of Failures of Wall Claddings and Finishes. It recorded only three incidents of tiling failure, all related to adhesion problems. In 1986 another survey of the collective experience of national and state government organisations involved in construction and facilities management did not list ceramic tiling as a matter for concern or further research.

The situation seems to have changed around the end of the decade. Prompted by Richard Bowman of the CSIRO, the Royal Australian Institute of Architects (RAIA) in December 1991 produced a one-page Cautionary Note titled Wall Tiling Failures. It hinted ominously at "...a number of recent failures". It identified nine causes of differential movement between tiles, bedding and substrates, including *deformation of load-bearing structures and concrete shrinkage.* The note also cited the use of *non-compressible spacers* and *hard (non-compressible) grout and/or too narrow joints* as possible causes of tiling failure. The significance of these cautions comes from how widely they have been ignored. The RAIA may face a dilemma in publishing more detailed warnings to its members. In determining the date at which a *normal competent practitioner* should become aware of such technical problems, courts tend to place a high value on the publications of professional institutes. Although the first of many well-researched and widely publicised failures of toughened glass due to nickel sulphide inclusions occurred in Australia in 1960, a recent court judgement in the state of Queensland has established that architects had no professional duty to be aware of the phenomenon until the RAIA belatedly published a Cautionary Note on the subject in 1994, by which time the problem had almost disappeared.

By some curious twist of fate, the number of requests for my company Building Diagnostics Asia Pacific (BDAP) to investigate serious defects in ceramic tiling and thin natural stone veneer cladding started to increase the same year the RAIA's note on tiling failures was published. We now receive twenty or so such requests a year in Australia and half that number in Southeast Asia. While investigations of defects in tiling and stone finishes represent less than 25% of BDAP's work, the same general field supports more specialised consultants in several Australian cities and Singapore. Part of the explanation is that the rate and severity of defects, including some concealed and dormant since the 1980s, are actually increasing. My efforts to understand why this has occurred and how the trend might be reversed led indirectly to my participation in QUALICER 2000.

## WHAT'S GOING WRONG?

Histories of architecture and construction technology record that decorated clay bricks and ceramic tiles are among the most durable of man-made building materials. One source recounts that when the Stepped Pyramid of the Egyptian pharaoh Zoser was excavated in 1803, blue-green glazed tiles lining the tomb were found to be "...as beautiful as on the day they were installed" more than six thousand years before. Intricate panels of original wall tiles remain intact in the Alhambra Palace of Granada after six hundred years. Eclectic mixtures of glazed tiles carried from Europe over many centuries as trade goods - and perhaps also as merchantable ballast - may still be found in old temples in port cities of Southeast Asia. In 1976 I observed tiles with hand-painted windmills and Dutch farm scenes decorating a 19th century Chinese temple in Singapore. They remained soundly fixed without the benefit of Portland cement and modern polymer-based adhesives.

By contrast, recent and widespread failures, often within a year or two of installation, have convinced some architects, building owners and contractors in Australia and Asia that conventional ceramic tiling is a problem-prone finish for even the most benign conditions of service. Designers are already specifying opacified and laminated glass, polished granite veneer and new forms of terrazzo for such mundane purposes as the walls of toilets and bathrooms in high-rise commercial and residential buildings. These alternatives have their own characteristic shortcomings which are slowly being discovered. In and around Bangkok there are examples of both faultless and disastrous tiling on facades of high-rise buildings. The most prominent of the successes involved "technology transfer" from Japan and Europe. The most prominent of the failures - two towers beside a major highway - repeated elementary errors of tiling onto precast concrete which were reported in English-language textbooks at least 35 years ago. Residues of formwork release agents remained on unnecessarily smooth concrete surfaces. These buildings were wrapped in plastic safety netting for two years. It is difficult to judge how much these incidents have prejudiced local architects against tiling in future high-rise facades, for Bangkok has a surplus of office and apartment buildings that may take five years or more to clear. White mosaic tiles have long been popular for exteriors of tall buildings in Bangkok, Hong Kong and Singapore. Government authorities in Singapore have prohibited their use. Mosaic tiles on recent buildings on the campus of Bangkok's Chulalongkorn University display tapered and diagonal cracks consistent with omission and obstruction of movement joints.

Since 1990, BDAP has investigated 40 or so major incidents of cracking, detachment and collapse of ceramic wall, floor and pool lining tiles in Australia, Southeast Asia and further afield. With two exceptions, these failures have been caused by errors of specification, design and workmanship in installation rather than by deficiencies in the properties of the tiles themselves. Tiling in contemporary architecture in the region commonly combines sophisticated factory-produced and rigorously tested materials with semi-skilled and poorly supervised workers not much influenced by the principles of engineering and materials science.

It can be difficult to convince a tile-fixer with little formal training that the rules-of-thumb followed in tiling over soft porous non-loadbearing brickwork of a two-storey house are probably not appropriate for tiling onto 75 MPa silica-fume concrete of a shear wall at the core of a fifty-storey hotel, or that expansion joints in a turbulent heated swimming pool must be installed progressively as the tiles are fixed rather than retrofitted in slots cut through finished tiling using diamond-abrasive blades. The situation is exacerbated in Australia, Singapore, Brunei and the Middle East where tile-fixers are increasingly unlikely to be fluent in the local languages. They may also be blissfully unaware - and even contemptuous - of specifications, standards, codes of practice, manufacturers' instructions and other impediments to fast work on unit rates of pay.

It is difficult for me to assess the extent of deskilling in the Australian tiling industry over the past decade. My perspective is probably distorted by too frequent involvement in disputes arising from defects. I rely on the others closer to the scene.[1] I have seen much tiling

[1] Colin Cass, another speaker at Qualicer 2000, trains tile-fixers in Australia. I readily defer to his views on the structure and skill levels of the industry.

work that displays extraordinary finesse, a high quality of finish and a profound misunderstanding of the behaviour of underlying materials and composites of materials. I am also aware that flawed techniques are sometimes repeated so consistently that they come to be defended as the conventional wisdom and standard practice of the industry, notwithstanding contrary advice in published guidelines and codes. This has certainly occurred in the past decade in Australia with regard to the location and configuration of movement and expansion joints in floor tiling. My colleagues have recently examined 34 luxury apartments in which perimeter isolation joints in tiling on large cantilevered and geometrically complex balconies have been completely omitted. The relevant clause of Australian Standard 3958.1-1991 - Guide to the installation of ceramic tiles - states: "Movement joints...should be inserted where the tiling abuts restraining surfaces such as perimeter walls, columns, kerbs, steps and plant fixed to the base". Hundreds of metres of urethane-sealed movement joints in another apartment development extend no deeper than the underside of the floor tiles. The relevant clause of the Australian standard states unambiguously: "It is essential that movement joints are carried through the tile and bedding". [My emphasis]

That advice is widely ignored. The unsurprising results include extensive cracks and adhesion failures. Of course it is possible for a floor or paving tile to delaminate completely from its bedding while remaining locked in place and able to resist normal downward loads. In Australia such a tile is termed *drummy*, from the hollow sound produced when it is tapped. It is almost impossible to extract and refix a cluster of drummy tiles without setting in train the rapid spread of drumminess. Many tilers wisely refuse even to attempt such repairs.

On two major projects where tiling with sporadic drumminess has been condemned, contractors are insisting that a distinction must be made between *patent defects*, a concept which covers obviously cracked tiles, and *latent defects* which conveniently includes drummy tiles, ie. intact tiles fully detached but not yet noticeably displaced from the bedding. The contractors argue that they should be relieved of liability for repairing latently defective tiling. By this expedient line of reasoning, a delaminated tile does not become genuinely defective until it cracks or springs upward. Before that defining moment, delamination and its other detrimental consequences presumably must be tolerated.

It has become evident that many tilers in Australia are not familiar with the essential published standards of their industry. In the course of investigating costly failures in Australia, Hong Kong and Thailand, we have confirmed that tiling and stone-fixing contractors could not read, or did not understand, the architects' specifications. In an unresolved dispute over the failure of tiling in a community swimming pool in Queensland in 1998, the contractor's advocate initially insisted that rejected work complied with AS3958.1, a standard not cited in the specification. The contractor was evidently unaware that the preface and first paragraph of that standard caution that it does not apply to "...specialised applications such as swimming pools". In another current dispute over defective tiles used to line a swimming pool, a supposed expert representing the tile supplier holds that tiling failed because installation did not comply with AS3958.1. Representatives of one of Australia's largest tiling contractors have lately argued that the concealment of dense plastic joint spacers under grout in wall tiling has become so commonplace that it should be accepted as *standard industry practice*. It seems to them to be irrelevant that the 1991 Australian standard for tile installation explicitly recommends the removal of joint spacers before grouting. The detrimental effects of embedded spacers are examined in detail below.

It is not the purpose of this paper to describe the most common tiling defects and their causes.[2] Those subjects are adequately covered in textbooks, journal articles and conference proceedings in Europe and North America. I am more concerned to identify lesser known problems and adverse trends before they spread and become ubiquitous. In the context of pre-empting errors that are theoretically avoidable, I am also interested in the ways cautionary advice can be made accessible across language barriers and to all participants in the construction process.

## BAD NEWS TRAVELS SLOWLY AND GETS LOST ON THE WAY

I suspect that most professionals in the field of building science variously known as building diagnostics, forensic engineering and failure analysis secretly long to be the first to discover or explain an intriguing or obscure new form of distress in buildings. Being the first to solve some mystery beyond doubt, whether it be catastrophic rupture of O-rings on the Challenger space shuttle, the collapse of a curtain wall or mundane adhesion failures of toilet wall tiles, brings its own satisfaction. The rapid development of construction technology and the tendency to market new products before they have been tested in all foreseeable circumstances should provide endless opportunities for pioneering studies of innovative defects and failures. In practice, they do not. Occasionally I suspect that I have discovered some unprecedented phenomenon. Almost invariably I soon locate published or anecdotal precedents.

In 1991 I spent months investigating severe and rapid deterioration of the reflective metal coating on architectural glass in the cladding of a new 50-storey hotel in Hong Kong. Sophisticated surface analysis, electron microscopy and spectrometry were employed to demonstrate an incontrovertible correlation between the degree of blue iridescence on the coating and the combination, on the external glass surface, of iron oxides flushed down the facade and acidic byproducts of step-wise oxidation of hydrogen sulphide in the island's famously polluted atmosphere. Nothing in the conventional technical literature on the behaviour of architectural glass hinted at a precedent.

I was briefly tempted to believe that the phenomenon and its explanation might forever become synonymous with the name of Hartog. Then I discovered a one-page

[2] The best English-language source of information on tiling defects, their causes and remedies remains Ceramic Floor and Wall Tile: Performance and Controversies by Carlo Palmonari and Giorgio Timellini. Field Reports of the Ceramic Tile Institute of America and Digests of the British Building Research Establishment from time to time address the subject. The Whitacre Report, a technical newsletter privately published in the USA between 1987 and 1991, is still a valuable source of practical experience. Raymond Blake's paper for QUALICER 98 includes a checklist of common causes of distress in tiling.

article titled *Exposed Metallic Coatings on Glass: A Cautionary Tale* in a 1989 issue of Construction Specifier, a US magazine not noted for highly technical subject matter. I contacted the author who explained that a confidentiality agreement prevented disclosure of all the details of the incident which had provoked his article. Nevertheless, it quickly became clear that reflective glass on a building in Oxnard, California, had suffered a similar fate to that of my client's Hong Kong hotel. A year or so later I recognised a more remote precedent. Almost 2000 years ago, Roman glassmakers created iridescent blue and turquoise surface effects by coating glass objects with tin oxide and burying them in high-sulphate soils. I next noticed iridescent blue haziness on reflective glass above sills of window frames in which embrittlement and cracking of uPVC coatings had exposed steel cores to rainwater and corrosion. By about 1996 I knew of seven similar examples in four countries. At an international conference on architectural glass held in Finland in June last year, I met the technical manager of the American company that in 1989 produced the coated glass for the Hong Kong hotel. He knew of other examples and candidly recounted the steps taken to overcome the problem soon after it was first reported. It had taken a decade to determine precisely the cause, by which time glass coating technology had moved on, leaving a few unhappy building owners with incomplete explanations for their strangely stained windows and curtain walls.

I recount this anecdote to illustrate several points. The first is the importance of timely reporting of bad news as well as good in professional conferences and technical journals. It is unarguably worthwhile to learn from mistakes, particularly if they are someone else's mistakes. Cautionary tales are, however, of little use in pre-empting avoidable defects if they are not quickly and widely disseminated. In the frenzy of the decade-long building boom that preceded the Asian economic crisis of late 1997, architects and builders in Southeast Asia did not allow themselves time to investigate the quality and potential deficiencies of materials and techniques imported or copied from Europe, North America, Japan and elsewhere in Asia.[3] With few exceptions, the suppliers and promoters of those products did not divulge their knowledge, however limited, of past shortcomings, almost all of which occur in installation, not in manufacture.[4] The

[3] During construction of a high-rise office building in Bangkok in 1994, consultants representing the foreign head contractor sought performance data for a locally manufactured thin-set tile adhesive offered by the preferred tenderer for floor and wall tiling. The supplier declined to identify the constituents of the adhesive other than to state that the base polymer was sourced from Germany "in blue drums". Under threat that the product would not be approved, the supplier next procured from the chemistry department of a local university a certificate confirming that the adhesive "...complies with all relevant national and international standards", none of which were identified in the document. To meet the construction program, the owner's representative independently approved the adhesive. It subsequently failed on external walls and balconies. The most likely explanation is that some constituents in the adhesive are soluble in rainwater.

[4] One of the notable exceptions is the catalogue of Latham International, a manufacturer of preformed movement joints for tiled flooring and paving. The catalogue contains diagrams, photographs and explanations of common errors in installation of the company's products. Since its first appearance in 1992, the catalogue has been translated into German, French, Italian and Spanish. I am a strong believer in instructions which in effect show (1) *This is the right way to use our product*, (2) *Here are some common wrong ways to use it*, and (3) *Here are some examples of what can happen if you don't follow the instructions*. Much proprietary technical literature is published in formats and language that ensure it will be misdirected or ignored. Architects and interior designers may need to be impressed by expensively printed catalogues with colour photographs from exotic locations, but people on building sites are better served by step-by-step diagrams inexpensively printed and easily photocopied. Many codes and standards may fairly be described as user-hostile. A printed instruction to comply with Clauses 9.15.3(a) (vii) and (ix) of the local code is not likely to be followed up if the code is written in quasi-legalistic language, costs $50 and falls apart the first time it becomes damp or is flattened out on a photocopier.

predictable result is that countless buildings in Jakarta, Kuala Lumpur, Bangkok, Hong Kong, Taipei and so on reproduce errors of design, specification, construction and performance long recognised and avoided but not widely discussed elsewhere.

There is a discernible sequence of events between the introduction of a new construction material or technique and eventual industry-wide recognition of its unsuspected limitations or weaknesses:

1. A new material or product is developed and tested exclusively for those conditions and configurations anticipated by the manufacturer.
2. It is released into the market and promoted for use in those conditions and configurations, typically as a marginal improvement over something already familiar to the construction industry.
3. It is treated and installed as if its properties are all more or less identical to those of the more familiar products with which it competes.
4. In practice, the new product turns out have subtle but critical differences or shortcomings. These may not appear until it is used for a purpose or in conditions which differ slightly from those envisaged by the manufacturer. A seemingly innovative advance on a familiar material or formulation may be more sensitive to humidity, acid rain and protracted storage at high temperatures. [5] It may be more dependent on accurate mixing ratios and mixing times or more sensitive to the quality of substrate preparation. It may have a shorter shelf-life or working time. It may be incompatible with materials never anticipated by the manufacturer. When exported far from its origin, it may be found to be unsuitable for dissimilar climates, conditions of more intense ultraviolet light, thermal shock and even local wildlife.[6] It may even be incompatible with local work practices, knowledge and industry skills.[7]
5. The first few failures are overlooked, tolerated or explained as isolated examples of poor workmanship. They may be discreetly rectified without publicity and with varying degrees of success since the ultimate causes of

[5] Plastics and synthetic rubbers used in sealants, laminated glass, waterproofing membranes and textured coatings have a very uneven track record in hot humid coastal cities of Asia. Part of the explanation has to do with how these products are handled and stored before installation.

[6] Australian cockatoos have taken a severe toll on synthetic rubber roofing membranes and imported red cedar used in balustrades. Ants in the vicinity of the Victorian Convention Centre in Melbourne appear to be able to digest urethane waterproofing sealants. Corrosion of Grade 316 linished stainless steel cladding on the roof of a recent building in Sydney has been provisionally attributed to the excretory habits of fruit flies sheltering in the warm and moist environment of cooling tower exhaust plumes. No precedent has yet been found for this phenomenon.

[7] For example, there is no point in expressing mixing ratios by mass where the only practical measure on a building site is likely to be by volume, ie. by use of whatever empty container is readily available. Waterproofing sealants based on silicone, urethane and polysulphide rubbers are all to some degree chemically incompatible. On building sites in Thailand, however, *silicone* has come to be used as a generic term for all categories of elastomeric sealants, so warnings on incompatibility may be misunderstood. In many countries in the region, cautions on a product's incompatibility with bitumen may not be recognised as probably applying to coal tar, asphalt and pitch. In seeking material solutions to deskilling in the tile-fixing trades, some manufacturers of tiling adhesives have inadvertently contributed to the problem by encouraging an overly simplistic view of selection criteria and work practices. This is reflected in the prevalence of supposedly *all-purpose* adhesives which are sooner or later used for purposes unforeseen, untested and inappropriate.

failure are typically not yet well understood. Similar failures occur across town, across a country or across a continent, but the similarities are not immediately recognised.[8]

6. A few major failures become newsworthy. Disputes develop which cannot be resolved by negotiation. Some of the parties (usually building owners and institutional investors) with *deep pockets* and remorseless determination provide sufficient resources to support rigorous scientific investigation, often in the course of preparing evidence for litigation or arbitration. Cautionary anecdotes start to spread informally within the design professions, typically when consultants engaged as potential expert witnesses network among their colleagues.[9] Salesmen and technical representatives reluctantly recount rumours about the problems experienced by users of competing products.

7. Reliable explanations for a newly-recognised syndrome of defects start to appear in court proceedings, specialist journals and construction industry magazines, often of limited circulation. Local industry associations sponsor research projects. Increasingly detailed technical papers are published in the proceedings of regional seminars and, later, at international conferences. By this time, the flawed products have probably been withdrawn from the market or quietly modified to overcome their recently-discovered deficiencies. For instance, the sudden disappearance of Lackadaze ®, followed by a marketing blitz for new improved Superlackadaze ®, Lackadaze II ® or Lackadaze XL ®, should instantly raise suspicions, moreso if one or two of the claimed properties for the latest product are slightly more conservative than those of the original product.

8. Knowledge of the problem is absorbed into the *conventional wisdom* of the building design professions and construction industry. Where appropriate, standards and codes are modified or tightened, as has occurred for the tile joint spacers described elsewhere in this paper.

9. The Lackadaze Corporation is taken over and changes its name to Turpitude Inc. ®. The Lackadaze ® fiasco is recounted as a case study in consumer law journals. A textbook, written for undergraduates by an eminent academic, guardedly hints at the hazards of using a product which sounds remarkably similar to....Lackadaze ®.

I know of dozens of products, materials and techniques which have followed this scenario. One of the great challenges for building diagnostics as a discipline within architecture and engineering is to accelerate the process between Stages 5 and 8. The

[8] In giving papers at conferences and seminars in Asia, Australia and most recently Finland, I have alluded to specific failures without identifying the affected buildings. From time to time this provokes audible muttering from individuals in the audience who assume that I am referring to a project known to them. The disturbing truth is that they are usually wrong. This confirms that two or more similar incidents have already occurred, often in the same city, and that each is separately believed to be unique.

[9] One of the most rewarding diversions of international conferences is coffee-break and happy hour gamesmanship, in which potentially competing consultants seek to elicit confidential information about specific defects without revealing how much - or how little - they already know. It is rumoured that a special ASTM Committee has been established and will meet later this year in Ft. Lauderdale, Florida, to formalise a code for this activity.

delay between the first alert and general knowledge is often 3 to 5 years. Past efforts to set up data bases and clearing-houses for information on construction defects have not met their sponsors' expectations. The internet may yet allow such information to be disseminated more quickly. Unfortunately, a few products and proprietary designs for cladding systems have been exported to developing countries even as their deficiencies were becoming common knowledge in the countries of their origin. [10]

There is sometimes a further stage in the sequence outlined above. Discredited materials and techniques occasionally disappear, only to return from a different direction long after knowledge of their flaws has faded from the collective memory. In the past year adhesion failures of imported glass mosaic tiles in Sydney have been attributed to water-sensitive backing glue. Tiling of one suburban swimming pool failed before the joints had been grouted. Tiling in a small unheated spa pool collapsed one day after the pool was filled for the first time. The cause has been identified as a polyvinyl acetate-based adhesive which swells to a white gel, about six times its dry volume, after two days' contact with water. The tile manufacturer in Guandong, China, is evidently using diluted PVA to attach 25 x 25 mm tiles to 300 x 300 mm backing sheets of plastic fibre mesh. The adhesive appears to have been applied in great excess by roller or spray.

While investigating these recent failures, I learned that similar incidents occurred in Australia in the 1960s with Japanese mosaic tiles attached to backing mesh with glues which dissolved or swelled when damp. The tiles were soon recognised as unsuitable for use in conditions of permanent immersion (swimming pools, spa baths, ponds) and frequent wetting. Producers either switched to more stable adhesives, such as epoxy resin, or mounted tiles on sheets of paper fixed to the outer surface. I have been unable to find any recent published warnings on the use of PVA and other soluble adhesives on backing meshes of mosaic tiles for wet areas. Few Australian tile suppliers and fixers now appear to appreciate the risk. As the first compensation claim heads to court, the importer of the glass tiles steadfastly denies that there is a problem.

The English-language technical literature on building defects and failures generally is quite diverse but it remains unfamiliar and inaccessible to most architects and contractors in the region. It is unlikely that more than one or two copies of any of the references cited below are readily available in Thailand. There is no equivalent literature in the languages of Thailand, Malaysia, Indonesia and Vietnam. In many of the countries where BDAP operates, there are also strong cultural disincentives to candid discussion of technical problems in the construction industry. An eminent Thai engineer, a professor at the country's leading university, gives instructive papers on construction defects at conferences in Singapore, Korea and Japan. He is unwilling to do so in Thailand where he fears that his views would be regarded as "unduly negative". Architects in the private sector are reluctant to discuss recurrent defects in even the most general terms, and there is much deliberate misinformation. Some recognise that during the boom period, the design professions were dangerously overstretched. Many practices operated at the margins of their technical competence, relying on inexperienced recent graduates to

[10] The export of outdated and discredited cladding technology is addressed in the author's paper in the proceedings of the Glass Processing Days Conference held in Tampere, Finland, in June 1999.

document designs for speculative high-rise office buildings, condominiums and shopping centres. Contractors were not reluctant to tender on incomplete documentation and to take over the task and responsibility of finishing the designs. The buildings of the boom era are already revealing very high rates of patent and latent defects in cladding, glazing and finishes.

Disputes over defective buildings in Asia tend to be resolved by negotiation or compensation without resort to litigation. While those of us in more litigious environments might applaud this approach, it tends to suppress information that could help others avoid the same problems. It also popularises misleading explanations. In disputes over ceramic tiling, responsibility for remedying distress often passes down the line to the tile supplier and tiling contractor. The contractor is most likely to be the party that caused the problem in the first place, typically through reliance on unskilled labour, lack of supervision and concealed cost-cutting measures. The contractor is also the party least likely to have the technical resources to diagnose the problem accurately and specify an appropriate remedy. That in turn leads to compromise solutions and futile remedial work. I believe that upwards of 50% of repairs to distressed tiling and thin stone veneer cladding in Southeast Asia are based on inaccurate diagnosis and are therefore ultimately unsuccessful.

A prominent example involves cracking of external wall tiling on a ten-level reinforced concrete carparking structure at the base of a 40-storey office building in Bangkok. The outer edges of concrete floor slabs were misaligned by as much as 110 millimetres. External faces of panels of infill brickwork between edge beams and columns were similarly staggered. To achieve the desired flush surface, the tiling contractor projected a vertical line from the slab edge furthest outboard. It then applied successive layers of cement-rich mortar up to a maximum thickness of 120 mm. The centres of gravity of some brick walls were thus shifted beyond their outer lines of support even before the ceramic tiles were fixed. A combination of creep in the concrete structure, differential shrinkage of the massive layers of cement render and thermal expansion of the tiles caused the infill panels to bow outwards. Tiles cracked and fell from the building. The problem was initially attributed to unidentified defects in the tiles, the adhesive and their application. The tiling contractor was already replacing tiles on noticeably distorted walls with ominously tapered cracks when a storey-height panel of masonry collapsed outward. Only then did the building owner and head contractor seek to identify the actual causes of defects in the tiling and, more importantly, in the masonry walls.

A common form of exterior masonry construction in Southeast Asia is a single skin of unreinforced non-loadbearing brickwork between reinforced concrete columns and beams. The quality of bricks and bricklaying are highly variable; low-temperature-fired bricks are used for external walls on buildings of 20 and 30 storeys. The brickwork is finished on both faces with cement plaster (also known as render) and painted, tiled or veneered with thin stone. Large panels of infill brickwork may be sub-divided by narrow concrete tie-beams and columns. These lightly reinforced concrete elements tend to be roughly formed and irregularly aligned within each level and vertically from floor to floor. It follows that straight slots scribed or trowelled in plaster around perimeters of infill panels do not always coincide with junctions between underlying brickwork and concrete. Such joints are intended to induce and conceal shrinkage cracking and accommodate expansion. In practice, plaster and tiles crack directly above the real junctions, not along the expressed joints. Networks of diagonal cracking, another characteristic form of distress in hard finishes on infill brickwork, usually indicate the absence or inadequacy of perimeter movement joints between loadbearing and non-loadbearing elements. A classic example occurs on the end-walls of Bangkok's Montien Hotel.

Another example of a systemic failure, which also has nothing to do with the quality of tiles, involves defects in floor finishes in a shopping centre. It is common in some parts of Asia for unskilled labourers and their families to live in temporary shelters on site, sometimes within buildings under construction. One result is that concrete surfaces, particularly floor slabs, can become contaminated by all the substances that might normally be expected to land on the ground of a slum village. Sub-contractors' temporary workshops also spill mysterious liquids onto concrete floors later to receive adhered finishes. Prior to laying of ceramic tiles and terrazzo, the floors slabs and graded screeds in the four-storey shopping mall were hosed and swept clean, at least to the satisfaction of the flooring contractors. Within weeks of completion, floor finishes on two levels started to crack, buckle and become dusty. Explanations offered by the likely contenders for liability included moisture expansion and mysterious "defects in production" of tiles, excessive deflection, vibration transmitted through the structure from fairground equipment, inadequate curing, excessive shrinkage of screeds and premature loading by fork-lift trucks. Eventually the adhesion failures at most locations were attributed to contamination of successive adhesion surfaces by sticky dust, cooking oil, food oil and fats, diesel fuel, lubricating oil, sugar from spilled beverages, detergent, urine and possibly candle wax and dilute hydrochloric acid. This incident should have prompted publication of a detailed cautionary note or case study, either by the appropriate contractors' associations (in Thailand more often known as *clubs* ) or a professional institute. It did not, possibly because the owner, consultants and contractors stood to be embarrassed if readers guessed the identity of the project. Only those directly involved learned from the incident.

## JOINT WIDTHS AND DIFFERENTIAL MOVEMENT

A fundamental principle of tiling, as with brick and stone masonry, is that grouted joints in the former and mortared joints in the latter should be softer than the large and more massive units they separate. Where joints are less easily deformed, cracks caused by creep, shrinkage, deflection and other differential movements tend to run through the body of the tile rather than within the joints where they may be concealed, heal or be easily repaired. The contribution of grouted joints in relieving compressive and shear stresses in ceramic tiling systems may be small, but it is often critical to their success.

No matter how regular the dimensions and straight the edges of machine-pressed tiles may be, tiling is essentially an aggregation of small modular units which cannot easily be disguised as an uninterrupted monolithic finish. The desire to produce smooth and completely undifferentiated planes in tiling runs counter to a fundamental aesthetic property of the material. Nevertheless, grouted joints and movement joints (ie. both expansion and isolation joints) have become anathema to many architects and interior designers. There is a widespread preference for tile-to-tile joints as narrow as possible, to the point where they almost disappear. It has become fashionable for joints in both wall and floor tiling in Australia and elsewhere to be reduced to 1.5 mm and 1.2 mm regardless of the sizes of the tiles. The concept of relating joint sizes to predictable movement seems to have been lost. Some designers also demand that deformable expansion joints be narrowed, concealed within excessively complex geometric patterns, spaced too far apart or eliminated entirely in order to give the appearance of uninterrupted planes. Nature often declines to co-operate.

We have lately reached and occasionally exceeded the limit of convergence of four historical trends which have almost eliminated the contribution of tile-to-tile joints to safe distribution and relief of stresses generated by thermal, moisture and structural movement:

## 1. Tiles have become larger. The spacing of joints has correspondingly decreased.

An Australian publication of the late-1980s categorised 200 x 200 mm tiles as large. German and Japanese manufacturers were already marketing tiles 25 times that size. A manufacturer in China has recently displayed flat and curved tiles with dimensions of 1.0 and 1.2 metres. It expects that these products will be mechanically fixed on facades and adhesively fixed in interior applications. Tilers in Australia have not hesitated to use epoxy resin to spot bond 450 x 600 mm granite veneer panels to concrete walls, so they will probably do the same with tiles of corresponding dimensions.

## 2. The widths of joints have decreased.

To judge from photographs, the proportion of jointing to tiles in floors of 14th century Spanish palaces and in mid-17th century wall tiling in Holland is about 3% to 5%. Joint widths were probably most influenced by the irregularity of tile edges. A 1949 survey of tiling practices in Europe recorded that the recommended minimum width for wall tiling in France was then 2 mm. The preferred widths were 3 mm or more. In Czechoslovakia the recommended minima were 3 mm for interior wall tiles of all sizes, 2 mm for paving tiles with sides up to 100 mm and 3 mm for larger paving tiles. Joints therefore represented between 1% and 2% of the net area of tiled surfaces.

The Australian CSIRO's guide notes of 1973 and 1987 recommended that "...joints between tiles should not be less than 2 mm wide for tiles up to 100 mm square and proportionally wider for larger tiles". Again, the proportion of joints was about 2%. I have investigated many defective installations with joints of 1.5 mm, a common width of cruciform plastic joint spacers, and less. Joints between 200 x 200 mm ceramic wall tiles in kitchens of a recently completed apartment building in Singapore vary down to 1.35 mm, ie. 0.67% of the net area. Joints between 300 x 300 mm polished granite wall tiles in bathrooms and 450 x 450 mm marble floor tiles in the same building are about 1 mm wide, respectively 0.22% and 0.33% of the net area. Less than a year after completion, the walls and floors display fine cracks and hollow-sounding tiles in more or less predictable patterns.

In 1999 my Sydney office investigated widespread distress in flooring and balcony paving of six luxury apartments on the shores of Sydney Harbour. The interior designers, locally acknowledged as style leaders, specified 1.5 mm wide joints between 600 x 300 mm tiles of polished Egyptian marble. They directed the contractor to omit movement joints over distances of up to 22 metres. The contractor prudently recorded its misgivings before executing the work as instructed. Joints nominally 1.5 mm wide represent 0.25% of the tiled surface in one direction and 0.5% in the other. Such narrow joints cannot contribute much to the relief of compressive stresses generated by diurnal and seasonal thermal movement in the order of 0.2 mm per metre. Not surprisingly, many of the tiles are cracked and drummy. I anticipate that the flooring will be completely replaced.

### 3. As the area ratio of theoretically deformable joints to hard brittle tiles has progressively declined from 2% to about 0.25% and less over the past 50 or so years, the hardness of joints has slowly increased.

Handbooks of the 1950s recommended cement-to-sand ratios of 1:4 and 1:5 for joint grout. One source noted that mortars of 1:6 were being used successfully for grouting wall tiles in Belgium. An instruction sheet published in 1951 proposed "...mortar weak enough to crush before any damage is done to the tiling". The CSIRO note of 1973 advised that joints in wall tiling "...should be filled with flexible material or crushable grout". The general rule seems to have been to minimise the proportion of cement and water, to reduce early shrinkage, while using hydraulic lime as a binder to maintain workability and *adequate* strength, not maximum strength. In Australia, premixed proprietary grouts have long been ubiquitous, but in Southeast Asia grouts are commonly mixed on site. Portland cement is recognised as the most expensive ingredient, capable of acting as an adhesive in its own right. It is often marketed with allusions to elephants, tigers and rhinoceroses to emphasise strength. This may contribute to an almost intuitive belief, among untrained workers, that there is no such thing as too much cement in mortar bedding and grout. The frequent result is excessively stiff joints, high shrinkage and pervasive lime staining. Indelible pattern staining of granite veneer is widespread in Asia, in large part due to the misapplication, to thin stone, of traditional fixing techniques for glazed ceramic tiles. This subject warrants further discussion in another forum.

There are also popular misconceptions about the purpose of latex additives in joint grouts. In the marble-tiled floors of the Sydney apartments described above, 8 to 10 mm wide resilient expansion joint strips, edged in stainless steel, zinc or brass and located at intervals of 5 metres, were not acceptable to the interior designer. To compensate for their omission, a proprietary styrene-butadiene-styrene additive was used in grouting all

1.5 mm wide tile joints. The intention was to turn each tile joint into a de facto movement joint by making it more compressible. The SBS latex does in fact improve the grout's bond, shear and cohesive strengths, its flexibility and durability. However, it significantly decreases compressibility. Whoever specified the grout evidently confused flexibility with softness and elasticity. According to the manufacturer's data sheets, the compressive strength of the SBS-modified grout, as measured by the appropriate ASTM procedure, may be as high as 25 MPa. That is almost equal the compressive strength of concrete in the supporting floor structure. The weakest elements in the system, the bedding, marble and their adhesive bond, are the first to fail under compression. The same pattern of failure would be occurring if ceramic tiles had been used in place of marble. The natural stone and ceramic tile industries are competitors but have many common errors in application of their products. In passing, it is worth recording that in China very large areas of external walls are successfully tiled without visible movement joints. The explanation appears to be the relative width and softness of tile-to-tile joints.

**4. As joints have become narrower, harder and are spaced further apart, building structures have become more flexible and more likely to undergo long-term irreversible movement. Substrates have become more articulated. The need for mechanisms to accommodate differential movement between loadbearing and non-loadbearing elements, in order to protect brittle finishes from distress, has increased. Recognition of that need has not kept pace with developments in structural engineering.**

The live-load and time dependent characteristics of contemporary high-rise and wide-span structures of reinforced concrete and steel are not comparable to those of buildings of the 1950s and 1960s. The phenomena of progressive elastic shortening, creep and irreversible shrinkage in high-rise towers did not receive much attention until the late 1960s. The combined effects were recognised and well-documented in engineering journals by the early 1970s. Accurate data from long-term monitoring of strain in several high-rise concrete structures in Chicago, Miami and Sydney were published in the 1970s and 1980s. The work was summarised in 1987 in Column Shortening in Tall Structures - Prediction and Compensation by Fintel, Ghosh and Iyengar. The following excerpts from their work are particularly relevant:

> In high-rise buildings, the total elastic and inelastic shortening of columns and walls due to gravity loads and shrinkage may be as high as 1 inch for every 80 feet of height [equivalent to 1.04 mm per metre]. The possibly large absolute amount of cumulative column shortening over the height of the structure of ultra-high-rise buildings is of consequence in its effects on the cladding, finishes, partitions and so on. These effects can be contained by providing details at every floor that would allow the vertical structural members to deform without stressing the non-structural elements...
>
> The shortening of columns [and walls] within a single storey affects the partitions, cladding, finishes, piping and so on, since these non-structural elements are not intended to carry vertical loads and are

> therefore not subject to shortening. On the contrary, partitions and cladding may elongate from moisture absorption, pipes from high temperature of liquid contents, cladding from solar radiation and so on. Details for attaching these elements to the structure must be planned so that their movement relative to the structure will not cause failure.
>
> Plaster and masonry partitions, which were quite common in the past, are characteristically rigid and brittle and have limited ability to undergo distortions without cracking. When a slab carrying such partitions is subject to differential support displacements, the partitions must be detailed around their peripheries to allow movement relative to the frame.

Movement Control in the Fabric of Buildings, a textbook published in Britain in 1983, warned that the cumulative effects of elastic shortening, long-term plastic deformation and shrinkage could continue for two or three years after initial application of load to concrete columns and walls. Such cautions had already been integrated into design practices for tall structures, elevator systems, piped services and curtain wall cladding. The implications for performance of thin brittle finishes in tall buildings were largely overlooked. Several early failures were fancifully blamed on wind sway and structure-borne vibration. The total cessation of irreversible movement after two or three years should not be taken as evidence that such movements do not account for wall tiling failures five or ten years later. Tiling can remain sound and stable for years at levels of compression very close to the threshold of adhesion and shear failure. A seemingly small change in the environment, for instance turning off air-conditioning in an untenanted office floor during summer, can raise in-plane stresses to critical levels. Cracking within or around a single tile or disturbance to a small cluster of tiles can cause instantaneous and, in the mathematical sense, catastrophic redistribution of stresses over large distances if tiling is already close to failure. Bowing and arching of wall tiles are still occurring in buildings in Sydney and Brisbane ten years after completion.

The long-term effects of post-tensioning on non-loadbearing partition walls and floor finishes are still being discovered, in part by trial and error. As recently as August 1997, a report by the US National Tile Contractors Association described post-tensioned concrete floors generally as "questionable substrates" demanding special preparation and the use of tile-laying techniques and proprietary materials "... designed specifically for that application". That is certainly not yet appreciated in Southeast Asia where post-tensioned flat plates are the favoured floor system for most high-rise offices and medium-rise shopping centres. I suspect that the recent combination of slender post-tensioned structures, air-conditioning and fast-tracked construction has sown the seeds of a series of floor tiling failures in the developing coastal cities of India, China and Vietnam. Serviceability problems in hard flooring at new airport terminal buildings in Asia should alone keep a large contingent of consultants busy for the next decade.

The conventional view is that rates of shrinkage and creep over long spans decrease progressively to almost zero after 18 months to two years. It is assumed that the moisture content of the concrete achieves some sort of equilibrium with the environment during this time. I suspect that much of the data supporting this view comes from measurement of civil engineering structures and buildings permanently open to the atmosphere. A paper by J W Parkin in the proceedings of a 1976 Concrete Institute of Australia symposium referred to an earlier study of a 203 mm thick post-tensioned concrete slab. The author observed:

> It is evident from the study of the plotted data that shrinkage strains were increased markedly upon air-conditioning of the building, and at 616 days were showing no signs of levelling off.
>
> Total strains in air-conditioned environments appear to be at least twice those of similar structures exposed to the weather. The additional shrinkage commences when the air-conditioning is commissioned. [11]

In 1997 our own investigations of floor tiling failures in a department store in Australia concluded that the rate of shrinkage of post-tensioned concrete floor slabs had suddenly accelerated when the building was fully enclosed and its interior first air-conditioned, ie. dehumidified and cooled, in 1993. This occurred eight or more months after the slabs were cast. Most of the total long-term shrinkage of about 0.58 mm per metre took place after the store's internal fit-out, including floor tiling, had been completed. [12]

Parkin's paper noted that "...cosmetic problems from long-term total movements - columns out-of-plumb, joints widths, cracking in attached brittle elements - can be predicted and controlled by normal good detailing practices". [11] Prediction of the onset and progress of instantaneous and long-term structural movements may require sophisticated computer programmes to account for variables such as construction sequence, staged occupancy and weather. The following excerpt comes, with minor changes, from the Whitacre Report:

It is difficult to compute the exact forces exerted at the tile or mortar concrete interfaces resulting from concrete shrinkage, creep and deflection and tile moisture expansion. There are precautions one can take to minimize bond failure, including:

1. Design for maximum predicted deflection.
2. Determine short and long-term creep characteristics of the structural deck [ie. floor system].
3. Determine the long-term concrete deck shrinkage.
4. Determine the maximum moisture expansion characteristics of the tile.
5. Determine the effect of temperature differentials on the structure both during and after construction.

[11] Parkin, J W, in Prestressed Concrete in Buildings, Concrete Institute of Australia, 1976, citing Currie, Smith, Roper and McKenzie: Site investigation of a prestressed concrete slab, a paper presented at the Symposium on Serviceability of Concrete, The Institution of Engineers, Melbourne, 1975.

[12] A summary of the findings of this investigation has been published as BDAP Bulletin 7/97 - *Hard Flooring on Post-tensioned Slabs*. Copies can be obtained from BDAP's Sydney office, Level 3, 101 Sussex Street, Sydney 2000, Australia.

6. Provide frequent soft joints in prestressed and post-tensioned slabs, as required by engineering design principles.
7. Provide soft joints through the depth of tiling at all perimeter areas.
8. Provide soft joints at frequent intervals within the floor area, at least on column centres and more frequently as dictated by conservative practices.
9. Determine additional factors which could affect delamination of the tile. [13]

Item 4 may be easily satisfied by certification of compliance with a national or international standard. Item 6 is necessarily a matter to be resolved in structural design. Items 7 and 8 are normally satisfied by following good industry practice, installation guidelines and codes. Items 1, 2, 3, 5 and 9 are properly matters to be considered by architects and engineers during design, not left to tiling contractors during construction. If design consultants cannot provide reliable estimates for such movement, they should make very generous allowances when detailing articulated joints in hard finishes. It is inappropriate to delegate this responsibility to skill-based trades through such devices as performance-based specifications and deliberately imprecise *typical details* which may illustrate "aesthetic intent" (ie. superficial appearance) but do not resolve specific joint configurations and dimensions at more failure-prone non-typical locations. [14]

In part summary, developments in structural engineering and building economics have increased the need for articulation and generous movement allowances in hard finishes. Meanwhile, other inexorable trends have all but eliminated the capacity of ceramic tiling to accommodate even moderate levels of in-plane compressive strain. If these trends are not arrested, the incidence of expensive and embarrassing failures will certainly increase. Such failures are already encouraging architects to select alternative materials in situations where conventional tiling has performed satisfactorily for 80 years or more. All segments of the tile manufacturing and fixing industries need to persuade consumers, notably architects and interior designers, that tile-to-tile joints and movement joints can be successfully expressed as part of the inherent aesthetic of a tessellated material, even one that now convincingly mimics metals, glass and natural stone. Of course any such campaign will be futile unless the decline in workmanship in tile-fixing, wherever it occurs, is also reversed. Among Australian designers, the main cause for reticence in choosing ceramic tiling is the lack of reliable workmanship.

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[13] The Whitacre Report, Vol. 1 Issue 5, May-June 1988.

[14] The client for BDAP's 1997 investigation of floor tiling failures in a department store was the tiling contractor. After carrying most of the cost of replacing drummy and cracked tiles for four years, the contractor declined to continue. It then received from the department store's lawyers a demand that it completely replace tiling on two floors of the building. The demand was backed by technical reports prepared by the proprietor, the head contractor, independent engineering consultants and representatives of the tile adhesive manufacturer. The authors of the reports had inspected the building but only one recognised that the floors are post-tensioned. No-one noticed that sliding metal covers over joints between separate post-tensioned areas had exceeded their movement capacity early in the life of the building. All attributed recurrent tiling failures to the convenient catch-all of poor workmanship. The tiling contractor insisted that it had faithfully followed the architect's specifications and directions, some of which had no been documented. It argued (1) that it had no duty to investigate structural movement characteristics and validate compensatory measures in architect's design, and (2) that it should not be held liable for defects arising from errors or omissions in that design. Those arguments were ultimately accepted after the architect conceded that crucial parts of the specification were unsuitable for tiling over post-tensioned floors. The tiling contractor was subsequently compensated for the cost of its earlier remedial work.

## PLASTIC JOINT SPACERS AND MOVEMENT

Since the mid-1990s my colleagues and I have had opportunities to investigate incidents in which the statistical populations of defective tiles were extraordinarily large and the consequences for building owners so drastic as to permit unusually rigorous failure analysis. The intransigence of other parties in the disputes also influenced the amount of physical evidence acquired. We have been able to monitor cause and effect of defects propagating over periods of up to three years in buildings with as many as 80 near-identical tile installations.

The work has convinced me that systemic failures in interior wall and floor tiling typically involve three or more distinct but overlapping errors or weaknesses in design and construction, none of which in isolation can account for the failures. We have demonstrated that tiling often tolerates the cumulative effects of many short-cuts and compromises in workmanship for many years and then fails, for no obvious reason, in so-called cascade events. As often happens, these conclusions were followed by discovery that someone else had already made them, in this instance before I was born and very close to home. The authors of a 1951 typescript report from the CSIRO in Melbourne observed:

> A characteristic of tiling failures is the apparently haphazard way in which they occur. For example we find cases where tiling has suddenly failed after as many as 50 years of satisfactory service; or of one or two bad failures in a large number of walls or floors which have, as far as the builder can tell, been installed in an identical manner.
>
> The reason for these apparently random failures lies in the fact that only rarely will any one cause be sufficient in itself to produce visible damage; the combined effect of two or more factors is usually required to produce stresses of sufficient magnitude to result in a failure. The immediate cause may well be a chance combination of circumstances which has raised long existing stresses beyond what the structure can withstand. As tiling may successfully resist for very long periods stresses only slightly less than those needed to produce failure, the change required may be quite small.

It is rarely possible to pin-point a single factor to account for the failures in tiling. It is also difficult to apportion the relative contributions of each of several factors, although lawyers, courts and insurers usually expect otherwise. It is, however, sometimes possible to identify a *sine qua non* factor, one without which the failure would not have occurred. That concept is not always easy to grasp. For example, it is not equivalent, by analogy, to the final straw that breaks the camel's back. Similarly, the ultimate cause of deforming stress is rarely a cause of material failure. Normal building movements cannot legitimately be regarded as the <u>cause</u> of tiling failures. That is logically equivalent to identifying rain as the cause of leaks through a wall or proximity to the sea as the cause of corrosion of galvanised steel.

Between 1996 and 1999 BDAP conducted some unusually detailed investigations of widespread distress in wall tiling of two office buildings, one of 65 storeys and another of 44 storeys. From the time these buildings were first occupied (and probably even before), walls in toilets suffered recurrent and seemingly spontaneous collapse of clusters of simple 150 x 150 mm pressed tiles. From time to time, areas of up to ten square metres delaminated over a few days, arched a few millimetres away from the rendered substrate and yet remained in place, hanging loosely like curtains, until further disturbed. The problems were initially attributed to isolated lapses of workmanship in tile-fixing. At first, walls were retiled without further investigation in the belief that the rate of failure would quickly diminish. No such trend eventuated. Similar failures occasionally occurred in areas previously repaired.

BDAP was engaged when negotiations between the building owners and head contractor reached an impasse. Working outside normal business hours, teams of students and recent graduates surveyed more than 300,000 tiles to identify patterns of drumminess and cracking and to monitor the propagation of distress. Approximately 2500 loose tiles and their adhesives were closely examined, labelled and stored for future reference. Using digital micrometers, trowelled ribs of adhesive on tiles and render were measured to an accuracy of 0.05 mm. This enabled precise calculation of the volume and thickness of thin-set adhesive. The study identified no fewer than twelve factors contributing to the failures:

- Inadequate depth and continuity of vertical expansion joints cut through render;
- Inadequate width of vertical expansion joints cut through render;
- Omission of movement joints over changes in substrate materials;
- Omission of horizontal expansion joints at skirting level;
- Omission of sliding movement joints in junctions between loadbearing and non-loadbearing walls;
- Fixing of tiles long after expiry of the working time of the thin-set adhesive;
- Insufficient thickness of the adhesive, including trowelling to feathered edges above and below horizontal string lines;
- Insufficient adhesive coverage to tiles, varying down to 5% and commonly less than 25%;
- Excessively rigid attachment of wall-mounted fittings and partitions through the tiling;
- Irregular spot-fixing of cut tiles abutting movement and expansion joints, contrary to the architect's specification;
- Inadvertent load transfer from suspended ceilings to the uppermost course of tiles and from steel beams supporting suspended partitions to slender piers in tiled blockwork walls;
- Embedment of stiff plastic spacer crosses in all joints.

The survey permitted certain patterns of distress to be correlated with specific defects affecting the capacity of the tiling layer to relieve compressive and shear stresses ultimately generated by gradual shortening of the reinforced concrete structure. Such forces would normally be accommodated without distress by irreversible narrowing of resilient expansion joints and by compression within fine grouted joints 1.5 mm to 2 mm wide. In theory, the amount of shortening per floor normally decreases with height up the building. In this instance, the distribution of drummy, cracked and collapsed tiles displayed no distinct pattern. Some walls low in the buildings displayed negligible distress, whereas others near roof level had failure rates above 70%. We gradually concluded the the *sine qua non* factor is obstruction of slight but predictable joint compression and shear due to embedment of hard plastic joint spacers. If these small inserts had been removed before joints were grouted, I suspect that most combinations of the remaining eleven defects listed above would have caused no noticeable distress in the tiling.

In Australian practice, consistent widths of horizontal joints in wall tiling were for decades set by inserting water-resistant string or nylon cord along the top edge of each finished course. Vertical joints were sized using matchsticks, plastic pegs, slips of plywood and corrugated cardboard. These spacers could be removed easily before joints were grouted. They have been gradually supplanted by small plastic crosses with arms typically 10 mm long, 1.5 mm to 3 mm wide and shallow enough to be permanently embedded under the surface of grouted joints. The 1.5 mm dimension probably originates from the minimum joint width for dust-pressed tiles recommended in AS 3958.1-1991. It is here worth recalling the RAIA's 1991 warning on the use of *non-compressible* spacers and much earlier recommendations to remove spillage of relatively hard bedding mortar and adhesive from joint cavities. Clause 5.4.6 (e) AS3958.1 advises:

> Where possible spacing inserts should be removed in conjunction with the preparation of grouting.

Clause 5.7.1 (a) is less equivocal:

> Remove spacers unless specifically designed to remain in situ.
>
> NOTE: Hard, relatively incompressible spacers may impair the performance of the system if left in place.

Similar advice appears in instructions published by tile adhesive manufacturers. An American handbook illustrates a device for dislodging spacers. Nevertheless, the embedment of cruciform spacers has become commonplace in Australian tiling practice. Small plastic crosses which are clearly very hard and incompressible are sold in packages with labels stating that they may be left in place. Where tightly embedded in joints, their effect is equivalent to using extremely stiff grout. A less severe effect is discolouration and flaking of shallow grout over spacers.

Commercial tile-fixers are understandably reluctant to modify their use of a cheap labour-saving device unless given compelling evidence that embedment is detrimental.

Such evidence has invariably been contentious, but the Standards Australia committee revising AS 3958.1 last year decided to strengthen and explain the proscription on embedment. It is hoped that accessory manufacturers will respond by developing spacers which are easy to extract or are at least as compressible as soft grouts. Curiously, some tilers approaching retirement are adamant that removal of spacers, even relatively soft ones, has been common sense practice for more than four decades, whereas a few large contractors rely on familiar arguments from silence: "We've been doing it this way for as long as anyone can remember and have never had problems".

Such claims deserve close scrutiny. Within 100 metres of the two office buildings noted above stands another of 32 storeys. It has suffered the same problem since first occupied, as have at least four other high-rise office towers, an apartment building and a geriatric nursing home in Sydney, two office towers and a shopping centre in Melbourne and a 45-storey office building in Brisbane. There is anecdotal evidence of many more examples in Australia and further north. A side column on the front page of the Sydney Morning Herald, the city's oldest newspaper, chronicles newsworthy trivia. In June 1997 it reported:

> Nature called yesterday while John Davis, of North Curl Curl, was visiting the Building Services Corporation's new offices in Castlereagh Street. In the men's toilets all the tiles were peeling off the wall. Whoever did the job sure chose the wrong place.

The Building Services Corporation is the organisation responsible for investigating consumer complaints over standards of workmanship in the building trades. It is located on the fifteenth floor of a high-rise office building.

The use of spacers recessed at corners has another adverse effect on tiling which has received little if any attention. Traditional methods of wall tiling with thin-set adhesives require that each tile be pressed into the adhesive paste a few millimetres above and to one side of its final position. The tile is then twisted slightly and drawn downward diagonally into place (see Diagram 1). The purpose of this so-called *twist and slide* technique is to force ribs of adhesive to flatten, roll, spread sideways and merge. The technique also tends the drag and rupture any thin dessicated film that may have formed on the ribs during the working time of the adhesive. Skinned-over adhesive may not wet or bond to porous tiles. Premature drying of thin-set adhesives is a common problem in hot climates, on highly porous substrates and wherever tilers assume that adhesive manufacturers published maximum working times are unnecessarily conservative.

Where spacer crosses are already embedded at the top corners of one course of tiles, their upward-protruding arms interfere with *twist and slide* action during setting of tiles in the next course (see Diagram 2). Tile-fixers overcome these obstructions by lowering the bottom edge of each tile directly onto the horizontal arms of spacers in the preceding course. The tile is then rotated or hinged on the spacers, pressed flat onto the adhesive ribs and beaten. This technique can be very fast, but it significantly degrades contact coverage and adhesion. It tends to flatten skinned-over ribs without dragging or tearing their surface, particularly in the centre two-thirds of the tile. The evidence from our studies is incontrovertible. We have examined thousands of tiles and can reliably correlate different tiling techniques with patterns of coverage, deterioration of adhesion and excessive working times. Typical coverage rates range from nil to about 20%. We can also confidently distinguish adhesives that have been retrowelled after expiry of their practical working times. Some recurrent patterns are shown in Diagram 3. For a government client in Queensland, we have proposed to reproduce and record these effects in tiles fixed onto sheets of frosted glass. Similar work has already been done by PCI, a manufacturer of tile adhesives in Germany and Britain.

## WORKING TIMES FOR TILE ADHESIVES

*Working time* is the maximum safe delay between spreading adhesive onto the substrate and covering it with a tile. *Open time* is the maximum delay between mixing or decanting an adhesive and spreading it on the wall or floor. The terms are, however, sometimes confused, in the sense that open time is taken to mean *open to the atmosphere* before and after application.

A fine print note in AS3958.1 suggests that:

> ...the working time specified by the manufacturer will vary according to...the prevailing atmospheric conditions, but it is usually not more than about 15 minutes to 20 minutes.

In practice, most manufacturers' data sheets give working times for supposedly *normal conditions* which make no practical allowance for variable atmospheric conditions and show little appreciation of the real worksite environment. Working times cited in numerous manufacturers' data sheets have been tested and assessed in conditions of about 22 degrees C and 55% relative humidity, that is, in air-conditioned offices or laboratories rather than on typical building sites. Good Tiling Practice, a handbook published in New Zealand in 1996, notes that "...the acceptable temperature range for adhesive fixing is 18 to 24 oC". That narrow range may be practicable in New Zealand, but in Singapore the annual minimum ambient air temperature is just on 24 oC. In Bangkok it is about 16 oC. Toilets, kitchens, storerooms, lift lobbies and corridors in central service cores of deep-plan buildings such as offices and hospitals typically have no windows. Tiling normally precedes installation of internal lighting and commissioning of mechanical ventilation. Tile-fixers in Australia therefore often use heavy-duty floodlights which can introduce 1000 watts of heat or more into confined spaces and cause radiant heating of nearby surfaces. To dissipate the heat, powerful portable fans are placed in doorways. In an Australian summer, the prevailing conditions in such work areas are more likely to be around 38 oC and 80% relative humidity, with air movement of perhaps 4 metres per second across work surfaces. The effects on working times of tiling adhesives are not widely appreciated.

Tile-fixers seem by nature to be optimists. If the recommended working time is 20 minutes, they will often assume that the practical time is really closer to 30 minutes. maybe more. In fact it may be 10 or 15 minutes. Directions to spread no more adhesive than can be covered in the product's working time are thus amenable to very broad interpretation. Common tile sizes in utility areas of commercial offices, hospitals and hotels are equivalent to between 44 and 50 tiles per square metre. To cover three square metres of trowelled adhesive with these tiles in 15 minutes, a tiler would need to fix one tile every six to seven seconds. The largest single application of trowelled thin-set adhesive recorded by BDAP is 5.8 square metres. This was exposed to view when more than 8 square metres of tiles collapsed from a wall. The trowelled area corresponded to 260 tiles. For an adhesive with an effective working time of 30 minutes, one tile would need to be fixed every nine seconds. I would be pleased to meet the tiler who can fix 72 square metres of such tiles in an 8-hour working day.

Precise relationships between open time, working time, elevated temperatures, radiant heat and air movement rates may be known to some adhesive manufacturers, but there is little reliable information in tiling industry publications. More than 30 years ago the US Ceramic Tile Institute published results of tests to assess the influence of extended open times on the bonding strength of ordinary thin-set Portland cement mortar. The bonding strength for a tile fixed after an open time of ten minutes was measured as 33.2 pounds per square inch. As open time was prolonged, the bond strength declined as follows:

| | |
|---|---|
| 15 minutes | 30.2 psi |
| 20 minutes | 10.8 psi |
| 30 minutes | 5.0 psi |

At 35 minutes, the tile could not be made to bond to the mortar. I guess that the practical working times for contemporary thin-set adhesives in the unexceptional conditions described above are about half those cited by manufacturers.

Codes and standards recommend that it is sound practice to remove a tile occasionally as fixing proceeds in order to confirm adequate contact and bonding. I have written that instruction into tiling specifications but I have seldom seen it followed. When hundreds of tiles delaminate and are removed for safety or repair, anomalies in the adhesive layer make it easy to discern where tiles were removed for inspection during fixing. The estimated direct cost for remedying the most extensive internal wall tiling failure investigated by BDAP is about $US1.65 million. Most of the systemic defects of workmanship in that building could have been identified by removing a few tiles at any stage of the project. We have seen no evidence that tiles were removed for this purpose.

In this example, a series of well-documented defects successively compromised the long-term stability of the tiled finish. The insertion of plastic spacer crosses at corners of wall tiles encouraged a fixing technique which severely reduced the initial contact coverage of trowelled thin-set adhesive in tiles. Fixing of tiles after expiry of the effective working time of the adhesive resulted in skinned-over ribs of paste which characteristically flattened against the tile but did not rupture and merge and did not wet and bond to the tile's porous surface. The volume of adhesive per unit area trowelled onto the wall often fell far short of the manufacturer's recommended "nominal" rate. As the thickness of the adhesive reduced, perhaps through use of worn notched trowels, the capacity of the hardened adhesive layer to accommodate shear strain correspondingly declined. Feather-edging of adhesive along horizontal string lines left narrow bands of nil adhesion from which bond failure later spread. The embedment of stiff spacer crosses in all joints eliminated the contribution of soft joint grout to distribution and relief of compressive stresses in the plane of the tiling. Recurrent errors in configuration of resilient silicone sealant-filled movement joints in effect prevented essential stress relief along free edges of large panels of tiling. The tiling was thus already highly predisposed to adhesion failure before any extraneous loads were applied.

As predicted by computer modelling, the tall concrete structure shortened by a few centimetres during construction and in the first year or two thereafter. The amount of compression was moderate and well below the structural consultants' worst-case estimates. Nevertheless, it was sufficient to overwhelm the adhesive and cohesive strengths of tile adhesives applied to concrete shear walls in the building's central core. The effects of small and unavoidable differential movement in the background were exacerbated by lack of separation between wall-mounted fittings and surrounding tiles. This caused transmission of concentrated gravity loads and vibration into the brittle finish. Finally, mechanical fixing of the perimeters of suspended metal pan ceilings to concrete walls, through the uppermost course of tiles, provided paths for transmission of unforeseen gravity loads into the finish. These loads increased slowly as the structural frame shortened a fraction of a millimetre per metre.

The detrimental effects of combinations of these defects have caused widespread drumminess. Occasionally, large areas of tiling between the skirting and top course suddenly arch or bulge from the substrate render and waver when touched. The plastic spacer crosses then act as hinges, holding the tiles together until one or two come loose and set off a progressive collapse. Given the accumulation of defects, it is amazing that most of the tiling remains sound after six years.

## CONCLUSION

Almost all defects in construction of conventional buildings have documented precedents and are therefore, as least in theory, avoidable by reference to others' experience. The title of this paper reveals my habitually sceptical view that efforts to forestall repetition of well-chronicled defects are largely futile. Many defects in conventional construction have long gestation periods. They remain dormant or concealed for years, suddenly cause unacceptable distress in the fabric of a building and leave insufficient evidence to allow immediate determination of the cause. Delays between genesis and discovery of a problem, and then between first alerts and widespread recognition of its occurrence, give some credence to the familiar argument from silence: "We've been doing it this way for years without problems". That often means that the bad news has yet to arrive or that it has been delivered and misunderstood.

The defects we repeatedly encounter in ceramic tiling are predominantly shortcomings in design and installation, not in manufacture of tiles and tiling accessories. There are, of course, defective products, but their occurrence tends to be geographically concentrated and short-lived. A sophisticated, well-capitalised and science-based manufacturing industry can respond efficiently to such problems. It can organise world congresses, support research and publish technical journals. By contrast, the service industry that applies the product, at least in the region of my experience, is skill-based, fragmented and conservative, often to the point of obstinacy. Its low entry and exit costs tend to immunize individuals and companies from the ultimate costs of rectifying their errors.[15] The tiling industy does not have the resources, organisation and incentive to identify and respond quickly to shortcomings in its work practices. For instance, as I note above, architects and the tiling industry in Australia were formally alerted to the detrimental effects of excessively hard joint spacers in 1991. The similar consequences of obstructed compression of tile-to-tile joints in high-rise concrete structures had already been addressed in the late 1970s in the context of uncrushable glaze-coated lugs on spacer lug tiles. Nevertheless, many tiling contractors continue to reject arguments against the practice of embedding spacers and, more generally, for the need to maintain the compressibility of joints.

In a time of resource depletion and evironmental degradation, it is disturbing to calculate the energy embedded in the thousands of metres of unflawed tiles that have ended up as landfill due to the installation defects I have reported. Education is the only reliable way to pre-empt recurrence of such defects in construction. In the case of installation defects in tiling, the initiative and resources probably have to come from outside the tile-fixing industry, as already seems to be the case in Spain. The same applies to educating architects and interior designers. To protect its own position, the manufacturing industry should be doing more to educate the design professions.

[15] Stated less euphemistically: Contractors in building trades which require little capital investment, and which rely on the skills of individuals who are in turn often short-term employees, have a propensity to liquidate and disappear (and sometimes quickly re-appear elsewhere in thin disguise) when confronted with liability for the costs of rectifying poor work. Popular anecdotes suggest that much tiling during the recent pre-Olympic construction boom in Sydney was performed by groups of visitors travelling from the Asian mainland on six-month tourist visas. That appears to have been the case in refurbishment of a ferry terminal in 1993. When paving tiles failed almost immediately, due to incorrect use of thin-set adhesive over a rough-textured exposed-aggregate concrete substrate, the six tilers engaged on the job could not be located. The hand-written notes they left on drawings were in Korean.

My Bangkok office has collected every readily available English-language book on ceramic tiling, including translations of texts from Italy and Japan. We find that lavishly illustrated histories of tiles outnumber technical primers. That suggests that commercial publishers see no market for the latter. If so, the manufacturing industry should subsidise the writing and publication of design handbooks. There is ample information in research journals and the proceedings of conferences, but it is characteristically too specialized to find its way into design office libraries and onto the desks of architects. There is a clear need to distill this knowledge into affordable reference books which address tile selection, testing, specification, design detailing, installation, maintenance and repair from first principles to everyday practice.[16] It would be better if such books were written or made available for translation into the languages of technically unsophisticated markets in Asia and elsewhere in the developing world.

[16] The Technical Design Manual for Direct Adhered Ceramic Tile, Stone and Thin Brick Facades, written for Laticrete International by Richard Goldberg, a frequent contributor to Qualicer conferences, is an excellent start. There is no English-language equivalent for the technically less challenging field of interior wall and floor tiling. Ceramic Floor and Wall Tile: Performance and Controversies by Carlo Palmonari and Giorgio Timellini deserves to be revised and elaborated. Notwithstanding the title, it deals almost exclusively with floor tiling.

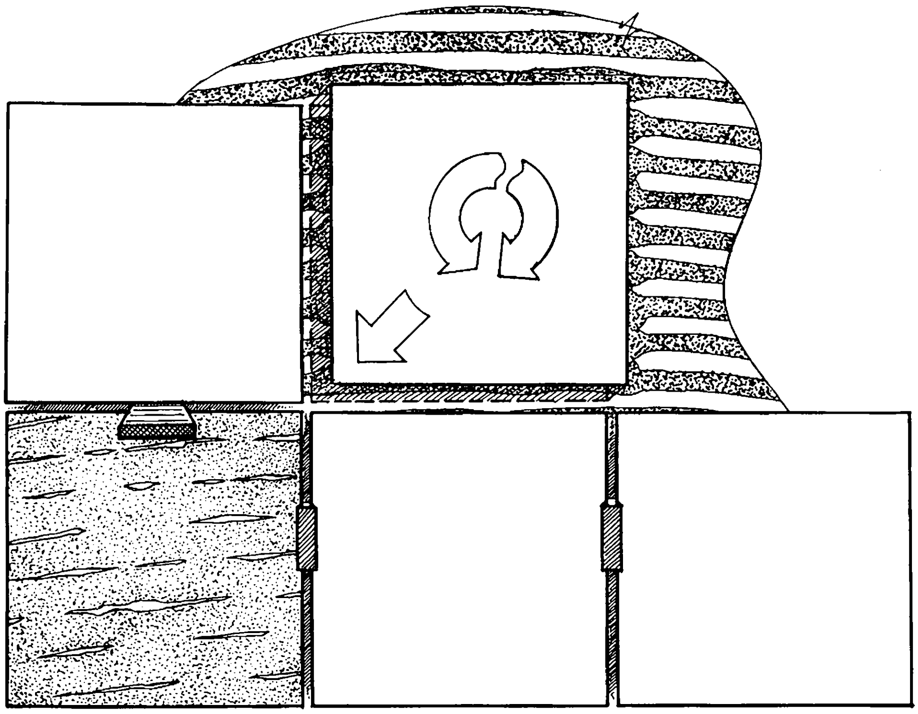


**Diagram 1**

*The preferred twist and slide technique of wall tiling. The tile is pressed into ribs of thin-set adhesive above and slightly to one side of its ultimate location. The tile is given a slight twist, both clockwise and counterclockwise, and then made to slide into position. This action causes ribs of adhesive to flatten and merge. Dried skins on ribs tend to be torn or dragged, thereby allowing contact between wet paste and the porous tile surface. Contact coverage is likely to be more or less uniform across the tile.*

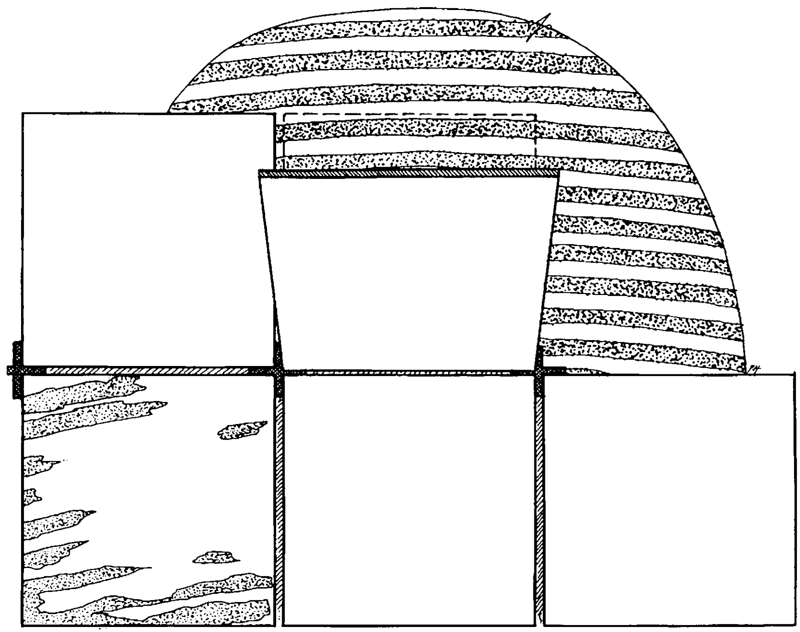
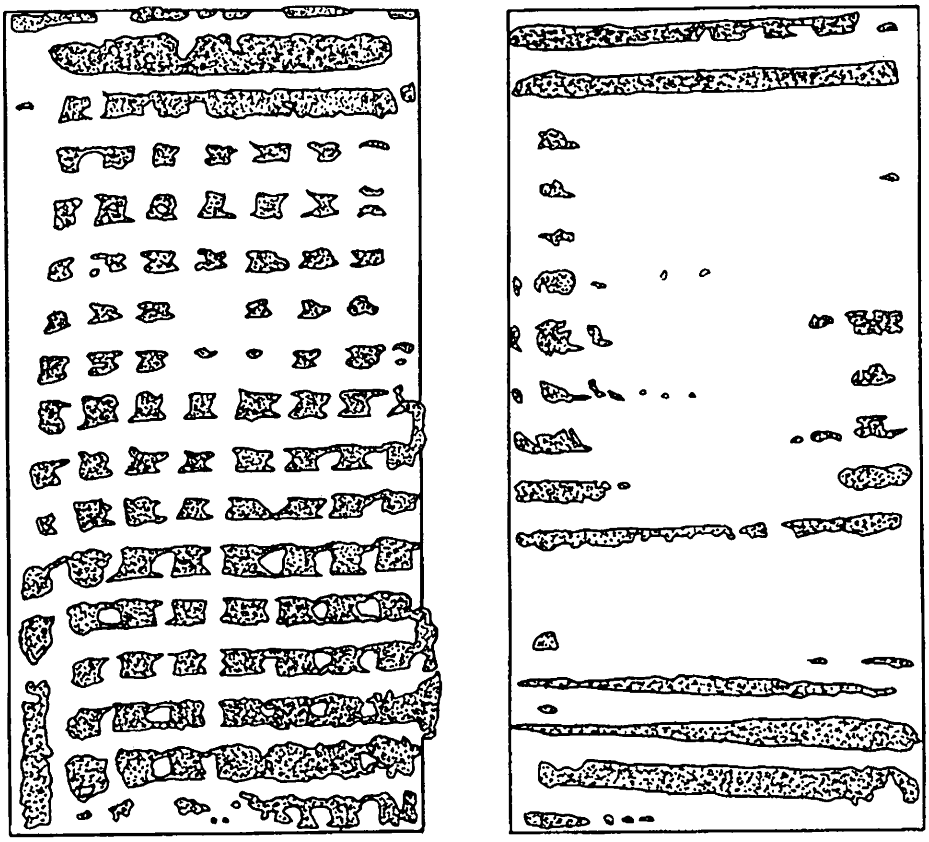


**Diagram 2**

*The fixing technique, here termed hinge and thump, adopted to overcome the problem of dislodging spacer crosses already in place along the top of the preceding course of tiles. The bottom edge of each tile is lowered onto the horizontal arms of two spacers. The tile may immediately compress and cut into the lowest two or three ribs of adhesive. The tile is then hinged towards the wall and beaten. This action flattens ribs of adhesive without forcing them to merge. There is an increased risk that ribs with slightly dessicated skins are pressed against the tile without wetting and bonding to it. BDAP's studies of delaminated tiles fixed by this method have shown that ribs of adhesive remaining on the substrate, in the area corresponding to the central two-thirds of the tile, tend to be flat, smooth-surfaced and bear neat impressions of embossments on the tile. However, they leave no residues of adhesive, other than milky stains, on the tile.*

*Diagram 3.*

*Patterns of coverage of thin-set adhesive on delaminated 100 x 200 mm wall tiles. The shaded areas represent adhesive which bonded to the tiles during fixing and remained attached after the tiling failed. These patterns are characteristic of ribs of adhesive retrowelled after expiry of the product's effective working time.*



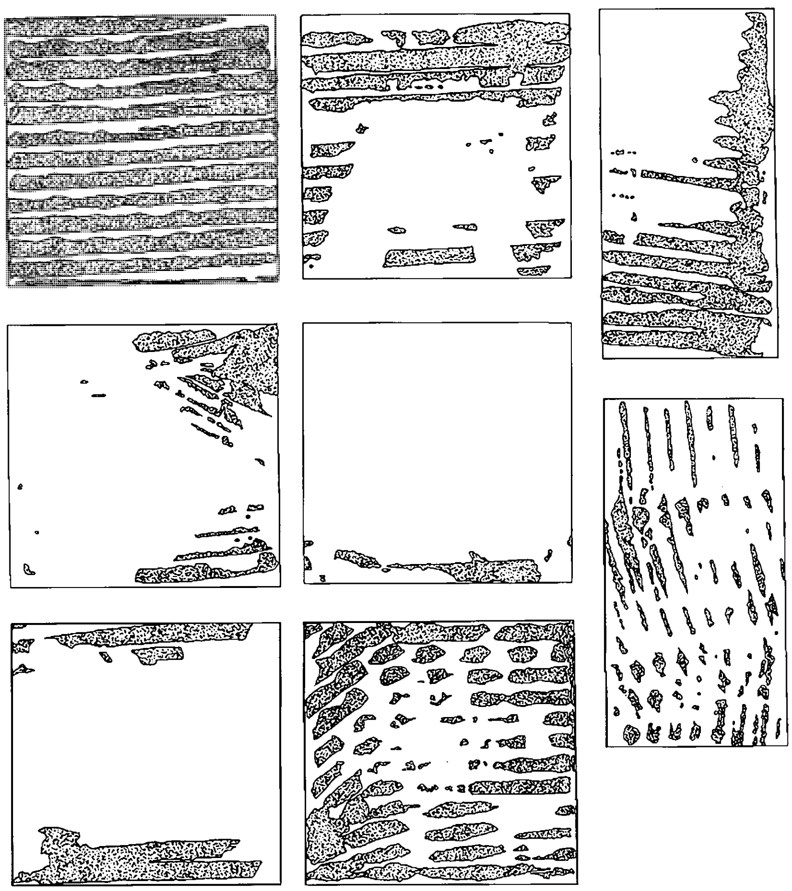


*Diagram 4.*

*Adhesive coverage patterns associated with the hinge and thump fixing method encouraged by prior embedment of cruciform plastic joint spacers along the tops of preceding course of tiles. The shaded areas represent thin set adhesive which bonded to 150 x 150 mm and 100 x 200 mm wall tiles during fixing and remained attached after the tiling failed. Adhesive elsewhere on the rendered substrate either did not come into contact with the tile or did not wet and bond to the porous surface.*

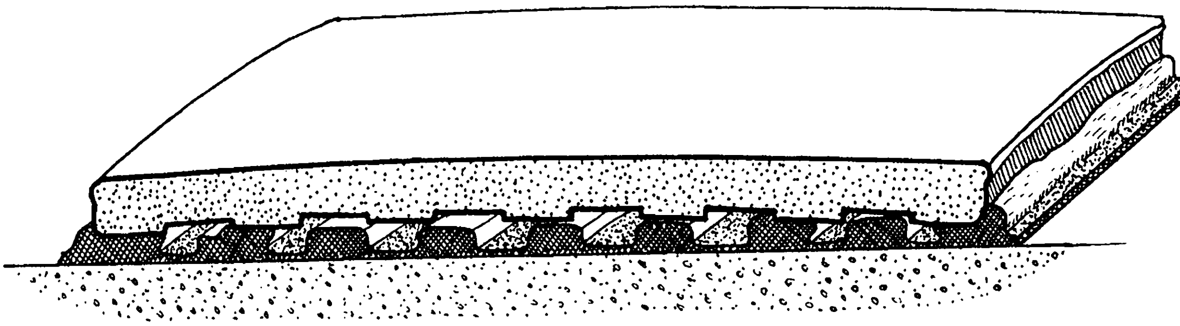


*Diagram 5.*

*Thin-set adhesives are generally defined in Australian and North American as being not more than 3 mm thick. Manufacturer's instructions commonly recommend use of trowels with square notches at least 6 x 6 x 6 mm to spread these adhesives. In theory, this produces ribs of adhesive 3 mm thick which, if fully compacted, give a uniform adhesive layer about 1.5 mm. 75% contact coverage would correspond to a 2 mm thick layer. Smooth substrates, wom trowels and incorrect application techniques occasionally combine to produce ribs of adhesive too shallow to be flattened during fixing of wall tiles with a slight but permissible concavity on the unglazed face. BDAP has recorded instances in which the average thicknesses of intact smooth-faced ribs of hardened adhesive paste is as low as 0.83 mm.*

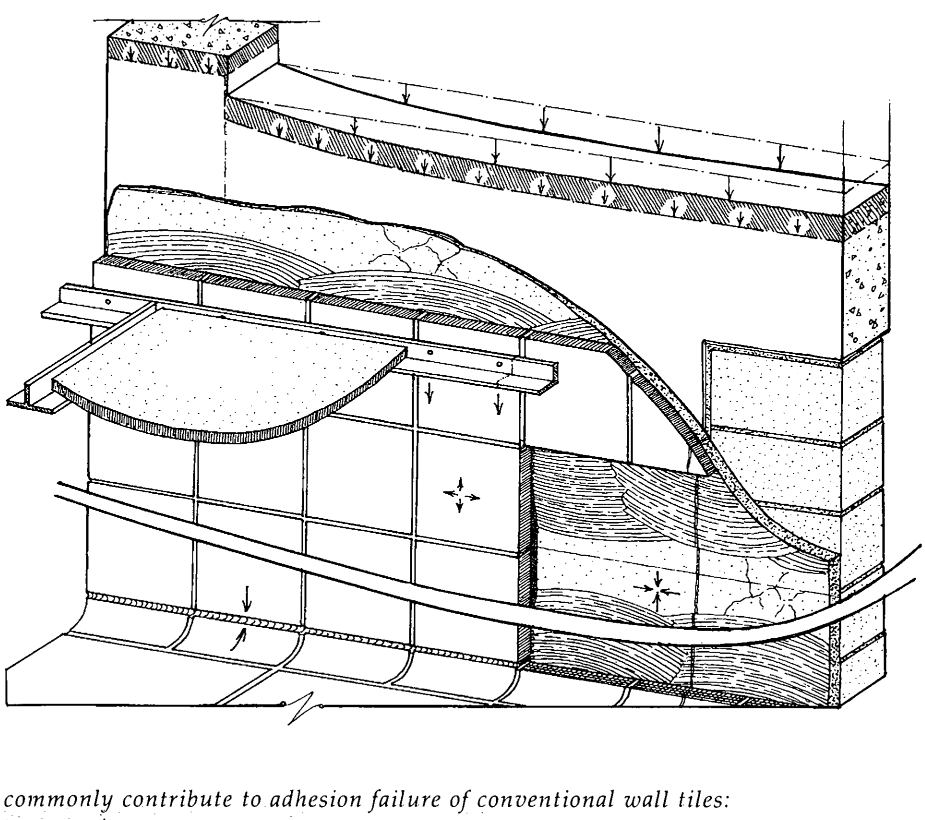


***Diagram 6.***

*Factors which commonly contribute to adhesion failure of conventional wall tiles:*

- *Progressive elastic shortening, creep and skrinkage of reinforced concrete columns and shear walls.*
- *Deflection of reinforced concrete elements such as wall beams and Vierendeel trusses.*
- *Omission or inadequacy of control joints around the perimeters of nonloadbearing infill panels in concrete walls such as elevator shafts.*
- *Inadvertent transfer of gravity loads from suspended ceilings into the top course of tiles and from wall-mounted fixures to wall tiles elsewhere.*
- *Skrinkage and cracking of cement substrates.*
- *Irreversible moisture-related expansion of ceramic tiles.*
- *Horizontal bands of weakness in the adhesive layer due to trowelling of thin-set adhesives to feathered edges parallel to string lines used to set out the tiling.*
- *Omission or obstruction of horizontal expansion joints at floor and skirting level.*

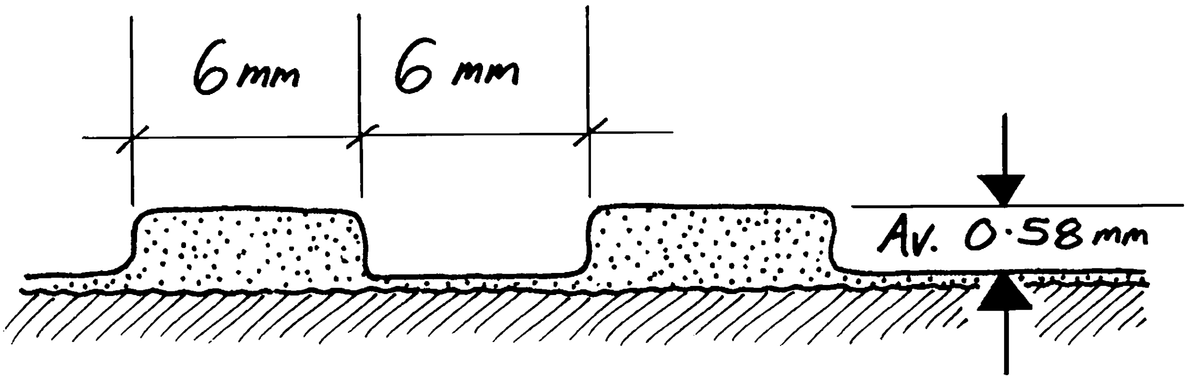



*Diagram 7.*

*A set of micrometer measurements of ribs of trowelled thin-set tile adhesive from the rendered substrate of wall tiling which failed in adhesion on the walls of a hospital in eastern Australia. The figures record in milimetres the distance from the smooth top surfaces of uncompressed ribs, ie. those which were undisturbed during fixing, to the thin film of adhesive paste scraped onto the render*

| | | | | | |
|---|---|---|---|---|---|
| 0.66 | 0.74 | 0.47 | 0.72 | 0.41 | 0.55 |
| 0.63 | 0.57 | 0.49 | 0.51 | 0.49 | 0.56 |
| 0.63 | 0.52 | 0.53 | 0.56 | 0.76 | 0.54 |

*The average thickness is 0.58 mm. To obtain such dimensions using a 6 x 6 x 6 mm square notched trowell, it would be necessary for the trowell to be drawn across the wall at an angle of less than 10 degrees. The calculated volume of adhesive on the walls is about 40% of that derived from the manufacturer's recommended minimum spread rate given in terms of mass per unit area.*