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Research on Adhesion Technologies for External Wall Tiles and Rendering Study Report

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Study Report

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EXECUTIVE SUMMARY

Research Background and Scope

This report considers issues related to adhesion technologies for external wall tiles and rendering in Hong Kong. Failure incidents involving adhered render and tiles on the external walls of buildings have occurred in Hong Kong and other places over the years. Reactions to these incidents have varied from one country to another with China and Singapore imposing restrictions on the use of external wall tiles above a certain building height. Other countries including UK and Australia have reacted by addressing areas such as training, materials specifications and testing but have avoided the imposition of building height limits.

In view of the incidents of detachment of wet fixed external wall tiles even in newly completed projects, the Construction Industry Council (CIC) noted the concerns of industry stakeholders and considered that the use of wet fixing of external wall tiles and rendering in buildings, in particular those high rise ones, in Hong Kong as well as the design and workmanship standards thereof should be reviewed. This research project covered the following major items of work in accordance with the Outline Brief:

1. Literature Review on Previous Research.
2. Review of Experience, Relevant Literature and Research in Overseas Countries.
3. Summary of Stakeholders feedbacks on technical aspects, social aspects, execution and related issues
4. Review of Local Regulations and Practise
5. Findings on site inspection and testing at four selected construction sites.
6. Discussion on Major Causes of Debonding.
7. Testing to justify the adoption of proposed tiling recommendations.
8. Recommendations on improvement of tile installation
9. Production of Practical Design and Construction Guidelines to Cover Specification, Design, Workmanship and Maintenance of External Wall Tiles and Rendering

Overseas experience from Australia, Singapore, Japan and the United Kingdom was covered for the overseas review. This review was completed in order to understand the types of problems encountered elsewhere and any solutions that could be considered for adoption in Hong Kong.

Failure or Detachment of External Wall Tiles and Rendering

Many of the failure incidents with wet fixed external tiles and rendering on buildings in Hong Kong can be traced back to either anomalous construction or deficiencies in the original design or specification. These problems will lead to the requirement for increased maintenance and repair efforts throughout the operational life of the building in order to maintain acceptable safety and functionality.

The failure to provide a level of maintenance and repair commensurate with the durability of the original building construction has lead to the occurrence of falling tiles / render over the years.

Proposed Solutions and the Way Forward

The current situation has been reviewed and information obtained by consulting stakeholders including government officials, an academic and a manufacturer of cementitious products related to external wall tiles and rendering. The information obtained from these sources was combined with a literature search of relevant materials, overseas studies, site inspection and testing at four selected construction sites and testing on the adhesive properties of commonly available tile adhesive and render materials.

A combination approach is proposed that includes provision of necessary information to stakeholders on technical, organizational and non technical matters in a way that can be conveniently obtained and understood – to be included in the Design and Construction Guidelines.

The way forwards is proposed as follows:

1. Provision of information to stakeholders that will include guidance on design, specification, materials, workmanship and maintenance;

2. Improved training of the workforce to improve the quality of render and tile installation work;

3. Review / improvement of existing tiling guidelines to include current best practice and to follow the recommendations of international standards;

4. Appropriate design and specification of materials together with acceptable installation work is recommended for tiles and rendering at different benchmark building heights;

5. Dissemination of information contained in the guidelines to interested industry stakeholders including owners, developers, design and construction professionals, operatives and building management/ maintenance professionals.

1 INTRODUCTION

1.1 BACKGROUND

Wall tiles are commonly used as finishes to external walls of buildings in Hong Kong. Ceramic or mosaic tiles are adhered/ bonded to a layer of cement and sand rendering (with or without adhesive materials) by cement and sand mortar (with or without adhesive) or a bed of proprietary adhesives. The cement and sand rendering is in turn adhered/ bonded to the surface of the external walls via spatter dash and/ or bonding agents.

In view of the incidents of detachment of wet fixed external wall tiles even in newly completed projects, the Construction Industry Council (CIC) has noted the concerns of industry stakeholders and considered that the use of wet fixing of external wall tiles and rendering in buildings, in particular those high-rise ones, in Hong Kong as well as the design and workmanship standards thereof should be reviewed.

1.2 OBJECTIVES AND SCOPE OF WORK

AECOM Asia Company Limited (AECOM) was commissioned in June 2010 by CIC to complete a scope of research as set out in the Outline Brief.

To review the design and workmanship standards for wet fixing of external wall tiles and rendering with reference to the common causes of debonding or failure of wet fixed external wall tiles, relevant international/ national standards, latest technological development and the expectations of the industry;

To study the suitability of the use of wet fixing of external wall tiles and rendering in buildings in Hong Kong in particular the high-rise ones and, where appropriate, specify improved adhesion technologies and fixing methods for external wall tiles and rendering in terms of design and workmanship requirements;

To consider the applicability of the improved adhesion technologies and fixing methods and where necessary, to set a benchmark building height beyond which the adhesion technologies and fixing methods for external wall tiles would be undesirable, and;

The key deliverables involved the identification of the problems, appropriate guidelines and recommendation taking into account both local and overseas experience, on wet fixing of external wall tiles and rendering.

The scope of the research is further elaborated in the following sections.

2 SCOPE OF THE STUDY

With a tight schedule to complete the Study, a systematic methodology was adopted to achieve the objectives stipulated for the Assignment. This has comprised the following:

A broad background desk study was carried out to locate the publicly available information that would be related to the Study. The studied information has included newspapers, technical publications of numerous Government Departments, technical papers, journals and books obtained from academic libraries and through internet searches.

Through introduction and liaison by CIC, meetings and consultations were arranged with the Government and non-Government officials to consolidate the relevant information. Findings from their previous studies, investigations, research and innovative measures were discussed. Separate consultations were also arranged with an academic and a tile adhesive and render manufacturer to understand the extent of the problem and how these problems could be mitigated from their points of view.

To obtain a broader and more objective feedback from the stakeholders. A set of Questionnaire was designed to collect their views on some technical aspects, social aspects, execution and related issues.

A technical investigation of the way render and tiles are applied to external walls was conducted. Critical items of detailing and use of materials that could improve the installation of external wall tile / render systems were evaluated.

External wall tile / render systems are also used oversees and have suffered many of the same problems experienced in Hong Kong. Experience on external wall tile / render systems defects were obtained from Australia, Singapore and the United Kingdom. Differences and similarities of the particular overseas circumstances were reviewed and some of their mitigation and preventive measures to minimise incidences of defects were identified and discussed.

Concise guidelines on installation of external wall tiles / render for all industry stakeholders according to the review results will be compiled. The guidelines will be targeted to all industry stakeholders and prepared in an easily comprehensible format.

3 REVIEW FINDINGS

Painting and rendering were the common external wall finishes in Hong Kong before the 1970s. Then tile finishes have become popular, which Ho et al. (2004) highlights that mosaic tiles, especially glass mosaic, came up with popularity in the early 1970s. Ceramic tiles and granite tiles, which are larger in size than mosaic tiles, have then become more and more popular since the 1980s. The popularity of external wall tiles is because of the durable and the almost maintenance-free property as well as the better aesthetic appearance and the stronger protection provided for the façades. These properties are of utmost importance for high-rise domestic buildings.

However, the recent spate of accidents caused by the delamination of external wall tiles in many cities raises a serious concern on the viability of applying external wall tile system in high-rise buildings. Tatlow (1994) and Wallis (1995) report the situations in Hong Kong, and Chew (1992) reports that in Singapore. Ho et al. (2005) reviews the external wall tile failure cases in Hong Kong and put forward a 4 x 4 matrix on the potential causes of the failure.

The following sections review the related literatures in different regions, and try to find any common patterns on the findings of the causes of external wall tile failures. The arrangement of sections is by regions, including the local (Hong Kong), the Asian Pacific, Europe and America.

3.1 LITERATURE REVIEW AND PREVIOUS RESEARCH FINDINGS

3.1.1 Local (Hong Kong) Studies

The popularity and the high numbers of accident of external wall tiles in high-rise residential buildings in Hong Kong make it necessary to carry out investigations and research on this aspect. A large-scale research study on external wall tiles was funded by the Housing Authority Research Fund (HARF) in 2003. The findings are published in several papers in international journals and conferences, including Lo et al. (2005), Yiu et al. (2006, 2007). They study the effects of static load, weathering and cyclic load on the performance of external wall tiles respectively.

Lo et al. (2005) found by laboratory studies and numerical simulations that static load can cause differential movement among tile, adhesive and substrate. In the experiment, 16 panels each of 3m x 1m x 0.1m wall tile (Fig 3.1) were erected, and a horizontal force was applied at the middle and increased incrementally by an actuator until the panel failed. The results showed that the lateral load withstood ranged from 28kN to 60kN, and the maximum deflection ranged from 11mm to 51mm. Furthermore, a large number of panels failed at the spatterdash layer, i.e. the interface between rendering and concrete substrate, and all failed at the edges first.

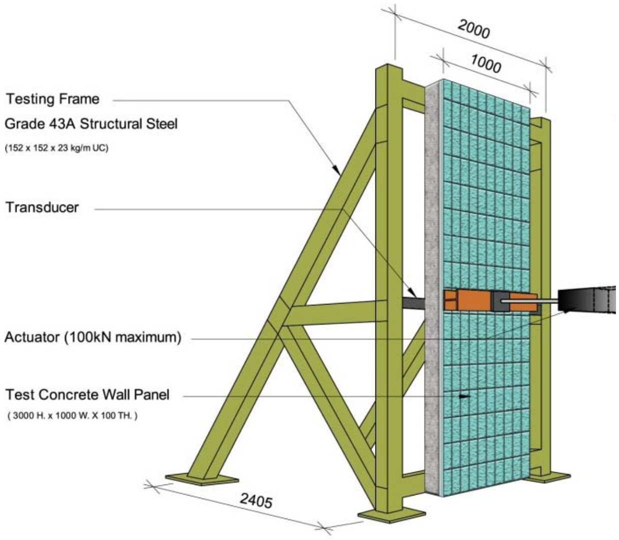

Fig.3.1 Schematic of the Set-up in Lo et al. (2005)

Yiu et al. (2006) found by an empirical analysis that weathering, such as thermal, wind and rain, imposes a significant effect on external wall tile adhesion strength. Actual field data of hammer tapping tests on the external wall tiles of 11 blocks of high-rise (27-33 storey) residential buildings of about 20 years of age were exploited to identify the weathering effects on tile delamination.

It found that the probability of failure of external wall tiles of this 20-year-old building was about 14% in average, and that orientation and shading attributes significantly affected the probability. For example, west and south-west facing façades were of 4.8% and 3.5% higher probability of failure, respectively in comparison with the north-east façade. Sun shading devices were also found to reduce 10% probability of failure.

Yiu et al. (2007) found by laboratory studies that thermal and moisture cycles can reduce adhesion strength substantially. 10 specimens of 300mm x 150mm x 100mm tiled blocks were fabricated and were undergone 200 thermal and moisture cycles (Fig 3.2). Shear strength test results showed that the adhesion strength decreased by more than 50% (from 1.7 to 0.8 MPa in Set A and from 1.2 to 0.6 MPa in Set B) after 100 cycles at the tile-rendering interface.

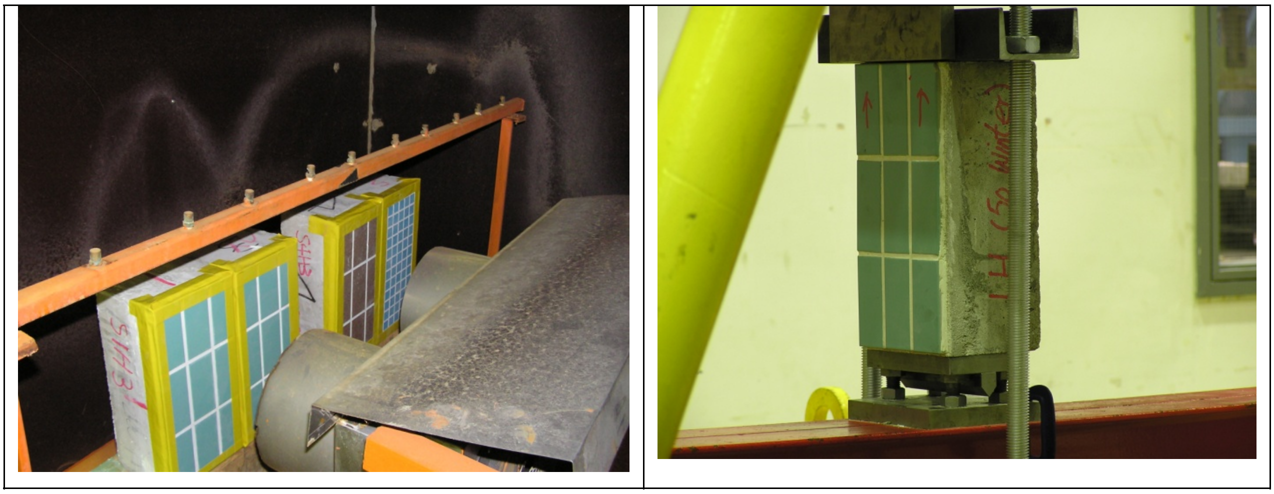

Fig. 3.2 Thermal and Moisture Cyclic Test and Shear Strength Test in Yiu et al. (2007)

Besides the HARF project on external wall tiles, there are at least two more indepth studies on wall tile failures in Hong Kong. The first one is Bowman et al.'s (2000) report to Hong Kong Construction Association for an investigation of the performance of ceramic wall tiling in Housing Authority residential buildings. Another one is Lo et al.'s (2007) study on the causes of wall tile failures at the corridors of public housing estates in Hong Kong. However, these two investigations were both on internal wall tiles and at housing estates owned by the Housing Authority. The former was based on site investigations and the latter was by means of semi-structured interviews and specifications comparison. The former found that it was the differential movement between materials that caused the failures, while the latter found that homogenous tiles may be too large and heavy to be supported by adhesive systems.

Bowman et al. (2000) emphasized the importance of grouting as it serves the purpose of movement joints and it explains the general success of mosaic tiling in harsh conditions. They pointed out that more than 20% of the exposed surface is joints in mosaic tiling system, and the increase of tile size would have a disproportional effect on the contribution of grouted joints in absorbing and dissipating strain as shown in Table 3.1:

Tile size (mm)	Width of grouted joint (mm)	Percentage of grouted joints to total finished surface area (%)
20 x 20	2	21%
50 x 50	2	8%
100 x 100	2	4%
200 x 200	3	2%

Table 3.1: Relationship between tile size and grouted joint %
Source: Bowman, et al. (2000)

Lo et al. (2007) provided a table (Table 3.2) comparing the differences in standards between public and private sectors in Hong Kong. The comparison highlights that homogenous tile is not commonly used in private sector, and the standards of adhesive are different in the two sectors.

Types of Tiles	Public Sector	Part	Year	Remarks	Private Sector	Part	Year	Remarks
Ceramic					BS 5383	Part 1	1990	
					BS 5383	Part 3	1989	
	BS6431	Part 1	1983	Class AIII or BIII	BS6431	Part 1	1983	
	BS6431	Part 5	1986		BS6431	Part 2	1984	
	BS6431	Part 9	1984		ANSI A108.1 A		1992	
					ANSI A108.6		1992	
					ANSI A137.1		1988	
Mosaic					BS 5383	Part 1	1990	
					BS 5383	Part 3	1989	
-Glazed	BS6431	Part 8	1986					
-Unglazed	BS6431	Part 1	1983	Class BI				
	BS6431	Part 6	1984					
Homogenous	BS6431	Part 1	1983	Class BI				
	BS6431	Part 6	1984					
Other Materials	**Public Sector**	**Part**	**Year**	**Remarks**	**Private Sector**	**Part**	**Year**	**Remarks**
Grouts	ANSI A118.6		1992		ANSI A118.6		1992	
					ANSI A108.10		1992	
					ANSI A118.1		1992	
Cement Mortar	BS 5385	Part 1	1995		ANSI A118.4		1992	
Adhesive	BS5980		1980		BS5980		1980	Class AA; 2 - 3 mm
	BS EN 12004		2001	0.5 N/mm2	ANSI A136.1		1992	
					BS6920	Part 1		
Suggested Adhesive	Laticrete				Laticrete 3030 Mega-Bond			
	Mapei - China				Mapei -Granirapi			
	E-mix				E -Mix Marble Fix			
Expansion Joints	BS 5385	Part 1	1995		7.3-11 m			
- exposed to direct sunlight or moisture					3.6-4.9 m			
Workmanship (Tile Installation method)	BS 5385	Part 1	1995		BS 5385			
Tile Setting Time (prior to grouting)	24 Hours				48 hours			

Table 3.2: Preliminary Comparison of Specifications of Internal Wall Tile in Public and Private Housings in Hong Kong (extracted from Lo et al., 2007 where the source of data is stated as: HKHA, 2004; Interviews with the stakeholders in the private sector)

There was also a laboratory test on adhesive strength under (1) cyclic load and (2) unidirectional shear carried out by a student Lo (1998). The test was carried out by a Universal Testing Machine (UTM). The three types of adhesives tested were (1) traditional cement paste (mix ratio: 0.5kg cement to 200ml water), CP; (2) a ready mixed proprietary adhesive, KM; and (3) a manufacturer pre-bagged mix, TB (cement based with polymer additives, mix ratio: 50kg powder to 5L water).

Under the cyclic test, the test specimens were cured and prepared as follows:

1. curing time schedule: 1hr, 2hrs, 4hrs, 8hrs, 18hrs, 24hrs, 3days, 7days, 10days, and 14 days

2. sample preparation: 2mm thick adhesive was applied with 10mm overhang between two 100x100 tiles; and

3. loading and deformation criteria:

    - 0.49kN > load > 0.001kN

    - 0.55mm > extension > 0.01mm.

While under the shear test, the specification and procedures of the destructive shear test were referenced to the BS 5980:1980 – Adhesives for use with ceramic tiles and mosaics, Appendix E – determination of shear adhesion strength. The test specimens were cured and prepared as follows:

1. curing time schedule: 1day, 3days, 5days, 7days, 10days, and 14 days;

2. sample preparation: 2mm thick adhesive was applied in ¼ of covered area between two 100x100 tiles; and

3. loading and deformation criteria:

    - 0.49kN > load

    - extension > 0.01mm.

The result showed that adhesive with polymer-additive achieved the highest strength with 7-day curing. CP achieved 2.58kN, whereas KM and TB achieved 1.67 and 2.96kN, respectively. BS 5980: 1980: 9 requires mean tensile adhesion strength >= 950N for 14 days curing under laboratory conditions and >= 560N for 7 days curing under laboratory conditions followed by 7 days of immersion in water.

In terms of ultimate shear strength per 0.88m x 0.98m area, TB achieved as high as 14.22 kN at 7-day curing, in comparison with 3.36 and 2.21kN in KM and CP. Almost 90% of the specimen failed at the adhesive failure mode. BS 5980: 1980: 10 requires mean a shear adhesion strength >= 8.9kN for 14 days curing under laboratory conditions and >= 4.5kN for 7 days of curing under laboratory conditions, followed by 7 days of immersion in water.

Earlier studies in Hong Kong include Davies (1998) and Wilkins (1991), but they were less rigorous and more general and descriptive. Yet, they also pointed at the same contention of differential movements due to loading and weathering. For example, Davies (1998) highlighted that these long-term irreversible movements are interrelated with environmental, as well as design and material, factors. For example, the differential movements may have resulted from the deflection under load\, as well as the progressive moisture expansion of ceramic tiles. Furthermore, these movements can be accommodated by a proper design of movement joints. Davies (1998) also reported a study by Casimir (1994) that poor suction control is a main cause of tiling system failures. They argued that unhydrated cement cannot achieve its bond strength. It is recommended that suction control is observed at any stages of application of the layers of the tiling system.

Wilkins (1991) showed that "quality control procedures, rather than design specifications, have failed to achieve appropriate standards. Poor workmanship in combination with climatic variations has caused failure on smooth, dense surfaces." Wilkins (1991) also argued that the improvements in concrete quality produced dense surfaces with low permeability, thus ensuring low porosity and very little suction. The bond performance of tile finishes on concrete substrate relies heavily on the mechanical key applied (spatterdash) after striking the formwork.

Wallis (1995) reported that there were about 90, 100 and 129 incidents of masonry tiles falling from buildings in November 1994, December 1994, and January 1995, respectively.

The high-density and high-rise built environment in Hong Kong further aggravates the severity of the incidents. According to the research project no. CB20030020 supported by Housing Authority Research Fund in 2005, the research team found that a similar phenomenon occurred in Singapore, where high rise residential buildings were common (Chew, 1992). Over the review period (April 2001 – November 2006), there are 104 incidents of external wall finishes failure, Altogether, they claimed one fatality and 47 injuries. This phenomenon was widespread throughout the territory and was not a localised problem in certain districts. Information on the cause(s) of these incidents is not available within the research project.

Many other local studies on external wall tiles are about testing and monitoring methods, for example, Lomas, (1997), Lo (1999) and Ho et al. (2003) on thermography, Hung (2003) on shearography, and Yiu and Chan (2009) on Fibre Bragg Grating, etc.

3.1.2 Japan Literature Review

Japanese have carried out many related studies on external wall tiles and adhesives, unfortunately, most of them are in Japanese, such as Kumagai et al. (1997) and Makoto and Yasunori (2003). Some of them are very comprehensive, for example, Ozkahraman and Isik (2005) tested 10 different cementitious adhesives on their dry, wet, hot and freezing–thawing adhesive strengths according to EN 1348 and EN 12004 standards, and they found that the highest pull-out adhesive strength was on samples that have high content (80–95%) of SiO_2 and with small amount (0.5–3.4%) of $CaCO_3$.

Japan's study on wall tile failures focuses on the thermal stress of the interface between concrete substrate and adhesive mortar, where the failure is often found in external wall tile structures in Japan. One of the major research teams in Japan led by Mahaboonpachai and Matsumoto, contends that shear stress, occurring due to thermal expansion mismatch among materials, is one of the main factors that deteriorate the external wall tile structure.

Rumbayan (2006), who was the supervisee of Professor Matsumoto in the University of Tokyo, carried out a detailed study on the temperature distribution on tile structure. He found that the maximum different temperature between concrete layer and tile layer is about 12 C when the tile surface temperature reaches 50 C, and believed this condition induces the maximum shear stress of about 2.6 MPa in adhesive mortar, which is one of the main factors that deteriorate the durability of tile.

Mahaboonpachai et al. (2008) developed a laboratory-scaled heating experiment which is designed to simulate a real external wall tile structure subjected to solar radiation, to investigate the delamination of the interface between concrete and polymer-cement mortar (PCM) in a tile structure under a thermal load. They found that the interfacial crack propagated up to approximately 3 mm in length along the interface between concrete and PCM when the temperature on the tile surface was 100 C. Further crack propagation along the interface was observed when the maximum temperature on the tile surface was equal to 105^{o}C and 120^{o}C.

The experimental results indicate that the thermal expansion mismatch among the materials is one of the main factors that deteriorate the external wall tile structure.

More recently, Mahboonpachai et al. (2010) further posited that the interfacial failure, initiated by fracture propagation, can be expected to be governed by interfacial fracture toughness than the bonding strength. A four-point bending test was developed based on an interface fracture mechanics theory.

3.1.3 Singapore Literature Review

Michael Chew has published at least 4 papers or chapters on external wall tiles, including Chew (1992, 1999a, 1999b) and Chew et al. (1998). They found by laboratory studies that bond strength of adhesive is affected by temperature during application, but polymer additives in adhesives can have a marked increase in bond strength (from +28% to +46%, when stored under a high temperature, say 60°C).

Chew (1999a), in particular, conducted a comprehensive experiment to evaluate the effect of temperature on the adhesive strength of four types of adhesives: (1) adhesive A: Cement: sand: water = 1:4:0.8, (2) adhesive B: same as A with 50% water replaced with a polymer as an additive; (3) adhesive C: Cement: sand: water = 1:3:0.4; and (4) adhesive D: same as C with 100% water replaced with a polymer as an additive. The results showed that adhesive B attained 10% higher shear stress than adhesive A. The reinforcement by adding polymer was confirmed. Yet, adhesive D attained 8% lower shear stress than adhesive C, which contradicted the above result. He contended that the over-dose of polymer resulted in the adhesive mix drying out too rapidly, and thus reducing its strength.

He also found that adhesives, with or without polymer as additives, perform poorer (-10% and -47%) in bond strength when applied under a high temperature (40°C) and under a low temperature (10°C). He conjectured that the preheated surface was dry and absorbed moisture rapidly from the adhesive, which hindered the hydration process.

Finally, he found thermally- and moisture-induced movements on adhesive strength to be significant. Thermal cycles resulted in 18%-21% reduction, whereas moisture cycles resulted in 6%-37% reduction in pull-off strength.

Chew (1999b) cited Ohama et al.'s (1986) theoretical justification for the temperature effect on adhesive strength as follows:

"With water withdrawal by cement hydration (accelerated owing to the higher storage temperature), the close-packed polymer particles on the cement hydrates coalesce into continuous films or membranes, and the films or membranes bind the cement hydrates together to form a monolithic network in which the polymer phase interpenetrates throughout the cement hydrate phase."

Another two Singaporean researches are Guan et al. (1997a, 1997b), which also studied thermal effects. Guan et al. (1997a) suggested that high temperatures accelerate the thermal degradation of polymeric materials in the adhesives, where a 10°C increase in temperature is likely to double the kinetic reaction rate.

Guan et al. (1997b) argued that a rapid cooling effect by rainfall produced a thermal shock, which will build up a high normal stress perpendicular to the tile plane. Hence, it is detrimental to the bonds and causes cracking and delamination. The changes in humidity also have influence on the tiling system.

3.1.4 Asia Pacific (other than Singapore and Hong Kong)

Zhao and Zhang (1997) studied the influence of workmanship on the bonding strength of tiles to external walls in China.

3.1.5 Australia

According to the Royal Australian Institute of Architects' (1991) and Hartog's (2000) findings, structural frame shortening was possibly one of the major causes of wall tiling failures in high-rise buildings. Regular measurements of progressive strain should be made on columns, which would be useful in further studies of the performance of external tiling finishes. Bowman et al. (2000) is also a report prepared by experts from Australia.

3.1.6 Europe

Material compatibility in tiling system is found to be crucial in minimizing stresses being built up. Greminger et al. (2009) found by a field study that two of the causes of porcelain tile failures are (1) the less porous and smoothness of the tile which results in poor adhesion with mortar; and (2) the large size tile makes the distance from centre to grout much longer which increases the strain at the tile edges. Zurbriggen et al. (2008b) also confirmed by an electronic micrograph scanning that polymers in the adhesive provide an important key to the adhesion properties onto porcelain tiles.

Zurbriggen et al. (2008a) also explained why the Reinmann's (2001) three recommendations on outdoor application of tiles are not commonly practiced, namely:

The first recommendation of providing proper wetting of the tile by the mortar, by the floating-buttering technique (DIN 18157), would require more material and consume more time compared to the simple floating technique;

The second recommendation of applying a flexible membrane (such as a screed) to absorb the differential shrinkage between the substrate and the tile would cost more and take longer time; and

The third recommendation of using adhesive mortars with an extended open time would also cost more.

Herwegh et al. (2009) found by a numerical modeling approach that shrinkage of the substrate induces stress concentrations in the mortar which can in particular cause mechanical failure at the rim regions of the tile. Zurbriggen et al. (2008a) also showed that the different shrinkage and expansion characteristics among tile, adhesive and substrate cause strong differential movements and shear stresses at the tile-mortar interface, especially at the tile edges.

Earlier studies were less rigorous and more descriptive, but they pointed at the same direction of research on differential movement due loading and weathering. For example, Fintel et al. (1987) reported that "the total elastic and inelastic shortening of columns and walls due to gravity loads and shrinkage may be as high as 1.04mm per metre. The possibly large absolute height of the structure of ultra-high-rise buildings is of consequence in its effects on the cladding."

Simmons (1990) also posited that movements in concrete substrate largely affect the finishes applied on its surface. As the substrate is subject to unavoidable movements, such as thermal movement, creep, concrete shrinkage, and vibration, the finishes on top should be able to accommodate these movements.

Aitkenhead (1995) listed 29 reasons for bond failure and the cracking of cementitious render and render but with neither categorization nor justifications. Wallis (1995) reported that "the mosaic tiles used to clad most buildings can become unglued from the structure's concrete core as a result of the city's polluted environment and harsh tropical weather." Simpson and Horrbin (1970) discussed various weathering factors that affect the performance of tiles, such as durability, permeability, cover to reinforcement, frost resistance, resistance to chemical attack, structural considerations, deformation, shrinkage, and creep. The elements of weathering factors include temperature, humidity, wind, sunshine, air pressure, etc. Addleson (1991) also considered climatic factors, such as humidity, temperature, rainfall, wind, and exposure to prevailing wind and rain, in building performance. Briffett (1991) argued that rain causes water penetration into the tiling system through hairline cracks and loosens adhesion with the cementitious bedding. Ransom (1987) also contended that a temperature gradient is built up across the thickness of the building facade, and the gradient caused significant differential movements between the external finished surface and the substrate. Since the facades are usually restrained from free movement, excessive thermal stresses lead to ruptures or distortions. Furthermore, the cyclical temperature change of facade surfaces can be deleterious if individual component parts have different coefficients of expansion. As a result, shear force will be induced internally between the interfaces of the tiling system. If these shear stresses cannot be accommodated with suitable movement joints, they can exceed the adhesion strength among component parts and thereby cause adhesive failure. Seah (1992) stated that pollutants affected the mortar bed through air absorption at the joints. This, coupled with moisture content, would have a detrimental effect on tile beds and mortars.

Coad (1985) assessed the shear strength of tile adhesives under different conditions in accordance with BS5980. He found that the gain in shear strength with time from joint assembly was highly dependent on temperature, and to a lesser extent on relative humidity. Furthermore, he showed that subsequent water immersion of the tile joints is critical to the ultimate performance of the joint.

Baziard et al. (1995) investigated the failure behavior of an adhesive-bonded single lap joint by the ASTM D2293-69 test. They found that the strain energy release rate observed for the cohesive failure of the joint was 10 times greater than that calculated for adhesive failure.

In line with the DIN 53265 (DIN, 1998) standard test, Riunno (1992) employed the shear test to investigate the flexibility properties of various tile adhesive and mortar systems. He showed that modified dry-sets with liquid added polymers and chemically reactive and ready-mixed adhesives are the most flexible systems.

Coad and Rosaman (1986) identified three possible causes of adhesive failure:

fissure in one of the substrates;

fissure in the body of the adhesive (cohesive failure); and

separation at the interface between the adhesive and the adherents (tiles or substrate) – hence, adhesive failure.

Adams and Wake (1984) analyzed failed samples microscopically and summarized the adhesive failures into the following symptoms:

- porosity or void – caused by air-traps during mixing or laying; or insufficient adhesive applied;
- poor cure – due to incorrect mixing of adhesive, etc.;
- surface unbond – caused by the uneven application of adhesive; and
- zero-volume unbond – insufficient setting pressure to build the bond strength.

3.1.7 America

It is commonly agreed upon that the fundamental cause of the failure of a tiling system is overstress generated by the system. Toakley and Waters (1973) developed idealized mathematical models of a tiling system to explain how failures could occur in practice despite very low normal stresses. They contended that “the shear stresses developed at the interface and the compressive stresses in the tiling itself are quite high [and are attributable to the failures].” Yet, the development of these shear stresses can be caused by multiple factors, including thermal and moisture stresses.

3.1.8 Long Term Accelerated Durability Test

The research team has experience of managing long term accelerated durability test programmes on external wall tiling. One of these programmes was project no. CB20030020 supported by the Housing Authority Research Fund (HARF), the long term durability test was conducted by the University of Hong Kong and the Hong Kong Institute of Surveyors in 2005. The research team, after completing its literature reviews, considered that weathering was one of possible reason for the failures of external wall tiles, in addition to poor workmanship. Hence, this research project investigated the current practices of the application of external wall tiling system against weathering effects. The HARF project findings are reviewed in this report and it is not proposed to repeat this exercise.

From the experience in the HARF project, it took 12 months to design and fabricate the artificial weathering equipment (from December 2003 to November 2004); it took another 7 months to carry out the artificial weathering process (from December, 2004 to June, 2005); and it took 6 months to carry out the shear bond strength tests, with overlapping processes to save time (from April 2005 to September 2005). Summing up, it took 22 months for the artificial weathering laboratory study in the HARF research project for 40 samples of 4 tile specifications undergone 200 summer cycles and 50 winter cycles. One of the issues with accessing results from such a large scale accelerated durability testing programme is the wide number of variables meaning that results can never be focused or conclusive on their own. It is proposed that for this research study, primary testing work will concentrate on the adhesion of various materials within the render and tile adhesive systems subjected to weathering in a typical Hong Kong environment.

An artificial weathering test was carried out on tiled concrete samples. The concrete samples were 300mm (L) x 150mm (W) x 100mm thick and tiled on the 300mm x 150mm surface. The test specimens including the application of tile finishes were prepared by qualified and skilled workers in a controlled indoor environment. Variations in weather conditions related to casting of these samples were eliminated.

The samples were divided into four groups: (1) Ceramic tiles fixed with 1:3 cement mortar; (2) Ceramic tiles fixed with tile adhesive; (3) Mosaic tiles fixed in accordance with the Hong Kong Housing Authority's specifications; and (4) Unglazed ceramic tiles fixed with 1:3 cement mortar.

The laboratory was air-conditioned and the room temperature during the tests was 24ºC. To simulate the weathering cycle, the samples were heated by a radiator to 45ºC and cooled down to room temperature by a mechanical fan. 50, 100, or 200 weathering cycles were assigned to the samples to investigate the effect of weathering on the shear strength of the external wall finishes. Each weathering cycle consisted of 30 minutes of heating, 10 minutes of cooling, 20 minutes of wetting, and finally 10 minutes of drying.

The remaining samples were assigned 50, 100, or 200 winter cycles, and then put into the freezers of three domestic refrigerators for the weathering process to determine the shear strength of external wall finishes against a cooling effect. Each winter cycle consisted of 40 minutes of cooling followed by 40 minutes of warming.

After the completion of the weathering cycles, the residual shear strengths of the finishes on the samples were determined by a specially designed setup. The setup consisted of an actuator and a set of steel fixtures for keeping the concrete samples in position during the shearing process. The shear strengths of the tile/rendering and rendering/concrete interfaces were determined in the tests.

The results showed that the shear strengths of the external wall finishes dropped after the weathering cycles. The percentage drop was as high as 67 percent of the original un-weathered values. The rendering/concrete interface was generally weaker than that of tile/rendering interface.

There are several limitations of the artificial weathering testing in the HARF project reported in the report:

- Limited number of test samples and tested specifications;
- Limited number of artificial weathering cycles carried out;
- Only shear bond strength is tested in the 16 samples of static load test;
- Heating, watering, and cooling effects are combined, and the number of cycles cannot be directly related to the age of the system;
- The shear strengths of the four sets of samples increased when they approached 200 weather cycles, which are not the expected trend;
- Workmanship variations among batches of samples cannot be perfectly controlled;
- Material variations (such as concrete) among batches of samples cannot
- be perfectly controlled; and
- Strength and quality of spatterdash are subject to the judgment and
- Skills of the applicant.

However, the artificial weathering test is still one of the most appropriate laboratory study methods for long term durability test of external wall tiling systems.

3.2 INTERNATIONAL STANDARDS AND OVERSEAS EXPERIENCE

The use of external wall tiles / render on buildings is not limited to Hong Kong. It was considered valuable to review overseas experiences to see if any problems similar to those found in Hong Kong have occurred and if yes, how have they been dealt with and if no, how have they been avoided?

Experience in Australia, Singapore and the United Kingdom was reviewed with a view to possibly considering the adoption of overseas solutions in the Hong Kong context. The studies broadly identified that the same problems and issues that exist in Hong Kong also exist overseas or/and have been considered and addressed.

Australia, Singapore and the United Kingdom (UK) have widely varying climates to each other and have different social housing needs due to population densities and the amount of available land for construction purposes. Singapore is similar to Hong Kong in that it has a small land mass and high population density with a wet and warm tropical climate, Hong Kong has a high population density and a similar wet and warm climate for approximately half the year.

Australia being a vast landmass has a much lower population density compared to Hong Kong with the majority of its population in discrete urban centers situated around the coastline. The pressure on high-rise construction is different and the majority of high-rise residential developments are at the luxury end of the market providing sea views for as many as possible. Exterior wall tiles are not commonly used in Australia as the preferred finish is render and paint.

The UK has a very different climate to Hong Kong as it is frequently cold and wet and like Australia the use of external wall tiles is less prevalent. The various overseas experiences are reviewed in this section with a view to identifying key findings in the Design, Workmanship and Maintenance aspects that could be benefit to the Hong Kong situation.

3.2.1 Environment and Design

a) Singapore

Singapore Environment

Singapore lies at approximately 1.5^{o}N compared to Hong Kong at approximately 22^{o}N. Because of its geographical location and maritime exposure, its climate is characterised by uniform temperature and pressure, high humidity and abundant rainfall. The climate of Singapore can be divided into two main seasons, the Northeast Monsoon and the Southwest Monsoon season, separated by two relatively short inter-monsoon periods.

North-East Monsoon Season - December to Early March

Northeast winds prevail, sometimes reaching 20 km/h. Cloudy conditions in December and January with frequent afternoon showers. Spells of widespread moderate to heavy rain occur lasting from 1 to 3 days at a stretch. Relatively drier in February till early March. Also generally windy with wind speeds sometimes reaching 30 to 40 km/h in the months of January and February.

Pre South-West Monsoon - late March to May

Light and variable winds with afternoon and early evening showers often with thunder.

South-West Monsoon Season - June to September

Southeast/Southwest Winds. Isolated to scattered late morning and early afternoon showers. Early morning 'Sumatra' line squalls are common. Hazy periods.

Pre North-East Monsoon - October to November

Light and variable winds. Sea breezes in afternoon. Scattered showers with thunder in the late afternoon and early evening.

Temperature: Diurnal range: Minimum 23 to 26^{o}C and Maximum 31 to 34^{o}C Extremes: Minimum of 19.4^{o}C and Maximum of 35.8^{o}C.

Relative Humidity: Diurnal range in the high 90's in the early morning to around 60% in the mid-afternoon. Mean value is 84%, During prolonged heavy rain, relative humidity often reaches 100 %.

Rainfall: No distinct wet or dry season. Rainfall maximum occur in December and April. The drier months are usually in February and July with a mean annual rainfall of approximately 2350mm.

Problems with External Wall Tiles and Rendering

Tiles delaminating and falling from height is reported as being a major safety hazard in Singapore which was first brought into the public gaze after a series of falling tile incidents in late 1980's to early 1990's. The use of external wall tiles in Singapore began during the 1970's, becoming very popular due to the attractive appearance with official reports of debonding tiles not appearing until 1987. A series of high profile incidents of delaminated and spalling external wall tiles occurred in the early 1990's which prompted the Authorities to issue a memo discouraging the use of external wall tiles on buildings exceeding 4 storeys. At approximately the same time, alternative external wall finish systems such as aluminum panels, stone cladding and curtain wall started to enter the market and quickly became popular choices for construction professionals keen to avoid all the problems associated with tiled external wall systems.

Failures of external tiles on a low rise commercial building in 1993, Haw Par Technocentre, almost marked the end of the use of bedded tiles on the external walls of buildings in Singapore and external wall tiling is hardly ever used today.

Whilst the buildings with tile failures tend to get headline prominence in the press, there are many buildings in Singapore with tiled external walls that are in acceptable condition and where the tiles are still providing acceptably defect free service with minimal, if any, maintenance.

The Singapore experience of debonding external wall tile failure can be broadly categorized as follows:

- Localised and isolated (possibly caused by localized poor workmanship or specific incidents either during or after construction)
- Widespread and random (also likely to be due to variable workmanship)
- Regular and consistent (e.g. along building corners, close to movement joints, around embedded steel, etc. usually related to design or building layout)

b) United Kingdom

United Kingdom Environment

The lower latitude of Hong Kong, almost 30^o south of London and only approximately 22^o north of the equator causes the weather to be markedly different from the UK. In addition some extremes of weather such as monsoon rains, typhoons and tropical cyclones peculiar to Hong Kong's position in Asia do not occur in the UK. Weather variations between Hong Kong and the UK are compared on Table 3.3 below.

Table 3.3 Weather Comparison Between UK and Hong Kong

		London	Hong Kong
Average Temperature (^oC)	Summer	18 (max. over 30)	31.5
	Autumn	11 to 15	27.9
	Winter	6 (min. < 0)	12.3
	Spring	11 to 15	28.7
Average Rainfall per year		600 to 800mm	1300 to 3000mm
Average Monthly Rainfall	Summer	50mm	390mm
	Winter	90mm	20mm

Hong Kong has one specific issue that the UK only very rarely experiences and usually to a much lesser extent, and that is an earthquake. The proximity of Hong Kong to the so called “Ring of Fire” where volcanic arcs and oceanic trenches partly encircles the Pacific Basin means that earthquake occurrences are much more frequent, stronger and more likely to cause damage to property, than anywhere in the UK.

Problems with External Wall Tiles and Rendering

There are many forms of external wall renders and tiles used in the UK, normally applied over a reinforced concrete substrate all aspects of which are covered by BS 5385 Part 2 in place since 1966. Tiles can include terracotta, faience, ceramic and glass materials and can vary in size from 15mm by 15mm up to dimensions in excess of 250mm, though rarely as big as 500mm.

External wall rendering has been covered by standards since 1960 with the issue of CP221 which has since been superseded by the current version of BS 5262:1991.

Although rendering on external walls is common in order to give an acceptable or desired surface where other types of finish such as cladding systems are not desired, the application of external wall tiles over the render are not used in the majority of the building population, with a few notable exceptions.

It appears that in the UK the performance of external wall tiling is mixed with some areas of tiles buildings exhibiting few defects and remaining well bonded and in near perfect condition for many years whereas other areas exhibit failures. It would be hard to find any one building with external wall tiling that exhibits no problems.

c) Australia

Australia Environment

Due to the vast land supply in Australia the pressures that exist in Hong Kong for dense low cost housing do not exist in Australia. The majority of low cost housing is low rise, often timber construction on low cost land at the fringes of cities and urban centers. High-rise properties tend to be in desirable locations such as city center or beachfront and are at the higher or luxury end of the market. These properties command a premium selling price and the developers are prepared to spend more money on finishes to avoid problems in the future than might otherwise be the case for low cost housing.

Weather conditions at various cities across Australia are compared with those in Hong Kong on Table 3.4 below. The data on Table 3.4 has been presented for equivalent seasons rather than months of the year to account for seasonal variations between the northern and southern hemisphere. Generally it can be seen that although Hong Kong has similar maximum average daily temperatures to some cities in Australia, the Hong Kong wind speed, rainfall and humidity are higher than those normally experienced in Australia. Deterioration of materials will be accelerated by warm and wet conditions, coupled with the additional wind suction particularly on external wall tiles, Hong Kong environmental conditions are generally more aggressive than those found in Australia. However, according to the Australian Cement and Concrete Association (C&CA) shrinkage, leading to cracking and debonding of renders is considered as one of the major causes of render debonding. This mechanism of delamination would be reduced in Hong Kong due to the higher average humidity and lower average wind speeds.

Table 3.4 Seasonal Weather Comparison between Australia and Hong Kong

Weather	Season	Location				
		Brisbane	**Sydney**	**Melbourne**	**Perth**	**Hong Kong**
Maximum Average Monthly Rainfall (mm)	Summer	123.8	131.2	47.4	18.5	391.4
	Autumn	58.8	128.1	46.8	148.8	144.8
	Winter	41.1	98.1	48.4	183.5	66.9
	Spring	101	83.1	57.8	50.6	316.7
Average Daily Maximum Temp. (^{0}C)	Summer	29	25.8	26.5	31.3	31.5
	Autumn	25.9	22.4	20.1	26	27.9
	Winter	24.3	19.9	16.4	20.1	12.3
	Spring	26.6	23.6	21.6	26.4	28.7
Maximum Average	Summer	66.5	69	58.5	48	82
	Autumn	63	66	75	68.5	73

Weather	Season	Location				
		Brisbane	Sydney	Melbourne	Perth	Hong Kong
Monthly RH %	Winter	58	61.5	73.5	68.5	81
	Spring	60.5	61.5	61	51.5	83
Maximum Average Wind Speed (km/h)	Summer	20.5	14.7	20.4	17.2	10.7
	Autumn	16.3	12.8	19.5	12.8	12.2
	Winter	19.6	15.5	22.9	14.8	12.6
	Spring	20.6	15.7	22.4	16.7	11.7
Maximum Wind Gust (km/h)	Summer	120.6	150.1	137.2	57.2	259
	Autumn	70.2	135.4	107.6	70.2	175
	Winter	83.5	131.4	124.2	72.4	108
	Spring	81.4	118.4	139	55.4	166

d) Related International Standards

The requirements of movement joints specified in BS 5385, Part 2: 20.1 (Movement joints – General) as follows are subject to temperature and humidity conditions:

"Consideration should be given at the design stage to the provision of movement joints. The type and location of movement joints are influenced by considerations of construction, materials, bedding systems, anticipated temperature and humidity conditions, areas involved and the setting out of the tiling."

BS 5385, Part 2:20 specifies the requirements of movement (expansion) joints in a tiling system. For example, it specified that all expansions in wall tiles shall run right through the render to the backing concrete. There are cases where expansion joints were formed to the upper surface of the render only.

The importance of joints and grouting has been raised in many previous studies. A run-through expansion joint is important for ensuring adequate space for the thermal movement of the tiles, and for minimizing the stress built up in the finishes. They also accommodate differential movements between the substrate and the tiles. But the details of movement joints, such as their distance between two joints, are left to the designers and cannot be found in the standards.

BS 5385, Part 2:20.1 (Movement joints – General) states that "a proper joint detailing can only isolate the debonding, bulging and cracking of the tiles due to drying shrinkage and moisture, thermal changes and creep, but not to eliminate all of these stresses". In other words, we cannot simply attribute tiling system failure to joints without further tests.

Besides, there is no recognized standard for adhesive strength in a tiling system. There are also two adhesion layers. One is between the render and the backing concrete substrate, and the other is between the wall tile and the tile adhesive.

The Hong Kong Housing Authority (HKHA) specification is commonly adopted in Hong Kong, and it is as follows:

"Mean Tensile Adhesion Strength required to pull-off adhesive applied between 200 x 200 x 7mm ceramic glazed wall tiles and panel wall partition with moisture sealer/off-formed concrete after the installation of tiles lapsed for 28 days: Not less than 0.168N/mm^2". (Test items 5 of Ref: FIN 5.T080.3 of HKHA specification library for building works 2000)

This mean strength is probably derived from the required mean tensile adhesion strength of adhesive in BS 5980[1]. It has been noted that the value is a mean instead of an absolute minimum. It is contended that the minimum strength required for tiles should be calculated from wind pressure with a factor of safety, in a requirement similar to the design and testing of curtain walls, glass, and aluminum panels, etc. Moreover, BS 5980's requirement is relatively low in comparison with ISO 13007 (ISO, 2004), which requires the minimum tensile strength of basic class 1 adhesives be 0.5 N/mm^2.

Although the standards are specified in the Specifications, sometimes some of the requirements are found not to be strictly followed in practice. For example: "Adhesives should preferably be used for fixing tiles externally. Cement: sand mortar is seldom used as the bed for external wall tiling…" (BS 5385 Part 2: 21.2 – Bedding methods). BS 5980 specifies adhesion strengths of adhesives for ceramic tiles and mosaics. However, cement: sand mortar is commonly used in external wall tile finishes in Hong Kong.

The improper mixing of the render layer is one of the main causes of tiling system failures. A lean mix would produce a render layer with low strength, while too rich a mix would result in excessive drying shrinkage. However, there is no simple rule in determining the cement: sand ratio. BS 5385, Part 2: 19.3 (Mix for rendering to various backgrounds) emphasizes the effects of the background on the required rendering mix. It suggests 1:3.5 to 1:4.5 by weight for dense and strong backgrounds, and 1:4.5 by weight for moderately weak and porous backgrounds. Similarly, BS 5385, Part 2: 27.2 (Bedding in cement: sand mortar) suggests using cohesive and water retentive mortar neither richer than 1:3 nor leaner than 1:4 cement: dry sand by volume (1:3.4 to 1:4.5 by weight). It is clearly different from Davies's (1998) recommendations of 1:1 to 1:1.5.

3.2.2 Workmanship

a) Singapore

Defects with external wall tiles / render have been investigated on numerous buildings in Singapore and the cause of debonding and spalling has been found to be at any of the possible positions within the laminate system. Either adhesive failures at the render to substrate interface, at the tile to tile bedding interface or the tile bedding to render interface. The problems may be associated with surface preparation of the concrete substrate but are typically caused by problems with

[1] Clause 9 – not less than 950 N after conditioning for 14 days under normal laboratory conditions (for 2 pieces of 75 x 75 x 9 mm ceramic tiles) adhered to by Class AA, A, or B adhesive.

the tile and render system itself however, defects in the concrete substrate such as reinforcement corrosion and spalling cover concrete were also frequently observed.

The problems could be due to any one or a combination of the various stages in the building delivery process including design, detailing, workmanship, materials, specification and maintenance. The exposure conditions in Singapore including rain, wind, temperature, humidity, thermal shock, etc. are also contributory factors.

Buildings constructed between the mid 1980's and early 1990's suffered from premature debonding (within 5 years of construction) of the external wall tiles / render. There are several possible explanations for this phenomena:

- Construction recession led to low tender prices which in turn led to poor workmanship and the use of low cost materials
- The increased speed of construction leading to insufficient curing and poor workmanship
- Lack of skilled workers in early 1990's leading to heavy reliance on unskilled imported workers from places like Thailand, India and Bangladesh.

b) United Kingdom

No single over riding or prevalent cause of failure is identified from the UK experience with just about every possible cause of failure having been experienced at some time. The potential causes of failure include material, design and workmanship related issues with conditions and causes varying from one site to another.

Potential causes of failure include:

- Specification shortcoming
- Inappropriate surface preparation
- Lack of sufficiently skilled operatives or close supervision
- Inadequate curing
- Rapid drying out and early drying shrinkage of render and tile bedding
- Manufacturing defects with the tiles themselves
- Provision and detailing of movement joints
- Specification and application of tile grouting allowing the movement of moisture.
- Failure of the concrete substrate and deterioration of reinforcement.
- Corrosion of metal lath or wall ties included in the render
- Being struck by objects such as access equipment (gondola, scaffold, etc.)
- Cracking due to strength differences in render layers

c) Australia

Workmanship

Strict immigration controls in Australia result in all construction work being completed by Australian residents rather than low cost imported labour that may sometimes be the case in Hong Kong. The Australian workers will be required to have the appropriate experience trade training in order to work on a site. Activities of industry specific trade unions will try to protect their members interests by enforcing the requirement that workers are both their members and have appropriate formal trade training.

Skilled trades people in Australia are well regarded and can command significant personal incomes, comparable with professionally qualified people. The difference that exists between tradesmen and professionals in Hong Kong does not exist to the same extent in Australia and parents often encourage their children to follow trades rather than the tertiary education and professional qualification route favored for capable students in Hong Kong.

The combination of these factors is that competent and capable people enter site trades in Australia and as a result of union activities and peer pressure these people will also have formal specific training from Technical and Further Education (TAFE) institutions which will enhance the quality and consistency of work.

Supervision

Rendering teams in Australia will normally be supervised by a “foreman” who will usually be a plasterer promoted to the position and can be expected to have good hands on experience of rendering works. The foreman will be from the same company as the plasterers and will be responsible for all aspects of the work including production and quality.

In addition to the “internal” supervision by a foreman there will usually be a Clerk of Works (CoW) responsible for managing and inspecting the works. The CoW will check the ratio of certified plasterers undertaking the application to the number of unskilled assistants carrying out mixing and other works under their supervision. No set ratio of skilled to unskilled workers is required but good judgment would be applied.

Construction Processes and Materials

Precast construction for external façade components of high-rise buildings in Australia allows external façade render (and if required tiles) to be applied in the more controlled environment of the precasting yard rather than on site.

The use of bond enhancing materials such as spatter dash and bond coat is uncommon in Australia with the majority of render systems being applied directly to the substrate with the use of adequate substrate wetting only. The lack of debonding render is an indication of acceptable workmanship having been achieved.

In the older building population render would have been a 1:3 cement : sand material with proprietary materials only gaining significant market share within the last 3 to 5 years.

Condition surveys on buildings in major Australian cities have identified that render defects are relatively uncommon and that the cause of delaminated or spalled render is a result of delaminated concrete caused by corroding reinforcement. Where render defects have occurred the cause of the defects is believed to be the same as in Hong Kong with poor substrate preparation / wetting, too long between substrate wetting and render application and inadequate curing of render.

Spalled or delaminated render usually results from delamination of the substrate concrete caused by either chloride or carbonation induced corrosion of the reinforcement. Chloride induced corrosion can be a problem in coastal areas where salt laden aerosol is deposited on the building by the prevailing winds and then the salt is left on the building surface when the water evaporates as a result of the hot and dry climate. Salts are then sucked and diffused onto the reinforcement over time.

d) Related International Standards

British Standards are so far the most commonly used wall-tiling standards in Hong Kong. In line with the findings above, requirements specified in the BS standards are also often dependent on environmental factors. For example, the notched trowelling requirements specified in BS 5385, Part 2: 22.4 (Application of adhesive and tiles) are subject to atmospheric conditions:

“Adhesives should be applied to the background with a trowel as a floated coat, pressing the adhesive into the surface, and then combed through a notched trowel of the type recommended by the adhesive manufacturer for external tiling…The period of time during which tiles can be adequately bedded after spreading the adhesive should usually be about 20 min but this will vary according to the prevailing atmospheric conditions”.

In addition, BS 5385, Part 2:19.1 (Cement: sand rendering - General) states clearly that a proper thickness of render is required for a wall tile system:

“Rendering should not have a total thickness in excess of 20mm as this may result in unduly high shrinkage stresses and consequent cracking. Each coat of rendering should be not less than 8mm thick, nor greater than 16mm thick.”

However, *“dubbed out thicknesses of 70mm in one coat have been found” (Davies, 1998).*

One of the reasons for applying rendering is to correct the unevenness of the concrete surface, and a variation of thickness in rendering is envisaged. However, how the thickness of render leads to any undesirable stress is not clearly known. It is therefore proposed “to carry out laboratory tests to investigate the pull-off strength of wall tiles as a function of the rendering thickness.” (Davies, 1998)

Poor surface preparation is always regarded as one of the main causes of tile failure. Spatterdash or mechanical key is commonly adopted. More recently, bonding agents, including slurry mixing with cement, are also specified in tiling work instead of conventional spatterdash. All the above may refer to the British

Standard as BS 5385, Part 2: 18.2.1 (Treatment of backgrounds to receive cement: sand rendering - General) recommends the following methods of background preparation to receive rendering:

- Mechanical preparation
- Indented keys
- Spatterdash
- Retarders
- Metal laths and reinforcement
- Bonding agents

Nevertheless, the effects of these bonding agents on the bonding strength between concrete and render are not well understood.

3.2.3 Repair and Maintenance

a) Singapore

One of the biggest problems with maintenance is accessing the condition of the tiles, particularly as many of the older buildings do not have provision for access in the form of gondola etc. There is a statutory requirement to conduct a 5 yearly periodic inspection of building for commercial buildings and a similar 10 yearly inspection for residential buildings. These inspections include the key structural members such as beams and columns but do not include the external façade. There is currently no mandatory inspection for building external wall tiles / render.

Investigation of the condition of external wall tiles / render involves checking the extent of debonding by mechanical tapping or infrared thermography, visual survey to see the extent of staining, movement joint defects, bulging, spalling etc. Investigation also requires intrusive examination of the concrete substrate to check for surface preparation, examination of movement joints to check full depth through the render and review of original materials and construction specifications. Frequently used test methods include:

Mechanical hammer tapping (striking the tile surface with a hammer or similar implement and recording the location of “hollow” sounds)

Infrared thermographic inspection (measuring and analysing the surface temperature of the building in order to assess the likelihood of external tile delamination)

Adhesion pull off test (used to assess the bond of the existing render and tiles to the substrate concrete. The figure of 0.4 N/mm^2 is recommended as the acceptance criteria for cladding bedded with adhesive)

Extraction for laboratory analysis (the use of petrography is reported to be widely used in Singapore to investigate failure of ceramic tiling)

Two repair systems for external wall tiles / render are described where the original appearance is to be retained. Debonded areas of tiles / render can be cut out and replaced or in certain situations (depending on type of failure and varying from project to project) pinning can be used to secure the debonded material back to the concrete substrate.

Where the appearance of the building is to be altered or “improved”, four systems are described:

- **Re-cladding / over-cladding** – This system involves attaching a new cladding system over the top of the failed tile and render system, typically aluminium panels or stone slabs mechanically fastened to the building substrate.
- **FRP wrapping** – This system maintains the original appearance to some extent if a clear epoxy coating is used. Essentially the system involves wrapping the building in epoxy impregnated polymer fibre sheet, which is pinned back to the concrete substrate.
- **Over coating** – involves the application of a cementitios skim coat over the tiles to cover the tile surface profile followed by the application of a painted coating system.
- **Total removal** – Total removal of all tiles and render followed by the application of another external wall finishing system, possibly re-application of tiles and render or any other system at the owners discretion.

b) United Kingdom

Maintenance and Inspections

Inspections fall into two broad categories; close up and standoff. Close up inspections frequently require the provision of access equipment and are an essential part of the inspection process for external wall tile / render systems. Survey methods include the following:

- Visual inspection (including observation of the drip detailing, movement joints, flashings, impact by access equipment, etc.)
- Rebound hammer testing
- Ultrasonic testing
- Transient dynamic response
- Impact echo
- Infra-red thermography
- Pull off tests

Evaluation of render defects indicates that failures in early life are largely to do with poor site practice. Failures of more aged renders may be attributable to specification or detail design aspects.

The UK experience shows that the need for un planned maintenance is a function of the amount of care put into the original construction. Appropriately designed, specified and installed external wall tiles / render are less likely to require extensive repair or maintenance than a system where any of these aspects are inappropriate. However, there may be a higher initial cost which will be offset over time by lower maintenance and repair costs.

Routine maintenance and inspection is recommended is recommended for external wall tiles / render in order to detect deterioration as early as possible and complete appropriate repairs before minor defects cause consequential problems which in turn may lead to more serious defects.

Another aspect of maintenance is to ensure that the maintenance system, particularly the provision of access, does not cause additional damage to the tiles or render. Damage can be caused by wall ties from scaffold or masts not being properly repaired or as a result of impact from gondola cradles etc. Any maintenance programme must be properly designed and considered in order to avoid these problems.

Repair

There are three main types of repair option available in the UK. Briefly these methods are:

- Tile and / or render replacement (suitable for both tiled and untilled render.
- Vacuum assisted chemical resin stabilization (used for tiles only)
- Over coating (used for tiles only)

It is hypothesized that due to the lower initial cost of render only systems compared to external wall tiles, complex repair systems for render have not been developed. Defective render is exclusively repaired by the removal and replacement method with its accompanying matching problems with colours and textures.

c) Australia

Repair Maintenance and Prevention

Render delaminations are normally repaired by cutting out all materials to expose the substrate followed by patch application of render. No new solutions are proposed for the Australian situation as render defects are relatively uncommon and the continued advance in the use of precast façade components and other types of external wall finishes are expected to cause a continued decline in the use of exterior render application.

Deterioration of concrete substrates as a result of reinforcement corrosion either in balconies or external walls is repaired in the same way by removal of concrete to expose clean reinforcement followed by the application of a repair mortar and a waterproof chloride barrier applied to minimise future water and chloride ingress. Preventative measures (particularly on balconies) include the use of greater reinforcement cover and the use of protective coatings together with a better understanding of the deterioration process and more focused maintenance inspections leading to early repairs before defects become significant. The use of sacrificial anode CP systems in patch repairs have been limited in the past due to initial cost concerns but are expected to gain more consideration in the future.

d) Related International Standards

BS 5385, Part 2: 32 addresses the requirements of cleaning and maintaining the tiles:

"Tiling should be regularly inspected for minor defects in the tiles or in the tile joints, which can sometimes occur due to movement caused by drying shrinkage of the background and climate changes. Minor defects should be treated early, in which case they can usually be rectified easily. Further deterioration may lead to water penetration into the tile backing/structure through cracks, and may give rise to a significant breakdown of the tiling."

3.2.4 Experience Available to Hong Kong

The overseas experience reviews have identified that the types of problems found are similar to those in Hong Kong varying mainly in frequency of occurrence. Significant differences however exist between how the problems are addressed and measures taken to prevent occurrence of the problems in the first place. It is some of these preventative and possibly repair and maintenance measures that could be considered for adoption in Hong Kong.

The Singapore experience shows how problems can be avoiding by restricting the use of external wall tiles / render, although this approach is not recommended. The Australian experience shows how the provision of appropriate training and supervision of tradesmen can lead to a reduced occurrence and severity of defects. This could be applied to repair works on aged building to avoid repeat defects or to new construction to avoid future defects over the operational life of the building.

The UK reported an alternative repair method in vacuum assisted chemical resin stabilization (a variation of the epoxy injection of defective areas method) that could be considered for adoption in Hong Kong as an alternative to the various repair methods currently in use.

The most directly relevant overseas experience for the maintenance and repair of aged buildings in Hong Kong is believed to be Singapore's mandatory requirement for Periodic Structural Inspection of Existing Buildings. In accordance with Section 28 of the Building Control Act all buildings in Singapore with the exception of detached, semi detached, terraced or linked houses and temporary buildings need to be inspected at regular intervals by structural engineers. The purpose of the inspection is to ensure that structural defects due to lack of maintenance can be detected and rectified early to keep buildings structurally sound and to facilitate the implementation of appropriate measures to prevent further deterioration.

At present the Singaporean periodic inspection of buildings requires residential buildings to be inspected at 10 yearly intervals and commercial, industrial and institutional buildings to be inspected every 5 years. The scope of the required inspection covers the structural components of the building only and does not include any inspection or investigation work on the external wall tiles / render.

It is believed that the best approach to tackle the problem of falling external wall tiles / render in Hong Kong is a combination of the Australian and Singaporean approaches i.e. improved worker training together with additional / strengthened legislation for enforcing inspections and maintenance together with stricter penalties for failure incidents.

3.2.5 Similarities and Differences

Despite the obvious weather variations between Australia, Hong Kong, Singapore and United Kingdom brought about by different geographical locations, overseas experience indicates that many of the problems with external wall tiles / render on aged buildings are the same.

With the exception of Australia, where few rendering defects were reported, both Singapore and the UK reported that defects with external wall tiles / render had been recorded with just about every aspect of the system, similar to Hong Kong. The cause of defects had also variously been attributed to design, detailing, material selection and workmanship again similar to the Hong Kong experience. Weather had been considered as a contributing factor only and not a major cause of defects.

Due to the vast size and availability of land in Australia, low cost housing tends to be low rise and constructed at the edge of urban sprawl. Due to the low cost of timber in Australia it is frequently used as a primary building material for these low rise low cost constructions. High rise construction is used for more expensive accommodation in city centres and areas such as the beach front where un-interrupted views are required. This contrasts sharply with Hong Kong where land is in short supply and low cost domestic accommodation is frequently high rise and in densely populated urban areas. The result is that Hong Kong now has a large quantity of aging buildings that were initially constructed very fast and at a low cost and that have been operated with little or no maintenance or repair since construction.

The Singaporean experience is similar to Hong Kong in that they are faced with an aging population of low cost high rise accommodation constructed rapidly during times of need. Singapore has addressed the structural problems with the periodic structural inspection scheme that requires commercial properties to be inspected every five years and residential properties to be inspected every ten years. These inspections address structural aspects only and do not cover the safety of external wall tiles / render. In Hong Kong the Buildings (Amendment) Ordinance 2011 introducing the Mandatory Building Inspection Scheme (MBIS) was enacted in June 2011. Under the MBIS, owners of buildings aged 30 years or above (except domestic buildings not exceeding 3 storeys) are required to appoint registered inspectors to carry out prescribed inspections, and prescribed repairs as necessary, of their buildings once every 10 years.

Criteria / Description for failure of external wall tiles / render	Details of Experience				Experience relevant to Hong Kong
	Australia	Hong Kong	Singapore	United Kingdom	
Failure in the concrete substrate e.g. reinforcement corrosion, ASR, etc.	Reported as being the most common cause of failure, particularly on balconies and particularly on buildings close to the sea where chlorides cause reinforcement corrosion where cover concrete is insufficient and where waterproof treatments have not been provided. ASR or other concrete deterioration not reported	Spalling concrete primarily as a result of carbonation where concrete cover was inadequate, chloride induced corrosion to a lesser extent. ASR can be a problem but no reported cases of ASR affecting tiles / render on external walls.	Reinforcement corrosion reported together with ASR deterioration of concrete as causes of debonded tiles / render. Causation attributed to either design, workmanship or material selection.	Deterioration of concrete substrates recorded as a cause of debonded tiles / render. Attributed to either workmanship or design. Deterioration of concrete e.g. ASR not recorded as a problem.	Regular inspections to identify problems together with early repair to prevent further deterioration, spalled material and other consequential defects such as spalled tiles / render or collapse due to structural inadequacy.
Adhesive failure of the render to concrete substrate.	Reported, but considered infrequent and localized due to workers training and use of appropriate materials and methods.	Common cause of failure in tile and render systems attributed to poor surface preparation of substrate, inappropriate use of bond enhancing systems such as bond coat or spatter dash, lack of surface wetting or inappropriate render materials. In addition, lack of provision for movement is also a cause of failure	Common cause of failure in tile and render systems attributed to poor surface preparation of substrate, inappropriate use of bond enhancing systems such as bond coat or spatter dash, lack of surface wetting or inappropriate render materials and lack of provision for movement	Reported as being a cause of tiles / render delamination along with other potential causes.	Inspection and repair of identified delaminations prior to material spalling off the building.

Criteria / Description for failure of external wall tiles / render	Details of Experience				Experience relevant to Hong Kong
	Australia	Hong Kong	Singapore	United Kingdom	
Cohesion failure within the render materials	Not recorded as a common mode of failure.	Recorded as a mode of failure but normally occurs as more of an adhesive mechanism where multiple layers of render have been used with failure occurring between the layers.	Recorded as a mode of failure along with other causes.	Recorded as a mode of failure along with other causes.	Inspection and repair of identified delaminations prior to material spalling off the building.
Adhesion failure between tile bedding and render	Not recorded as a common mode of failure.	A known failure mechanism but considered to be less common than render debonding from substrate or tiles debonding from bedding. Potentially caused by inadequate wetting of render substrate prior to application of tile bedding or other surface preparation inadequacies together with inadequate provision for movement.	Recorded as a defect and included in photographs assumed as a result of similar causes to those in Hong Kong.	Recorded as a mode of failure along with other causes.	Inspection and repair of identified delaminations prior to material spalling off the building.

Criteria / Description for failure of external wall tiles / render	Details of Experience				Experience relevant to Hong Kong
	Australia	Hong Kong	Singapore	United Kingdom	
Failure between tile and tile bedding	Recorded as a localized defect only potentially caused by workmanship variability or lack of provision for movement within the system.	Common cause of failure particularly with glass mosaics which react with the cement bedding, expand and debond. Also a problem where inappropriate bedding materials are used e.g. mortar bedding used with homogenous tiles where tile adhesives should have been used.	Similar to Hong Kong, common cause of defects for all the same reasons. Thermal shock also considered as a possibility where tile surface temperatures can reach 70^oC before being rapidly cooled by sudden rainfall and rapidly warmed again by the sun when the rain stops.	Recorded as a defect probably due to the same reasons as Hong Kong together with the additional possibility of freeze thaw actions.	Inspection and repair of identified delaminations prior to material spalling off the building.
Tile Failures	Not recorded as a common problem.	A known problem where glaze can crack and debond from the tile substrate normally due to tile manufacturing problems or use in inappropriate exposure conditions. Deterioration of glass mosaics as a result of reaction between the glass tile and cementitious bedding.	Similar experience to Hong Kong.	Tile defects not recorded as a common cause of failure.	Inspection and repair of identified delaminations prior to material spalling off the building.

Criteria / Description for failure of external wall tiles / render	Details of Experience				Experience relevant to Hong Kong
	Australia	Hong Kong	Singapore	United Kingdom	
Movement joints	Not recorded as a common cause of failure	Common cause of problems particularly where movement joints are not provided (possibly due to the designer wishing to avoid the visual impact of a joint). Movement joints not cut through the full depth of the tile bedding and render or not placed in the correct locations. Failure of joints over time due to deterioration of sealants that need to be replaced.	Similar experience to Hong Kong.	Similar experience to Hong Kong.	Inspection to identify defects that might allow water penetration and consequential defects. In addition inspections should identify the detail of the joints to confirm effectiveness (i.e. detailed to BS5385 Part 2).
Design deficiencies	Provision of inadequate cover or protection to reinforcement e.g. lack of waterproofing measures allowing reinforcement corrosion and consequential spalling of tiles and render.	Failure to provide correctly detailed movement joints as required. Failure to specify appropriate and compatible materials. Fins and other architectural details that can cause problems for tile and render systems.	Similar to Hong Kong with the problems associated with architectural fins and details not recorded as an issue.	Despite the availability of British Standards giving design guidance design related issues such as materials selection, detailing and use of flashings still cause defects.	To be identified in aged buildings by appropriate inspections with repairs being designed to address any design deficiencies and to realize safe structures.

<table>
<tr><th rowspan="2">Criteria / Description for failure of external wall tiles / render</th><th colspan="4">Details of Experience</th><th rowspan="2">Experience relevant to Hong Kong</th></tr>
<tr><th>Australia</th><th>Hong Kong</th><th>Singapore</th><th>United Kingdom</th></tr>
<tr><td>Inspections</td><td>Inspections organised and paid for by owners on a voluntary basis to address defects identified by owners or occupants</td><td>Inspections on a voluntary basis coordinated by owner's committees or building managers generally in response to identified defects. Inspections may be required by an order from BD in the event of delapidation or UBW being discovered.</td><td>Structural inspections required to be completed by the owners on a 10 yearly basis with inspection of external wall tiles / render on a voluntary basis.</td><td>No requirement for mandatory inspections or maintenance and any inspections believed to be on a voluntary basis by the building owners or occupants.</td><td>Consideration of a mandatory inspection scheme to incorporate inspection of the structural elements including inspection of external wall tiles / render.</td></tr>
<tr><td>Maintenance and repair</td><td>Repair of delaminated tiles / render is generally only carried out by breakout and replacement of localized delaminations.</td><td>Maintenance often neglected until repair is required. Repairs by a combination of cut out and replacement and pinning back to substrate. More holistic repairs or refurbishment include over coating or over cladding or complete removal.</td><td>Similar experience to Hong Kong with maintenance often going no further than cleaning of the tiles and repairs completed after specific failure incidents.</td><td>Similar to Hong Kong and Singapore. Render only systems generally repaired by cut out and replacement whereas systems including tiles may be repaired by tile replacement, vacuum assisted chemical resin stabilization or overcoating</td><td>A general lack of awareness with respect to the importance of maintenance and how to go about maintenance has contributed to the current problems with aged buildings. More information is required by owners on maintenance and repair aspects.</td></tr>
</table>

3.2.6 Other international standards

Table 3.5 shows some of the links to international standards, and Table 3.6 lists the relevant international standards on wall tiling:

Table 3.5: Links to International Standards

Country:	Standards:	Abbreviation:	Link:
Australia	Australia Standards	AS	http://www.standards.com.au
Europe	European Standards	EU	http://www.cenorm.be/
International	International Standards	ISO	http://www.iso.org/iso/home.html
Japan	Japanese Standards	JIS	http://www.jsa.or.jp/default_english.asp
Singapore	Singapore Standards	SS	http://eshop.spring.gov.sg/cgi-bin/singaporestandards.pl
United Kingdom	British Standards	BS	http://bsonline.techindex.co.uk
USA	American Standards	ASTM	http://www.astm.org

Table 3.6: Related International Standards on Wall Tiling

Country	Standard Code	Title
ISO	ISO13007-1:2004	Ceramic tiles – Grouts and adhesives – Part 1: Terms, definitions and specifications for adhesives
ISO	ISO13007-2:	Ceramic tiles – Grouts and adhesives – Part 2: Test methods for adhesives
ISO	ISO13007-3:	Ceramic tiles – Grouts and adhesives – Part 3: Terms, definitions and specifications for grouts
ISO	ISO13007-4:	Ceramic tiles – Grouts and adhesives – Part 4: Test methods for grouts
ISO	BS1348:2007	Adhesives for tiles – Determination of tensile adhesion strength for cementitious adhesives

UK	BS 5262: 1991	Code of practice for external renderings
UK	BS 5385-2: 1991	Wall and floor tiling – Part 2: Code of practice for the design and installation of external ceramic wall tiling and mosaics
UK	BS 5980: 1980	Specification for adhesives for use with ceramic tiles and mosaics
UK	BS 6431-1: 1983 EN 87:1991	Ceramic floor and wall tiles – Part 1: Specification for classification and marking, including definitions and characteristics
UK	BS 8000: Part 10: 1995	Workmanship on building sites – Part 10: Code of practice for rendering and rendering
UK	BS 8000: Part 11.1: 1989	Workmanship on building sites – Part 11: Code of practice for wall and floor tiling – Section 11.1: Ceramic tiles, terrazzo tiles and mosaics
UK	BS EN12004:2007	Adhesives for tiles – Requirements, evaluation of conformity, classification and designation

Singapore	CP 68: 1997	Code of practice for ceramic wall and floor tiling
Singapore	SS 301: 1985	Ceramic floor and wall tiles
Singapore	CONQUAS 21	Enhancement Series - Good Industry Practices Guide Book: Good Ceramic Tiling Practice

Australia	AS2358-1990	Adhesives – for fixing ceramic tiles
Australia	AS3958.1-2007	Ceramic tiles – Guide to the installation of ceramic tiles
Australia	AS3958.2-1992	Ceramic tiles – Guide to the selection of a ceramic tiling system

Australia	AS4459.1-16 1997-2005	Methods of sampling and testing ceramic tiles
Australia	AS4662-2003	Ceramic tiles – Definitions, classification, characteristics and marking
Australia	AS4992.1-2006	Ceramic tiles – Grouts and adhesives – Terms, definitions and specifications for adhesives
Australia	AS4992.2-2006	Ceramic tiles – Grouts and adhesives - Test methods for adhesives (ISO 13007-2:2005)
EU	CEN EN 100-91	Ceramic Tiles – Determination of Modulus of Rupture
EU	CEN EN 101-91	Ceramic Tiles – Determination of Scratch Hardness of Surface According to Mohs
EU	CEN EN 102-91	Ceramic Tiles – Determination of Resistance to Deep Abrasion – Unglazed Tiles
EU	CEN EN 103-91	Ceramic Tiles – Determination of Linear Thermal Expansion
EU	CEN EN 104-91	Ceramic Tiles – Determination of Resistance to Thermal Shock
EU	CEN EN 105-91	Ceramic Tiles – Determination of Crazing Resistance – Glazed Tiles
EU	CEN EN 106-91	Ceramic Tiles – Determination of Chemical Resistance – Unglazed Tiles
EU	CEN EN 12002-97	Adhesives for Tiles – Determination of Transverse Deformation for Cementitious Adhesives and Grouts
EU	CEN EN 12003-97	Adhesives for Tiles – Determination of Shear Adhesion Strength of Reaction Resin Adhesives
EU	CEN EN 122-91	Ceramic Tiles – Determination of Chemical Resistance – Glazed Tiles
EU	CEN EN 12808-1-99	Adhesives and Grouts for Tiles – Part1: Determination of Chemical Resistance of Reaction Resin Motars Ratified European Text
EU	CEN EN 1308-96	Adhesives for Tiles – Determination of Slip Ratified European Text
EU	CEN EN 1308-96	Adhesives for Tiles – Determination of Slip Includes Amendment A1:1998

EU	CEN EN 1322-96	Adhesives for Tiles – Definitions and Terminology Ratified European Text
EU	CEN EN 1322-96	Adhesives for Tiles – Definitions and Terminology Includes Amendment A1:198
EU	CEN EN 1323-96	Adhesives for Tiles – Concrete Slab for Test Ratified European Text
EU	CEN EN 1323-96	Adhesives for Tiles – Concrete Slab for Test Includes Amendment A1:1998
EU	CEN EN 1324-96	Adhesives for Tiles – Determination of Shear Adhesion Strength of Dispersion Adhesives Ratified European Text
EU	CEN EN 1324-96	Adhesives for Tiles – Determination of Shear Adhesion Strength of Dispersion Adhesives Includes Amendment A1:1998
EU	CEN EN 1346-96	Adhesives for Tiles – Determination of Open Time Ratified European Text
EU	CEN EN 1346-96	Adhesives for Tiles – Determination of Open Time Includes Amendment A1:1998
EU	CEN EN 1347-96	Adhesives for Tiles – Determination of Wetting Capability Ratified European Text
EU	CEN EN 1347-96	Adhesives for Tiles – Determination of Wetting Capability Includes Amendment A1:1998
EU	CEN EN 1348-97	Adhesives for Tiles – Determination of Tensile Adhesion Strength for Cementitious Adhesives Ratified European Text
EU	CEN EN 1348-97	Adhesives for Tiles – Determination of Tensile Adhesion Strength for Cementitious Adhesives Includes Amendment A1:1998
EU	CEN EN 14099-01	Space Product Assurance – Measurement of the Peel and Pull-Off Strength of Coatings and Finishes Using Pressure-Sensitive Tapes
EU	CEN EN 154-91	Ceramic Tiles – Determination of Resistance to Surface Abrasion – Glazed Tiles
EU	CEN EN 155-91	Ceramic Tiles – Determination of Moisture Expansion Using Boiling Water – Unglazed Tiles
EU	CEN EN 163-91	Ceramic Tiles – Sampling and Basis for Acceptance
EU	CEN EN 202-91	Ceramic Tiles– Determination of Frost Resistance

EU	CEN EN 87-1-83	Ceramic Floor and Wall Tiles – Part 1: Specification for Classification and marking, Including Definitions and Characteristics
EU	CEN EN 87-91	Ceramic Floor and Wall Tiles – Definitions, Classification, Characteristics and Marking
EU	CEN EN 98-91	Ceramic Tiles – Determination of Dimensions and Surface Quality
EU	CEN EN 99-91	Ceramic Tiles – Determination of Water Absorption
EU	CEN EN ISO 10545-13-97	Ceramic Tiles Part 13: Determination of Chemical Resistance
EU	CEN EN ISO 10545-15-97	Ceramic Tiles – Part 15: Determination of Lead and Cadmium Given off by Glazed Tiles ISO 10545-15:1995
EU	CEN EN ISO 10545-16-00	Ceramic Tiles – Part 16: Determination of Small Colour Differences ISO 10545-16:1999
EU	CEN EN ISO 10545-4-97	Ceramic Tiles – Part 4 : Determination of Modulus of Rupture and Breaking Strength ISO 10545-4:1994
EU	CEN EN ISO 10545-5-97	Ceramic Tiles – Part 5: Determination of Impact Resistance by Measurement of Coefficient of Restriction ISO 10545-5:1996, Including Technical Corrigendum 1:1996
EU	CEN EN ISO 10545-6-97	Ceramic Tiles – Part 6: Determination of Resistance to Deep Abrasion for unglazed Tiles
USA	ASTM C 1026-87 (Reapproved 2002)	Standard Test Method for Measuring the Resistance of Ceramic Tile to Freeze-Thaw Cycling
USA	ASTM C 1027-99	Standard Test Method for Determining Visible Abrasion Resistance of Glazed Ceramic Tile
USA	ASTM C 1028-96	Standard Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method
USA	ASTM C 1212-98	Standard Practice for Fabricating Ceramic Reference Specimens Containing Seeded Voids
USA	ASTM C 126-99	Standard Specification for Ceramic Glazed Structural Clay Facing Tile, Facing Brick, and Solid Masonry Units
USA	ASTM C 1274-00	Standard Test Method for Advanced Ceramic Specific Surface Area by Physical Adsorption

USA	ASTM C 1505-01	Standard Test Method for Determination of Breaking Strength of Ceramic Tiles by Three-Point Loading
USA	ASTM C 212-00	Standard Specification for Structural Clay Facing Tile
USA	ASTM C 482-02	Standard Test Method for Bond Strength of Ceramic Tile to Portland Cement Paste
USA	ASTM C 483-95 (Reapproved 2000)	Standard Test Method for Electrical Resistance of Conductive Ceramic Tile
USA	ASTM C 484-99	Standard Test Method for Thermal Shock Resistance of Glazed Ceramic Tile
USA	ASTM C 485-83 (Reapproved 1999)	Standard Test Method for Measuring Warpage of Ceramic Tile
USA	ASTM C 488-83 (Reapproved 1998)	Standard Test Method for Conducting Exterior Exposure Tests of Finishes for Thermal Insulation
USA	ASTM C 499-78 (Reapproved 1999)	Standard Test Method for Facial Dimensions and Thickness of Flat, Rectangular Ceramic Wall and Floor Tile
USA	ASTM C 502-93a (Reapproved 1999)	Standard Test Method for Wedging of Flat, Rectangular Ceramic Wall and Floor Tile
USA	ASTM C 609-90 (Reapproved 2000)	Standard Test Method for Measurement of Small Color Differences Between Ceramic Wall or Floor Tile
USA	ASTM C 627-93 (Reapproved 1999)	Standard Test Method for Evaluating Ceramic Floor Tile Installation Systems Using the Robinson-Type Floor Tester

3.3 LOCAL REGULATIONS AND PRACTICES INCLUDING BUILDING REGULATIONS, PNAP'S AND CURRENT PRACTICES

The majority of defects encountered with external wall tiles / render can be traced back to either design or construction problems at some point in the construction process from design to work completion. These defect causing problems can be conveniently broken down into two categories; design and workmanship. For the purposes of this assessment design is taken to include all aspects of material selection, specification, design, detailing and provision of resources. Workmanship covers all aspects of construction under the control of the site tradesmen such as surface preparation, mixing, application timing, correct use of materials, etc.

3.3.1 Design

Design guidelines for external wall tiles / render are given in British Standards (BS). The following BS are currently available to provide the necessary design guidance and for historical reasons are the international standards must commonly referred to in Hong Kong:

- BS 5385 Part 2: 2006 Wall and Floor Tiling. Code of practice for the design and installation of external ceramic wall tiling and mosaics.
- BS EN 12004: 2007 Adhesives for tiles. Definitions and specifications. (replacement for the old BS 5980:1980 Specification for adhesives for use with ceramic tiles and mosaics)
- BS EN 13914-1: 2005 Code of practice for external renderings

The majority of Hong Kong specifications (e.g. Housing Society General Specification and ASD General Specification) are based on these BS or the older versions that have been withdrawn and superseded.

Relevant Hong Kong Building Regulations and PNAP's include the following:

- Regulation 38 of Building (Construction) Regulations – External Wall of Buildings
- PNAP ADV-31 Building External Finishes – Wet-fixed Tiles
- Building (Minor Works) Regulations
- PNAP APP-147 – Minor Works Control System
- Draft Code of Practice for Mandatory Building Inspection Scheme and Mandatory Window Inspection Scheme

Reinforced concrete (including the majority of tiles / render substrate) is normally designed in accordance with Code of Practice for Structural Use of Concrete 2011 (second edition) or BS 8110 Part 1: 1997 Structural use of concrete. Code of practice for design and construction.

Specifications and standards relevant to external wall tiles / render have been reviewed. The key clauses reviewed vary somewhat in detail but essentially synthesise to a two-fold structure:

- direct application of tile/tile bedding to a parent concrete substrate or the use of an intermediate render stratum to smooth irregularities in the parent substrate.
- the application of three alternative tile/tile bedding systems directly or indirectly (via the render intermediate) to the parent concrete substrate.

For external wall finishes completed with the wet fixing methods, its performance and limitation under the conventional cementations bonding system has not been subjected to any details scientific investigation or proof, to substantiate it's designed purposes / life span.

Although there are claims that workmanship is the main cause for the delamination of external wall finishes (i.e. Under wet fixing method), the contractors have different views because causes for such default can be complicated. Design faults, wrong specification, selection of material, lack of movement joints, differential movement on background material, cyclic wind load, vibration, torsion, elastic shortening, creep, shrinkage, allowable tolerances, humidity and temperature changes will also have impacts to such problem.

3.3.2 Workmanship

The following discussion reviews the tiling system substrata in turn. All mix ratios presented refer to batching by volume.

(a) Parent Substrate

Normally concrete or blockwork must satisfy certain requirements for cleanliness, soundness/integrity and dimensional flatness. Such requirements are stated in most specifications and standards in broad terms with particular flatness/smoothness criteria. Failure to achieve the latter necessitates the use of an intermediate render substrate.

BS 5385 Pt 2, recommends the concrete substrate is allowed to dry for 6 weeks before render or tile bedding application. The intention is to reduce shrinkage and the risk of debonding.

(b) Spatterdash

Spatterdash is used at the concrete/render interface to improve mechanical bond over smooth concrete surface, and is applied to partially cover the concrete surface. It is common in local specifications but tends to be optional in international specifications and could be replaced by or used in conjunction with a bond coat. Typically a 1:2 cement: granite fines mix (with polymer emulsion) is used in Hong Kong. Well-defined spatterdash performance criteria are stipulated in the Hong Kong Housing Authority Specification. Spatterdash is provided for in the current HKHS Specification. Since the spatterdash mixtures are always prepared on site by workers, they are difficult to control and the quality may vary significantly. In some cases, inferior or sub-standard spatterdash mixtures were applied onto the concrete wall, they could reduce the bond strength of the subsequent render layer applied over them.

(c) Bond Coat

The bond coat is normally applied to the cleaned concrete/ spatterdash (if used) surface just prior to render application. Typically specifications insist “apply the render whilst the bond coat is still tacky”. The bond coat is normally a mix of cement and water with polymer emulsion as an additive.

The “bond coat application” is one of the possible methods in achieving acceptable adhesion bond strength for the rendering and tiling system, because the common failure position is at the concrete substrate to render interface. However, if the bond coat is not used properly, it may become a debonding layer which can affect the adhesion of subsequent render layer.

(d) Render

Render forms the intermediate substrate and is normally a 1:3 cement: sand/ crushed rock mix applied to a maximum thickness not exceeding 20mm, but more commonly to 15mm or less. Site mix of 1:3 cement sand render is only found and used in small projects only. Proprietary pre-bagged dry mortars or ready mixed wet mortars are commonly used to form the intermediate substrate for fixing wall tiles. These are not to be confused with "tile bedding mortars" or tile adhesives.

In Hong Kong, due to the common manufacturing practice of wet mortars by the concrete suppliers, the ready mixed wet mortars are only produced either in the early morning or late evening. In order to ensure the supplied wet mortars to the construction sites are still usable, they are heavily dosed with retarder or equivalent admixture for a typical 24hours or even 30 hours extended retardation to slow down cement hydration. As a result, the wet mortar applied onto the concrete wall may only start hydration after the expiration of the retardation period. Hence, some of the water within the mortar may have been lost via absorption by the concrete substrate and evaporation into the air before hydration is completed. Consequently, the wet mortar does not have adequate water to ensure proper hydration to build up the intended strength. Therefore, it has been known and verified in many site pull-off tests, the wall renders with ready mixed mortars are usually relatively weak in bond strength. The adhesion strength of render to concrete substrate may be typical at around 0.2MPa.

On the other hand, for proprietary pre-bagged dry mortars, they are only mixed before use and applied onto the wall immediately after mixing. No special retardation is imposed on hydration of the mortars and the strength development has been followed as normal cement chemistry. Therefore, a comparatively higher bond strength to the concrete substrate is expected and often achieved. A typical value on adhesion strength of 0.5MPa or above is achievable with proprietary pre-bagged dry mortars for use as wall renders.

The current Singaporean specification contains adhesion strength performance criteria for external renders combined with paint systems (these are not applied to renders with tiling since Singapore generally does not use external tiling). These external adhesion strength requirements for render range from 0.25 to 0.4 MPa depending on the application criterion concerned.

Typically renders are required to air dry for 2-3 weeks before tiling application under British Standards. Consequently tiling should not be applied until a minimum period of 8-9 weeks has elapsed to accommodate shrinkage of the concrete and render substrates.

Rendering for external wall applications should comply with BS EN 13914-1: 2005 whether or not tiles are to be installed on the rendering. Where tiles are to be installed on the rendering there are additional requirements contained in BS 5385 Part 2: 2006 principally with respect to the positioning of movement joints which must pass through the full depth of both the tile bedding and render.

Where tiles are to be applied, render is normally used to provide an acceptable level surface prior to the application of tiles or render may be used as a finish on its own (not common in Hong Kong). As a component of this level surface it is often necessary to "dub out" significant localized irregularities prior to the application of the general rendering. Dubbing is most frequently required at joints between formwork panels where movement of the panel during concreting has caused a significant level difference between the two sides of the joint. Dubbing out should be completed prior to the general application of render in layers not exceeding 8mm thick to a maximum permissible thickness of 20mm.

Render for external use is a blend of appropriately graded fine aggregate (either sand or crushed rock fines) mixed with cement or a proprietary external rendering product that may contain other additives in addition to fine aggregate and cement. The render material should be mixed by volume with approximately 1 part of cement to 3 parts of fine aggregate. The grading of the aggregate is important as too fine an aggregate will require excessive water in order to produce a workable material which in turn will cause excessive drying shrinkage and potential for cracking and debonding.

(e) Tile Bedding

Tile bedding is perhaps the most confusing application in terms of diversity and terminology. Two principal form of tile bedding exist:

- Thick and Thin Bed “Adhesives”
- Cement and Sand Mortar Bedding

The type of tile bedding applied depends on the nature of the tile and that of the substrate. Normally two basic classifications of tile are provided: ceramic tiles and mosaics tiles. The relationship of each to the different bedding systems in local and BS codes are discussed below.

(f) Mosaic Tile Bedding Systems

BS 5385 strongly recommends that adhesives (thick and thin-bed) are used for external tiling. The only exception is the option to use cement:sand mortar bed for mosaic tiles. Both systems are applied as float coats to the background. The cement:sand mortar bed is applied to a depth not exceeding 10mm and has to stiffen slightly before tile application. A 1:1 cement sand “grout” mix should be used to pre-grout paper-backed mosaics or should be floated on the mortar bed in the case of synthetic strip or mesh back mosaics.

The three local specifications (HKHS, HA and ASD) are very similar to each other but differ from the British Standard with respect to the application of mosaic tiling.

(g) HKHS Mosaic Tile Specification

For mosaic tiles the HKHS specification permits the use of thin-bed adhesive (but not thick bed adhesive) or alternatively thick bed cement: sand mortar. The HKHS specification requires a bedding coat (i.e. a float coat) 10mm thick (comprising 1:3 cement: granite fines) and “slurry” application to the back of the tiles and to the float coat before fixing. Hence the key difference to the BS is the use of slurry instead of a 1:1 cement:sand “grout” or mortar, the application of the slurry to the float coat and the fact that the thickness of the slurry is not defined.

(h) HA Mosaic Tile Specification

The Housing Authority specification (SL 2008 Edition) is similar to the HKHS in its treatment of mosaics as far as bedding in cement:sand mortars are concerned. A float coat (not exceeding 10mm) is applied to the background while cement slurry of undefined thickness is applied to the back of the tile and to the float coat.

Alternatively a thin-bed slurry method is also provided for in the HA specification which essentially omits the mortar float coat. As in the case of the HKHS specification, the thickness of the slurry which is applied to the background and in this case to the back of the tiles is not defined: it could perhaps be presumed to be a maximum of 3mm given the thin-bed definition.

(i) ASD Mosaic Tile Specification

The ASD specification is similar to both of the above for the thick-bed mortar method but specifies that the bedding mortar should be a maximum depth of 10mm thick. Again, a cement slurry is applied to the backs of the tiles and to the surface of the mortar float coat before tiling application. Like the HKHS specification is the thin-bed method uses proprietary adhesives to the manufacturer's recommendations.

(j) Ceramic Tile System

As discussed above BS 5385 Pt 2, 1991 recommends thick and thin-bed proprietary adhesive systems be used for ceramic tiles since there is greater quality control in the production of proprietary products. It no longer recommends or describes cement:sand mortar bedding systems for ceramic tiles since they are not considered strong enough.

Because of the wide ranging types of proprietary adhesives available, specifications stipulate a "catch-all" that they should be used in accordance with manufacturer recommendations. This is particularly important when manufacturer guarantees are provided.

Unlike cement:sand mortar systems, laboratory performance criteria are specified to classify and test the five different types of adhesives. These stipulate shear and adhesion test criteria, among others. Since the three local standards refer to BS 5385 by default they must also infer that BS EN 12004:2007 applies with its attendant requirements. BS EN 12004:2007 stipulates laboratory adhesion strength testing requirements with a minimum of 0.5MPa. This is greater than the values used in the Singaporean Specification for pull-off testing (0.18MPa). However, it should be noted that laboratory test and insitu test performance seldom match (e.g. laboratory adhesion strength test data for pre-bagged renders cannot be achieved in situ). Consequently it cannot be assumed that laboratory test criteria are applicable to site.

It is evident from earlier discussion that the term "slurry", as used in local standards, refers to cement and water (with or without admixtures) applied to "thick-bed cement:sand mortar bed system". It is not defined or termed an adhesive. Consequently no performance or QC criteria are applied to its use since it is not classified as part of an "adhesive" system.

(k) Local Ceramic Tile Specification

All three local specifications provide thin-bed adhesive options for ceramic tiling. These basically require compliance with the manufacturer's recommendations, grouting up afterwards and forming joint widths to respective tile sizes.

There are no thick-bed adhesive systems in the local specification. The only thick bed systems specified involve cement: sand mortar bedding systems and/or slurry.

The HKHS and ASD thick-bed specification require ceramic tiles to be fixed to walls by buttering the back of the tiles with a cement:sand or crushed rock fines mortar (1:3) to a thickness of 5-15mm. The HA specification (SL 2008 Edition) in contrast refers to fixing of external ceramic wall tiles to BS 5385-2:1991 which recommends fixing of external wall tiles with adhesive.

It is interesting to observe that the cement and sand mortar bedding is not classified in BS 5385 as being either thick or thin bedded but by definition (up to 10mm thick) falls into the thick bed category which refers to all bedding applications exceeding 3mm.

Cement and sand mortar systems that are applied using the “buttering” method directly to the back of ceramic tiles without a floating coat should comprise 1:3-4 mortars and are only specified in BS5385 Pt 1 for internal tiling (not external tiling).

(l) Homogenous Tiles

The issue of tiling specification is further complicated by the use of homogenous tiles, which require special precautions during installation. Homogenous tiles have a very low moisture absorption value and therefore cannot be confidently fixed using cement slurries or hydraulically hardening mortars which require some penetration into the surface of the tile. Homogenous tiles require the use of tile adhesives as their bedding system in order to avoid delamination failure at the tile to tile bedding interface.

(n) Movement Joint

During the life of a building it can be reasonably anticipated that certain movements within the structure will occur and it is important that relatively inflexible finishes such as tiles / render are isolated from the movement. Movement can be caused by shortening of the building over time (inevitable in high rise concrete structures), thermal effects (surface temperatures can reach 70^{o}C compared with internal air conditioned temperatures that may be 20^{o}C), deflections from structural loadings, earthquake, wind load and other environmental factors. These factors that will cause movement of the building are reasonably predictable and the design should therefore be sufficient to accommodate them without significant failure of the tiles / render.

Provision for these movements is conventionally accommodated by the use of movement joints. In order for movement joints to be effective they must be correctly placed and properly detailed. Design guidance on the use of movement joints is given in relevant BS codes of practice.

(o) External Render (without Tiles)

BS 5262 covers the code of practice for external rendering and describes measures that should be taken to control cracking of the render, including movement joints, in section 27. According to BS 5262 render bonded to a structural background requires movement joints to coincide with structural movement joints in the building and also where the rendering is continued over dissimilar backgrounds e.g. from beam to infill wall. If it is not possible to place a movement joint over the joint between dissimilar backgrounds then metal lathing can be incorporated in the render over the joint to minimise the effect of cracking in these areas.

(p) External Render with Tiles

Section 20 of BS 5385 Part 2 covers movement joints in external tiling. Movement joints are required to be as follows:

- Formed to coincide with existing structural movement joints
- Junctions between dissimilar backgrounds
- Around the perimeter of tiled areas
- At storey heights horizontally
- Vertical movement joints to be spaced at approximately 3 – 4.5 meters
- At external angles of the building

Workmanship with respect to the application of external wall tiles / render is covered in BS 8000 Section 11.1: 1989 Workmanship on building sites. Code of practice for wall and floor tiling. Ceramic tiles, terrazzo tiles and mosaics and BS 8000 Section 10: 1995 Workmanship on building sites. Code of practice for render and rendering.

These standards describe the recommended practices to be followed by site workers when engaged in rendering and tiling activities.

3.3.3 Maintenance

Once a building is constructed it is the responsibility of the owners to maintain it in a safe condition for the occupants, users and passers by. There are three major aspects related to the maintenance of a building in safe condition including the way it is used, inspections to identify defects/deterioration and the completion of appropriate repairs in a timely fashion.

The various aspects of repair and maintenance are discussed in this section. The laying, repair or removal of external wall tiles may be regarded as minor works under the Buildings Ordinance. Reference should be made to Building (Minor Works) Regulations, the General Guidelines on Minor Works Control System, Technical Guidelines on Minor Works Control System and PNAP APP-147 on Minor Works Control System. Furthermore it should be noted that the Mandatory Building Inspection Scheme covers the inspection and repair as necessary of external elements. Reference should be made to the Draft Code of Practice for Mandatory Building Inspection Scheme and Mandatory Window Inspection Scheme regarding the inspection requirements and repair methods.

(a) Inspection

Inspection and checking of the condition of external wall tiles / render is the essential first step to maintaining them in a safe condition. Without inspection, defects are likely to go un-noticed and un-repaired which in turn exposes them to the possibility of further deterioration and ultimately spall or collapse from the building.

Due to the specialized nature and equipment required for external wall tiles / render inspections the majority of the general public will only be able to complete simple visual inspection in order to detect obvious problems such as spalled materials, cracks, staining, missing sealant etc. and then only where sufficient access is available. Consequently it is believed necessary to engage a third party such as the building manager or construction professional on say an annual basis to inspect the external wall tiles / render and in addition to engage a construction professional to complete a detailed investigation say every five years with investigation findings and repair recommendations.

Annual inspections would be expected to identify the following potential problems for either repair or more detailed investigation:

- Spalled tiles, render and concrete
- Stains (rust, water, efflorescence)
- Significant cracks
- Bulging tiles / render
- UBW/ overloading
- Major sealant defects
- Discoloration, mould growth, etc.

More thorough investigations on say a five yearly basis would identify all of the above together with:

- Extent of tile, render or concrete delamination
- Condition of the concrete including reinforcement
- Adhesion strength of applied tiles / render
- Construction system of external wall tiles / render (needed once only)
- Provision of repair and other recommendations

(b) Repair

It is considered unlikely that owners or occupants will have the necessary skills, equipment or inclination to complete their own external wall tile / render repairs. There is not a culture of DIY in Hong Kong which is known to exist in other countries and so a repair contractor will most likely be engaged to complete the repairs.

It is important that a contactor with the required technical competence is engaged to complete the works and it would be prudent to engage an independent organisation (again with the necessary technical competence in repair works) to supervise the repair contractor including the completion of appropriate quality control testing.

The quality (and consequently price) of materials used for concrete repair, render, tile bedding and tile grout can vary considerably. At one end of the scale site mixing of simple sand and cement can be used to create repair mortars, render, tile bedding and tile grout with extreme variability likely in both the raw materials and the mixing ratios to give a similar variability in the finished results. At the other end of the scale are pre-bagged proprietary dry powder materials that only require the addition of water on site. These materials are specifically blended for particular applications (e.g. concrete repair, tile adhesive, render, etc.), are less workmanship sensitive and are designed to give consistent results. These materials also include workability additives that prevent the incorrect addition of water on site, if either too much or too little water is added, the materials will simply be unusable in terms of workability.

A key step that is often omitted in repair specifications (particularly if a consultant is not engaged to supervise repair works) is quality control testing. Once a repair has been completed it should be subject to quality control testing to ensure that it actually complies with the specification requirement. Appropriate quality control testing for external wall tile / render repairs may include the following:

- Bond adhesion strength testing for tiles and render
- Delamination checking for concrete patch repairs, tiles and render
- Tile removal during tile installation works to check fullness of tile bedding on back of tile
- Cube compression strength test for concrete repair mortar
- Water flood or holiday detection test for waterproof membranes

External Wall Tile / Render Repair Systems

There are a number of different repair systems that can be selected for the repair of defective external wall tile / render systems and the choice of repair system will depend on a number of factors including; condition of the existing installation, intended building life, cost and owners preference. It is possible that more than one repair system could be used in combination to achieve the required results in the most efficient manor e.g. a combination of breakout and pinning repairs with either an over coating or over cladding solution.

The selected repair works will be significantly influenced by the thickness of render at each delamination and the delamination size; in particular mechanical pinning (Options B, D and E below) can only be carried out with a minimum render thickness of say 15 to 20mm and subject to render quality.

The following repair options are available :

Option A	-	No repair. This option is normally not possible due to the potential safety hazard from free falling tiles / render
Option B	-	Mechanical Pinning of Defective Areas
Option C	-	Epoxy Injection of Defective Areas
Option D	-	Mechanical Pinning with Epoxy Injection
Option E	-	Mechanical Pinning of Bonded Areas
Option F	-	Replacement of Delaminated Areas
Option G	-	Remove and reapply all exterior tiles / render and re apply tiles / render finish

Option A – No Repair

In the event that delamination defects have been discovered this option is not normally possible due to the risk of spalling materials causing damage or injury. However it may be an option for example, if the building is planned for demolition in the near future and acceptable protective measures such as catchfans, safety netting and covered walkways can be provided until the risk is removed i.e. the building is demolished.

Option B – Mechanical Pinning of Defective Areas

The existing delaminated tiles / render of render thickness greater than 15 to 20mm could be pinned to the concrete substrate as follows :

a) Drill a hole through the render at a tile pointing joint junction, or by removing and reinstating a tile, into the substrate concrete at spacings to be determined by a structural analysis.

b) Clean the hole carefully.

c) Install the stainless steel pin with or without an associated adhesive (i.e. dry or adhesive fastening of the pin).

d) Apply an epoxy based sealant in a 4mm recess into the render to cap the hole for dry fix applied pins.

e) Clean off and repair the surface as necessary.

The design of the mechanical pinning system would be part of the repair specification. The render to be retained for pinning would be checked by the Engineer as part of the supervision works.

Option C – Epoxy Injection of Defective Areas

The existing delaminated tiles / render could be bonded to the existing substrate concrete using epoxy resin. Where large scale delaminations occur the tiles / render would have to be pinned first to prevent potential failure due to the pressure of the resin behind. The process would be as follows :

a) Drill holes through the tiles / render on a regular grid (at a tile pointing joint junction, or by removing and reinstating a tile).
b) Clean the holes carefully.
c) Install injection ports.
d) Prepare the delamination perimeter and seal any gaps between render and concrete.
e) Commencing at the bottom of each repair area inject low viscosity epoxy resin until it appears at adjacent ports.
f) Seal off first port and continue to the next checking progress of the resin by hammer tapping.
g) Remove ports and repair surface profile on completion.

Option D – Mechanical Pinning with Epoxy Injection

This option combines option B with C to give a more comprehensive repair (i.e. option B leaves a void between the render / concrete interface, and option C only uses epoxy without the addition of pinning).

Option E – Mechanical Pinning of Bonded Areas

This option includes pinning of presently bonded areas, particularly adjacent to existing delaminations, to reduce the risk of future delaminations forming and ultimately developing into free falling hazards.

Option F – Replacement of Delaminated Areas

The existing delaminated tiles / render would be removed and replaced as follows:

- Saw cut a perimeter area of tiles / render to be removed, and a nominal 3mm into the concrete substrate (the saw cut area is required to be a whole number of tiles).
- Hack off all tiles / render within the saw cut area.

- Roughen concrete surface and remove all contaminants and remaining bond coat by wire brushing and high pressure water jetting.
- Apply a polymer modified bond coat and polymer modified render to reinstate the profile.
- Apply replacement tiles in the approved manner.

Option G – Remove and reapply all exterior tiles / render and re apply tiles / render finish

This would involve the complete removal of all materials down to the concrete substrate, preparation of the concrete and repair of existing cracks prior to application of new render and tiles to an approved method statement. This method would completely remove the risk of future defects from existing uncertain tiles / render and subject to suitable materials, methods and workmanship would provide an acceptable long term repair option.

(c) Maintenance

Testing and Detection

The first step to repairing any problem is identifying the problem, if problems are not detected they are unlikely to be rectified. Consequently testing and detection of problems is a critically important aspect of external wall tiles / render repair and maintenance.

The detection of defects in external wall tiles / render primarily involves the visual identification of surface anomalies, the detection of delaminations beneath the tiles / render surface and confirmation of acceptable construction and bonding in bonded areas of the tile / render system.

Accurate records of all completed investigations and tests should be retained as measure of the buildings deterioration over time. These records will be useful in accessing the propagation of defects and whether or not the condition is deteriorating or remaining stable.

Visual Survey

This is the most simple inspection method requiring only knowledge of what to look for and necessary equipment such as access, binoculars (possibly), etc. Despite visual inspection being the most simple and least intrusive of all inspection and test methods, it is one of the most useful. An experienced inspector will be able to identify the following defects or ‘tell tails’ that indicate possible defects:

- Cracks in tiles / render
- Bulging of tiles / render
- Defective (cracked, debonded, discolored) sealant in movement joints

- Staining (efflorescence, rust, water, mould, etc.)
- Discoloured tile grout, render or tiled areas
- Spalled materials (plain of failure, reinforcement corrosion, etc.)

Careful visual inspection will identify significant defects and give a good general idea of the state of dilapidation of a building and therefore whether or not more detailed inspection is required urgently or can be delayed until the next convenient maintenance cycle. Visual inspection can also identify discoloration, staining, mould growth, efflorescence, etc., which might not be significant defects with respect to falling materials but may indicate the presence of defects such as delaminations and retained moisture which may in turn lead to falling incidents.

Delamination Testing

Before tiles / render spall off a building they must first delaminate or loose contact and therefore adhesion with their immediate substrate. Once delaminations have formed they may be retained in place by surrounding materials and cause disturbance for many years. Alternatively, delaminations once formed may deteriorate or increase in size rapidly and result in spalled tiles / render with potentially serious or fatal consequences. Consequently it is desirable to detect and address (repair or monitor) delaminations as early as possible.

Delaminations are conventionally detected by hammer tapping which involves striking the surface of the tiles / render with a metallic object (typically a small hammer or metal rod, possibly with a sphere on the end) and listening for differences in the sound produced. Bonded areas will produce a ‘solid’ sound with no surface vibration detectable by placing a hand on the surface adjacent to the strike location. Debonded areas by comparison will produce a higher pitch ‘hollow’ sound accompanied by some vibration detectable by placing a hand on the surface adjacent to the hammer strike. Various pieces of equipment have been developed to either roll or rub across the tile / render surface in an effort to speed up this rather cumbersome detection method but the principle of listening for hollow sounds remains the same.

Although hammer tapping is considered the most accurate and dependable means of identifying and confirming the size of delaminations it requires close physical contact with all surfaces to be tested. In the case of high rise construction this close inspection requirement can lead to the necessity for expensive (and potentially inconvenient) temporary access systems in the form of either platforms, gondola or scaffold. To address the time, cost and nuisance issues infrared thermography has been developed as a technique for rapidly and economically surveying building external wall surfaces to detect delaminated tiles / render.

The infrared thermo graphic technique works by using infrared emissions to very accurately measure the surface temperature of the wall. Differences in surface temperature give an indication of possible subsurface delamination defects as a delamination will cause a built-up of surface temperature as a result of the disconnection causing a reduction in the efficiency of heat dissipation from the surface to the structure into the building. Significant operator skill is required to interpret the photographs produced in order not to be mislead by shadow and sun light effects, internal air conditioning or the heat from other building services, etc. It is recommended that infrared thermography is completed together with some limited hammer tapping to calibrate and confirm the accuracy of the thermo scans produced.

An emerging technology for detection of delaminated tiles / render and currently the subject of research and development in Hong Kong is Shearography. The technique is currently not fully developed and not commercially available. The technique works by using a laser interferometric method developed originally for full-field observation of surface strains of components. Flaws within the sample being inspected usually induce strain concentrations around them, and shearography can be employed to detect those flaws. The device being researched in Hong Kong is essentially a camera system on a wheeled carrier that needs to be run over the surface of a wall to give an indication of possible sub surface defects. The technique could conceivably be incorporated into a robotic devise to inspect the wall surface automatically. No further information is presently available (outside of the confidential research studies) on the application of shearography to the detection of external wall tile / render delaminations.

Adhesion Strength Testing (pull off test)

Adhesion strength testing is used to confirm the adhesion strength of currently bonded tiles / render and is necessary in the consideration of whether or not to retain existing tiles / render as part of the chosen repair system.

Essentially adhesion strength testing is completed as follows:

- Coring through the external wall tiles / render and a nominal 5mm or so into the substrate concrete. Typically the core diameter will be 50mm but diameters of 20 to 75mm are used by different types of testers.
- The cut core remains in situ i.e. it is not removed from the core hole with the various layers remaining bonded to each other and the substrate. If the core detaches during coring, this is an indication of either inappropriate coring practice or low adhesion within tile / render laminate system.
- A metal ‘dolly’ is attached to the end of the core sample by means of an epoxy adhesive. The dolly allows the attachment of an adhesion strength tester to ‘pull out’ the cored sample.
- Once the epoxy on the dolly has cured an adhesion strength tester is attached to the dolly and used to pull out the sample until failure.

- The load at failure is recorded and divided by the cross section area of the core to give the test result in MPa.

Cored adhesion strength testing (as described above) is the most common form of adhesion strength testing for external wall tiles / render although this is sometimes varied to saw cut through the tiles / render with the use of a square dolly.

After completion of the adhesion strength testing, the recovered core samples can be used to visually access the construction of the tile / render system. Useful information can be obtained on the thickness of the render (necessary to decide repair method e.g. pinning), number of render layers, quality and compaction of render material, other construction anomalies.

Laboratory Testing

With respect to checking the safety condition of external wall tiles / render; visual survey, delamination testing and adhesion strength testing are normally sufficient. However, if additional information is required on the materials used (helpful in determining the cause of failure and the potential for further deterioration and future failure).

Suitable testing may include:

- Aggregate to cement ratio testing for renders and tile bedding materials
- Polymer detection for render and tile bedding material to detect the presence of organic mater within the cementitious materials
- Petrography for cementitious materials to give information on constituents, possible cause of cracking, ASR, etc.

3.4 STAKEHOLDERS CONSULTATION

It was illustrated in the Review Report, it summaries this section considers the views of the building professionals and industry stakeholders which were consulted in order to assess the impact created by falling tiles and render.

3.4.1 Information Collection

Information was collected via consultation from those building professional and industry stakeholders, within related disciplines including Architectural Services Department, Building Department, Housing Department, Real Developers Association of Hong Kong, Hong Kong Contractors Association, academic institutions, Hong Kong Institute of Architects, Hong Kong Institution of Engineers, Hong Kong Institute of Surveyors and the other organizations in the construction industry.

3.4.2 Consultation for Building Professional and Industry Stakeholders

After reviewing the relevant literatures and experiences from overseas including the United Kingdom, Australia and Singapore, it was noted that the types of problems in these countries, where are similar to those in Hong Kong varying in frequency of occurrence. the questionnaire was designed to capture the views from this narrower group of people to retrieve the more technical perception of the various issues related to failure of wet-fixed external wall tiles / render. During the consultation stage, at least one meeting was arranged with each of the stakeholders mentioned above.

3.4.3 Consultation Outcome

During the consultation with the stakeholders, we consulted with the stakeholders with respect to the incidents of falling tiles or other matters associated with tiling before and after the issue of General Guidelines for the Design and Construction of Wet-fixed tiles on Building External Finishes (PNAP 303) which is now renumbered as PNAP ADV-31. This guideline was issued in 2003, and after consultation with stakeholders none of the consulted individuals had noticed a change in either the incidence of falling tiles or other aspects of their work related to tiling.

It was however observed that for the government projects, the use of external wall tiles had been restricted and that this may have had an effect on the number of incidents dealt with by stakeholders. However, it was observed that private projects still rely extensively on external wall tile finishes but none of the stakeholders had observed a particular change as a result of the PNAP and it would likely take many years for the effect of the PNAP to be felt on buildings constructed after 2003. Buildings constructed before 2003 may continue to have falling finishes problems so accident statistics will not reflect the introduction of the PNAP for many years to come.

It is also believed that the best approach to tackle the problem of falling external wall tiles/render in Hong Kong is a combination of the Australian and Singaporean approaches i.e. improved worker training together with additional / strengthened legislation for enforcing inspections and maintenance together with stricter penalties for failure incidents.

We tried to find out and consolidate any common patterns from the stakeholders on the findings of the causes of the external wall tile failures, a summary table is attached in Appendix B.

Over 50% of the stakeholders agreed that the failure of external wall tiles could be due to any one or a combination of the various stages in the building delivery process including design, detailing, workmanship, materials, specification and maintenance in overseas countries. Take for example, the exposure conditions in Singapore including rain, wind, temperature, humidity, thermal shock, etc. are also contributory factors. There are numerous cases of detachment of external wall finishes occurred in varies buildings during the past years. The consequence on public safety will be catastrophe, when it occurs on High Rise Buildings.

Over 50% of the stakeholders agreed that poor surface preparation is always regarded as one of the main causes of tile failure. Spatterdash or mechanical key is commonly adopted in the construction industry in Hong Kong. The cement/ sand rendering and wall tiles are both commonly used as external wall finishes for buildings. Wall tiles are bonded or adhered to the cement/ sand rendering (i.e. with or without adhesive) by bonding agents such as mortar or a bed of proprietary adhesive. The cement/ sand rendering in-turn bonded or adhered to the external surface of the buildings. Any inadequate bonding developed between the wall/ substrate/ screeding/ tiles will certainly increased the risk of detachment. Detachment of external wall finishes tends to occur on finishes completed with wet fixing method, while dry fixing methods associated with scientific calculation seems to be less problematic. For external wall finishes completed with the wet fixing method, its performance and limitation under the conventional cementitious bonding system has not been subjected to any detail scientific investigation or proof, to substantiate it's designed purposes/ life span.

Although over 50% of the stakeholders agree that workmanship is the main causes for the delamination of external wall finishes (i.e. under wet fixing method), the contractors have different points of views because causes for such default can be complicated. They believed that design faults, wrong specifications selection of material, lack of movement joints, differential movement on background material, cyclic wing load, vibration, torsion, elastic shortening, creep, shrinkage, allowable tolerances, humidity and temperature changes would also have impacts to such problems.

Over 50% of the stakeholders agreed to provide with the relevant training courses and seminars to the plasterers in order to educate them the importance of implementing the guideline and code of practices. They also agreed to that providing trade test certifications to the plasterers are essential.

Some stakeholders claimed that design to reduce the height of external tiling works, e.g. architectural fins/ feature, may be considered to minimise the failure of external wall tiles. The suitable site tests (i.e. On-site pull-off test, infra-red scan) should be specified in the contract to ensure the tiling works are installed to the required standard.

4 SITE INSPECTIONS AND ONSITE TESTING

As advised by CIC, 4 building sites with ongoing activities in various stages of the render and tile installation cycle and using the 4 commonly used types of tiles were identified according to the criteria set below:

Each site should have either ongoing activities or uncovered (i.e. open for inspection) elements in the following construction stages:

a) Unprepared/ exposed concrete external wall substrate;

b) Prepared concrete substrate including any bond enhancing measures such as spatter dash, bond coat, etc. prior to application of render or tiles;

c) Ongoing render and tile installation so that material batching, mixing, preparation and application can be witnessed;

d) Completed areas of tile and render for site testing/ inspection.

The Outline Brief required the Consultant to carry out site inspections and on-site testing at 5 building sites but, in the event, CIC was only able to specify 4 sites as a fifth suitable site was not available. For this reason, site inspections and on-site testing was completed at only 4 building sites.

4.1 DESCRIPTION OF THE SITES

4.1.1 Site 1 – Government School at Wylie Road

It was a government site of 8-storey primary school with classrooms, assembly hall etc. The major tiles used for external façade were 225 x 19.5mm artificial granite tiles and 45 x 45 mm ceramic tiles

4.1.2 Site 2 – Residential Building at Cheung Sha Wan

The site was a 29-storey residential block by private developer, the major tiles used for external façade were 95 x 45mm ceramic tiles

4.1.3 Site 3 – Residential Building at Yuen Long

A residential development site by private developer consist of three high-rise 23-storey residential blocks and eight low-rise blocks, the major tiles used for external façade were 145 x 45mm ceramic tiles

4.1.4 Site 4 – Composite Redevelopment at Hung Hom

The site was a 25-storey composite redevelopment site; the major tiles used for external façade were 95 x 45mm ceramic tiles.

4.2 DESCRIPTION OF INSPECTION

Site inspection of completed tile and render installations were performed at five selected external wall locations where safe access could be provided to the research team:

1) Hammer tapping survey to an area of maximum size of 100m^2 to check for delamination at all five locations;

2) Visual inspection at all five locations (maximum size of 100m^2). The selected locations to include features such as joints, internal and external corners, openings and edge of tiling on at least one out of the five selected locations;

4.2.1 Site 1 – Government School at Wylie Road

The selected areas for inspection were located at Ground floor (Three areas) and Roof floor (Two areas). The general condition of tile installation was acceptable, significant visible defects were not found in the visual inspection. However five localized minor hollow sound areas were found during the hammer tapping survey, the size of these areas ranged from 0.07 to 0.005 m^2 with total of 0.0975m^2 (out of surveyed area of 100m^2).

4.2.2 Site 2 – Residential Building at Cheung Sha Wan

Five selected areas located at 6/F (two areas), 16/F and 31/F (two areas) were performed visual inspected and hammer tapping. Inspected Tiled external surface were generally with acceptable condition, there were no significant visible defects found, only minor cracks on filler between tiles were observed. Besides, there was no hollow sound areas found during the hammer tapping survey (out of surveyed area of 100m^2)

4.2.3 Site 3 – Residential Building at Yuen Long

An approximately 10m^2 area at each floor from 17/F to 6/F were selected for visual inspection and hammer tapping. Inspected Tiled external surface were generally with acceptable condition, there were no significant visible defects found. However 36 localized minor hollow sound areas were found during the hammer tapping survey, the size of these areas ranged from 0.165 to 0.005 m^2 with total of 0.648m^2 (out of surveyed area of 100m^2)

4.2.4 Site 4 – Composite Redevelopment at Hung Hom

The selected areas for inspection were located at Third floor podium. The general condition of tile installation was acceptable, significant visible defects were not found in the visual inspection. However nine localized minor hollow sound areas were found during the hammer tapping survey, the size of these areas ranged from 0.029 to 0.004 m^2 with total of 0.0903m^2 (total surveyed area of 74.2m^2)

4.3 DESCRIPTION OF SAMPLE AND MEASUREMENTS

Site testings listed below on completed tile and render installations were performed at selected external wall locations with safe access,

1) Opening up inspections on movement joints at two locations to check construction method and dimension measurement at the joint.

2) Tape measurement survey of joint locations and sizes together with other salient features that would be recorded on site sketches at each of the five locations;

3) Adhesion strength testing at cored samples, three individual pull off tests to be completed at each sample location. The extracted cores were also used to identify thickness of materials up to the concrete layer.

4.3.1 Site 1 – Government School at Wylie Road

The five selected areas for opening up inspection are located at Ground floor. The movement joint were opened approximate 100mm in length for the inspection, the width and depth of movement joint were ranged from 20 to 46 mm and 12 to 22 mm respectively. The movement joints were reached the concrete substrate; the construction method of movement joint was acceptable.

Four selected areas at G/F (three locations) and 5/F were tested for adhesion strength, three individual pull off tests were completed at each sample location. The adhesion strength of bonding materials were ranged from 0.06 to 1.49 MPa, the major failure types were at render/substrate interface and tile/tile adhesive interface.

4.3.2 Site 2 – Residential Building at Cheung Sha Wan

Opening up inspection were conducted to four selected areas located at 6/F and 16/F. The movement joint were opened approximate 100mm in length for the inspection, the width and depth of movement joint were ranged from 18.5 to 20 mm and 17 to 22 mm respectively, however, it was observed that inspected movement joints did not reach the concrete substrate. Besides, the distance between movement joints at four location were measured, the separation between horizontal movement joints were approximately 3.5m and no vertical movement joint was observed, the construction method of movement joint was not acceptable.

Adhesion strength testing were performed in five selected areas on tiled external façade, three individual pull off tests were completed at each sample location. The adhesion strength of bonding materials were ranged from 0.06 to 1.32 MPa, the major failure type was at render layer and render/substrate interface.

4.3.3 Site 3 – Residential Building at Yuen Long

The five selected areas for opening up inspection are located at 8/F and 9/F. The movement joint were opened approximate 150mm in length for the inspection, the width and depth of movement joint were 30 mm and ranged from 20.25 to 20.62

mm respectively. All of inspected opening up were extended beyond render layer, the construction method of movement joint was acceptable. Besides, the distance between movement joints at four location were measured, the separation between horizontal movement joints were approximately 3.2 m and no vertical movement joint was observed.

Three selected areas at 6/F and 8/F were tested for adhesion strength, three individual pull off tests were completed at each sample location. The adhesion strength of bonding materials were ranged from 0.12 to 0.63 MPa, the major failure types were at render layer and Tile/Tile adhesive interface.

4.3.4 Site 4 – Composite Redevelopment at Hung Hom

Opening up inspection were conducted to five selected areas located at 3/F podium. The movement joint were opened approximate 150mm in length for the inspection, the width and depth of movement joint were ranged from 24 to 31 mm and 18 to 27 mm respectively. The movement joints were reached the concrete substrate; the construction method of movement joint was acceptable. Besides, the distance between movement joints at four location were measured, the separation between horizontal movement joints were approximately 2 m and no vertical movement joint was observed.

Adhesion strength testing were performed in three selected areas at 3/F, 17/F and 25/F, three individual pull off tests were completed at each sample location. The adhesion strength of bonding materials were ranged from 0.01 to 0.83 MPa, the major failure type was at render layer and render/substrate interface.

4.4 TEST RESULTS AND FINDINGS

With reference to the site inspection, only minor localized debonding and fine cracks at grouting between tiles was observed, it is reasonable for a newly constructed tiling surface such that significant defects will not be observed. However, a wide range of bond strength was measured from site test results, some of them were below the recommended bond strength 0.2 MPa. The major failure types of these low bond strength samples were either the render to concrete interface where spatterdash may also have been incorporated (12 out of 16), or at the tile to tile adhesive interface (4 out of 16). The suspected cause of weak bond strength was inadequate surface preparation before application of render layer or adhesive layer. Besides, it was observed that the vertical movement joint of tile façade were generally not install. The details of major causes of debonding will be discussed in later section.

5 MAJOR CAUSES OF DEBONDING

Factors affecting the causation of debonding render and tiles were studied through the literature review process and consultation with stakeholders. Materials may spall from the external wall of buildings as a result of either adhesive failure between the applied material layers and the substrate or via cohesive failure within an individual component of the built up system. Through the study process it was established that adhesive or debonding failure was the most common failure mechanism and that cohesive failure within the render or tile adhesive was not common.

Causes of debonding then relate to adhesion failure at either the render to concrete interface where spatterdash may also have been incorporated, at the tile adhesive to render interface or at the tile to tile adhesive interface. Failure at one or a combination of these three interfaces was believed to represent the majority of debonding incidents.

Underlying causes for adhesion failure would include;

1. Differential movement between adhered layers where the strain created by the differential movement exceeded the adhesion strength at the interface;
2. Inadequate bond adhesion between layers which may result from incompatible materials, workmanship or deterioration due to water ingress or other deterioration mechanism. Bond adhesion strength may be inadequate to support loading conditions such as dead weight of the render and tiles, wind suction loads, etc.

The reason for a debonding failure incident will likely result from a combination of the above and it is thus important to implement solutions that address both the movement and bond adhesion strength. With adequate allowances made for building movements and the use of materials and methods providing adequate adhesion strength the occurrence of debonding failures can be minimized.

Concrete buildings including the external wall elements deform as a result of loading, if this movement exceeds the movement in the render and tile system, stresses will build up between the different materials which may result in failure. Concrete is also subject to creep & drying shrinkage, which results in shortening of the structure under load or deformation of beams & cantilevers. Relative humidity affects the rate at which concrete dries out which will affect the rate at which the concrete shrinks and thus both the incidence of failure and the time from construction that failure may occur. In humid climates such as that in Hong Kong, drying shrinkage will be reduced compared to dryer environments but may still result in failures if adequate provision is not allowed to accommodate shrinkage movement.

Thermal effects on the surface of a building can also set up differential movement between the render and tiles and the concrete substrate. The external or render/ tile surface of an external wall subject to solar radiation may significantly exceed that on the inner face which may be airconditioned. This temperature gradient between the concrete wall and the external tiles and render will cause differential expansion and apply additional loading to the bonded interfaces.

Concrete and render may also expand at different rates even if they are maintained at the same temperature due to the effects of relative aggregate size and quantity which will normally be approximately 6 :1 in the concrete but only say 3:1 in the render

The above aspects mean that adequate provision for movement is critical to the success of any render or tile external wall system. Expected movements can be accommodated by the appropriate use of correctly placed and detailed movement joints. BS 5385-2:2006 gives guidance on both the detailing and placement of movement joints and this advice should be followed in order to minimize failure incidents.

The four sites visited during the course of this research may be typical of render and tile installation on buildings in Hong Kong where the recommendations on joint placement and detailing were not adhered to. In particular joints were not always correctly detailed including cutting through the full depth of the render to the concrete substrate. Vertical joints were not spaced at the recommended 3 to 4.5 meters apart or at external angles. Horizontal joints at storey height were observed but vertical joints were not used.

As mentioned above, relative differential movements at the interface between the render & concrete substrate & render & tile generate shear & tensile stresses which need to be accommodated. It is therefore important to achieve adequate bond strengths between the different materials, in order for them to be capable of resisting any imposed stresses due the combined effects of structural movement & temperature.

Tests completed as part of this research project on samples of different materials commonly used in Hong Kong demonstrated that acceptable bond adhesion strength can be developed subject to acceptable workmanship. Tests completed on adhesion strength at the render to concrete interface included both samples with and without spatterdash. The completed testing indicated that there was no significance difference between applications with or without the spatterdash. However, as a thin layer of cementitious material in an exposed external wall application (particularly exposed in the case of high rise construction) it is difficult to control the quality and consistency of spatterdash which may result in a weak bond and subsequent delamination failure.

6 LABORATORY TESTING

A critical review approach was adopted for the laboratory testing information available in previous researches and technical assessment and consideration of the available data were performed, the results will be presented in follow section. Only laboratory testing where existing test results were not available from other sources was conducted in this study.

6.1 PREVIOUS RESEARCH FINDINGS

Laboratory testing information available in previous researches such as those listed in section 3.1 were reviewed and assessed, the key findings were summarized below:

1) Yiu et al. (2007) found by laboratory studies that thermal and moisture cycles can reduce adhesion strength substantially. 10 specimens of 300mm x 150mm x 100mm tiled blocks were fabricated and were undergone 200 thermal and moisture cycles. Shear strength test results showed that the adhesion strength decreased by more than 50% (from 1.7 to 0.8 MPa in Set A and from 1.2 to 0.6 MPa in Set B) after 100 cycles at the tile-rendering interface.

2) Yiu et al. (2006) found by an empirical analysis that weathering, such as thermal, wind and rain, imposes a significant effect on external wall tile adhesion strength. It found that the probability of failure of external wall tiles of this 20-year-old building was about 14% in average, and that orientation and shading attributes significantly affected the probability. For example, west and south-west facing façades were of 4.8% and 3.5% higher probability of failure, respectively in comparison with the north-east façade. Sun shading devices were also found to reduce 10% probability of failure.

6.2 TESTING CONDUCTED BY THE RESEARCH TEAM

In addition to the above available test results from previous studies, laboratory tests were conducted in this study to justify the adoption of proposed tiling specifications/ recommendations to be presented in the guidelines. And the details of tests will be presented in following sections

6.2.1 Test Objectives

Five Mock up panels were built to evaluate the effectiveness of application of spatterdash on concrete substrate before application of render layer, and the affect on bond strength of premix adhesive product with three types of common tile material (glass mosaic, ceramic and artificial granite).

First two panels were built identically, except the application of spatterdash layer on concrete substrate before application of render layer, and the bond strength of render layer with substrate were measured by pull-off test.

Another three panels were built with same render and adhesive layers but with different tiles, and bond strength of were measured by pull-off test.

6.2.2 Test Results

The results of laboratory test are listed in following table 6.1 and 6.2:

Table 6.1: Table of effectiveness on averaged Bond Strength with Spatterdash

	Averaged Bond Strength (MPa)	
Type of Render Material	With Spatterdash	Without Spatterdash
Premixed Render Type 1 (Designed Bond 0.5 MPa)	0.61	0.59
Premixed Render Type 2 Designed Bond 0.5 MPa With Water Resistance	0.76	1.01
Premixed Render Type 3 Designed Bond 1.0 MPa With Water Resistance	2.10	1.65
Premixed Render Type 4 With Thermal insulation properties	0.20	0.34
Ready Mixed Mortar 5 hrs after Batching	0.90	0.72
Ready Mixed Mortar 25 hrs after Batching	0.47	0.24

Table 6.2: Table of effectiveness on averaged Bond Strength with various tiles

	Averaged Bond Strength (MPa)		
Type of Render Material	Artificial Granite (100x100x18mm)	Ceramic (45x95x7mm)	Glass Mosaic (20x20mm)
Premixed Tile adhesive Type 1 Standard BS 5980	1.03	0.79	0.76
Premixed Tile adhesive Type 2 BS EN 12004 C1	1.17	0.98	0.95
Premixed Tile adhesive Type 3 BS EN 12004 C2	1.24	0.95	0.75
Premixed Tile adhesive Type 4 BS EN 12004 C2 S1	1.02	1.42	1.19

	Averaged Bond Strength (MPa)		
Type of Render Material	Artificial Granite (100x100x18mm)	Ceramic (45x95x7mm)	Glass Mosaic (20x20mm)
Premixed Tile adhesive Type 5 BS EN 12004 C2 S2	1.06	1.80	0.68
Cement Paste	0.82	0.44	0.53

6.2.3 Test Findings

From the above results, it was observed that the effect of spatterdash was varied, and it could not enhance the bond strength significantly. Besides, the types of tile used did not affect the bond strength of different types of adhesive, most bond strength results met expected target strength value, however, some results were below the target value of those adhesive types, such as result of Type 4 and 5 Adhesive for Glass Mosaic and artificial Granite, which were below the target value 1.5 MPa, it may due to variance of site conditions during the preparation of panel and failure of substrate interface.

6.3 REMARKS

All of the above tests were conducted in laboratory controled environment (i.e. under constant supervision, workmanship and proper curing), certain tolerance shall be allowed for any application on construction site.

According to the review on previous studies and time limitation of the study, the accelerated durability tests were not performed in the study but results from previous and existing long term exposure tests were used. Previous studies completed for the Housing Authority had identifiedthat meaningful and conclusive results would have been difficult to obtain within the study parameters and time frame.

7 RECOMMENDATIONS

7.1 IMPROVED AREAS AND PROPOSED SOLUTIONS

7.1.1 Design

The design process sets the scene for all subsequent stages and early in the design process is where key decisions on a building including selection of the external wall façade system would be made. The decision to use a render and tile system will affect the fundamental design of the building and once the decision has been made to use render and tiles, the building design concept can be finalized.

A key point identified through stakeholder interviews and other industry interaction was that during the design process the designer needs to consider constructability and maintainability of the external wall render and tiling.

Clear guidance on the detailed design of external wall tile systems is given in the relevant British Standards BS 5385-2:2006 Wall and floor tiling – Part 2: Design and installation of external ceramic and mosaic wall tiling in normal conditions – Code of practice. And for rendering without tiles BS EN 13914-1:2005 Design, preparation and application of external rendering and internal plastering Part 1: External Rendering. Provided the recommendations contained in these two standards are followed, adequately designed and specified systems can be achieved. In this regard consideration needs to be given to movement accommodation which is normally achieved by installing correctly detailed movement joints as set out in the code of practice

1. Over existing and or structural movement joints;
2. Where tiling abuts other materials;
3. Junctions between different background materials, where tiling is continuous across them;
4. Storey heights and approximately 3 to 4.5 meters apart vertically;
5. At external angles vertically.

The provision of correctly detailed and placed movement joints will significantly affect maintainability and occurrence of debonding incidents over the operational lifetime of a building.

The designer then needs to consider constructability of the external wall render and tiling. The main factors affecting constructability are access to working areas, clear space to work, logistics for material movements and programme. It would normally be the Contractor's responsibility to work out the details of temporary works, access and logistics, etc. but the designer must ensure that any site restrictions on programme, temporary access, availability of materials handling equipment such as hoists, etc. would not prevent the Contractor from completing his works. It is common now for designers to work with experienced contractors at the design stage to ensure that constructability is considered at the time of design. This collaboration can result in both time and cost savings at the construction stage and is to be encouraged as it would benefit all parties.

Building maintenance also needs to be considered at the design stage and the embodied maintenance requirements of different systems should be consistent with the expectations of the owner/ end user. Further more, provisions should be made during the design stage to access the external wall for maintenance inspections or repairs if defects are identified. This would normally be achieved by a permanently installed building maintenance unit (BMU) or gondola. Alternative arrangements could be temporary gondolas mounted on the roof (adequate space needs to be provided). Whilst this access may be adequate for inspections, any significant repair work will require the erection of scaffolding or climbing work platforms and the design/ building arrangement must allow for this type of temporary access.

As building heights increase, design for constructability and maintainability become more important/ significant. For high rise construction it is imperative that the designer carefully considers these aspects at the design stage in order to minimize difficulty/ cost and inconvenience during the construction and operation phases of a building.

7.1.2 Workmanship

Workmanship is a complex issue that involves many different interrelated factors.

a) Supervision and Training

Tile and render work is a skilled trade requiring staff with suitable training and experience. In the absence of appropriately skilled and experienced staff at both the operative and supervisory level it is unlikely that acceptable rendering and tiling could be achieved.

Practice in some other countries including the UK and Australia is that render and tiling workers complete lengthy apprenticeships (several years) where they are supervised and trained by an experienced worker. This period in a workers training will include both theory and practice to produce workers with knowledge of the principles, materials, methods and skills of their trade. Workers will often be further regulated by trade union membership to ensure that skills are kept up to date and relevant. These types of systems have not developed in Hong Kong but the local industry should strive to replicating some of the key training and experience factors.

The Construction Industry Council Training Acadamy (CICTA) (formerly the Construction Industry Training Authority) provides trade testing for plastering and various types of tiling. These trade tests include both practical and written elements. This trade test is intended to set a standard qualification for craftsmen, to assist the industry in selection of skilled craftsmen, to facilitate the acquisition of a recognized qualification and to enhance the status and career development of skilled craftsmen.

The CICTA also provides training for craftsman for render and tiling operatives a two year full time course entitled Bricklaying, plastering and tiling is available. Single day courses for either plastering or tiling are also available. No specific courses were available for specific trade supervisors but courses for general supervisory level staff were available.

As described above, local trade testing and training is available in Hong Kong and it is recommended that where possible all site operatives have completed recognized training and trade testing within the trade in which they work together with appropriate experience within the trade. Supervisory staff should also have completed recognized training and trade testing plus completed training to a supervisory level. Where it is not possible to engage staff with recognized qualifications and training due to lack of availability in the industry, experienced operatives only should be engaged who can demonstrate the necessary skills and experience to complete the required work.

Where proprietary products are to be used, all operative and supervisory grade staff should be appropriately trained by the product manufacturer. This will help ensure that manufacturers' recommendations that may vary from one product to another are fully understood and implemented.

Supervisory staff should be provided with sufficient authority over the operatives to require full specification compliance and ensure that work is completed in accordance with industry best practice.

b) Site Organisation and Management

The way a construction site is organized and managed can significantly impact on the ability of operatives to complete render and tiling works to an acceptable standard. It is the responsibility of the site management to provide an environment conducive to the completion of render and tiling in accordance with good working practices.

It is a significant challenge for the construction industry to attract the type of school leavers that it wants in the face of competition from other industries which offer working environments that are very different from a construction site. Site management needs to provide safety, welfare, toilet, rest and other facilities so that the construction site can be a safe and rewarding workplace where unnecessary discomforts can be excluded. This must be a long term industry aim for which site organization and site management is on the frontline – there is a need for the construction industry to improve its image and the management of well organized and planned sites will contribute to this improvement. The ultimate aim will be to attract and retain competent people in order to improve the overall quality of work including render and tiling.

Consideration needs to be given to the transportation of people and materials around site, provision of adequate clear and clean space for material storage, material preparation and mixing, distribution of mixed materials to operatives while it is still fresh. Provision of power, lighting and water in adequate quantities and at the required locations will significantly improve the ability of operatives and supervisors to deliver acceptable work.

Sequencing and planning of site works on the construction programme such that the render and tiling trades are not competing with other trades to work at the same location at the same time. Not only will this improve the quality, efficiency and productivity of the works but it will also help avoid damage to completed works from other activities in the area.

The area for tiling should be as clear and clean as possible to allow the operatives to work in an unobstructed way. It is particularly important to avoid concrete breaking or other work that may cause vibration or disturbance to the render or tiling and thus affect it's adhesion and long term performance.

As one of the last trades on the external wall it is important that the programme for the render and tiling work is realistic. The construction process should be managed in such a way that this finishing trade is not expected to recover time at the end of a programme beyond that which is possible. The time required prior to render application, between render coats, prior to tile adhesive application, etc. Should not be compressed unreasonably. Unreasonable programme demands would not be conducive to the completion of acceptable tiling by the operatives and may lead to increased maintenance/ repair costs and future failure incidents.

c) Concrete Substrate Preparation

Provision of a surface suitable for the application of the intermediate render substrate or tile adhesive is critically important if acceptable bonding is to be achieved between the concrete and the render. In the case of external walls, the surface will usually be off form concrete either precast or cast in situ and some form of concrete surface preparation will normally be required.

Smooth concrete surfaces produced by metal or plastic faced shuttering or dense surfaces produced by controlled permeability forms are most at risk of failure but it should not be assumed that concrete with a rough surface can be rendered satisfactorily. Adhesion of render to concrete can also be inhibited by formwork release agents, mould release oils or curing agents applied after stripping shutters. It is therefore important to check with manufacturers recommendations and ensure that any such contaminants can be either acceptably covered or can be completely removed prior to rendering. The concrete surface must be clean and free of dust, laitance, oils or any weakly bonded materials prior to the application of render.

Where ready mixed mortar is to be used as the render material or other render relying on hydraulic mortar action such as a non-polymer modified proprietary material, it may be necessary to roughen the concrete surface to provide a key. Preparing the surface of concrete by scabbling or shot blasting will remove any contamination on the concrete surface and roughen a smooth surface. Such treatment will help improve adhesion of the render but will not increase surface absorption and alone may be insufficient to prevent debonding failure of the render.

Where dense, closed textured, low permeability concrete surfaces are produced by metal or other formwork types hydraulic mortar action alone may not produce adequate adhesion and the use of proprietary render materials incorporating polymer emulsions to enhance adhesion may be required to achieve acceptable adhesion strengths.

Spatterdash is another option to improve surface roughness of concrete, but as an additional layer applied to the concrete, debonding or poor adhesion of the spatterdash to the concrete is a way that may adversely affect the successful bonding of the render. It is therefore of great importance that (if used) spatterdash is correctly batched, mixed and applied to cleaned and dampened concrete with no standing surface water as soon as possible after striking the shutters, preferably within 24 hours. Spatterdash is a very thin layer on the concrete surface and in the absence of protection it may dry out prior to cement hydration which would produce a week and poorly bonded layer on the concrete surface – the exact opposite of the intention for using spatterdash. Spatterdash should be sprayed with water or otherwise protected during at least the first three days after application to allow proper hydration of the cement. The laboratory testing on adhesion strength carried out as a part of this research project looked at the effect of render adhesion both with and without the use of spatterdash. The findings indicate that the inclusion of appropriately applied spatterdash did not significantly improve the bonding of render to concrete. The spatterdash layer had no significant benefit over the prepared concrete substrate in terms of render adhesion but significant potential to reduce render to concrete adhesion if not properly specified, applied and cured. Where appropriate, the designer should consider the opportunity to delete the spatterdash layer and thus avoid any potential negative impact it could have on the render to concrete adhesion if not appropriately executed.

Probably the most risk free option (in terms of future render spall problems) for concrete surface preparation prior to rendering would be to mechanically secure a stainless steel mesh to the concrete surface. This approach is recommended in BS 5385-2 for work above first floor level and in situations where differential movement is expected. A disadvantage of this method is that it can be expensive. If this method is adopted it needs to use appropriate corrosion resistant materials with an open type mesh that is spaced off the concrete substrate by approximately 5mm so that the render can be pushed through the mesh to fully encapsulate it and to bond to the concrete surface to resist moisture movement that could be an issue if the render were not bonded to the wall.

Rendering will follow the surface profile of the concrete substrate and it is thus important to provide a reasonably level substrate for application of the render. Step joints between shutter panels, concrete voids, exposed aggregate, tie bolt holes, other concrete repairs, etc. All need to be repaired or “dubbed out” prior to the application of render so that the applied render can be of a reasonably consistent thickness which will avoid problems with differential curing rates or thermal effects that may cause cracking and debonding.

d) Render Application

Render should be applied to the prepared concrete substrate in strict accordance with manufacturers’ recommendations where a proprietary render material is being used or in accordance with good rendering practice where ready mixed mortar is being used. Prior to render application the concrete substrate should be allowed to dry out and complete its initial shrinkage for a period of at least 6 weeks. This six week period can be used to complete the necessary surface preparation, fixing steel mesh or concrete repair/ surface preparation activities.

The concrete surface should be wetted prior to render application to prevent excessive moisture suction from the freshly applied render. The wetting operation should be synchronized with the render application such that the surface remains wet when the render is applied but so there is no surface water that could mix with the render.

Unless otherwise permitted for proprietary materials, render should not be applied to an overall thickness greater than 20mm in coats ranging between approximately 8 to 16mm. Each coat should be allowed to cure, dry out and harden prior to the application of subsequent coats and where subsequent coats are to be applied the render surface should be roughened at time of application to provide a key for following coats.

Curing of render coats will be required together with surface protection particularly in the case where external render is exposed to hot, dry or windy conditions. Curing can be achieved by water spraying in conjunction with shading and sheeting if required to maintain surface moisture levels.

The final render layer should be finished to an acceptable level finish such that tiles can be applied with a thin bed tile adhesive (typically approximately 3mm thick) with the tile surface in compliance with specified surface levels.

The final render coat should be cured and allowed to dry out for at least two weeks prior to application of the tile adhesive and tiles. All time frames given in this section comply with best practice for render application but may be altered based on manufacturers recommendations where proprietary materials are used.

e) Application of Tile Adhesive and Tiles

Materials should be carefully checked upon delivery to site and this is particularly important for tiles. Simple checks on colour, thickness, style will be necessary to avoid expensive and time consuming rework if incorrect tiles were installed. For mesh backed tiles where the mesh is glued to the back of the tile it is important that the mesh and glue do not cover too much of the back of the tile, preventing contact between the tile and tile adhesive. If the mesh and glue obscure more than approximately 25% of the back surface of the tile, the tiles should not be used.

Handling and management of materials on site is always an important issue and manufacturers recommendations should be followed in this regard. The handling of tiles is particularly important to avoid damage or contamination, generally tiles should be stored dry and in their original packaging. If tiles become contaminated during storage e.g. by dust, dirt, oil, mould growth or any other contaminant that may affect adhesion or appearance the tiles should be either cleaned prior to use or discarded.

Fixing of tiles should commence on the upper floors of buildings and work down. This will avoid contamination of completed work from work above and allow more time for building movement/ creep on the lower floors.

Prior to tile application the accuracy of the render surface should be checked and as a general rule, for external wall tiles to be secured with tile adhesive any gaps beneath a 2m long straight edge should not exceed 3mm. If larger gaps exist, excessive tile adhesive will be required (which may cause thermal and shrinkage problems) or there will be voids in the tile backing. The render substrate should also be cleaned as required by brushing, vacuuming, etc. prior to tile adhesive application.

As with many construction activities, setting out and planning of the tile application will be important if acceptable, specification compliant finishes are to be achieved. Joints between tiles or sheets of tiles should be set out with a consistent specified width, and that joints are aligned particularly where tiles are in different planes e.g. at internal or external corners.

Final surface preparation of the render prior to tile adhesive application should be in strict accordance with the tile adhesive manufacturers recommendations. Tile adhesives will normally require a dry background and wetting of either the render or the tile back will normally not be required. The render surface may however require priming and if required should be primed in accordance with manufacturers recommendations.

Tile adhesive should be applied to the wall to the required thickness with a flat trowel and then ribbed using a notched trowel to the manufacturers' recommendations with the ribs in one direction only. The notched trowel should not be pushed through the full depth of the adhesive layer to expose the render surface in the depressed sections of the adhesive layer. The notches provide consistent adhesive layer thickness and allow air to escape from behind the tile thus avoiding voids behind the tile. The notches in the tile adhesive should all run in one direction and not cross each other in different directions.

Only sufficient adhesive should be applied such that it can be tiled within the open time of the tile adhesive. The open time may vary between different products but will typically be in the order of 20 or 30 minutes which will reduce in hot, dry and windy conditions. Tiles should not be applied if the tile adhesive has "skinned over" and dried on the surface and the adhesive must not be re-tempered by adding water. The material must be removed and a fresh layer applied.

Where individual tiles are being placed (i.e. tiles that are not mesh backed or paper faced) they should be 'back buttered" i.e. a layer of tile adhesive applied to the back of the tile prior to placing in position and the tile should be placed with a twisting or sliding motion and then taped into position to form joints of at least 1mm width.

For mesh backed or paper faced glass mosaic or ceramic tiles it is not possible to back butter the sheet of tiles in which case the tiles should be tapped firmly into position ensuring that the back of each tile is fully bedded in the tile adhesive applied to the wall.

In the case of paper faced mosaic tiles, it is advisable to pre-grout the tiles prior to installation in accordance with the tile grout manufacturers recommendations. This will save the need for a separate grouting operation after tile installation thus saving time, cost and cleaning work.

f) Joint Grouting

If grout is to be used it should be ensured that the joint grouting material (particularly in the case of sanded and pigmented grouts) is compatible with the tiles being used. Manufacturers' advice can be taken on this matter but it is beneficial to conduct a grouting trial with the approved tile and proposed grout to make sure that acceptable grouting can be achieved. Some known problems that could be identified by this simple trial include scratching of the tile surface (can be caused by sanded grouts) or staining of the tile surface which may be a problem with coloured grouts.

Joints should be grouted as soon as practicable after completion of tile installation to prevent dirt accumulation in joints and to better ensure that the grout and tile adhesive movement through drying occur at the same time. Typically, joints should be grouted with a maximum of three days after tile installation.

Grout should be batched and mixed in strict accordance with the manufacturers recommendations and used within its pot life. The grout material should be worked into the joints to fill them to their full depth with no void between the grout and the tile adhesive. This will require the use of suitable grouting tools such as flexible edged trowels designed to help squeeze grout into joints.

Joint grouting can be a messy operation and the surface of tiles should be cleaned off as work proceeds (and before the grout fully hardens) with a moist cloth or similar. Minimal water should be used in this cleaning operation so that the uncured grout is not affected by excessive moisture.

External wall tiling should be protected from extreme weather conditions until the adhesive and grout have completely set and this protection will be required for a period of approximately 2 weeks after grouting. Sufficient protection is generally provided by scaffolding where boarding and safety nets provide shading and some degree of weather protection. In situations where this minimal protection is not provided or where extremes of weather are expected, consideration should be given to the provision of additional protection measures.

Once the grout and adhesive have set the tiling can be cleaned/ polished with a dry cloth or other suitable method to remove the thin veneer of grout which can otherwise give a dull or dusty appearance to the tiled wall. The use of proprietary cleaning materials can also be used but must follow manufacturers recommendations. Many of these products contain acids which need to be thoroughly rinsed off after use and care must be taken not to affect other site activities such as window/ glazing work which may be adversely affected by tile cleaning operations.

7.1.3 Maintenance

a) Design for Inspection and Maintenance

At the design stage of a project, key decisions will be made on building size, use, structural system, etc. At the design stage it is also important to consider how other stages in a buildings life cycle will be realized. For example, the building designer should consider constructability to better ensure that the building could be built within project expectations. After construction, the operational phase of a buildings life will commence – typically the longest phase in the life of most buildings. During this phase it will be necessary for the owner to perform maintenance operations on the building. Similar to considering constructability, the designer should also consider how the building will be maintained as decisions during the design may significantly impact on the maintainability of a building.

Key decisions that will need to be made during the design stage with respect to the external wall system will include selection of the façade system. If a render and tile system is selected, the design process will need to consider how that façade system is to be maintained. This section gives guidance on the types of maintenance inspections that will be required and the repair systems that could be used if the inspections identify problems.

An external wall render and tile system should be designed to minimize problems the most significant of which will include delamination, debonding and spalling problems. Through this research project it has been identified that adhesion (or failure of adhesion) between material layers within a system is the principle cause of debonding rather than cohesive failure within a material. Of these interface layers, the render to concrete interface has potentially the lowest bond due to reduced adhesion potential of the render material together with higher potential for contamination or movement of the substrate both of which could reduce the adhesion strength of render to concrete.

In addition to the potentially lower adhesion strength at the render to concrete interface, being the first interface in the system it will be carrying more deadweight (render, tile adhesive and tile) compared to the tile to tile adhesive interface for example that only has to support the weight of the tile.

The design process then should focus on how adequate adhesion is to be provided at these interfaces such that future failures that could be a maintenance problem can be minimized. The external wall design should seek to remove potentially problematic areas or features that could result in maintenance problems for external wall render and tile systems.

Provision of movement accommodation is a particularly relevant area that should be considered during design as it will impact on a number of things including building architectural appearance. Movement joints should be placed and detailed to accommodate expected movements and guidance is given on both detailing and joint placement in BS 5385-2. This includes horizontal joints at floor heights and vertical joints at between 3 and 4.5 meters spacing, at external angles at junctions between different background materials and at any existing structural movement joints.

Selection of materials and methods should also consider the ease to repair delaminations and the consequence of failure. The incorporation of mechanically fixed stainless steel mesh within the render material will significantly reduce the possibility of spalling incidents and potentially the need for maintenance repairs. The use of stainless steel mesh in render and tile systems above first floor height is recommended in BS 5385-2 and should be considered for adoption by the designer.

External wall systems for render and tile finishes should also be designed to avoid including features such as fins, sun shades, and other architectural items within the render and tile finished areas. Tiling around these types of feature cause problems, tiles may have to be applied by buttering only with no float coat applied to the wall which can cause quality problems. Movement provisions around such features can also be difficult to accommodate and may be either architecturally unappealing or omitted. Tiling on these types of features can often prove to be a maintenance issue and if such features are considered desirable then consideration should be given to using alternative finishes such as mechanically fixed cladding or paint on the features.

b) Provision of Access

Provision of access to the external wall for cleaning as well as maintenance inspections and potential repairs should be considered by the designer. This is particularly the case on taller buildings or ones with difficult roof access/ multiple ownership roofs. Access for inspections and cleaning on high rise buildings will typically be provided by a BMU which may be either permanently installed or temporarily installed to provide access as required. Both arrangements will require roof space/ access.

A BMU or gondola is generally a small platform suspended from the roof via cables that can typically hold approximately two people but has limited capacity for materials or other heavy objects. It moves slowly and cannot be easily or conveniently replenished except at either roof or ground level. This type of access arrangement to the external wall may be acceptable for cleaning or maintenance inspections but is a challenge to complete repairs from or protect from dropping objects/ debris to the ground below. Consequently, the designer may have to consider the need to provide alternative temporary access arrangements (in addition to a BMU for inspections) such as scaffold or mast climbing work platforms to complete repairs from. This certainly needs to be considered at the design stage such that there is space to install scaffolds or mast climbing platforms and that the ground, podium deck or wall fixing is adequately provided for such temporary access and have the required load carrying capacity.

c) Maintenance Inspections and Testing

The first step to repairing any problem is identifying the problem, if problems are not detected they are unlikely to be rectified. Consequently testing and detection of problems is a critically important aspect of external wall tiles / render repair and maintenance.

The detection of defects in external wall tiles / render primarily involves the visual identification of surface anomalies, the detection of delaminations beneath the tiles / render surface and confirmation of acceptable construction and bonding in bonded areas of the tile / render system.

Accurate records of all completed investigations and tests should be retained as measure of the buildings deterioration over time. These records will be useful in accessing the propagation of defects and whether or not the condition is deteriorating or remaining stable.

Visual inspection is the most simple inspection method requiring only knowledge of what to look for and necessary equipment such as access, binoculars (possibly), etc. Despite visual inspection being the most simple and least intrusive of all inspection and test methods, it is one of the most useful. An experienced inspector will be able to identify the following defects or ‘tell tails’ that indicate possible defects:

- Cracks in tiles / render
- Bulging of tiles / render
- Defective (cracked, debonded, discolored) sealant in movement joints
- Staining (efflorescence, rust, water, mould, etc.)
- Discoloured tile grout, render or tiled areas
- Spalled materials (plain of failure, reinforcement corrosion, etc.)

Careful visual inspection will identify significant defects and give a good general idea of the state of dilapidation of a building and therefore whether or not more detailed inspection is required urgently or can be delayed until the next convenient maintenance cycle. Visual inspection can also identify discoloration, staining, mould growth, efflorescence, etc., which might not be significant defects with respect to falling materials but may indicate the presence of defects such as delaminations and retained moisture which may in turn lead to falling incidents.

Before tiles / render spall off a building they must first delaminate or loose contact and therefore adhesion with their immediate substrate. Once delaminations have formed they may be retained in place by surrounding materials and cause disturbance for many years. Alternatively, delaminations once formed may deteriorate or increase in size rapidly and result in spalled tiles / render with potentially serious or fatal consequences. Consequently it is desirable to detect and address (repair or monitor) delaminations as early as possible.

Delaminations are conventionally detected by hammer tapping which involves striking the surface of the tiles / render with a metallic object (typically a small hammer or metal rod, possibly with a sphere on the end) and listening for differences in the sound produced. Bonded areas will produce a 'solid' sound with no surface vibration detectable by placing a hand on the surface adjacent to the strike location. Debonded areas by comparison will produce a higher pitch 'hollow' sound accompanied by some vibration detectable by placing a hand on the surface adjacent to the hammer strike. Various pieces of equipment have been developed to either roll or rub across the tile / render surface in an effort to speed up this rather cumbersome detection method but the principle of listening for hollow sounds remains the same.

Although hammer tapping is considered the most accurate and dependable means of identifying and confirming the size of delaminations it requires close physical contact with all surfaces to be tested. In the case of high rise construction this close inspection requirement can lead to the necessity for expensive (and potentially inconvenient) temporary access systems in the form of either platforms, gondola or scaffold. To address the time, cost and nuisance issues infrared thermography has been developed as a technique for rapidly and economically surveying building external wall surfaces to detect delaminated tiles / render.

The infrared thermo graphic technique works by using infrared emissions to very accurately measure the surface temperature of the wall. Differences in surface temperature give an indication of possible subsurface delamination defects as a delamination will cause a built-up of surface temperature as a result of the disconnection causing a reduction in the efficiency of heat dissipation from the surface to the structure into the building. Significant operator skill is required to interpret the photographs produced in order not to be mislead by shadow and sun light effects, internal air conditioning or the heat from other building services, etc. It is recommended that infrared thermography is completed together with some limited hammer tapping to calibrate and confirm the accuracy of the thermo scans produced.

An emerging technology for detection of delaminated tiles / render and currently the subject of research and development in Hong Kong is Shearography. The technique is currently not fully developed and not commercially available. The technique works by using a laser interferometric method developed originally for full-field observation of surface strains of components. Flaws within the sample being inspected usually induce strain concentrations around them, and shearography can be employed to detect those flaws. The device being researched in Hong Kong is essentially a camera system on a wheeled carrier that needs to be run over the surface of a wall to give an indication of possible sub surface defects. The technique could conceivably be incorporated into a robotic devise to inspect the wall surface automatically. No further information is presently available (outside of the confidential research studies) on the application of shearography to the detection of external wall tile / render delaminations.

Adhesion strength testing is used to confirm the adhesion strength of currently bonded tiles / render and is necessary in the consideration of whether or not to retain existing tiles / render as part of the chosen repair system.

Essentially adhesion strength testing is completed as follows:

Coring through the external wall tiles / render and a nominal 5mm or so into the substrate concrete. Typically the core diameter will be 50mm but diameters of 20 to 75mm are used by different types of testers.

The cut core remains in situ i.e. it is not removed from the core hole with the various layers remaining bonded to each other and the substrate. If the core detaches during coring, this is an indication of either inappropriate coring practice or low adhesion within tile / render laminate system.

A metal 'dolly' is attached to the end of the core sample by means of an epoxy adhesive. The dolly allows the attachment of an adhesion strength tester to 'pull out' the cored sample.

Once the epoxy on the dolly has cured an adhesion strength tester is attached to the dolly and used to pull out the sample until failure.

The load at failure is recorded and divided by the cross section area of the core to give the test result in MPa.

Cored adhesion strength testing (as described above) is the most common form of adhesion strength testing for external wall tiles / render although this is sometimes varied to saw cut through the tiles / render with the use of a square dolly.

After completion of the adhesion strength testing, the recovered core samples can be used to visually access the construction of the tile / render system. Useful information can be obtained on the thickness of the render (necessary to decide repair method e.g. pinning), number of render layers, quality and compaction of render material, other construction anomalies.

With respect to checking the safety condition of external wall tiles / render; visual survey, delamination testing and adhesion strength testing are normally sufficient. However, if additional information is required on the materials used (helpful in determining the cause of failure and the potential for further deterioration and future failure).

Suitable testing may include:

- Aggregate to cement ratio testing for renders and tile bedding materials
- Polymer detection for render and tile bedding material to detect the presence of organic matter within the cementitious materials
- Petrography for cementitious materials to give information on constituents, possible cause of cracking, alkali silica reaction (ASR) potential, etc.

d) Repair / Remedial Works

There are a number of different repair systems that can be selected for the repair of defective external wall tile / render systems and the choice of repair system will depend on a number of factors including; condition of the existing installation, intended building life, cost and owners preference. It is possible that more than one repair system could be used in combination to achieve the required results in the most efficient manner e.g. a combination of breakout and pinning repairs with either an over coating or over cladding solution.

7.2 BENCHMARK BUILDING HEIGHTS

Effect of Building Height

Consideration was given in this consultancy to whether or not recommendations should be given on restricting the maximum height of buildings where external render and tiling could be used. Examples of such restrictions exist in Singapore and the PRC but, it was considered unnecessary to promote similar restrictions in Hong Kong.

In terms of available materials and methods, there is no reason for designers not to select render and tile systems for the external wall finish of high rise construction. That said, consideration should be given at the design stage for how the installation of render and tiles would be realized on site. Sufficient provisions must be made in terms of access for the number of people and quantity of materials required, mixing, movement, curing and protection. Adequate provision for all these activities and matters should be allowed in the overall development programme. If all these matters are considered together with material selection and workmanship, acceptable external wall render and tile systems can be delivered.

For high rise construction in particular the risk and consequence of adhesion failure and spalling materials needs to be considered very carefully. Not only should the potential consequence of failure drive this process but other issues such as access to the external wall that may compromise maintenance inspections prior to an incident and repair works after an incident. BS 5385-2:2006 recommends the use of anchored reinforcement for render above first floor height and so consideration should be given to following this recommendation or deleting the requirement for the render intermediate substrate in the first place. If acceptably level concrete surfaces can be produced, the need for a render layer can be deleted and the tile adhesive directly applied to the concrete substrate. Even if tiles are applied directly to the concrete substrate movement provisions in the form of detailed and placed movement joints will still be required.

Maintenance issues will also need to be considered at the design stage, including the provision of adequate access for necessary inspection and maintenance works. Access in these cases would conventionally be provided by a permanently installed building maintenance unit (BMU) or 'gondola' installed on the roof that will be able to quickly and safely access all areas of the external wall. This type of access provision would be adequate for inspections and minor repairs but may not be suitable for the repair of extensive failures where scaffolding could be required.

Further investigation into the suitability of wet fixed external wall tiles for the external wall finishes on high rise construction is suggested. Such investigation should include mathematical/ computer based modelling of high rise render and tile systems. This work could then be used to establish benchmark height limits above which wet fixed external wall tiles would be undesirable or confirm that no height limit should be applied.

8 CONCLUSIONS

In the study, findings from previous studies, investigations, research and innovative measures were discussed and reviewed. Separate consultations were also arranged with an academic and a tile adhesive and render manufacturer to understand the extent of the problem and how these problems could be mitigated from their points of view.

Questionnaires were designed and distributed to stakeholders to obtain a broader and more objective feedback and collect their views on some technical aspects, social aspects, execution and related issues.

External wall tile / render systems are also used overseas and have suffered many of the same problems experienced in Hong Kong. Experience on external wall tile / render systems defects were obtained from Australia, Singapore and the United Kingdom. Differences and similarities of the particular overseas circumstances were reviewed and some of their mitigation and preventive measures to minimise incidences of defects were identified and discussed.

A technical investigation of the way render and tiles are applied to external walls was conducted, and site inspection and testing were performed to four selected construction site. Critical items of detailing and use of materials that could improve the installation of external wall tile / render systems were evaluated through laboratory testing of mock-up panels.

The research study was initiated partly as a result of detachment incidents involving wet fixed external wall tiles and rendering. The review stage research identified that detachment problems generally occurred at the adhesive interfaces (render to concrete, tile adhesive to render and tile to tile adhesive) rather than cohesively within material layers and thus the focus of the testing conducted after the review stage was on adhesion values. In particular, the bond between the render and concrete was scrutinised as this was identified through the review and stakeholder consultation process as the most common failure location and was confirmed by the testing to be the weakest bond, particularly when ready mixed mortar was used. In order to ensure that adequate adhesion is obtained at the interfaces, proprietary render materials incorporating polymer emulsions to improve adhesion should be used, particularly on high rise construction together with appropriate workmanship and verification testing.

The use of metal and other formwork systems that produce smooth, dense surfaces reduces the effectiveness of hydraulic mortar bonding which requires a rough open texture surface to achieve acceptable bonding. These surfaces require the adhesive action of polymer emulsions incorporated in the render to achieve acceptable adhesion together with acceptable workmanship.

In order to maintain the bond strength achieved during construction (by the use of appropriate materials and workmanship) movement joints shall be provided to accommodate anticipated movements. Weather protection shall also be considered to reduce the effect of moisture or other contamination affecting the various adhesion interfaces (e.g. by grouting tile joints and be sealing movement joints and free edges).

Design and Construction Guidelines (issued separately) on installation of external wall tiles / render for all industry stakeholders according to the review and investigation results will be compiled. The guidelines will be targeted to all industry stakeholders and prepared in an easily comprehensible format. The guidelines form a major output of this research and should be effectively disseminated to interested industry stakeholders including owners, developers, design and construction professionals, operatives and building management/ maintenance professionals for information, guidance and use.

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Acknowledgements

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Table 9 Cross reference between Reference for Design, Construction and Maintenance of Wet Fixing of External Wall Tiles and Rendering and the Study Report

Reference for Design, Construction and Maintenance of Wet Fixing of External Wall Tiles and Rendering		**Study Report**
Section Ref:	**Description**	**Section Ref:**
1	**Introduction**	**1**
2	**Scope and recommendations on use**	**N/a**
3	**Commonly available materials and selection guidelines**	**3.1, 3.2, 3.3, 4, 6, 7.1, 8**
3.1	Materials selection	6
3.2	Concrete substrate	3.3.2 a), 7.1.2 c)
3.3	Render	3.3.2 d), o), p), 7.1.2 d)
3.4	Tile adhesive	3.3.2 e) to l), 7.1.2 e)
3.5	Tile	7.1.2 e)
3.6	Tile grout	7.1.2 f)
4	**Design and specification of external wall tile adhesive and render systems**	**3.2.1, 3.2.6, 3.3.1, 4, 5, 6.2, 7.1.1, 8**
4.1	Render and tile systems	3.3.1, 3.3.2
4.2	Movement joints	3.3.2 n), 7.1.1
4.3	Testing and acceptance criteria	3.2.6, 6.2.2
4.4	Trial installations	6.2
5	**Workmanship and site organisation/ management guidelines**	**3.1, 3.2.2, 3.2.5, 3.3.2, 3.4, 5, 7.1.2, 7.2, 8**
5.1	Best practice guidance	3.3.2, 7.1.2
5.2	Supervision and training	3.4.2
5.3	Site organisation and management	3.1, 7.2
5.4	Concrete substrate preparation	7.1.2 c)
5.5	Render application	7.1.2 d)
5.6	Application of tile adhesive and tiles	7.1.2 e)
5.7	Joint grouting	7.1.2 f)
5.8	Acceptance of completed tiling	N/a (acceptance tests could be

		trialled)
5.9	Effect of building height	7.1.2 b), 7.2
6	**Site quality control testing and checking**	**3.3, 4.2, 4.3, 4.4, 6.2, 8**
6.1	Types of tests	3.3.3 c), 4.3
6.2	Testing or checking frequency	N/a (research on statistical analysis of testing frequency could be considered)
6.3	Assessment of results	4.4
6.4	Action on results	N/a
7	**Practical guidance for inspection and maintenance after construction to minimise tile debonding incidents**	**3.2.3, 3.3.3, 7.1.3, 7.2, 8**
7.1	Design for inspection and maintenance	7.1.3 a), 7.2
7.2	Provision of access	7.1.3 b), 7.2
7.3	Maintenance inspections and testing	7.1.3 c)
7.4	Repair/ remedial works	3.2.3, 3.3.3 b)
8	**References**	**9**