Pool Tiling Failure Report

Devonport Splash Aquatic Centre

HYDRAUTECH DESIGNS

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CONSULTING ENGINEERS

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HYDRAUTECH DESIGNS

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1 INTRODUCTION

Hydrautech Designs has been engaged by the Devonport City Council (Council) to prepare a Pool Tiling Failure Report (the report) relating to pool tiling failures at Devonport Splash Aquatic Centre (the centre).

The purpose of this report is to provide our professional opinion relating to the nature of tiling failures at the centre and to provide our advice concerning the proposed method of tiling rectification as proposed by Council.

This report is issued Without Prejudice. Our company has no prior history with the centre and we have no interest in supporting any party on this matter. This advice is based on our observations made on site and our expertise in Aquatic Engineering. Our company has provided Aquatic Engineering design (pool structures, pool water treatment, pool finishes / tiling and pool fixtures / metalwork items) for many aquatic facilities comparable to Devonport Splash Aquatic Centre.

2 POOL FACILITIES

The centre features the following pools;

- Indoor 25m pool.
- Indoor combined Leisure / Learn to Swim and Toddler pool.
- Outdoor 50m pool (not part of this report).
- Outdoor Wading pool (not part of this report).
- Outdoor Splash Pad (not part of this report).
- Outdoor Water Slides (not part of this report).

3 SITE OBSERVATIONS

Ross Weight c/- Hydrautech Designs attended site on August 11, 2023.

At the time of inspection, almost all of the floor and wall tiles in the 25m pool had been removed with only tiles above pool water level remaining. Tiles remain at the pool steps and ramp although tiles on the ramp walls have delaminated in sections. Pool tiles have been removed by Council in preparation for planned retiling works.

Tiles in the Leisure pool were intact except for a nominal 2m2 area on the floor of the pool at the deepest point as indicated by the images below.

25m pool. Only above water tiles remaining.

25m pool. Remaining step tiles.

25m pool. Headwall tiles removed.

25m pool. Typical below water tiles removed.

25m pool. Typical damaged edge tiles.

25m pool. Ramp section with failed wall tiles.

25m pool. Typical wall section.

25m pool. Typical wall section.

25m pool. Typical adhesive residue with notches.

25m pool. Typical adhesive residue.

Leisure pool. Tiles missing on base at near wall.

Leisure pool. Toddlers zone.

4 KNOWN CONTRIBUTING FACTORS TO POOL TILING FAILURES

Instances of pool tiling failures have been observed at other aquatic facilities over recent years which has resulted in extensive investigation into this issue.

Hydrautech Designs Pty Ltd has invested significant resources including scientific research, laboratory testing, field testing and data acquisition to fully understand pool tiling failures in the commercial aquatic industry and the causes of these failures.

The exact mode of pool tiling failure often cannot be identified as it is likely that a number of factors may contribute to tiling and other failures experienced at aquatic facilities.

Key factors that may contribute to pool tiling failure include;

- Installation not in accordance with the applicable Australian Standards.
- Not understanding the full extent of the applicable Australian Standards as they apply to swimming pool installations, especially requirements specific to the thickness of concrete elements and concrete shrinkage.
- Not understanding and/or complying with the manufacturer's instructions applicable to pool tiling adhesives and grouts applicable to swimming pool installations.
- Not understanding and/or accommodating movement of the substrate (surface accepting tiles) including the manufacturer's requirements for a stable substrate without movement.
- Failure to adequately inspect and prepare the surface of the substrate in preparation for pool tiling.
- Failure to adequately apply pool tiling adhesives and grouts in accordance with manufacturer's instructions.
- Failure to use and apply compatible materials designed specifically for swimming pool applications.
- Not understanding how the thickness of concrete elements can affect the extent and duration of dry shrinkage of the swimming pool structure (floor slabs and walls).
- Not understanding the importance of climatic conditions applicable to the installation, namely periods of wet, humid and cold conditions during the curing and drying periods.
- Not understanding the importance of keeping concrete elements forming the swimming pool construction (floor slabs and walls) dry after the curing period to promote shrinkage to design limits prior to applying the pool tiles.
- Not understanding the importance of keeping concrete elements dry during the tiling installation for outdoor pools (not tiling in wet conditions).

- Failure of the design and/or contract documents having jurisdiction over the work to adequately provide instruction and/or detail the items listed above as they apply specifically to the designed project.

4.1 CONCRETE SHRINKAGE AND MOVEMENT

Concrete structures shrink during and after curing. Australian Standards that provide guidance and instruction applicable to concrete structures including liquid retaining structures (swimming pools) detail how concrete shrinkage must be understood and considered for the design of concrete structures.

Concrete shrinkage occurs as water leaves the structure throughout the curing process. Excessive concrete shrinkage can cause shear stress at the connection between the concrete structure and the tiled surface. Other factors including creep under loads, thermal movement and hydrostatic pressures also contribute to pool structure movement.

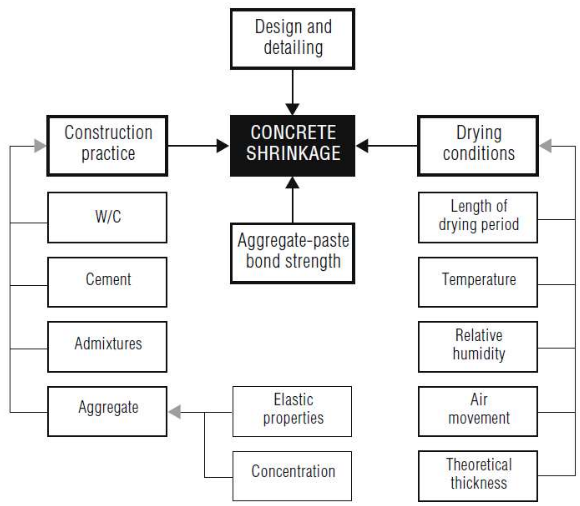
Pool tiles are inert and dimensionally stable. Pool tiles and grouts offer virtually no movement in themselves when applied to the concrete pool surface. Problems can arise when the concrete structure below the tiles shrinks to a point where the shear stresses exceed the bond strength of the tile adhesive. It is important to understand that pool tiling adhesives are capable of providing high tensile (pull-off) strengths, however shrinkage of the substrate applies lateral shear (sideways) stress on the pool tiling adhesive well beyond design limits of any tile adhesive product.

In order to minimise the effect of shrinkage of the concrete pool shell, it is important to allow the concrete structure to fully cure and shrink before applying the tiled surface.

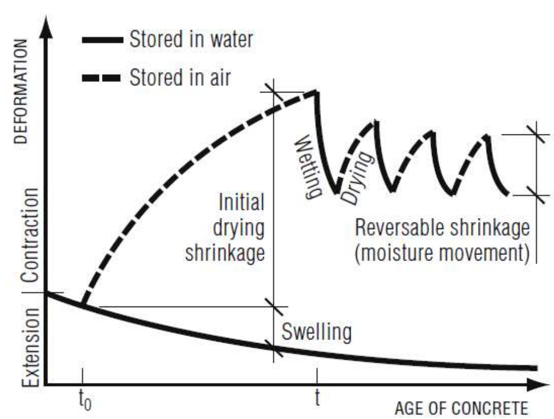
Shrinkage of concrete occurs by moisture leaving the concrete as it dries. In order to facilitate the drying and therefore the shrinkage of the concrete structure, it is important to allow the pool shell to dry after the curing period. Concrete must be hydrated in order to cure correctly however after the curing period has been reached, it is important to dry the concrete to induce the shrinkage to stabilise the concrete structure prior to the application of any cladding system (tiles).

In order to dry the concrete adequately, the pool structure must be kept dry with standing water in the pool base removed throughout the drying period. Water will not leave the structure (to dry and shrink it) when the pool is left to fill with water. It is important to understand that curing and drying are not the same; curing can occur when wet (or underwater), however drying can only occur in the absence of water or extreme humidity.

Drying concrete adequately can be problematic if the pool is being constructed as a part of a large aquatic facility which may be subject to time constraints (for the completion of the overall building project). It may also be problematic to keep the pool dry if it is built before the roof of the building is completed.



Contributing Factors to Concrete Shrinkage.



The Process of Initial Drying Shrinkage followed by Reversable Shrinkage.

4.2 LABORATORY TESTING Vs SITE CONDITIONS

For estimating the design shrinkage strain of concrete, AS 3600 provides the option of a theoretical calculation method or the AS1012.13 (10) drying shrinkage test method. This test serves to assess the accelerated drying shrinkage characteristic of a concrete mix design, normally determined at 56 days.

The method involves preparation of three 75mm x 75mm x 280mm specimens, placing them in a curing tank under standard moist curing conditions for the first 7 days, taking an initial length measurement and then placing the specimens in a drying room, maintained at 23°C and 50% relative humidity.

Measurements are taken again at 14, 21, 28 and 56 days after the initial reading. Specimens are unrestrained and free to shrink. The drying shrinkage of the specimen is generally expressed in microstrain and is determined by taking the average reduction in length of the specimens, dividing it by the original effective length and multiplying by 10^6. For example, a total shrinkage of 650 microstrain represents a reduction in length of 0.65mm per 1 metre.

It is important to understand the 56-day concrete shrinkage test result. A common misconception is that the AS1012.13 drying shrinkage test indicates the value of final concrete shrinkage experienced by the concrete element (in-situ) and that all the shrinkage occurs within 56 days. This is incorrect. While the drying shrinkage test can help distinguish between a good quality, carefully designed concrete mix, the test results are not representative of the actual volume change of the in-situ concrete element produced from the same concrete mix.

The difference is predominantly due to the test specimens having been carefully prepared for testing, they have a high surface area to volume ratio, they are subject to a very dry and constant 50% relative humidity and they are not subject to external loads or external restraint from shrinkage due to steel reinforcement or adjoining elements.

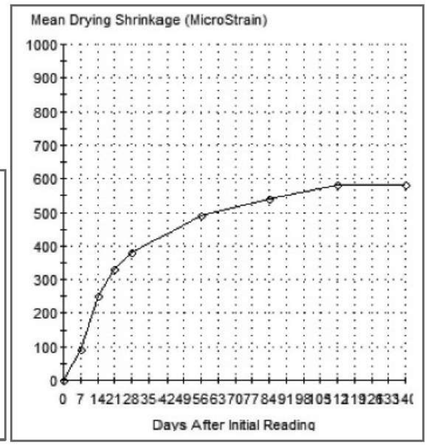
Concrete in the in-situ element is a thicker section, it will invariably be subject to fluctuating temperature and humidity conditions and may be subject to wet weather which may significantly delay the rate of shrinkage development. It is technically incorrect to take the theoretical AS1012.13 drying shrinkage test result and apply the rate of shrinkage to the in-situ concrete element.

It is also incorrect to assume that the shrinkage will occur within any given timeframe given that it depends greatly on the concrete element thickness and the environmental / climatic conditions.

Typical AS1012.13 concrete drying shrinkage test data for a 40MPa pool concrete mix is shown in Figure 1 below. The drying shrinkage strain can be seen to plateau beyond 112 days for the test specimen in this case. For the in-situ concrete for which drying conditions are likely to be less than ideal and the member thickness greater, it may take significantly longer for the drying shrinkage to plateau.

Figure 1 – Typical concrete drying shrinkage test data for a typical 40MPa concrete mix for a pool application

Drying Period (days)	Test Date	Drying Shrinkage (MicroStrain)			
		Specimen S6013A	Specimen S6013-B	Specimen S6013-C	Average
7	23/03/2016	84	80	108	90
14	30/03/2016	284	220	248	250
21	6/04/2016	348	332	308	330
28	13/04/2016	400	392	356	380
56	11/05/2016	496	500	464	490
84	8/06/2016	552	552	520	540
112	6/07/2016	592	596	560	580
140	3/08/2016	596	564	568	580
168	31/08/2016				
364	15/03/2017				



4.3 WATER BALANCE

An unstable pool water balance can contribute to pool tiling failures.

In nature, water comprises many compounds in addition to its hydrogen and oxygen structure. Water attracts a balance of minerals, salts and metals (among others) from its environment to achieve a natural balance in nature which needs to be understood from a pool water management perspective.

For example, Tasmania has soft water, having low levels of calcium and magnesium, being the primary constituents of hard water. When soft water comes in contact with surfaces that contain elements that can increase the hardness of the water (primarily calcium), the soft water may leach these elements from surfaces that it contacts to reach the natural balance. Soft water in pools has caused failures with tile grouts that contain calcium compounds as a binding agent. If the calcium is leached out of the tile grout, the grout can be compromised which may further lead to tiling failures.

Tasmania's average water hardness is approximately 23 mg/L ranging from 11 mg/L (minimum) to 38 mg/L (maximum). Pool water quality standards prescribe a minimum water hardness value of 100 mg/L with an upper limit of 500 mg/L.

In order to achieve minimum hardness levels, Calcium Chloride must be added to pool water to increase the water hardness levels to an acceptable and complaint range.

The concentration of Total Dissolved Solids (TDS) in pool water can also be damaging to the pool surfaces. The sodium base of Sodium Hypochlorite (liquid chlorine) contributes to the TDS concentration in the swimming pool water. High levels of TDS or level of salts in the pool water also contributes to the corrosion potential of pool water.

4.4 CARBON DIOXIDE Vs HYDROCHLORIC ACID Vs SODIUM BISULPHATE

Acid is required as a part of pool water treatment to maintain pH levels. The most prevalent forms of acid used for swimming pool applications are carbon dioxide gas (forming carbonic acid in water) and hydrochloric acid (liquid). These chemicals are preferred as they provide pH correction without imparting undesirable chemical reactions or by-products to the pool water.

Sodium bisulphate (granular) may also be used for swimming pool applications and offers some advantages with respect to handling the raw product, however sodium bisulphate contributes sulphates to the pool water and cannot be used for tiled swimming pools if sulphate concentrations exceed 300 ppm (parts per million). High sulphate levels react with tiling grouts and erode the tiling materials.

AS 3958.2 Section 5.11 specifies that sulphate concentrations of water in swimming pools should not exceed 300 ppm.

The use of sodium bisulphate for swimming pool applications is not recommended as pool water testing required by regulation does not include testing for sulphates which can lead to concentrations exceeding upper limits if not detected by routine testing.

If sodium bisulphate is used as a part of the permanent pool chemical dosing system, periodic laboratory testing must be undertaken to ensure that the maximum concentration of 300 ppm is not exceeded.

5 AUSTRALIAN STANDARDS

The applicable Australian Standard for ceramic tiles including pool tiling is AS 3958 Parts 1 and 2.
AS 3958.1 - Ceramic tiles Part 1: Guide to the installation of ceramic tiles.
AS 3958.2 - Ceramic tiles Part 2: Guide to the selection of a ceramic tiling system.

Both parts of the standard identify requirements and the importance of concrete shrinkage.

AS 3958.1, Section 4.3 - CONCRETE FLOORS details the requirements for tiling where concrete floors are to be used as the background for tiling. This section refers to Table 4.3 for the requirements of concrete floor preparation including the minimum drying time of concrete.

TABLE 4.3
CONCRETE FLOOR PREPARATION

Fixing method		Applicability of finish				Minimum drying time of concrete	Maximum variation in plane of concrete*
Fixative	System	Screed	Wood float or broom	Power float	Steel trowel		
Mortar	In situ underlay	Yes	Yes	Yes	Yes	4 weeks	5 mm in 3 m
	Separating layer	Yes	Yes	Yes	Yes	4 weeks	5 mm in 3 m
	Sand/cement mortar bed	Yes	Yes	No	No	6 weeks	20 mm in 3 m
Adhesive	Thick-bed	Yes	Yes	Yes	No†	6 weeks	10 mm in 3 m
	Thin-bed	Yes	Yes	Yes	No†	6 weeks	5 mm in 3 m
	In situ underlays‡	Yes	Yes	Yes	No†	4 weeks	5 mm in 3 m

* Unless concrete surface is prepared in accordance with adhesive manufacturer's requirements.
† Surface preparation may make this surface satisfactory.
‡ Refer to manufacturer's instructions for installation.

AS 3958.1 Table 4.3 specifies a minimum concrete drying time of 6 weeks / 42 days for both thick-bed and thin-bed adhesives as applicable to pool tiling installations.

AS 3958.1 Table E1 provides further reference to the drying requirements, stating that the minimum time intervals between successive stages in tiling is based on concrete effective thickness of 150mm at 23°C and 50% relative humidity.

TABLE E1

MINIMUM TIME INTERVALS BETWEEN SUCCESSIVE STAGES IN TILING

Mosaic (mesh-backed)	Mosaic (paper-faced)	Ceramic tile	Membrane* (liquid applied)	Gunite (sprayed concrete)	Stages			
					1† week	2 weeks	3 days	4 weeks
✓					6	0	1	1
	✓				6	0	N/A	1
		✓			6	1	1	1
		✓	✓		6	1*	1	1
		✓		✓	6‡	1	1	1
✓				✓	6‡	0	1	1
	✓			✓	6‡	0	N/A	1
✓			✓		6*	0	1	1
	✓		✓		6*	0	N/A	1

LEGEND:

* Moisture meter reading of <15% required before membrane applied.

† Assumes concrete effective thickness of approximately 150 mm (Table 4.2) at 23°C temperature 50% RH. The drying time required may increase with increased thickness, increased RH and decreased temperature.

‡ Cement polymer scratch coat (1:1:1) before rendering.

NOTES:

1 Where there is turbulent agitation of the water, the grout will require superior erosion resistance.

2 For mineral content water, a membrane may be required.

3 Based on continuous air-drying.

AS 3958.1 provides numerous references regarding to the relationship between drying times and environmental conditions, for example "a longer period may be necessary in wet weather" (Section 4.3.2).

AS 3958.1 imparts responsibility to the designer for project specific conditions including *"the designer should make known to the tiling contractor any structural or environmental conditions such as excessive deflection or the likelihood of excessive or delayed shrinkage onset of the substrate"* (Section 1.1)

AS 3958.2 Table 4.2 specifies rates of concrete shrinkage according to concrete element thickness. This provides a direct correlation between the thickness of concrete and the time required for dry shrinkage to occur.

TABLE 4.2
RATE OF SHRINKAGE OF CONCRETE

Effective thickness* of element	Period			
	14 days	28 days	3 months	1 year
mm	%	%	%	%
100	20	40	60	80
200	15	25	45	70
400	10	15	30	50

* Effective thickness is twice the volume of the concrete divided by the exposed surface area.

Both parts of AS 3958 make numerous references to the importance of understanding how the thickness of the concrete and environmental conditions have a direct impact on concrete shrinkage and the suitability of the substrate for tiling.

Although not applicable to Australia, the German Standard, DIN 18157, specifies a minimum concrete age of 6 months prior to tiling. The German Standard needs to cater for the lower average air temperatures prevalent in most of Europe (which limits the drying process) however the extended period of 6 months provides an indication of the importance to allow sufficient time for the concrete to dry and shrink prior to tiling the pool.

6 SPECIFIED PROJECT REQUIREMENTS

Documents provided by Council for reference to the initial design of the project include specifications prepared by David Powick and Associates Pty Ltd (DPA) for the aquatic scope of work including pool tiling.

The DPA specification prepared for the pool tiling scope of work includes the following applicable requirements;

- 40 MPa concrete specified for pool structures with a maximum dry shrinkage of 600 microstrain at 56 days.
- Concrete finishes specified as Class 2 suitable for direct application of tiling adhesives.
- Testing for Watertightness – specifies “the minimum age of the concrete in the structure under test must be 28 days before any filling with water is commenced”.
- Laying of Tiles – specifies “concrete must be a minimum of 42 days old before any render or tiling works”.
- Tiling adhesives specified are PCI Nanolight, PCI Durafug NT grout and PCI Durapox NT epoxy grout.
- A pool membrane is not specified.

6.1 AUSTRALIAN STANDARDS Vs SPECIFIED PROJECT REQUIREMENTS

If we accept the 42 day drying time requirement of AS 3958.1, irrespective of the concrete element thickness, the following timing would apply in accordance with the standard;

Day 1 - completion of concrete structure.
Day 28 – completion of curing period.
Day 29 – commencement of hydrostatic testing.
Day 40 – completion of hydrostatic testing.
Day 41 – commencement of 42 day drying period.
Day 83 – completion of drying period.
Day 84 – earliest commencement of tiling.

The project documents prepared by DPA specify that "concrete must be a minimum of 42 days old before any render or tiling works".

It is important to understand the distinction between ageing, curing and drying.

- Ageing refers to a constant passing of time and applies to all durations including curing and drying.
- Curing refers to the time required for the concrete to achieve its design strength and can occur in either wet or dry conditions.
- Drying refers to the time required for drying and can only occur in dry conditions.

On this basis, considering the specified "age" of at least 42 days, it would be reasonable for the builder and tiling contractor to allow for the following durations in accordance with the specified requirements;

Day 1 - completion of concrete structure.
Day 28 – completion of curing period.
Day 29 – commencement of hydrostatic testing.
Day 40 – completion of hydrostatic testing.
Day 42 – specified concrete age achieved for commencement of tiling.

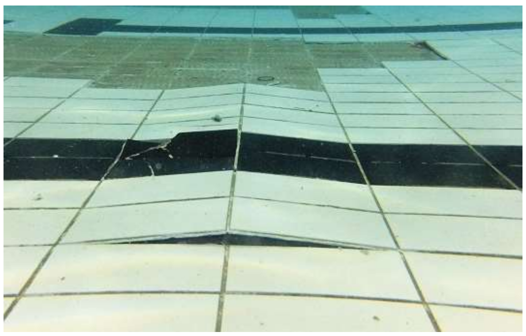
This comparison indicates that a period of 42 days of drying is lost between the requirements of the standard and the specified requirements.

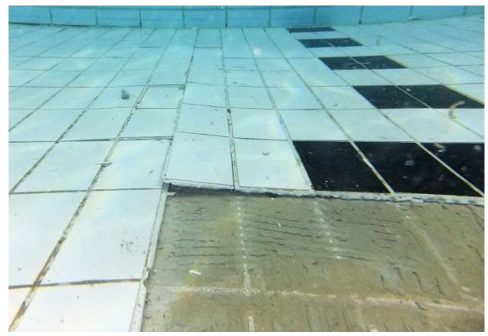
Drying means without water, whereas curing can occur with or without water (concrete will cure below water). This distinction is critical to understand and for the success of the tiling installation. If the concrete has fully cured and reached full strength, it may still not be suitable for tiling as it may not have shrunk as a result of drying.

If the curing period has been during a dry period, then the concrete may well have both cured and dried. If the curing period has been during a wet and/or humid period, the concrete may have cured, however may not have dried sufficiently for concrete shrinkage to occur. This exact situation is referenced throughout the applicable standards, that is the time allowed for concrete shrinkage to occur to an acceptable level will vary according to the environmental conditions.

7 MODE OF POOL TILING FAILURE

It is important to understand the mode of tiling failure. As the tiles delaminate from the substrate, they pitch upwards often forming a gable roof type shape as shown below.



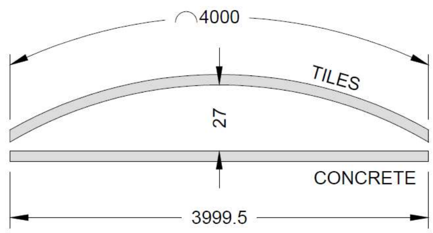


Often tiles can delaminate in sheets, forming a domed layer of tiles clearly suspended above the substrate. In these circumstances, the delaminated tiles cannot be repositioned or reinserted back into their original position (they don't fit, they're too big). This indicates that the substrate layer has shrunk to a size smaller than the original size when the tiles were initially adhered to the substrate. This mode of failure clearly indicates concrete shrinkage.

Consider this; the tiling adhesive is irrelevant in this mode of failure. If we were to place tiles onto the floor of a pool without adhesive, then fill the pool with many tons of water, the tiles don't want to lift from the floor, they certainly don't want to push together and pitch up from the pool floor.
The tiles don't want to push together and crush themselves; this is not an issue of tile adhesive, this is the result of the pool substrate shrinking and compressing the tiles to the point of failure.

If the tiling adhesive was a contributing factor to tiling failures, we would expect to observe failures on the pool walls more so than on the floors as the wall tiles are subject to gravitational forces whereas gravitational forces applied to the floor tiles are arrested by the pool base. In practice we tend to observe a higher occurrence of failures on the pool base rather than on the pool walls, although failures can occur on both surfaces in some instances.

In order to appreciate the affect that a very small movement of the substrate has on the tiling layer, consider this; pool tiles installed in a 4m x 4m sheet between tiling expansion joints will undergo a vertical deflection of 27mm if the concrete substrate shrinks only 0.5mm over the 4m distance. No adhesive will resist this deflection in either tensile or shear.



Example of pool floor tile delamination.

Example of concrete shrinkage crack not present before tiling, now present below row of failed pool tiles

7.1 THERMAL EXPANSION AND FILLING RATES

Concrete will expand according to temperature changes. Consideration must be given to swimming pool applications where a tiled pool structure (tiled at ambient temperatures) will be filled with water and heated.

In practice, thermal expansion is less critical in terms of stresses applied to pool tiling. Expansion does not apply the compressive forces applicable to concrete shrinkage. Furthermore, the stresses applied are controlled by the requirements of the standard.

AS 3958.1 Section E2.12 specifies that pools should be heated (or cooled from operational temperature) at a rate not exceeding 0.25°C/hour. The water fill (or empty) rate should not exceed 750mm every 24 hours or 31.25mm/hour.

8 CONCLUSION

Based on our review of the original design documents, our understanding of tiling failures specific to swimming pools and our observations on site, we conclude that the tiling failures have occurred primarily as a result of insufficient preparation of the concrete structure prior to tiling.

Notch marks in the tiling adhesive are clearly visible in areas where tiles have failed. This indicates that the ridges of adhesive between the notches were not collapsed when bedding the tiles. This does not necessarily indicate that the 90% coverage as required for swimming pool tiles was not achieved, although total adhesion would be required at the ridges to achieve the 90% coverage requirement.

Not providing a membrane as a decoupling layer (not specified for the project) is also a contributing factor. Not having a decoupling membrane exposes the tile cladding layer directly to any movement of the substrate structure on account of concrete shrinkage as detailed in this report.

9 RECOMMENDATIONS

We understand that Council will be engaging contractor(s) to retile both indoor pools to rectify the current tiling failures.

We have been provided with the specifications prepared for the retiling work including the nominated tiling materials and procedures. The specification is well prepared and includes the necessary requirements to execute a successful pool tiling contract.

We provide our comments further to our review of the provided documents as follows;

- The tiling specification references the relevant standards and requires compliance with these standards as a part of the works.
- Back-buttering is specified for the application of the pool tiling adhesive. This requirement will add significant cost to the tiling contract sum on account of doubling the installation time. Although back-buttering provides a predicable coating method, it may be beneficial to specify a performance requirement for the application of adhesive, that is a minimum of 90% coverage and for adhesive notches to be collapsed. All tiles for swimming pool applications must be provided with minimum 90% adhesive coverage in accordance with AS3958.1.
- Given that the existing condition of the pools is directly connected to the scope of work, we'd recommend that a separate requirement be added stating that a full assessment on site is necessary for the contractor to satisfy themselves of the required extent of work for the new tiling, particularly the extent of work required to prepare the existing pool surfaces. This is particularly important for the render thicknesses that will be required to achieve the finished tolerances.
- With respect to the tiling tolerances, we would include a requirement for the wet edge tiles to match the existing water levels such that the pools can be returned to their existing water flow conditions.
- Consider deleting the 10,000PSI pressure requirement for the water blasting. The performance requirement for the water blasting has been sufficiently detailed, specifying a minimum pressure may be a problem if that pressure is too high for the existing surfaces.
- The requirement for a membrane is listed generally as a scope item in Section 1.0 and in further detail in Section 7.0, however Section 5.0 states "if waterproofing membrane is to be applied". The Section 5.0 reference should be deleted.
- Just a minor issue; all references to the 25m pool should be 25 metre, not 25 meter or can be simply 25m.
- The Metz products specified have been nominated to comply with the performance requirements including an adhesive test (this is a good inclusion).

Importantly, we would recommend that a period of 3 weeks be provided to keep the pools completely dry after draining, prior to the application of the new pool membrane. This time will allow for the existing pool structures to shrink and relieve internal stresses. Tiling preparation including removal of the existing tiles can occur during the 3 week period. The pool hall air temperature should be maintained during the drying time and throughout the new tiling work.