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Mortar Quality Assessment for an Iconic Building Repair in Sydney Australia

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ABSTRACT

Remedial work for an iconic building in Sydney, Australia is currently being carried out. Two façade mortars, capable of matching the current exposed quartz aggregate finish and achieving a 40 years design life, are required. In order to ensure the quality of the imported quartz aggregates for this project, test have been carried out for particle size distribution, density, wet/dry strength variation, sodium sulphate soundness and Los Angeles Abrasion value. The two mortar mixes employed for repair work (Form & Pour and Hand Applied mixes) were comprehensively assessed for mix workability, compressive strength in warm and cold conditions, drying shrinkage, bond strength and coefficient of thermal expansion. The mortar durability assessment included chloride resistance as per NT443 and NT492 specifications, electrical resistivity as per AASHTO TP95 requirements, together with accelerated carbonation and accelerated weathering for colour variation assessment. The chloride resistance and the accelerated carbonation data was further used for the service life prediction. The paper presents the results of the aggregates and mortar assessments. The mortar mixes properties are important to be taken into consideration for any other similar façade repair works.

Keywords: mortar durability, façade repair and rehabilitation, service life prediction.

1.0 INTRODUCTION

The MLC Centre building in Sydney was completed in 1977, being designed by Harry Seidler and Associates and constructed by Civil and Civic, while the internationally renowned engineer Pier Luigi Nervi was the structural consultant (Wikipedia MLC Centre).

The MLC Centre is a thriving hub in Sydney centre, offering office retail and open space in the Sydney CBD (Fig. 1). The main building is 244m high, having 67 floors and the tower was reported as the tallest reinforced concrete office building in the world on completion in 1977. It was Australia's tallest building from 1977-1985.

The concrete structure of the octagonal building contains:

- 8 reinforced concrete columns located around the exterior of the tower supporting the spandrel beams and the concrete floors.
- 8 reinforced concrete spandrel beams at each floor supporting the reinforced concrete floors slabs
- A central reinforced concrete core supporting the floor slabs.

Fig. 1. Photo of MLC building

The reinforced concrete columns and spandrel beams were cast in-situ using exposed aggregate finish reinforced concrete panels.

The façade of the tower consists almost entirely of 90 mm thick off-white exposed aggregate finished precast concrete column panels and spandrel panels with dark grey anodized aluminum window frames, grey-tinted tempered glass and deep marble veneered windowsills.

As part of the ongoing maintenance programs, and in order to preserve the building in its original form, remedial works has included cleaning of the existing concrete and repairing eroded and cracked concrete, with the scope to ensure the long-term preservation of the façade.

There are two repair mixes which were developed to make good the deteriorated precast panels. The Foreva Form and Pour (F&P) mix was the main material used on the column panels. The Foreva Hand Applied (H&A) mix was the main material used for patch repair of the spandrel panels, rendering of the podium column panels and for general patching purposes. Both mixes were initially assessed under laboratory conditions and further improved to meet the insitu requirements. The challenging task was the F&P mix for winter application where sufficient early compressive strength is required. The data presented blow refers to the performance of F&P mix in winter (cooler) conditions, including its plastic and hardened properties and durability performance.

2.0 EXPERIMENTAL PROGRAM AND RESULTS

The experiments carried out include:

- Quartz aggregate assessment.
- Plastic and hardened properties assessment, including workability, cyclic lower temperature curing, compressive strength gain, bond strength, and drying shrinkage.
- Durability performance assessment, including chlorides and sulphates content, water permeability, voids content, coefficient of thermal expansion, surface electrical resistivity, coefficient of chloride diffusion tests, accelerated carbonation test, accelerated weathering test.
- Discussion of service life estimation, considering potential carbonation induced and chloride induced corrosion.

2.1 Quartz Aggregate Testing

Bags of white quartz blend were randomly selected for the particle size distribution (PSD) assessment as per AS 1141.11.1 and the 75 µm with AS 1141.12. The PSD of the imported MLC Quartz blend is presented in Fig. 2 together with a graphical representation.

The PSD is very consistent and complies with specified envelope; including as low as 1% of 75 µm fraction, a sign of a clean aggregate. The quartz sand has its particle density of 2.63t/m^3 and very low water absorption at 0.4%, tested by AS 1141.6.1.

The sodium sulphate soundness test AS 1141.24 furnishes information helpful in judging the soundness of aggregate subject to weathering action. The total mass loss was very low at only 0.1%, indicating excellent weathering resistance.

The wet/dry strength by AS 1141.22 shows that this quartz aggregate has dry strength 184kN and the wet strength of 173kN. The wet/dry strength variation is very low at only 6%. The Los Angeles Abrasion loss by AS 1141.23 is 24%.

All above results show the good quality and high durability of quartz aggregates for this project.

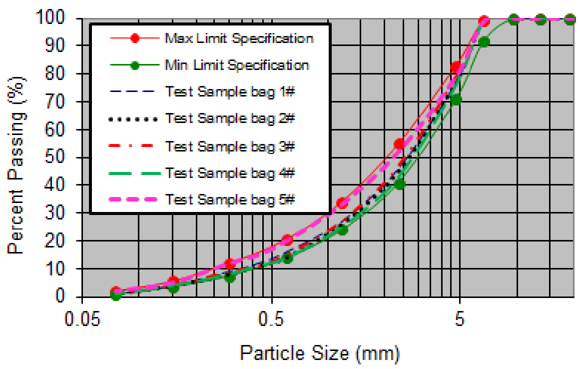

Fig. 2. Particle Size Distribution of Quartz sands

2.2 Plastic and Hardened Properties

In general, the Foreva F&P winter mix contained approximately 36% hydraulic binders, including ordinary Portland cement, calcium sulphoaluminate cement, gypsum and lime, blended with quartz sand, accelerator, super plasticiser and some polymers. The water binder ratio of the mix was 0.43. In fact, the mix proportion for 50 litres of mortar contains:

53.2 kg white quartz sand
43.5 kg binder and filler
15.0 kg water

Before mixing, all raw materials and tap water were pre-conditioned at 9°C for 24 hours. However, this F&P mix was mixed at a normal laboratory condition, 23±2°C and Relative Humidity (RH) of 50±5%. The mix has an excellent workability, with the slump of 280mm when tested according to AS 1012.3.1. The fresh density was 2200 kg/m^3 and air content 2.6% when tested as per AS 1012.5 and AS 1012.4.2, respectively.

This mix has sufficient working time. The initial setting time was 4 hours and final setting time was 5 hour and 10 minutes, tested as per AS 1012.18.

To assess the early compressive strength gain, the first 24 hours curing regime was carried out in a cyclic environmental chamber in order to simulate the cooler ambient condition in winter in Sydney. However, after 24 hours, all samples were wet cured in the saturated limewater at 23±2°C till testing ages.

- 7 hours at 9˚C
- 8 hours at 15˚C
- 9 hours at 9˚C

The compressive strength was determined using standard cylinders 100mm diameter and 200mm height as per AS 1012.9.

The individual strength results are presented below and the strength values are very consistent. The quicker strength gain even at a low temperature has guaranteed the normal operation in winter time.

- 24 hours: 19.0, 20.5, 19.5MPa
- 7 days: 28.5, 27.0, 27.0MPa
- 28 days: 44.5, 44.5, 43.0MPa
- 56 days: 49.0, 48.5, 47.5MPa

2.3 Bond Strength

Due to the nature of repair work to be carried out, bond strength as per AS 1012.24 was carried out. The fresh F&P mortar was applied on old concrete panel by the field operators in the same way as they worked on site. The substrate concrete was about 40MPa and half year old. The surface was prepared in the same way by the field operators. The prepared sample was air cured in the ambient air till age of 28 days for the bond test.

The bond strength values are 1.1, 1.5, 1.5, 1.2, and 1.5MPa with average of 1.36 MPa. The constant bond strength indicated the good operation quality of the field operators. The bond strength itself was higher than the required 0.8MPa, confirming the suitability of this mix as a non-structural repair material. In addition, the failure mode was through the interface of repairing mortar and the substrate, concluding that the bond of the Foreva Form & Pour winter mix is very good.

2.4 Drying Shrinkage

Dimension change is another concern for the repair material. When tested according to AS 1478.2 the results were well within the project requirements as follows:

- 7 days: 120 microstrains
- 14 days: 320 microstrains
- 21 days: 430 microstrains
- 28 days: 480 microstrains

2.5 Chloride and Sulphate Content

The results for total acid soluble chloride and sulphate which were tested as per AS 1012.20.1 were 0.094% and 2.61% by weight of concrete, or equivalent to approximately 1.8kg/m^3 of concrete and 7.2% by weight of hydraulic binder content, respectively. Both chloride and sulphate values are higher than the limits of reinforced concrete. Normal reinforcement for concrete bridge structures (RMS B80 specifications), where the chloride limit is less than 0.3kg/m^3 of concrete and maximum sulphate is 5% of cement. However, the chloride content 0.094% of concrete is still less than the corrosion threshold of chloride of 0.5% for SS316 stainless steel (Life-365™). Therefore, for the MLC maintenance project, stainless steel Φ6mm SS 316 reinforcing bars were used and would be appropriate.

2.6 Water Permeability and Permeable Voids

The apparent volume of permeable voids (VPV) was determined as per AS 1012.21 and the value was 11.9% at 28 days, demonstrating that the Foreva MLC Form & Pour winter mix performed satisfactorily, from permeability point of view, in comparison with the acceptable value in VicRoads 610, where the maximum VPV value is 14% for a 40 MPa concrete mix at age of 28 days.

Water permeability was determined at age of 28d as per EN 12390-8. The mean maximum depth of water penetration was 10.5mm. This is a very good result considering that 25-30mm maximum depth of penetration is allowed for concrete (RMS B82).

2.7 Chloride Migration and Diffusion Tests

The chloride migration and diffusion coefficient tests - Nordtest NT Build 492 and NT Build 443, now are extensively used to determine the chloride migration/diffusion coefficient of concrete and to estimate the service life of structures exposed to chloride rich environments. The RMS B80 specifications, also, prescribes NT Build 492 and NT Build 443 chloride test coefficient limits as a durability requirement in its B80 Concrete Work for Bridges specification.

Both NT492 and NT443 tests started when concrete was wet cured for 28 days. The migration coefficient by NT 492 test was 2.88E-12 and diffusion coefficient by NT443 was 1.66E-12 m^2/sec. Both values are well within Classification B2 limits in terms of NT Build 492 (<8.0E-12m^2/sec) and NT Build NT443 (<3.5E-12m^2/sec) and even meet requirements of Classification C limits in terms of NT Build 492 (<4.0E-12m^2/sec) and NT Build NT443 (<2.0E-12m^2/sec). As a result, the MLC Form and Pour winter mix is expected to have good durability performance.

2.8 Surface Electrical Resistivity

The surface electrical resistivity was performed by a four-point Wenner probe as per AASHTO TP 95. The measured value was 22.2 kohm-cm at 28 days, suggesting the low chloride ion penetration and would result in low corrosion rate, if any.

2.9 Coefficient of Thermal Expansion

The coefficient of thermal expansion (CTE) was carried out in accordance with AASHTO T36 method at age of 28 days. The average CTE was 12.4 micro-strain/°C. This value is higher than the existing concrete, 9.8 micro-strain/°C. On the other hand, it is expected to have a lower CTE with the passage of time thereby resulting in the repaired layer developing compatibility with the existing substrate concrete.

2.10 Accelerated Carbonation Test

The accelerated carbonation assessment was carried out considering local research work and field data in 1980's by CSIRO (Ho 1987) and also referring to research work at Dundee University (Dhir 1989).

The Environmental chamber for accelerated carbonation has set up CO_2 at 4%, temperature of 23˚C and relative humidity (RH) of 60%.

The 100mm mortar cubes were cast and wet cured for 28 days, and then air dry for 21 days at 23°C and 50%RH. During the air cured period, all faces except one face of each sample were coated with epoxy. The face free of coating has been exposed to CO_2 gas in the accelerated carbonation test. To simulate the insitu practice, a thin layer of hydrophobic silane was applied on the concrete surface, approximately 1.6 gram per 100x100mmm surface, assisting in improvement of durability and corrosion protection.

After exposure of 1, 4, 9 and 16 weeks, the depth of carbonation was measured by the traditional phenolphthalein method RILEM CPC-18 as presented in Fig. 3.

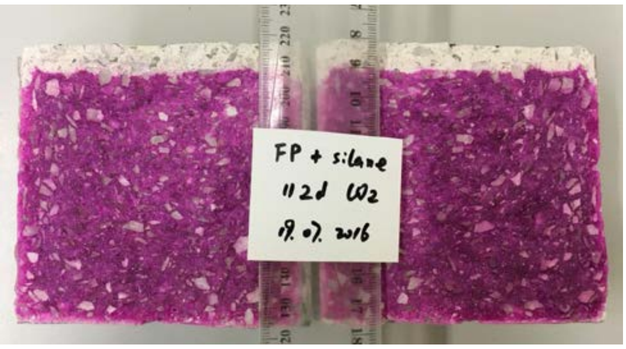

Fig. 3. Foreva MLC Form & Pour winter mix + Silane after 112 days CO_2 expose

Considering the previous research work, as above noted, the carbonation depth and exposure time generally follows the Fick's first law. The coefficient Ka can be calculated.

$$X = K_a \times \sqrt{t} \tag{1}$$

where, X: the carbonation depth, mm

Ka: the coefficient from the accelerated carbonation test, mm/week0.5,

t: the exposure time, week

Based on previously research work (Ho 1987 and Dhir 1989), the coefficient *Ka* from the current acceleration test (4% CO_2, 23°C, 60%RH) is approximately 7 times of the coefficient Kn at natural carbonation in laboratory conditions. For concrete in open air structures sheltered from rain (i.e. XC3 in EN standard) urban exposure, Neves (2013) reported the statistics of *Ka/Kn* =11.7±4.3 (mm/week$^{0.5}$), indicating the lower limit is about 7.4 times. Therefore, the ratio *Ka/Kn* =7 were used conservatively for the service life estimation due to carbonation induced corrosion. The results are presented in Table 1.

Table 1. Estimated service life due to carbonation

Concrete type	Coefficient mm/week$^{0.5}$		Cover depth (mm)	
	Ka	*Kn*	25	*20*
FP no silane	2.30	0.33	112	72
FP+silane	2.23	0.32	118	76

Therefore, assuming a good construction quality (consistent compressive strength, no voids and good concrete compaction, fully coated with silane), the service life is estimated at 76 years for the winter Form & Pour mix, exceeding the required service life of 40 years.

The benefit of application of silane was noted, reducing the *Ka* from 2.30 to 2.23mm/week$^{0.5}$. Furthermore, at the same exposure condition (4% CO_2, 23°C, 60%RH), a control concrete has *Ka* of 2.95mm/week$^{0.5}$. The control concrete has 330kg Portland cement, Water/Cement ratio of 0.55 and 28 days compressive strength 47.5MPa. This suggests the MLC Form & Pour winter mix would have better carbonation resistance when compared with a 40MPa concrete with Portland cement only in 1970s.

2.11 Chloride Induced Corrosion and Service Life Estimation

MLC building is located approximately 1km away from the surrounding ocean. By the exposure classifications in AS 3600, it would be a coastal zone B2 exposure. As a result, chloride induced corrosion is the major concern for the service life of this repaired work.

It is widely accepted that diffusion is the predominant process for chloride penetrating into the concrete structures exposed to marine environment. Therefore, using Fick's second law, the initiation period T_0 can be calculated. The propagation period T_1 was referred to the time when the corrosion reached an unacceptable level. The propagation time was adopted as about 6 years from Life-365™ model.

Different models using a range of software are being used in order to estimate the service life prediction.
Several concrete properties, as above discussed, and parameters in Table 2 were taken into consideration for estimated service life T_0+T_1.

Table 2. Concrete properties and parameters used

Items	values
Compressive strength at 28 days	44.0MPa
Yearly temperature in Sydney	26 ~ 8°C
Background chloride content	0.094%
Surfaces chloride deposition	0.5%
Chloride diffusion by NT 443	1.66E-12m^2/sec
Voids at 28 days	11.9%
Electrical resistivity at 28 days	22.2kΩ cm
Concrete cover	21mm
Diameter and type of reinforcement	6mm SS316

The estimated service of life of the MLC Foreva Form & Pour winter mix was 61 years, well above the project requirements of 40 years.

2.12 Accelerated Weathering Test

The appearance of MLC building is beautiful white quartz aggregate grains. The colour change is the aesthetic concern. Two combined programs were designed to simulate the possible environmental features, including (1) ultraviolet exposure and rainfall, and (2) temperature and humidity.

Although Ultraviolet (UV) light makes up only about 5% of sunlight, it is responsible for most of the photochemical damage to materials exposed outdoors. The mechanical surface wearing by rainfall, and subsequently drying, may contribute to the surface deterioration as well. Therefore, a combined testing program was designed with cyclic wet/dry together with UV exposure. One cycle taking 24 hours (hr) is equivalent to 41.6 days UV exposure.

---UV 17hr – cooling 1hr – wetting 5hr – drying 1hr--

In addition, the cyclic humidity and temperature change may influence the surface appearance variation over time. According to local meteorology information, the following testing program was used. Therefore, one-day test would simulate 12 days of natural exposure to temperature and humidity changes.

---38°C90%RH 1hr --- 38°C30%RH 1hr ----
12°C58%RH 1hr ---- 12°C90%RH 1hr ----

Foreva Form & Pour winter mix was prepared and two concrete panels were cast. The concrete surface was washed to expose the quartz aggregate grains. One panel was cured for 24 hours in a cold environment in the same chamber for early strength assessment, followed by air cure. Another panel was directly air cured at the ambient environment. Silane was applied afterwards. After 28 days curing, several 70 x70 x70mm cubes were prepared. In addition, one old concrete block with exposed aggregate finishing from existing façade was prepared for parallel tests.

Colour of each cubic sample was measured by Konica Minolta Chroma Meter CR 410 model before and after 355 days tests. Duration of 355 days in both weathering facilities is equivalent to approximately 40.1 years for sunlight and rain exposure, and about 11.5 years for temperature and humidity change exposure.

The colour change was assessed on the basis of Hunter Lab Scale interpretation. The calculated colour change – before and after 355 days exposure – is presented in Table 3.

Table 3. Colour change summary

Exposure	Initial cold curing	Initial air curing	Insitu samples
Control (sealed in the bag)	1.07	1.18	0.69
UV + cyclic wet/dry	3.34	2.11	1.20
Humidity+Temperature	1.87	2.26	1.17

All samples show some colour change by the readings from a colour meter, even the control ones sealed in the plastic bag. However, the colour change to naked eyes (half meter away) is so small that the appearance variation in practice would be negligible when it is looked from meters away.

3.0 CONCLUSIONS

The MLC Centre Tower in Sydney CBD was designed by the Australian architect Harry Seidler and constructed by Civil and Civic. Many aspects of the design and construction of the MLC Centre Tower were pioneering and in 1977. It was reported to be the tallest reinforced concrete office building in the world.

As part of the ongoing maintenance program to preserve the building in its original form, remedial work was carried out to ensure the long-term preservation of the façade using a combination of standard repair methods and a process known as Hybrid catholic protection.

For façade repair work one of the mortar mix used – Foreva MLC Form & Pour - winter mix has been comprehensively assessed in order to ensure that the building’s original façade is being maintained and the mortar properties were conforming to the project specification.

Extensive laboratory assessments of the Foreva MLC Form & Pour winter mix have demonstrated the suitability of the quartz aggregate, the plastic and hardened mortar properties, and durability performance in achieving the project requirements for the remediation work of the iconic MLC Centre Tower in Sydney CBD.

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