Pavement Flexural Fatigue Capacity, and the influence of Mix Charging Sequence

Justin Moss

Abstract

The durability of concrete pavements is greatly dictated by their capacity to resist fatigue induced by flexural stresses. Known to be a critical factor in fatigue behaviour is the quality (or deterioration under loading) of the bond between the cement paste and aggregate. This paper reports on lab and large-scale trial applications of a range of modified mix charging sequences in terms of their ability to improve the flexural fatigue life of concrete pavements, and also on conventional concrete plastic and hardened properties. Flexural fatigue resistance was assessed using the ASTM C1550 round panel loading test over a range of target failure loads, eg 10^2 to 10^6 cycles. Whilst source research was initially focussed on improved distribution of SCMs, this paper demonstrates that similar techniques significantly affect rheology, setting, strength and, in some cases, fatigue capacity and bond quality – all thought to be the result of a modified transition zone (between aggregate and mortar). Importantly, each modified charging sequence was selected or adapted on the basis that such new charging techniques, if shown to be beneficial, could be readily adapted to the common dry batch concrete plants already in use in readymix batching and on-site batching or mixing plants.

This study will show that, for a matched mix design, the RILEM method of batching improves the fatigue resistance (and life) of a typical Australian pavement quality concrete by 23% when compared with the conventional batching sequence presently used by premixed and typical on-site concrete batch plants.

Introduction

The durability of concrete pavements is greatly dictated by their capacity to resist flexural fatigue. Known to be a critical factor in fatigue behaviour is the quality or, more specifically, the deterioration (under loading) of the bond between the cement paste and aggregate (Murdoch 1960). Previous research has shown that fatigue specimens have fewer broken aggregate particles than statically loaded specimens

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(Bate 1956) indicating that bond quality is prominent in terms of ultimate pavement life .

This paper will report on a laboratory program and subsequent large-scale repeat load evaluation of four distinctly different concrete mix charging sequences. The candidate mixes have been drawn from Scandinavian and Japanese research (as well as RILEM committee reports) that document techniques for improved distribution of cement and SCMs. To ensure practical outcomes, each mix was selected on the basis that new charging techniques could be readily adapted to the common dry batch concrete plants (readymix and on-site).

The comparison of flexural fatigue resistance will ultimately be assessed in this paper using the results from ASTM C1550 round panel loading tests, however, smaller laboratory-scale mixes will also compare the selected charging sequences (using identical mix design) in terms of difference in plastic properties (workability, slump loss and setting time), traditional hardened properties (compressive strength, splitting strength, and third-point modulus of rupture), as well as hardened properties thought to be influenced by bond interface quality (eg, water permeability).

The large scale trial will involve the assessment of flexural fatigue capacity for each of two mixes of 30 no. 1200mm diameter ASTM C1550 specimens tested over a target failure range of 10^2 to 10^6 cycles at a loading frequency of 2Hz using servo controlled equipment.

Included in this paper is a qualitative assessment of differences in bond quality between alternative charging sequences assessed by a review of the failure zones in the ASTM C1550.

This paper will be divided into two parts (1) Process Selection and Laboratory Evaluation, and (2) Fatigue Testing. Part 1 will include a review of the four charging sequences evaluated and the physical test properties observed during their evaluation. Part 2 will review the large-scale preparation of specimens and their fatigue testing.

Research Significance

In a climate of increasing traffic, persistent economic pressures, unprecedented 'green' scrutiny on the use of materials with high embedded carbon levels (eg, cement), the minimisation of the use of virgin quarry materials, and record levels of concrete pavement construction, the Roads and Traffic Authority NSW (Australia) is looking for cost-efficient techniques to extend the service life of newly constructed concrete pavements.

A 5% to 10% increase in fatigue capacity, for negligible increase in costs arising from change in processes or material quantities, would have extended the current NSW concrete pavement asset by about 180 lane years or 2 years per lane kilometre. Such improvements could be applied in future pavement construction by a decrease in the use of cement (and thus 1.25MT of CO_2) or an extension of the service life of pavements, thus postponing demolition and reconstruction costs – the reality to which Australia has not yet been exposed in its 30 years of concrete pavement construction.

PART 1 – PROCESS SELECTION AND LABORATORY EVALUATION

Selection of Charging Sequences

Four variations of concrete batch charging sequences were to be assessed, including a control mix which would emulate the batching sequence of normal operations in concrete dry mix batch plants. Notably, for the Control mix, this required a deviation from the Australia Standard AS1012 for laboratory concrete mixing, in that 95% of the mix water needed to be added in advance of all other materials – whereas AS1012 requires the addition of aggregate components first. This change was seen as necessary in order to properly evaluate of differences between mix sequences.

Mixing Sequence 1 "Control" – This charging sequence most closely matches that of a standard Australian dry mix batching plant. It required precharging the mixing bowl with 95% of the target mix water and admixtures, following by the integrated addition of coarse and fine aggregate, cement, and fly ash. In practice the 5% remaining water would be added by the truck driver at the slump stand. In the laboratory, water is normally added after the bulk of the aggregate. A timeline based illustration of the Control sequence is shown in Figure 1.

Mixing Sequence 2 "Slurry" – This charging sequence required the preloading of all coarse and fine aggregates following by a separately prepared mix of slurry (cement and water). To maximise the fluidity of the slurry, fly ash was not included in the slurry and superplasticiser was blended gradually during mixing with a variable-speed helical mixing head. The addition of the slurry was anticipated to achieve an improved transition zone due to direct combination of the slurry with the aggregate that was not pre-flooded with water (as it is in the case of Control and in practice). A timeline based illustration of the Slurry sequence is shown in Figure 2.

Mixing Sequence 3 "RILEM" – This process was adapted from findings in research paper and journals published in Europe (RILEM 1981). It required all binders and coarse aggregates to be premixed briefly, before 80% of the anticipated water, the fine aggregate and then the remainder of the added water. Like the slurry sequence, this process was thought to achieve an improved aggregate-paste bond by more thoroughly and effectively coating the coarse aggregate with paste in advance of the addition of fine aggregate (which represented a much greater proportion of specific surface area) had an opportunity to demand wetting from the paste. A timeline based illustration of the RILEM sequence is shown in Figure 3. Also refer Figure 11.

Mixing Sequence 4 "Sand Enveloped Concrete" – The Sand Enveloped Concrete (SEC) sequence required the premixing of approximately half the water (0.24 by weight of cementitious materials) and the aggregates. Binder was then added and, after a period of thorough mixing, the remainder of the water. A timeline based illustration of the SEC sequence is shown in Figure 4.

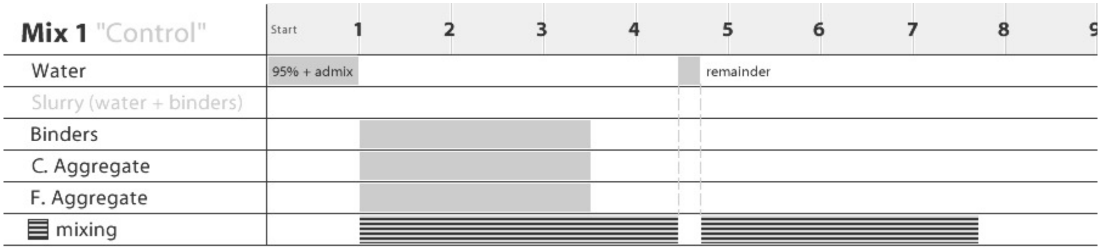

Figure 1 – Control sequence (timeline)

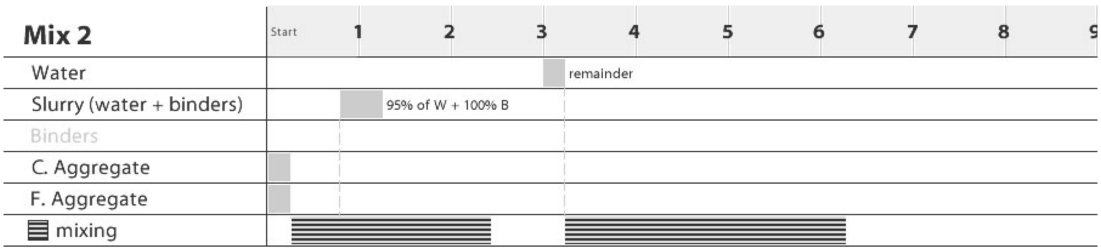

Figure 2 – Slurry sequence (timeline)

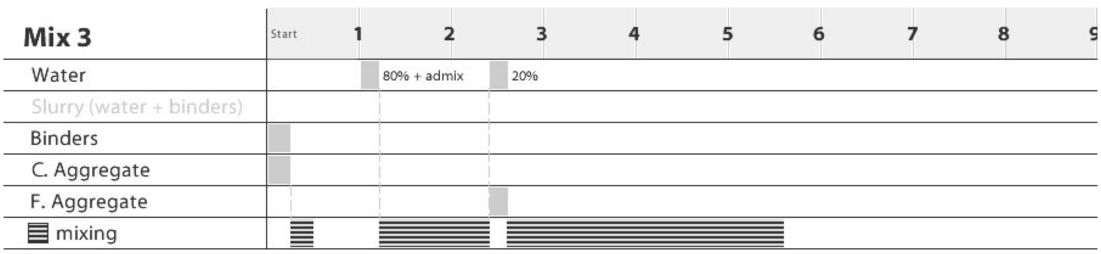

Figure 3 – RILEM sequence (timeline)

Figure 4 – SEC sequence (timeline)

Precision of Mixes and Conditions

As the net differences expected from this testing program were less than 10%, the consistency of the material and laboratory conditions, the execution of processes and storage of specimens were considered crucial to the outcome of the work. For this reason the following additional quality control measures were taken:

• laboratory was temperature controlled with 23±2ºC,
• all mixes were piloted in advance to evaluate timings and refine processes,
• the same lab staff in the same roles were used for all pilot and laboratory mixes,

• the final lab mixes were conducted on two subsequent days, and
• all aggregates were prepared in advance at constant moisture and temperature.

Aggregates were prepared to constant moisture by mixing large batches of each type in a pan mixer and adding water to bring each to a calculated saturated surface dry condition (SSD) with an additional extra amount of water (1% and 0.1% for fine and coarse aggregates, respectively) to offset the possibility of any remaining sorptive potential in the aggregates. This 'saturated plus' moisture condition was also required to mimic the aggregate storage conditions in a typical batching plant, where aggregate is delivered wet and stored in open stockpiles. This also represents a tightening of the Australian Standard trial mixing requirements, where aggregates can be used in any moisture condition.

Where aggregates were significantly wetter than SSD, they were dried back to the target moisture content. Once prepared, the aggregates were set aside for a minimum of 48 hours to allow their adjusted moisture states to stabilise. Moistures for all materials were double checked prior to mixing and the water subsequently

The Standard Mix

The properties of the standard mix – was identical for all four batching sequence variations, were targeted as those considered suitable for PCP or CRCP concrete base (referred to as "pavement" in the USA). As such, the mix was designed to meet RTA requirements (RTA 2007), namely – a characteristic compressive strength of 35MPa, a flexural strength of 4.5MPa and, using a low fly ash content and SL (shrinkage limited) cement. All materials were considered 'typical' for current pavement construction practices, with special attention being paid to proportions and source of all mineral aggregates. Whilst the greatest volume of paving in Australia is machine placed, the target slump for the standard mix was chosen from a range suitable for hand placed paving – thus allowing the maximum range for expected slump changes in the modified mix batching sequences. An overview of the mix is shown in Table 1. The proportions of the standard mix are shown in Table 2.

Table 1 – Target Properties of The Standard Mix

Characteristic	Value
Compressive Strength	35 MPa
Flexural Strength	4.5 MPa
Slump	60mm
Air Content	4.5%
Bleeding	3% max
Drying Shrinkage	450 µm at 21 days
Mix Size	140L

Table 2 – Proportions of The Standard Mix

Component	Proportion (kg/m^3)
20mm. aggregate (crushed basalt)	770
10mm aggregate (crushed basalt)	360
Coarse Sand (River)	500
Fine Sand (Manufactured)	220
Cement (SL)	300
Fly Ash (Fine Grade)	40
Water Reducer	300mls/100kg cementitious
Air Entrainer	300mls/m^3
Water Cement Ratio	0.49

Results and Discussion

Plastic properties: Table 3 is a summary of the plastic properties of each mix. Figure 5 summarises the comparison of slump reversion. The most dramatic variation in plastic properties, was the consistence, particularly the RILEM mix, which was double the consistency of the Slurry and SEC mixes (for identical mix proportions and moisture contents). This mix was observed to be notably wetter (surface wet) with commensurate improvements in compatibility reported by lab statff. So dramatic was the difference in rheology that the mix proportions, moisture contents and water additions were checked twice more.

Table 3 – Setting Times - Compared

Component	Control	Slurry	RILEM	SEC
Slump (mm)	65	50	100	50
Air Content (%)	5.4	4.9	5.7	4.7
Wet Density (kg/m^3)	2360	2380	2350	2380
Bleeding (%)	1.2	0.6	1.8	0.6
Initial-Final Set (h:mm)	6:20-7:40	6:05-7:30	5:35-7:05	5:40-7:00

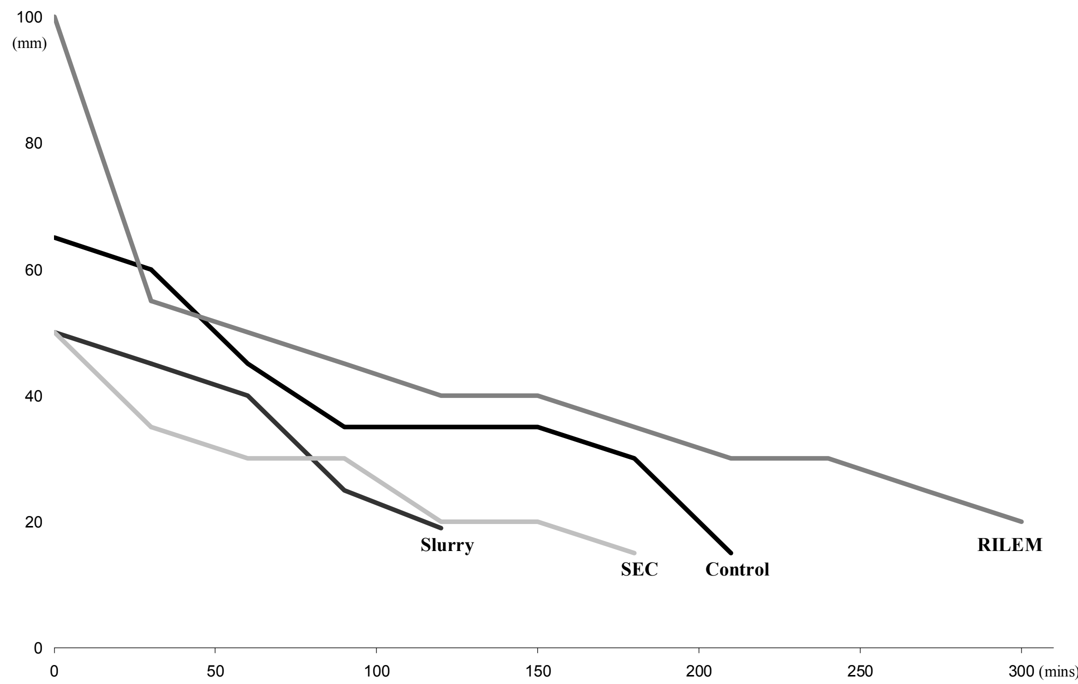

Figure 5 – Slump Reversion (four mixes compared)

Whilst a moderate variation in air content and fresh density was observed, they are considered consistent with the dramatic change in rheology. All plastic properties are in conformance with RTA pavement specifications, with the exception of the RILEM slump, 100mm. In preparation for the mixes, the possibility of controlling slump (rather than water content) was considered, however was eliminated on the basis that variation in water cement ratio may affect a larger range in the results, thus eliminating the identification of the effect of mixing sequence changes on hardened properties.

Hardened properties in terms of compressive and flexural strength is shown in Figures 6 and 7, respectively.

Compared with Control, compressive strength is consistently higher for all three alternate mixes between 7 and 70 days by up to a range of about 10%. The SEC and Slurry mixes exhibited the highest compressive strengths.

Flexural strength was demonstrated a simlar range with 10% variation at both 7 and 70 days of age. Only two flexural samples were tested at 28 days to arrive ath the average strength reported, compared with 3 samples at the other ages. SEC and RILEM outperformed the other three mixing sequences.

Shrinkage results exhibited a spread of about 15% range with the Slurry and Control sequences performancing significantly better at all measured intervals. All shrinkages however were below the maximum specified shrinkage of 450 microstrain at 21 days.

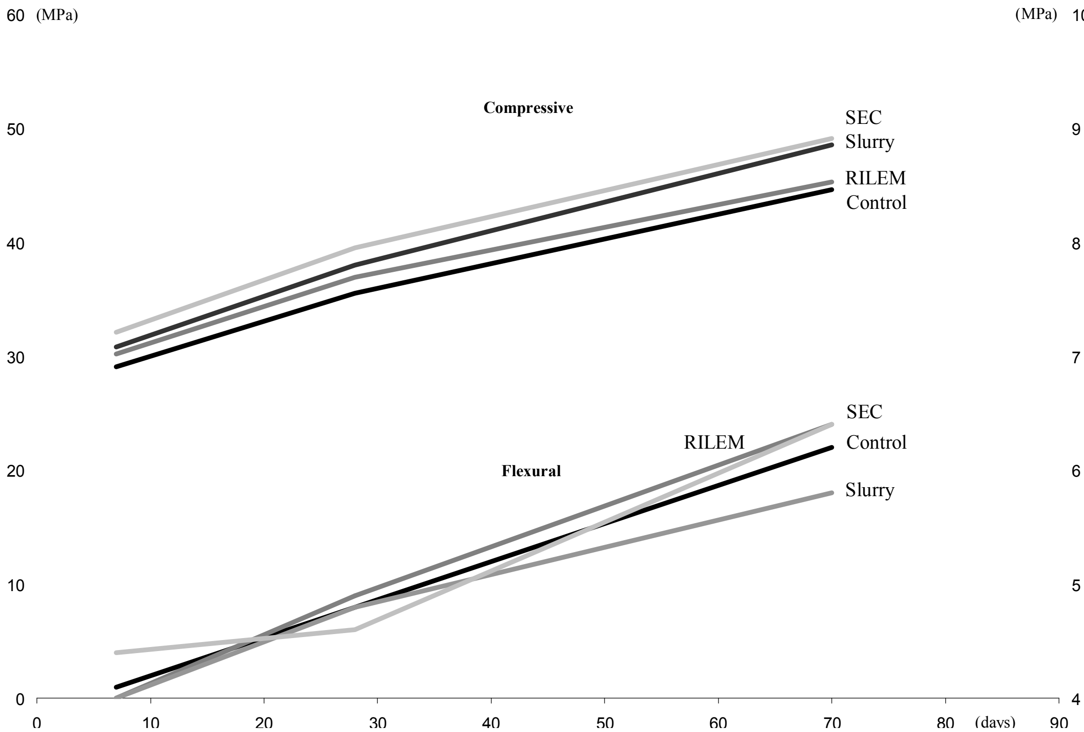

Figure 6 – Compressive and Flexural Strength

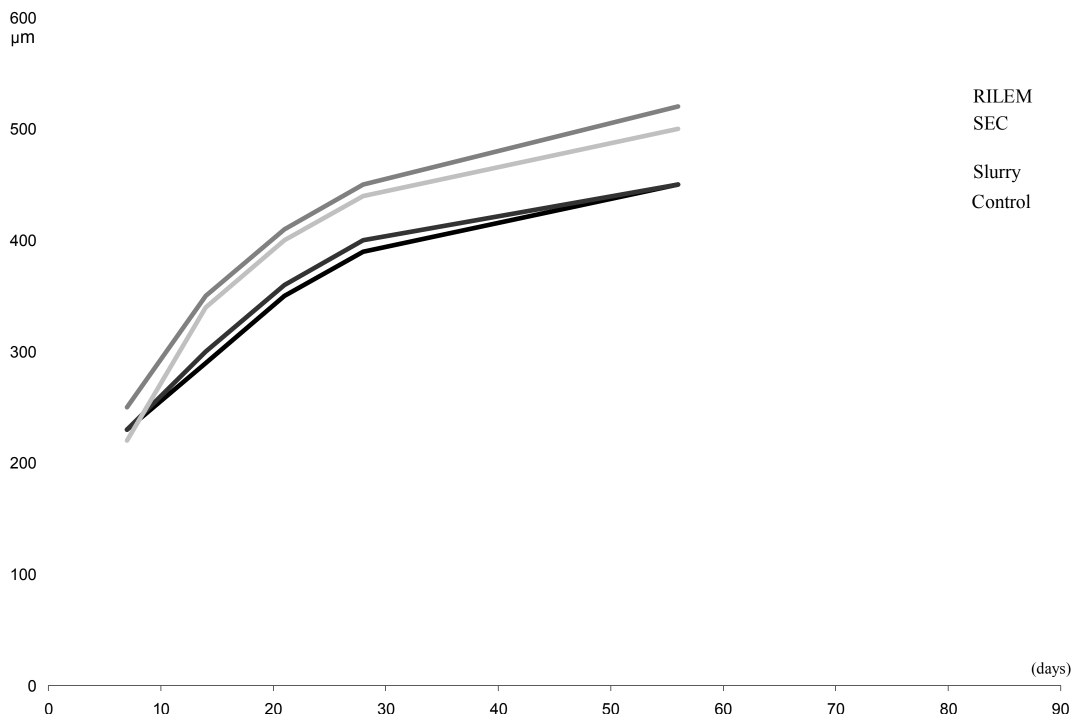

Figure 7 – Drying Shrinkage

Overall, and with a bias towards flexural strength (for reasons mentioned n the introduction), the SEC and RILEM mixes suggest the most improved performance.

The lower comparative compressive strength for the RILEM mix may also also be explained by it having the highest air content - a difference of 1.0% (absolute) air content compared with the SEC sequence. Had the RILEM mix been rerun with a lower air entrainment doseage, in order achieve an air content of around 5.0%, the RILEM compressive strength results might have matched that of the SEC. The dip shown in Figure 7 or 28 days may be anomalous and influenced by the fact that only two samples were tested to obtain this data point.

Selection of Mixes for Fatigue Evaluation (by Round Panel Testing)

Due to limited funding, one mixing sequence variation could be chosen from the three alternative mixes trialled in the laboratory. The chosen mix would be compared with Control. Pending the provision of future funding, evaluation of the remaining two charging sequences would be investigated at some point in the future.

Whilst the Slurry mix was anticipated to provide the greatest improvement noticeable from the physical testing results, it was not clearly superior in any particular characteristic. As a result of this observation, and the fact that it translated to the greatest change in practice (namely, preparation of the slurry as a separately charged component), the Slurry sequence was overlooked in favour of the RILEM mix. Although the RILEM mix did similarly not out-perform the Control sequence, the stark contrast of its rheology (checked to a high level of confidence), in relation to the Control, suggested that bond characteristics (and therefore performance) might also be substantially improved

In view of the above, the RILEM mix was selected for comparison with Control in the large-scale fatigue tests.

PART 2 – FATIGUE TESTING

Reasons for Round Panel Testing

With a typical coefficient of variation of about 7%, the ASTM C1550 panel test was chosen as the method that would provide a highest certainty of measurement than other methods for the determination of repeat load evaluation (fatigue) - other methods are estimated to have a typical coefficient of variation of about 15%, particularly three-point modulus of rupture 'beam' testing which is shown. This level of confidence was seen as mandatory for effective evaluation of relatively minor differences.

To achieve this level of confidence for each load range (10^2 through 10^6), a target of four specimens (plus two reserves for repetition to eliminate anomalous results) would be cast – that is, about 40 round panels specimens, nominal 1200mm diameter. Such a large volume of concrete eliminated the laboratory mixing environment as a casting environment – leaving a commercial batch plant the only viable option.

Mixing and Casting

Approximately $6m^3$ of concrete would be required to produce 40 samples for each mix sequence. In fact, the volume of concrete required was significantly larger than the regular Australian premix concrete batch of $4m^3$, requiring the use of a higher capacity $6m^3$ transit mixer. The use of this mixer, the only mixer in this premix plant's fleet, had the benefit of ensuring that for each mix, the same truck, driver, metering equipment, blade condition, loading and mixing conditions were employed.

To minimise the effect of natural variances in materials supplied, the impact of weather and other time-related factors, the mixes were scheduled to be conducted over a three day period, during which, as hoped, similar weather conditions were experienced on both days – 25ºC and overcast. The Control mix was cast on Day 1, stripping of moulds on Day 2, then the RILEM mix on Day 3.

Photographs of the casting processes are shown in Figures 12 through 16.

Challenges Addressed

Batching – whilst the dry batching of the first Control load represented no changes to normal batching process, the RILEM mix on Day 3 required the careful control and manipulation of the batching process by the lead plant engineer. Table 4 shows the actual batch quantities drawn from the batching records.

The batch plant used was a modern and busy plant located in a rapid growth area of Sydney. The above records demonstrate a high level of tight control. Moisture contents were taken on both days to ensure accurate correction for absorbed water. The RILEM mix water was calculated of 5% of total and added at the slump stand without concern for the resulting slump.

Casting – Casting 40 samples from each load presented several challenges. When this work, has previously been undertaken by the RTA, a variable has been added to the study as a result of a) the duration of casting, and b) the labelling and testing of samples in the order they were cast. The variable is a function of the time between casting the first and last sample. On hot days this would sometimes more than an hour – with the slump reducing from 60 mm to 15mm over the course of the casting process. This would result in a variability during sample preparation which would be mirror in the results, particular because they were tested in the same order. These issues (dry back and testing as cast) were addressed as follows:

• 6 staff were used for panel casting (average casting time was 25 mins),
• a standardised poker vibration process was adopted (two vibrators used),
• the specimens were then vibrated with a motorised screed to close the surface,
• all staff were clearly briefed in their roles, and
• specimens for each load range were taken in a staggered pattern from the lot.

It was felt that these measures satisfactorily addressed all concerns.

Curing time: in view the wide test window for a range such samples (sometimes in the order of a two months), testing is often delayed until 12 months of curing is complete. In this case, samples were cured at 38 deg C (in the lab and field) for 10 weeks. This was considered sufficient to bring samples to maturity without distorting the normal curing process.

Report on Field Casting

Consistent with the laboratory work, the two mixes were significantly dissimilar in rheology. The Control mix had a measured consistency of 50mm, whilst the RILEM mix with exactly the same total water content indicated a consistency of 100mm. Consequently, and as observed in the lab, casting of samples was a significantly different process, with the mix more likely to 'spatter' as it was being vibrated. Table 4 shows the actual batch quantities drawn from the batching records as well as the air contents and slump measured at the point of delivery.

Table 4 – Batching Records and On-site Plastic Properties

Component	**Control, Dec 10**	**RILEM, Dec 12**
20mm. aggregate (crushed basalt)	770	770
10mm aggregate (crushed basalt)	360	370
Coarse Sand (River)	480	480
Fine Sand (Manufactured)	210	200
Cement (SL)	305	295
Fly Ash (Fine Grade)	40	40
Water Reducer	300mls/100kg cementitious	300mls/100kg cementitious
Air Entrainer	300mls/m^3	300mls/m^3
Water Cement Ratio	0.47	0.48
Air Content	5.1%	6.0%
Slump	50mm	100mm

Photographs of the casting process for both days are shown in Figures 9 through 13. at the end of this paper.

Results

Flexural Fatigue (Round Panel Testing) **–** Flexural fatigue capacity of each of the Control and RILEM batches was assessed using the ASTM C1550 'Round Panel' method – a repeat load flexural test using a 1.2m diameter round panel supported at three perimeter points (refer photographs in Figures 17 and 18).

Forty specimens were tested for each batch over a range of stress ratios (the ratio is the ratio between load at failure after *n* fatigue cycles and the single cycle ultimate load) of between 1.0 and 0.6. The intent of this range of load ratios is to bracket a target number of cycles to failure between 1 and 1 x 10^6. The overall maximum number of measured cycles to failure was between 1.6 million and 2.0 million cycles. These extremes took several days to achieve finalise.

The results of this testing, in terms of Load versus Cycles to Failure and Stress Ratio to Cycles to Failure are shown in Figures 8 and 9, respectively. In both cases, results for both the Control and RILEM batches are plotted on the same chart for the purposes of direct comparison.

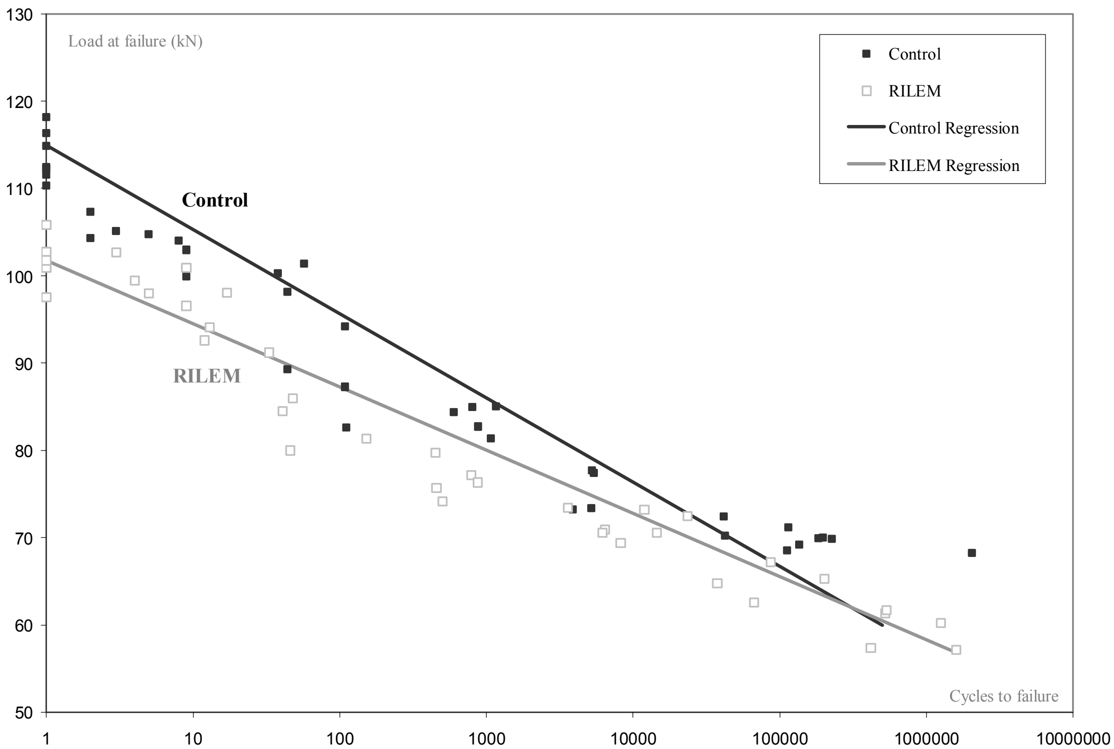

Figure 8 – Fatigue Testing (ASTM C1550) – Load vs Cycles to Failure

The gradients of Load versus Cycles to Failure, based on the linear regression lines shown in Figure 8, for Control and RILEM were 0.011% and 0.003%, respectively.

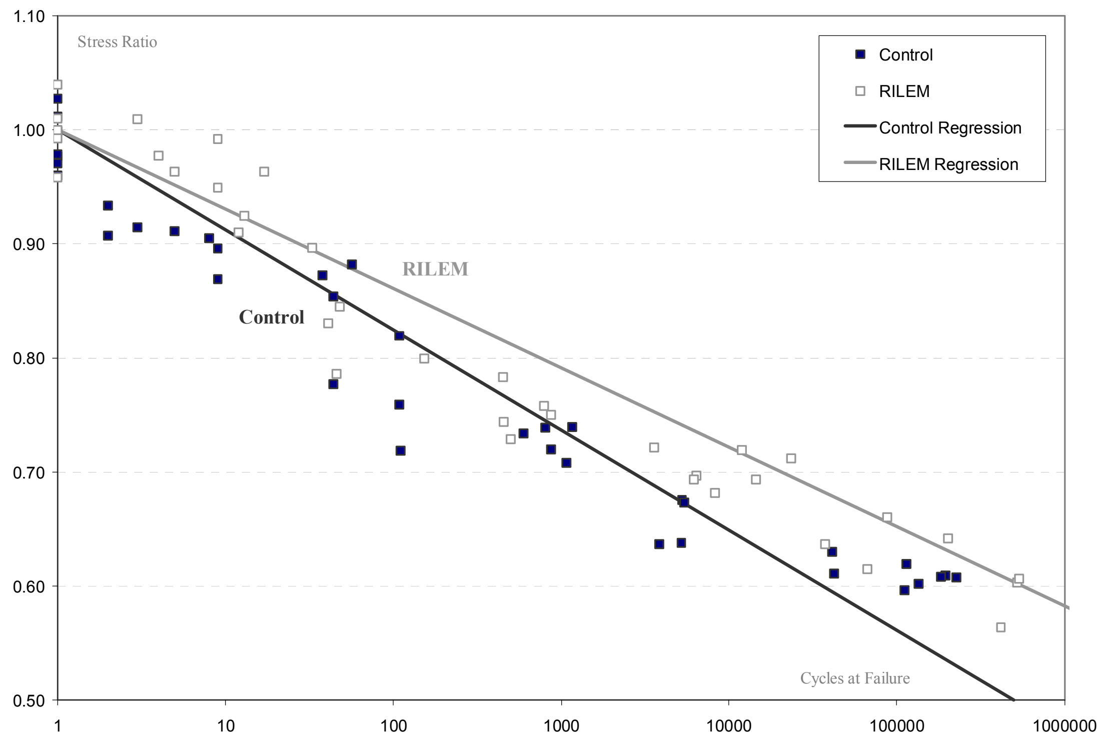

Figure 9 – Fatigue Testing (ASTM C1550) – Stress Ratio vs Cycles to Failure

The gradients of Stress Ratio versus Cycles to Failure, based on the linear regression lines shown in Figure 9, for Control and RILEM were 0.00010% and 0.00003% respectively.

Hardened Properties – In order to confirm that the concrete produced for both batches was of similar quality, four cylinders were cast from each mix of the day's casting which indicated, contrary to the goals of the work, that their existed a differential in compressive strength and density. These results are shown in Table 5.

Table 5 – Compressive Strength and Densities (90 days)

Component	Control, Dec 10	RILEM, Dec 12
Compressive Strength (MPa)	65.0	57.0
Saturated Bulk Density (kg/m³)	2490	2420

When assessed by the single cycle loading of five specimens from each batch to failure using the round panel test, the average load at failure was 114kN and 101kN for Control and RILEM respectively.

Assessment of aggregate-mortar interface – A visual assessment of around a dozen samples considered to represent the extent all results from the Control and RILEM mixes revealed no observable trends. The number of fractured particles and the count of 'pulled out' particles was similar, as was condition of the fracture at the mortar-aggregate transition zone. Further investigation with a scanning electron microscope may be carried out at a later date or on a repeat of the large-scale series of tests where, in view of the differential between the two mixes (discussed above), the concrete batches are assessed to be identical. Photographs of the specimens after testing are shown in Figures 19 and 20.

Discussion of Results

Hardened Properties Differentials (field trials) – The differentials observed in results for hardened compressive strength (-9%), density (-3%) and single point loading (using ASTM C1550) (-11%) are not thought to have been the direct result of the increase in air content (from 5.1 to 6.0%), nor the slight increase in water-cement ratio (0.47 to 0.48).

Despite the high level of supervision and preparation, it is suspected that the ad hoc changes required in weigh-hopper operation (at the premix plant) and the resulting abnormal batching sequence may have inadvertently resulted in an error in batching, in spite of records (refer Table 4) that indicate that batch quantities were within reasonable tolerances. This issue is presently under investigation by means of an assessment of compressive strength of 10 cores from each batch of round panels, as well as the determination of cement and silica contents of representative samples.

Flexural Fatigue Loading Adjustments – In an effort to predict the likely Load vs Cycles to Failure behaviour of both batching sequences when prepared to perform more similarly (as they did in the laboratory trials – refer Figures 6 and 7), a theoretical adjustment can be made to account for the differentials in hardened concrete properties discussed above. This adjustment can be determined in terms of a normalisation of load from the single cycle loading results (as determined using ASTM C1550). When applied to the Load vs Cycles to Failure chart, the starting load is normalised from 101kN (recorded for the RILEM batching sequence) to 115kN recorded as the average single cycle point load for the Control batching sequence. The adjusted plot is shown in Figure 10.

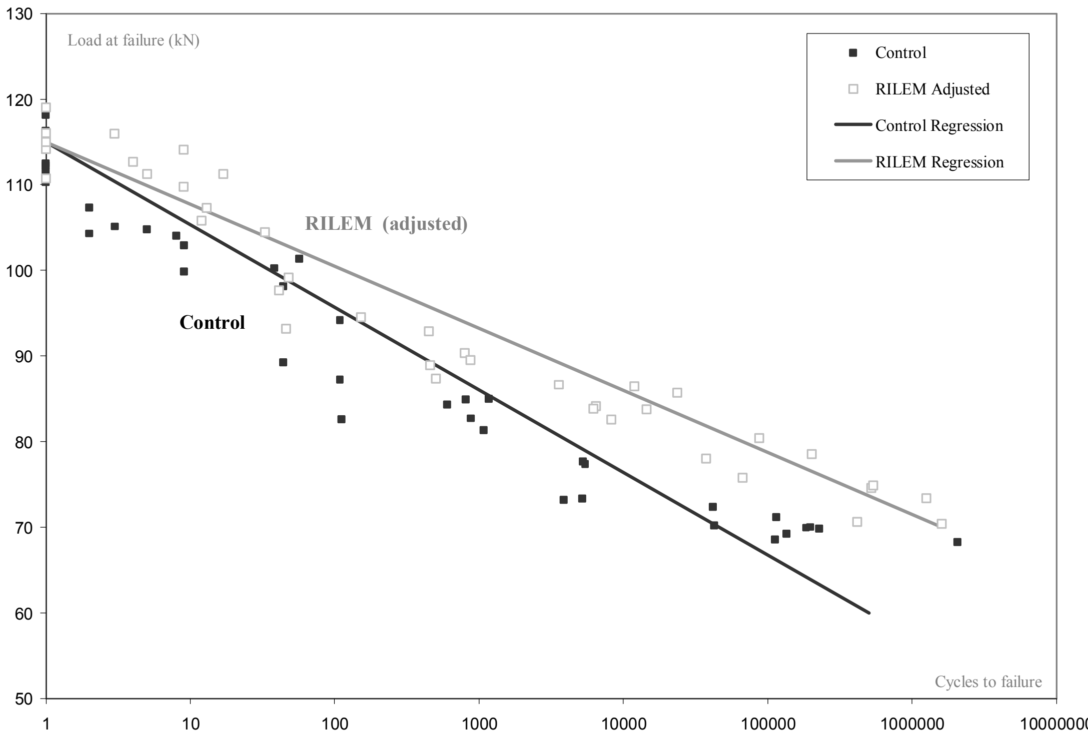

Figure 10 – Fatigue Testing (ASTM C1550) – Load vs Cycles to Failure

This adjustment is, of course, based on an implied high level of confidence in the single cycle failure load results. As five points were used to define this starting point for each batch, this assumed level of confidence is considered reasonable.

The discussion of results that follow is based on the above adjustment, however, it is important to note that the discussion of stress ratio gradient is unaffected by this modification.

Flexural Fatigue Testing - In both cases, lower gradient values achieved for the RILEM mix, suggest a higher fatigue resistance – that is, at a given number of Cycles to Failure, the required to load (or stress ratio) to fail the specimen is higher.

Expressed another way, and based on the linear regressions shown in Figures 9 and 10, material prepared using the Control batching sequence and subjected to 1 x 10^6 repeat load cycles would require a target load of 58kN and a stress ratio of 0.47 to achieve failure, whilst the material prepared using the RILEM mixing sequence would require a *adjusted* target load of 71kN and a stress ratio of 0.58 to achieve failure.

In other words, the flatter gradient for the RILEM batching sequence stress ratio (and adjusted load), when compared with Control, suggests a 23% improvement in fatigue stress resistance.

Confidence Levels and Future Work – Although the ASTM C1550 method is recognised as providing an improved level of uncertainty when compared with other forms for repeat load fatigue capacity test methods, and despite the high number of samples tested in this program (2 x 40), the scatter of points either side of the regression lines shown (with R-squared values of 0.91 and 0.93 for Control and RILEM batches), together with the lack of absolute parity between the field mixes, dictates the requirement for a repeat of the work to confirm and refine the findings herein.

PART 3 – CONCLUSIONS

This work suggests that, for a typical 35MPa paving quality concrete mix, non-fatigue related hardened concrete properties are unaffected by changes in the concrete mix materials batching sequence, although marked contrasts in initial rheology and slump reversion can be observed.

However, this study suggests that the RILEM batching sequence may provide a 23% improvement in flexural fatigue resistance and, presumably, concrete pavement life, when compared with conventional Australian premix and on-site batch plant concrete batching sequences.

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Figure 11 – Lab Mixing (RILEM before addition of sand)

Figure 12 – Casting Process (Control)

Figure 13 – Casting Process (Control)

Figure 14 – Casting Process (RILEM)


Figure 15 – Casting Process (RILEM)

Figure 16 – Curing Preparation (Typical)

Figure 17 – The ASTM C1550 Test Rig (with test specimen)

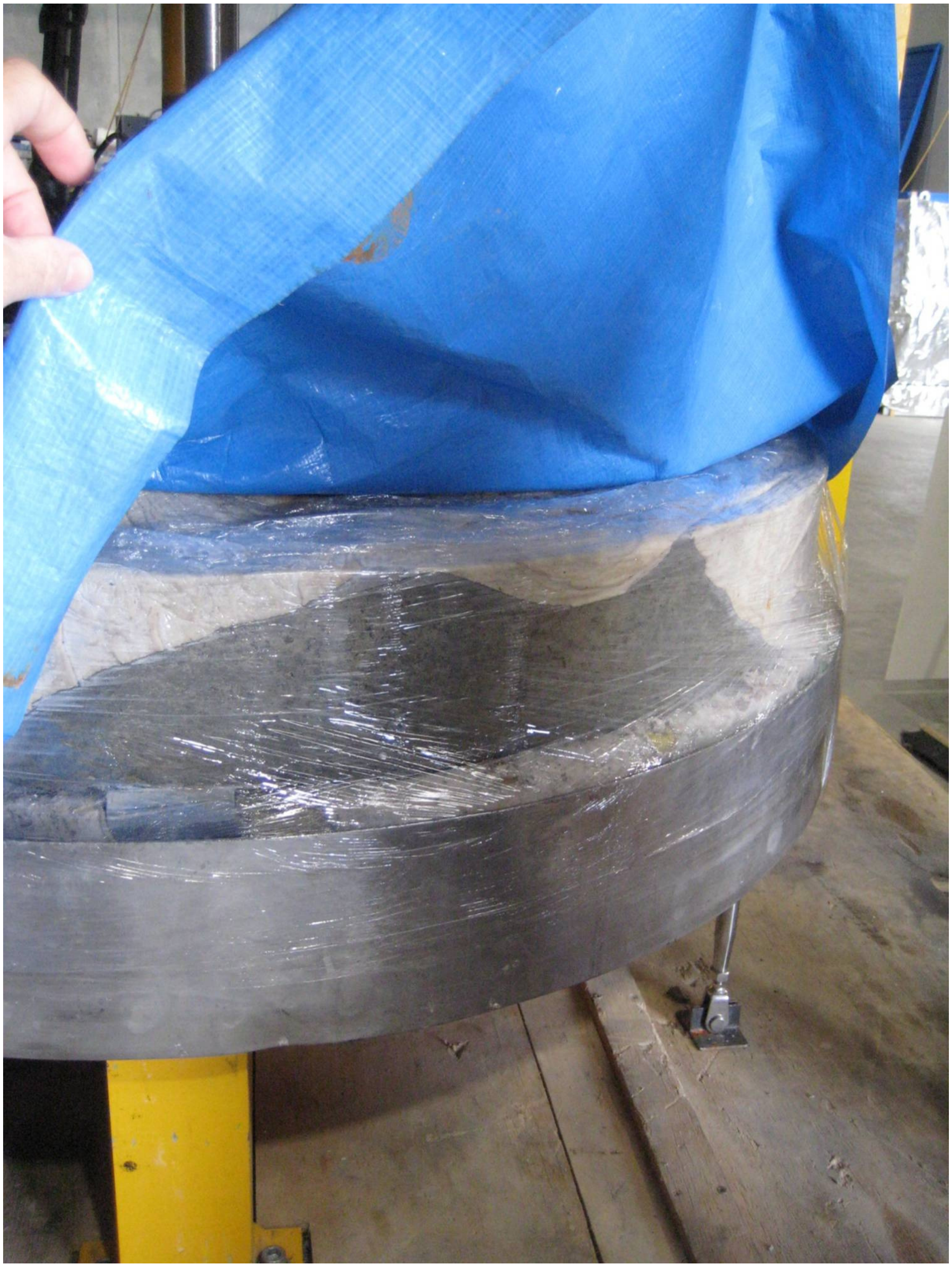

Figure 18 – Moisture Condition Protection for Long Term Testing (test underway)


Figure 19 – ASTM C1550 panels after testing

Figure 20 – Typical broken faces of 'Round Panel' specimen