External Research Report

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Ensuring Affordable Concrete Supply Post 2020 for New Zealand

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Research Plan and Outcomes

Construction growth in the Auckland-Waikato region has increased the demand for Waikato river sand, which is known to be a reactive aggregate in terms of alkali silica reaction (ASR). Concrete producers could better utilise this resource if research could show it was safe to increase the concrete alkali limit above the current 2.5 kg/m^3 for normal concrete. Research was therefore started in 2017 and the test programme set out to answer several questions that included the following:

- Can the default concrete alkali limit be lifted from 2.5 – 2.7 kg/m^3
- How do accelerated mortar bar and concrete prism testing compare with quick chemical tests
- Can these modern expansion tests be used to detect pessimum proportion effects and the influence of elevated curing temperature

This research report summarises the findings to date and make recommendations for further action, most notably on revision of CCANZ TR3. Funding for this research was from BRANZ through the Building Research Levy together with funding from MBIE and the NZ Readymix Concrete Association.

Experimental Program

A range of New Zealand aggregates was sent to Australia in 2016 and tested using a range of chemical, petrographic, mortar and concrete tests. These techniques varied in duration from short-term chemical and petrographic methods to concrete prisms that will be monitored for up to two years. Testing was started in late 2017 and will be completed by the end of 2019.

Material supplied for this testing program in Australia included local GP cement and typical aggregate combinations used in the Auckland construction market. Other aggregates combinations known to be inert or slowly reactive were also included in the testing program to provide some benchmarking of performance. Details of materials used for this experimental testing are shown in Table 1 below. Concrete mix designs used for concrete prism testing are shown in Appendix A.

Table 1: Materials supplied for alkali silica reaction assessment

Material	Name	Symbol	Location
Portland cement	Golden Bay GP	-	NZ
Coarse aggregate	Auckland greywacke	GWC	NZ
Coarse aggregate	Peats Ridge basalt	InC	Australia
Fine aggregate	Akld. greywacke (PAP7)	GWF	NZ
Fine aggregate	Waikato river sand	W	NZ
Fine aggregate	Rangitikei river sand	R	NZ
Fine aggregate	Maroota river sand	InF	Australia

Details of the testing protocol used to undertake this research is shown in Table 2, which shows test methods and aggregates investigated. The test schedule is given in the order that was noted by Boral that consists of petrographic analysis, concrete prism testing, accelerated mortar bar testing and chemical analysis. Note that this order is different from recommendations given in guidelines such as the Rilem AAR testing protocol.

Table 2: Test methods used in the Concrete NZ research program

Test schedule	Standardised ASR test	Description of test	Specimen ID	Aggregates
1	Petrographic assessment AS 1141.65:2008 (agg.) ASTM C856 (mortar& conc.)	Qualitative petrographic screening of potential ASR	N/A	W, R, GWC & GWF
2	Concrete prism test at 38 ^{0}C AS 1141.60.2:2014	Potential alkali-silica reactivity CPT-38/RMS T364 (specimen 2e)	2a&2b 2c 2d 2e	W+InF+InC W+GWF+GWC GWF+GWC R+InC
3	Concrete prism test at 60 ^{0}C AS 1141.60.2:2014	Potential alkali-silica reactivity CPT-60	3a 3c 3e	W+InF+InC W+GWF+GWC R+InC
4	Accelerated mortar bar test (AMBT @ 80 ^{0}C) AS 1141.60.1:2016	Potential alkali-silica reactivity using AMBT conducted at 80 ^{0}C	4a 4b 4c 4d	W+InF W+GWF GWF W
5	Chemical reactivity test ASTM C289-07	Chemical method for potential alkali-silica reactivity	N/A	W, GWC, W+GWF

Material Characterisation

Analysis of the alkali content of GP cement used in the testing programme was carried out by three laboratories in NZ and Australia. An average cement alkali level of 0.58% was found, which was consistent with the findings from the supplier Golden Bay cement but both Australian laboratories found significant differences as shown in Table 3. These differences were 12-14% above or below mean and in concrete tests represent an error of 0.3 kg/m^3 when using a cement content of 420 kg/m^3.

Table 3: Alkali content of GP cement supplied by Golden Bay Cement

Laboratory	Test method	Number of tests	Average alkali (%)
Lab A	ICP	8	0.65
Lab B	XRF	3	0.51
Lab C	XRF	3	0.58

Petrographic assessment was undertaken on both aggregate and mortar samples and was found to be consistent with accepted knowledge of these materials. AS 1141.65 was developed specifically to identify the presence of potentially reactive components in concrete aggregate, therefore was used as the basis for the petrographic analyses carried out in this programme. Unlike TR3, this method does not allow an aggregate source to be classified as non-reactive based on the absence of potentially reactive components. ASTM C856 was used to examine hardened concrete and includes specific clauses relating to the detection of deleterious reactions in concrete, including ASR.

Petrographic analyses of Waikato and Rangitikei river sands gave results consistent with existing knowledge. The Hunua greywacke material was found to contain material that may cause mild or slow AAR, including small amounts of intermediate and devitrified acid volcanic rock fragments. Waikato river sand was found to have significant amounts of free strained silica and was classified as potentially reactive in concrete.

Rangitikei river sand was found to contain 12.7% strained quartz together with traces of microcrystalline quartz and volcanic acid clasts and should therefore be considered to have mild potential for deleterious ASR.

Post mortem analysis of AMBT specimens was done in accordance with ASTM C856 and found that expansion was caused by ASR gel formation, which was significantly higher in mortar containing Waikato river sand than that made with greywacke sand. Minerals associated with ASR gel formation were glassy shards, acid volcanics and quartz grains in the case of Waikato river sand and acid volcanics in greywacke.

Chemical Reactivity

Chemical assessment of the potential reactivity of aggregate was done using ASTM C289, which has been used as a preliminary screening test for ASR in New Zealand. The method is quick and requires only a small sample of ground aggregate that is exposed to an alkaline solution at 80 ^{0}C for 24 hours before measuring the dissolved silica content and reduction in alkalinity. The potential reactivity of aggregate can then be classified by plotting against an empirical curve. Most typically, reactive aggregates do not cause significant reduction in alkalinity (e.g. less than 50 millimoles per litre that indicates material has low pozzolanicity than can cause significant reduction in alkalinity) while having significant dissolved silica (e.g. more than 50 millimoles per litre).

Chemical analysis of results done on NZ aggregates in accordance with ASTM C289 are shown in Table 4. Findings indicated that Waikato river sand or a blend of this material and greywacke sand was potentially deleterious while greywacke sand when tested on its own was found to be innocuous. These findings are consistent with results previously reported in TR3 Appendix D.

Table 4: Results of quick chemical analysis in accordance with ASTM C289

Aggregate combination	Dissolved silica (millimole per litre)	Reduction in alkalinity (millimoles per litre)	Classification (ASTM C289)
Waikato sand	124.9	40.1	Deleterious
60% W + 40% GWF	99.1	38.5	Deleterious
Greywacke	29.1	40.1	Innocuous

Accelerated Mortar Bar Testing

Accelerated mortar bar test (AMBT-80) measures the expansion of mortar specimens stored in sodium hydroxide solutions (using either 0.6M, 0.8M or 1.0M solutions) at a temperature of 80 ^{0}C for 28 days. The rapid nature of the test using high temperatures to increase reaction rates but the test may induce expansion in normally non-reactive aggregates (false positive results). AMBT-80 testing was used to characterise the reactivity of Waikato river sand alone, when blended 60/40 with greywacke and when blended 60/40 with a non-reactive control sand. Greywacke fine aggregate was also tested to assess reactivity and to assess its suitability as a New Zealand inert control material.

AMBT testing found that greywacke aggregate was slowly reactive at high concentrations of sodium hydroxide whereas Waikato river sand was found to be reactive when tested on its own on blended with other sands. Results are shown below in Table 5.

Table 5: Accelerated mortar bar test results for NZ and Australian aggregates

Sample No.	Agg. type	Storage NaOH	Expansion (%)						
4a	W+InF	0.6 M	0.010	0.088	0.418	0.650	0.773	0.873	0.942
		0.8 M	0.015	0.205	0.488	0.650	0.753	0.845	0.945
		1.0 M	0.035	0.247	0.465	0.578	0.662	0.740	0.812
4b	W+GWF	0.6 M	0.010	0.075	0.392	0.635	0.767	0.887	0.997
		0.8 M	0.013	0.125	0.390	0.548	0.658	0.790	0.935
		1.0 M	0.023	0.187	0.413	0.548	0.652	0.763	0.883
4c	GWF	0.6 M	0.000	0.000	0.005	0.018	0.050	0.168	0.275
		0.8 M	0.000	0.000	0.020	0.105	0.185	0.325	0.445
		1.0 M	0.000	0.010	0.087	0.200	0.295	0.432	0.558
4d	W	0.6 M	0.013	0.068	0.282	0.520	0.683	0.863	0.960
		0.8 M	0.013	0.062	0.220	0.368	0.503	0.668	0.798
		1.0 M	0.030	0.193	0.415	0.580	0.698	0.807	0.932

Comparison of testing conducted in 0.6M solution of NaOH is shown in Figure 1 below and shows only the greywacke (PAP7) was innocuous. Samples containing Waikato river sand showed significant expansion with blends containing inert sands of either basalt or greywacke showing higher expansion. All mortar samples containing Waikato river sand showed significant expansion that indicated the aggregate should be classified as reactive in terms of ASR.

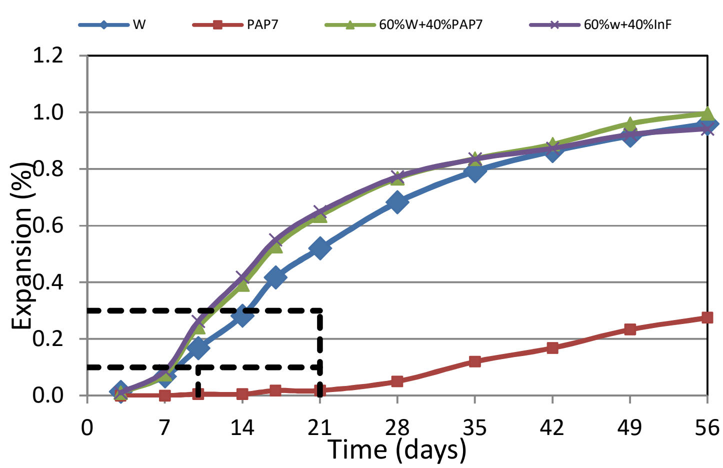

Figure 1: Comparison of expansion results for AMBT-80 using 0.6M NaOH solution

Concrete Prism Testing

Concrete prism testing to assess the potential for alkali silica reaction has the advantage that mix designs used are similar with those found in practice. Details of concrete mix designs are shown in Table 6 and were used for both CPT-38 and CPT-60 testing. Alkali contribution from cement was assumed to be approximately 2.44 kg/m^3 with extra alkali being added to the fresh concrete in the form of analytical grade sodium hydroxide.

Table 6: Concrete mix designs used for concrete prism testing (kg/m^3)

Material	a W+InF+InC	b W+InF+InC	c W+GWF+GWC	d GWF+GWC	e R+InC
GP cement	420	420	420	420	420
Water	189	189	189	189	189
Fine aggregate	411 ^{W}	429 ^{W}	410 ^{W}	751 ^{GWF}	840 ^{R}
Fine aggregate	274 ^{InF}	286 ^{InF}	273 ^{GWF}	0	0
19.0-13.2 mm agg.	413	389	367	367	348
13.2-9.5 mm agg.	413	389	367	367	348
9.5-4.75 mm agg.	413	389	367	367	348

Testing protocol for concrete prisms was as follows:

- Series a and d used Rilem protocol with alkali levels of between 2.5 and 5.25 kg/m^3
- Series b had a fixed alkali level of 5.25 kg/m^3 and fine aggregate proportions varied as a pessimum study
- Series c was similar to series a but an extra test was conducted at an alkali content of 5.25 kg/m^3 and with thermal curing at 70 ^{0}C to model temperature extremes possible with mass concrete or some precasting processes
- Series e had a slightly different alkali levels (e.g. 2.5-5.8 kg/m^3) to be consistent with previous testing of Rangitikei aggregate done using RMS T364 testing protocol

A summary of CPT-38 test results comparing the potential expansion of concrete made with different aggregate combinations is shown in Table 7. Testing is recommended to run for at least 12 months with expansion above 0.03% considered significant for potentially reactive combinations.

Table 7: Summary of CPT-38 expansion (%) reported by Boral/UTS in January 2019

No.	Agg.	Alk.	1m	2m	3m	4m	5m	6m	7m	8m	9m	10m	11m	12m
2a	W+InF +InC	2.50	-0.013	-0.014	-0.014	-0.014	-0.014	-0.013	-0.016	-0.015	-0.013	-0.014	-0.015	-0.017
		3.00	-0.013	-0.012	-0.010	-0.010	-0.008	-0.008	-0.011	-0.007	-0.009	-0.011	-0.013	-0.013
		3.50	-0.006	-0.004	-0.003	-0.002	-0.001	0.000	0.000	0.000	0.000	0.000	0.000	-0.001
		3.80	-0.008	-0.004	-0.004	-0.004	-0.003	-0.003	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002
		4.00	-0.008	-0.003	-0.003	-0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	-0.001
		5.25	-0.002	0.001	0.004	0.004	0.005	0.008	0.009	0.009	0.011	0.012	0.013	0.015
2c	W+GWF +GWC	2.50	-0.008	-0.010	-0.010	-0.010	-0.011	-0.010	-0.010	-0.011	-0.010	-0.011	-0.010	-0.011
		3.00	-0.018	-0.018	-0.019	-0.019	-0.016	-0.016	-0.017	-0.017	-0.018	-0.019	-0.018	-0.017
		3.50	-0.011	-0.012	-0.009	-0.008	-0.009	-0.009	-0.009	-0.009	-0.008	-0.008	-0.008	-0.009
		4.00	-0.015	-0.014	-0.013	-0.015	-0.015	-0.014	-0.012	-0.012	-0.012	-0.011	-0.012	-0.013
		5.25	-0.012	-0.012	-0.010	-0.007	-0.005	-0.004	-0.004	-0.003	-0.002	-0.003	-0.003	-0.003
2d	GWF+GWC	2.50	-0.007	-0.010	-0.010	-0.010	-0.010	-0.011	-0.011	-0.011	-0.010	-0.010	-0.010	-0.009
		3.00	-0.009	-0.013	-0.013	-0.013	-0.012	-0.012	-0.012	-0.011	-0.012	-0.012	-0.012	-0.012
		3.50	-0.003	-0.008	-0.007	-0.007	-0.006	-0.006	-0.007	-0.006	-0.005	-0.005	-0.004	-0.005
		4.00	-0.005	-0.009	-0.007	-0.007	-0.007	-0.008	-0.009	-0.009	-0.015	-0.016	-0.016	-0.016
		5.25	-0.003	-0.004	-0.004	-0.003	-0.002	-0.003	-0.003	-0.001	-0.001	-0.001	-0.003	-0.003
2e	R+InC	2.50	-0.004	-0.002	-0.002	-0.002	-0.004	-0.003	-0.002	-0.003	-0.004	-0.004	-0.004	-0.004
		3.00	-0.003	-0.002	0.000	0.000	-0.001	-0.001	-0.001	-0.001	-0.002	-0.003	-0.003	-0.002
		3.50	-0.002	-0.001	0.001	0.003	0.002	0.001	0.001	0.002	0.001	0.001	0.001	0.002
		4.00	-0.001	0.003	0.003	0.004	0.003	0.003	0.004	0.003	0.003	0.002	0.002	0.002
		5.00	-0.002	0.004	0.005	0.006	0.006	0.005	0.005	0.007	0.008	0.007	0.007	0.009
		5.80	0.002	0.006	0.008	0.010	0.011	0.011	0.012	0.018	0.038	0.060	0.084	0.139

Expansion measured using four aggregate combinations is shown in Figure 2. Significant expansion was only found when concrete had alkali levels exceeding 5.0 kg/m^3 and in some cases even this high concentration did not cause expansion during the 12 months of testing that has recently been concluded (e.g. Auckland greywacke).

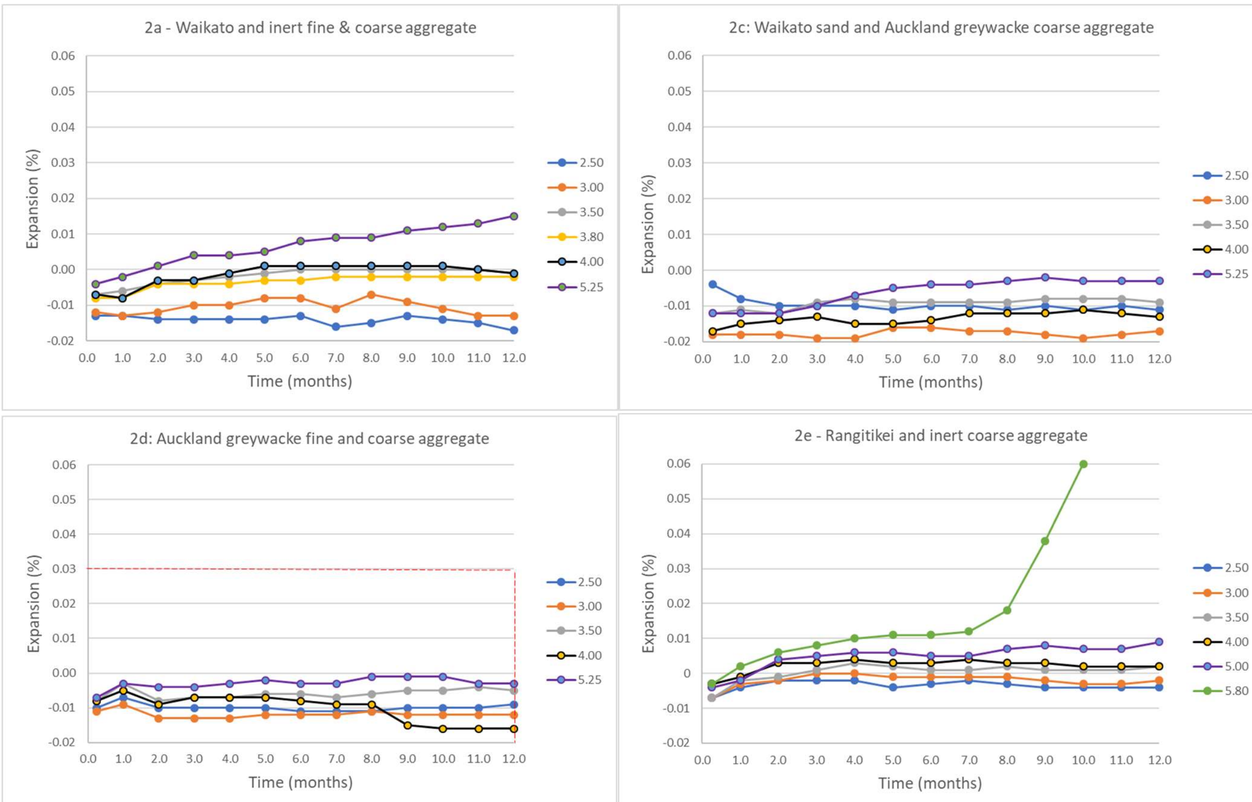

Figure 2: CPT-38 expansion results for different aggregate combinations

Significant expansion in CPT-38 is generally assumed to be above 0.03% after 12 months exposure but slowly reactive aggregate may take longer for expansion to occur. The testing was therefore continued beyond 12 months and will be completed after 24 months in late 2019. In contrast, CPT-60 uses a higher temperature of 60 ^{0}C with significant expansion usually assessed after 3-4 months and the testing completed after 8 months.

A summary of expansion measurements recorded for CPT-60 testing is shown in Table 8. Results were found to be similar with results from CPT-38 testing with the same general ranking and performance. CPT-60 testing was found to have higher levels of expansion once significant expansion had started compared with similar concrete tested using CPT-38. Note that only three aggregate combinations were assessed using CPT-60 compared with four used for CPT-38.

Table 8: Summary of CPT-60 expansion (%) reported by Boral/UTS in January 2019

No.	Agg.	Alk.	0.25m	1m	2m	3m	4m	5m	6m	7m	8m
2a	W+InF +InC	2.50	-0.003	0.000	0.000	0.000	-0.001	-0.001	0.000	0.000	0.000
		3.00	-0.006	-0.001	-0.002	-0.003	-0.003	-0.004	-0.002	-0.002	-0.002
		3.50	-0.002	-0.003	-0.001	-0.001	0.002	0.001	0.002	0.001	0.002
		4.00	0.001	0.005	0.004	0.005	0.005	0.005	0.006	0.005	0.006
		5.25	0.000	0.007	0.009	0.014	0.030	0.042	0.055	0.070	0.105
2c	W+GWF +GWC	2.50	-0.009	-0.011	-0.008	-0.010	-0.008	-0.009	-0.009	-0.009	-0.007
		3.00	-0.009	-0.012	-0.009	-0.009	-0.010	-0.010	-0.013	-0.007	-0.005
		3.50	-0.009	-0.009	-0.007	-0.006	-0.007	-0.005	-0.009	-0.010	-0.009
		4.00	-0.008	-0.006	-0.006	-0.007	-0.007	-0.007	-0.008	-0.007	-0.006
		5.25	-0.003	0.002	0.004	0.006	0.007	0.013	0.015	0.016	0.017
2e	R+InC	2.50	-0.006	-0.003	-0.002	-0.001	-0.003	-0.003	-0.002	0.001	0.001
		3.00	-0.007	-0.003	-0.003	-0.002	-0.001	-0.001	-0.001	0.000	0.001
		3.50	-0.001	0.003	0.003	0.004	0.000	0.002	0.002	0.003	0.003
		4.00	0.001	0.004	0.007	0.006	0.006	0.005	0.005	0.006	0.006
		5.00	0.002	0.009	0.013	0.013	0.016	0.016	0.017	0.016	0.016
		5.80	0.001	0.012	0.025	0.045	0.060	0.075	0.195	0.310	0.333

Figure 3 shows expansion results for CPT-60 testing with results plotted on the same scale to allow simple comparisons to be made. No significant expansion was found when alkali contents were below 4.0 kg/m^3 but both Waikato river sand and Rangitikei river sand showed significant expansion within 6 months when exposed to alkali levels above 5 kg/m^3.

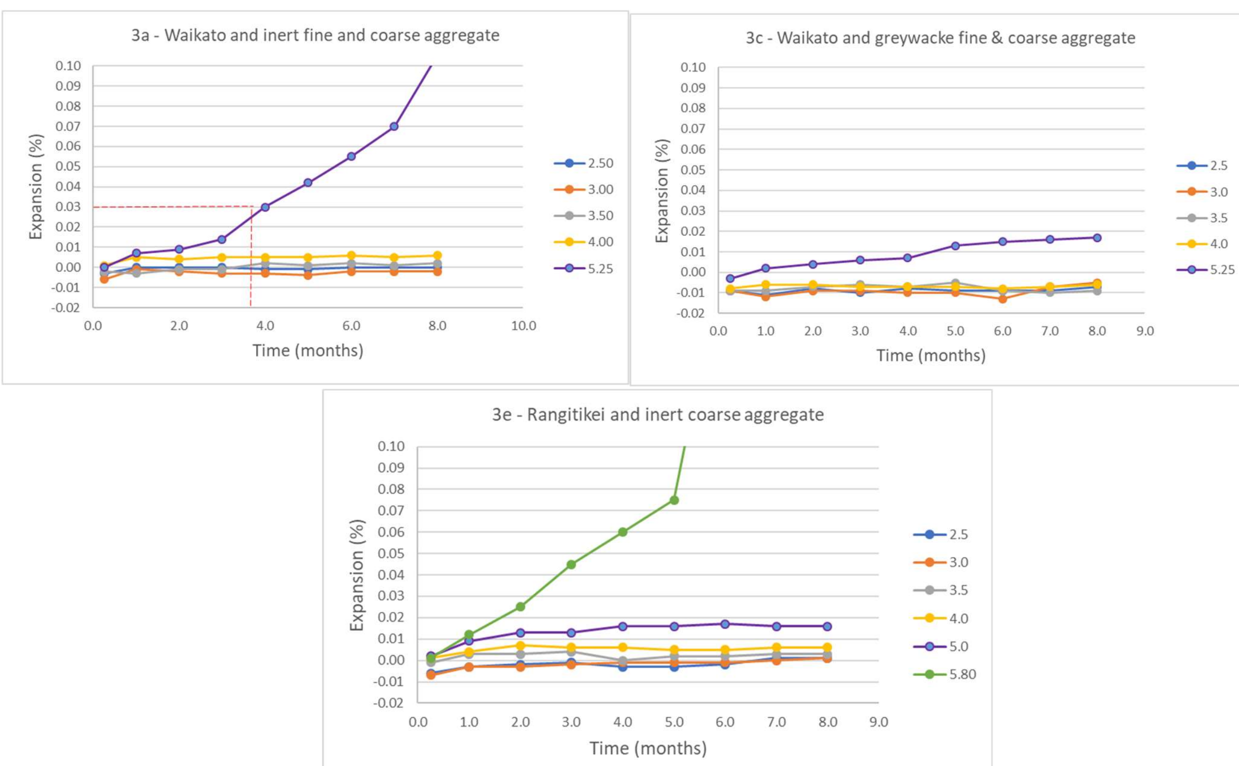

Figure 3: CPT-60 expansion results for different aggregate combinations

Figure 4 shows the correlation between CPT-38 and CPT-60 results using the default periods of 12 and 4 months respectively. There was similar expansion found for each test but the strength of the relationship is questionable since there is only two data points where both test methods showed significant expansion of 0.03% or greater. Further analysis of the correlation between tests will be undertaken when longer-term data is available after 24 months since slowly reacting aggregates may show some further expansion after 12 months.

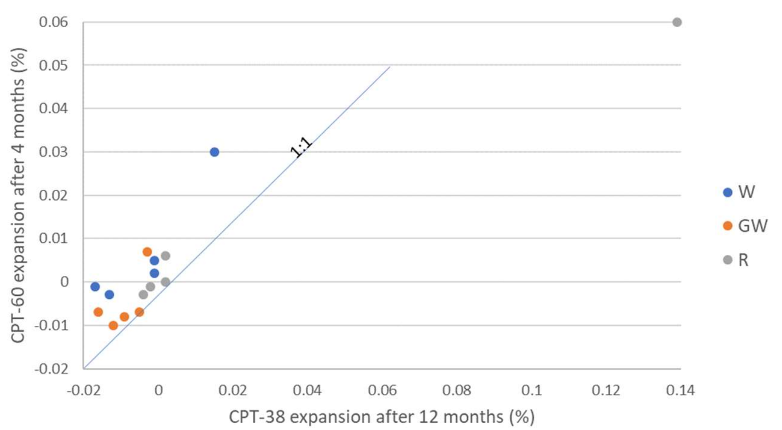

Figure 4: Correlation between CPT-38 expansion after 12 months and CPT-60 expansion after 4 months

Pessimum studies were also undertaken with CPT-38 testing using series 2b that investigated varying amounts of Waikato river sand in the overall aggregate blend. This was undertaken at an alkali content of 5.25 kg/m^3 and found that as the component of Waikato river sand was increased the expansion occurred more rapidly and resulted in larger overall expansion. Waikato river sand was found to be reactive at all proportions with an increased level merely triggering earlier expansion. Using and elevated curing temperature also had the same effect of accelerating expansion.

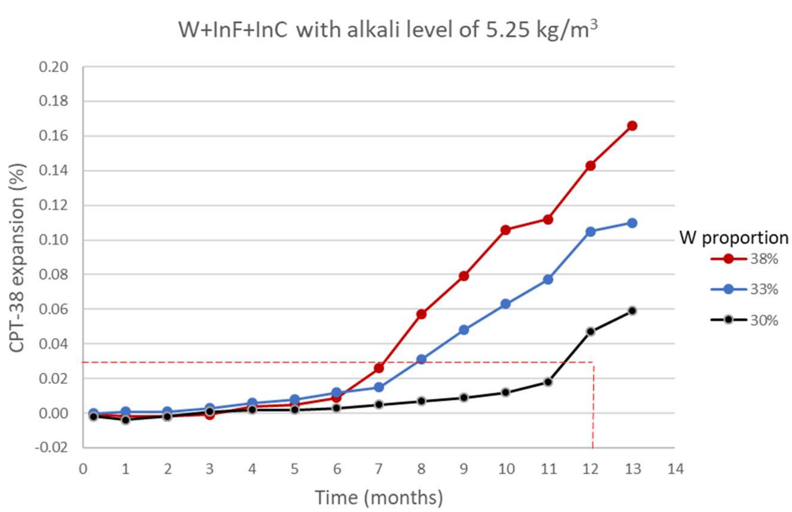

Figure 5: Pessimum study using CPT-38 with W+InF+InC at an alkali content of 5.25 kg/m^3

Recommendations

Based on findings from this research, there are several recommendations that should culminate in the revision of CCANZ TR3.

Characterisation of aggregate

Petrographic analysis of aggregates was able to identify minerals and phases that cause deleterious expansion due to ASR in concrete. Post-mortem analysis of AMBT samples confirmed this and showed that petrography is an extremely useful screening testing for ASR assessment. Chemical assessment of the potential reactivity of aggregate (ASTM C289) was found to provide useful information and is particularly useful when assessing greywacke where petrography indicates potentially reactive minerals and/or phases.

Accelerated mortar bar testing (AMBT)

AMBT found Waikato river sand to be reactive even when blended with other inert aggregates. The technique is however extremely severe and can cause even non-reactive aggregates to expand. Given the value of initial screening tests such as petrography and that some concrete prism tests can evaluate the potential reactivity of aggregate within four months, AMBT testing does not appear to add much value when assessing the reactivity of aggregate for concrete.

Concrete prism testing (CPT)

CPT-38 and CPT-60 were found to produce consistent results such that estimates of alkali thresholds for concrete could be reliably undertaken. Both Waikato and Rangitikei river sand were found to only cause significant expansion when exposed to alkali levels above 5.0 kg/m^3, which is significantly higher than current limits given in CCANZ TR3. Some conservative assumptions would need to be taken to allow for leaching of alkalis, scale effects and uneven concentrations found in larger structures (currently Rilem assumes these may contribute 1.0 kg/m^3). Findings from this research also found that CPT-60 appears able to replicate trends found in CPT-38 but in less that half the time and further assessment of this more rapid technique should be undertaken.

Proposed testing methodology

Before a revised testing methodology is included in TR3 it would be useful to validate the proposed testing methodology with a known reactive aggregate combination from New Zealand. Consultation with the working group for this research project identified Bay of Plenty andesite that is used in Tauranga and surrounding areas where rapid expansion is occurring. The testing protocol proposed for the assessment of this aggregate is given in Table 9 and this testing is expected to take nine months and will hopefully be started in March/April 2019.

Table 9: Proposed testing protocol for BoP andesite ASR assessment in 2019

Testing technique	Specifics	Comments
Petrography	Fine and coarse aggregate	Identify reactive minerals
Chemical assessment	Fine and coarse aggregate	Confirm petrography
CPT-60	As per previous mix designs	2.5 – 5.25 kg/m^3 alkalis

Conclusions

Characterisation techniques used for initial screening of potentially reactive aggregates were found to be reliable in that known reactive and slowly reactive aggregates were clearly identified while known non-reactive aggregate did not indicate reactivity. The most important findings were those derived from CPT results looking at alkali thresholds for different aggregate combinations. This found that at an alkali level of 4.0 kg/m^3 known reactive or slowly reactive aggregates such as Waikato and Rangitikei river sand was found to exhibit no deleterious expansion in concrete. Applying a conservative reduction of 1.0 kg/m^3 to allow for alkali leaching (to be verified empirically) and 0.3 kg/m^3 to cover uncertainty in alkali analysis of cement, then the safe alkali limit would be 2.7 kg/m^3.

Currently the general alkali limit given in CCANZ TR3 is 2.5 kg/m^3 for normal concrete and indications from this research are that this may need to be reviewed. As long-term data becomes available and with further confirmation from validation trials, review of TR3 will be initiated by reforming the committee. This will occur during 2019 such that findings from this research will help ensure affordable concrete supply in 2020 and beyond.

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