

INVESTIGATION OF ALKALI THRESHOLD LIMITS AND BLENDED AGGREGATE IN ASR RISK-ASSESSED CONCRETES

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Abstract

Concrete structures are designed for a specific design life to tolerate deterioration caused from various aggressive environmental loads such as carbon dioxide, chloride and aggressive soil conditions. The approach to prevent deterioration in concrete due to alkali-silica reaction (ASR) is by the avoidance of any such dissolution reaction taking place in concrete. ASR can in part be prevented by limiting the alkali content and restricting the use of potentially reactive aggregates. In this paper, the alkali threshold of several aggregates originating from New Zealand were determined using a modified version of RILEM AAR-3.2 and AAR-7.1. The AAR-2 accelerated mortar bar test (AMBT at 80°C) and AAR-3.2 concrete prism test (CPT at 38°C) were replaced with Australian Standard AS 1141.60.1 and 60.2 test methods, respectively, to evaluate expansion. Additional accelerated CPT in accordance with AAR-4.1 (ACPT at 60°C) was also conducted to examine the adequacy of shortening the test period. Petrographic examination taken before and after expansion testing was also carried out to qualify the presence of reactive silica and ASR gel contributing to expansion. The findings of this study suggest the potential for specifying the alkali threshold in concrete based on the reactivity classification of aggregates allowing a relaxation of the CCANZ Technical Report TR 3 alkali limit of 2.5 kg/m³ that is currently in place in New Zealand. This approach allows greater flexibility in the use of potentially reactive aggregates as sustainable concreting making materials.

Keywords: alkali limit, aggregate reactivity, alkali silica reaction, alkali threshold

1.0 Introduction

The alkali-silica reaction (ASR) occurs between aggregates containing reactive silica and hydroxyl ions found in the pore solution of concrete. The dissolution reaction that takes place results in the formation of an alkali-silicate gel. Due to the semi-permeable nature of the gel formed, it tends to absorb moisture and expand. Deleterious expansion of the gel leads to the eventual deterioration of the mechanical properties and serviceability limit state of the concrete structure (Hanson 1944; Stanton 1940).

ASR initiates with the dissolution of silica in the presence of high alkali content (Broekmans 1999). Most of the alkalis available for reaction in concrete are known to originate from Portland cement. However, other potential sources of alkalis can also include those originating from within the aggregates used in the production of concrete. However, these alkalis are released

over much longer periods of time when compared with those alkalis released from Portland cement hydration. The initial hydration of Portland cement releases calcium (Ca^{2+}), potassium (K^+), sodium (Na^+), hydroxyl (OH^-) and sulphate (SO_4^{2-}) ions into pore solution. The concentration of alkali cations (Na^+ and K^+) present at any given age primarily determine the alkalinity of the pore solution.

At elevated pH, such as attained in concrete pore solution, silica (nominally SiO_2) dissolves forming charged $\equiv\text{Si-O}^-$ species, which are charge balanced by Na^+ and K^+ ions forming alkali silicates. The alkali silicate then polymerizes when the pore solution is saturated with dissolved silica and ASR gel is precipitated (Broekmans 1999; Walther & Helgeson 1977). Ca^{2+} ions react to substitute alkali ions in ASR gel forming a calcium-alkali-silica hydrate complex (Walther & Helgeson 1977). The process of releasing alkali ions back into the pore solution allows the regeneration of a high pH that in turn results in further dissolution of the silica network and the continuity of ASR.

To reduce the risk of ASR, aggregates that demonstrate the potential to be reactive are often restricted from use in concrete. Preferential use of non-reactive aggregates in the production of concrete places a significant burden on the demand and availability of quarry suppliers to provide these aggregate sources. With increasing construction activity, non-reactive aggregate sources are becoming increasingly scarce in New Zealand. In addition, guidelines have been imposed on the alkali limit allowed in concrete to reduce the amount of alkali available to react with reactive silica in aggregates. This limit is conservative and has been generalised in New Zealand as $2.5 \text{ kg/m}^3 \text{ Na}_2\text{O}_e$ for all aggregates used in concrete (CCANZ 2012). To achieve the set alkali limit in concrete, low alkali cements are employed in the production of concrete. Low alkali cements are cements with alkali content would below an alkali limit of $0.6\% \text{ Na}_2\text{O}_e$ (Standards New Zealand 2009; Thomas et al. 2006). Achieving low alkali contents in cement manufacture is both an environmental and economic challenge. There are however instances reported in literature where concretes containing low alkali cement also experience ASR (Bérubé et al. 2000). The alkali content that will induce ASR is primarily dependent on the mineralogical composition of the aggregate used in concrete (Thomas et al. 2006). Consequently, it is important to identify appropriate alkali limits for distinct aggregates and aggregate combinations to ascertain their reactivity in the presence of alkali to form expansive ASR.

This study therefore investigates the potential reactivity of commercially available aggregates in New Zealand using standard laboratory expansion tests to determine the behaviour of these aggregates with variations in alkali content. The purpose of introducing a variable alkali content is to establish the alkali threshold, the alkali content at which initiation of expansion due to ASR becomes evident (Hester, McNally & Richardson 2005). Consequently, the study also hopes to recommend the potential of using concretes with higher alkali limits exceeding the current 2.5 kg/m^3 (CCANZ Technical Report TR 3) thus conserving natural resources and reducing cement manufacturing costs.

2.0 Experimental Procedure

2.1 Materials

For this study, two New Zealand fine aggregates classified by petrographic examination as slowly reactive and reactive were selected for use to determine their effectiveness in combination to reduce expansion resulting from ASR. Two Australian aggregates of known reactivity tested in accordance to AS 1141.60.1 and 60.2 requirements have also been used to evaluate the reactivity potential of the two New Zealand fine aggregates under investigation. A cement with alkali content of $0.58\% \text{ Na}_2\text{O}_e$ conforming to the current alkali limit for cement

in New Zealand was selected as the source of the binder for use in mortars and concretes. A description of the aggregates used, and their reactivity classification are given in Table 1.

Table 1. Selected aggregates under investigation

Aggregate	Symbol	Reactive Minerals	Reactivity Classification
New Zealand Aggregate A	NZ-A _f	Glassy volcanic clasts, quartz, cherts and feldspar	Reactive
New Zealand Aggregate B	NZ-B _f	Hornblende, pyroxene, feldspar, quartz and epidote	Slowly reactive
	NZ-B _c		Slowly reactive
Peats Ridge	PR _c	Not Applicable	Non-reactive
	PR _f		
Maroota sand	M _f	Not Applicable	Non-reactive

*c = Coarse Aggregate; f = Fine Aggregate

2.2 Methods

Throughout this study, AS 1141.60.1 accelerated mortar bar tests (AMBT) and AS 1141.60.2 concrete prism tests (CPT) were conducted to assess the amount of expansion and classify the reactivity status of aggregates and aggregate blends. CPT tests have been conducted at 38°C and 60°C. Prior to undertaking AMBT and CPT studies, aggregates were prepared conforming to the grading requirements stipulated in AS 1141.60.1 and 60.2. Petrographic examination has also been undertaken to ascertain the presence of ASR.

Petrographic Examination

Prior to undertaking any AMBT and CPT studies, RILEM AAR-0 recommends that petrographic examination be undertaken to determine the potential of aggregates to alkali reactivity. In this study, both petrographic analysis and assessment were conducted following the requirements of the AS 1141.65 test method and CCANZ Technical Report TR 3 guidelines.

At the conclusion of undertaking AMBT studies, mortar bars were subjected to petrographic examination to establish the presence of any ASR and whether any other cement-aggregate reaction might have taken place. Aggregates used for mortar bars were also examined to determine if a reactive constituent had contaminated them. The extent of the reaction, the nature of the reaction products and the effects of the reaction produced in exposure to a chemical aggressive environment were also evaluated. Test methods covered under the requirements of ASTM C856 (Clauses 5.5.1, 5.5.3, 5.5.4, 5.5.6 and 5.5.8) were used to undertake these petrographic analyses.

Accelerated Mortar Bar Test

The AMBT method is primarily intended for use in the screening of aggregates and aggregate blends for ASR reactivity potential (Thomas et al. 2006). In this study, three alkali environments of 0.6M, 0.8M and 1.0M NaOH were selected for use as varying the alkali concentration for an extended test period of 56 days. Expansion results were compared at the standard ages of 10 and 21 days; however, the expansion of aggregates and aggregate blends at the end of the 56 days has also been studied to determine the reactivity status of aggregates changing with age. The standard expansion limit of 0.1% at 10 days and 0.3% at 21 days (Standards Australia 2014) were applied for all AMBT mixes including those AMBT mixes evaluated under the modified AMBT conditions of 0.6 M and 0.8 M NaOH.

Concrete Prism Tests

Expansion tests on CPT mixes for alkali contents exceeding the current alkali limit of $2.5 \text{ kg/m}^3 \text{ Na}_2\text{O}_e$ were conducted for a test duration of 12 months. This was carried out to establish the alkali threshold of the fine aggregate combinations. Five alkali contents of 2.5, 3.0, 3.5, 4.0 and 5.25 kg/m^3 have been used. The alkali threshold was determined in accordance to RILEM AAR-3.2 (Nixon & Sims 2016b) with an additional alkali content of 5.25 kg/m^3 incorporated into the test programme to mimic the 1.25% alkali content used in AS 1141.60.2. These alkali contents were achieved by adding high purity NaOH to the concrete mix water.

Due to the longer timeframe required to undertake CPT at 38°C (12 months), AS 1141.60.2 is more likely to identify aggregates that exhibit a change in reactivity status with time. However, to obtain some early indication of an aggregates' reactivity potential in a rapid method, CPT carried out at 60°C (ACPT) was also evaluated. In ACPT, results on ASR assessment are typically obtained at the end of a 6 month test period (Thomas et al. 2006). However, for this study, the aggregate combinations assessed by this method have been extended to 8 months duration to further capture any change in reactivity status resulting with time. ACPT follows a similar procedure to CPT for classifying the reactivity potential of aggregates. A review of available test data show that applying the CPT expansion limit of 0.03% at 3 months for ACPT gives the same indication of an aggregate's reactivity classification as that obtained at 12 months for CPT (Fournier et al. 2004; Thomas et al. 2006). Consequently, ACPT was also carried out at the five alkali contents chosen in the CPT study at 38°C .

Aggregate Combinations

Mortar and concrete mixes consisting of combinations of the aggregates under investigation were tested by the designated test methods. Table 2 describes the mix composition and test programme that were adopted in this study. In the CPT method, coarse and fine aggregates were tested together in a standard mix combination. In general, one component of the standard mix combination, coarse or fine aggregate, has known reactivity such that at any point in time the reactivity status of the unknown aggregate can be determined. However, certain variations of RILEM AAR-3.2 suggest that aggregates of unknown reactivities can also be evaluated as an aggregate blend (Nixon & Sims 2016b).

In this study, fine aggregate blends that were identified as reactive in AMBT were selected for further assessment using CPT and ACPT. Non-reactive coarse aggregate sourced from Australia and slowly reactive coarse aggregate NZ-B sourced from New Zealand were used to determine the long term alkali reactivity potential of the fine aggregate blends. A fine aggregate blend comprising of 3 parts reactive aggregate to 2 parts of non-reactive/slowly reactive aggregate was used as the basis of the mortar and concrete mixes to determine the alkali reactivity potential of the proposed fine aggregate blends.

Table 2. Experimental Test Programme

Standardised Tests	Mix ID	Aggregate and Aggregate Blends
AS 1141.60.1 at 80°C 3 alkali solutions: 0.6, 0.8 and 1.0 M NaOH	1a	NZ-A _f
	1b	NZ-B _f
	1c	NZ-A _f + NZ-B _f
	1d	NZ-A _f + PR _f
AS 1141.60.2 at 38 and 60°C 5 alkali contents: 2.5, 3.0, 3.5, 4.0 and $5.25 \text{ kg/m}^3 \text{ Na}_2\text{O}_e$	2c	NZ-A _f + NZ-B _f + NZ-B _c
	2d	NZ-A _f + M _f + PR _c

3.0 Results and Discussion

3.1 Accelerated Mortar Bar Test at 80°C (AMBT)

The expansion data of AMBT mixes as a function of age up to 56 days for the three alkali solutions assessed are shown in Figure 1. By applying the standard AMBT expansion limit of 0.1% and 0.3% at 10 and 21 days, respectively, for classifying aggregate reactivity (AS 1141.60.1), Mixes 1a, 1c and 1d showed expansion exceeding these 2 limits. Therefore, in accordance with these expansion limits, aggregate NZ-A_f and its blends can be classified as reactive for all the alkali concentrations tested. Under these test conditions, it is observed that the reactivity of the fine aggregate blend is dominated by the reactivity of the aggregate NZ-A_f. For Mix 1b, mortar bars in 1.0 M NaOH showed expansions of 0.03% at 10 days and 0.20% at 21 days. In accordance to AS 1141.60.1 expansion limits, this behaviour is indicative of a slowly reactive aggregate.

In general, an increase in expansion with increasing alkali concentration was observed for all AMBT mixes. At 10 days, the mortar mix composed of reactive aggregate NZ-A_f (Mix 1a) showed a lower expansion (0.13%) in 0.8 M NaOH compared to the additional expansion (0.30%) noted in 1.0 M NaOH. A similar trend in expansion was also observed at 21 days. For all the alkali concentrations assessed, the blends containing reactive aggregate (Mixes 1c and 1d) showed similar expansions. This finding suggests that as a function of increasing alkali concentration, the AMBT method appears to be limited in screening aggregate blends for their reactivity level and effectiveness in reducing expansion.

As the AMBT study was extended to 56 days, an increase in expansion was noted for all aggregates assessed including the slowly reactive aggregate NZ-B_f (Mix 1b). What is of interest is the expansion noted for aggregate NZ-B_f (Mix 1b) in 0.8 M and 1.0 M NaOH at 56 days. Based on the 21-day 0.3% expansion limit, this aggregate may also be classified as reactive with expansions of 0.44% and 0.56% noted, respectively. Overall, the fine aggregate blends comprising reactive aggregate NZ-A_f showed the highest expansion in 0.6 M NaOH, which again suggests the limitation of using AMBT to screen for reactivity levels in aggregates.

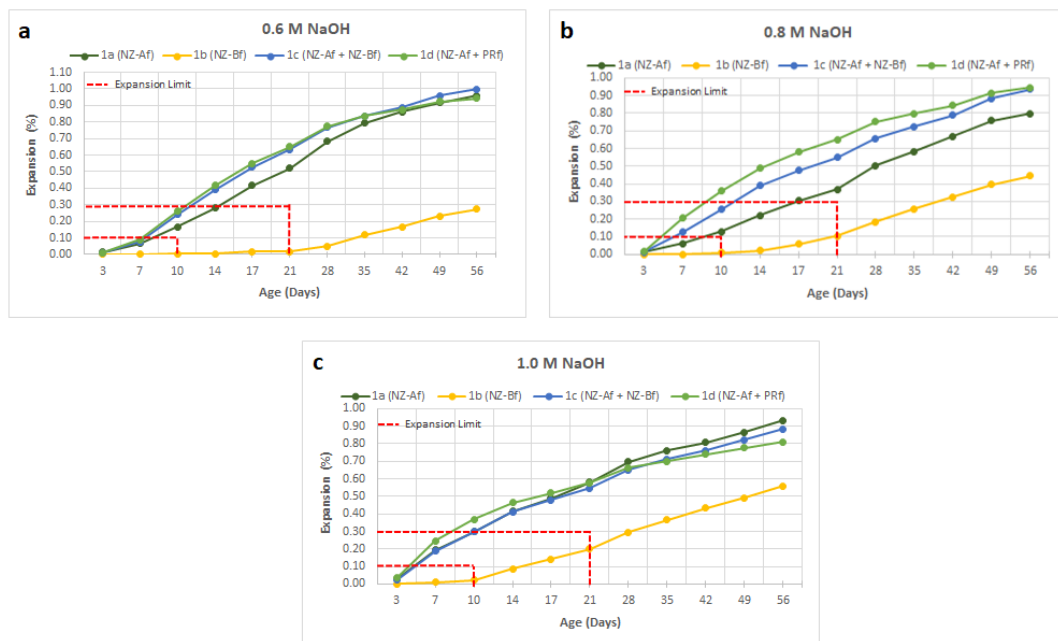


Figure 1. AMBT expansion results in (a) 0.6 M, (b) 0.8 M and (c) 1.0 M NaOH storage solution for tested aggregates

3.2 Petrographic Examination of AMBT Mixes

Following the AMBT studies, petrographic examination was conducted on mortar bars to determine if any ASR gel was present and if this gel had contributed to the expansion observed. Assessments conducted on thinly sliced representative samples of mortar bars classified as reactive under AMBT conditions showed the presence of hydrated gel containing scattered regions of calcium hydroxide. Remnants of isotropic ASR gel were also observed in the micro-fractured space of the hardened cement regions. Cracks filled with ASR gel were found to emanate through and around the periphery of aggregate components identified as glassy shards, acidic volcanics and quartz grains; components with perceived potential for ASR. Grains affected by ASR were also found to be porous from the depletion of silica. Although further microscopic studies and phase analyses are recommended, these observations are indicative of expressions of alkali silica reactivity.

3.3 Concrete Prism Tests

At present, the criteria for ascertaining aggregate classification for CPT involves the use of prescribed expansion limits taken from 3 standard test methods, as described in Table 3. For this study, however, the expansion limits set out in AS 1141.60.2 were adopted for determining the reactivity classification of the fine aggregate blends assessed.

Table 3. Assessment of aggregate reactivity based on current CPT standard methods

Interpretation	1-year Expansion Limit (%)		
	AS 1141.60.2	ASTM C1293	RILEM AAR-3
Non-reactive	< 0.03	< 0.04	< 0.05
Reactive/Potentially Reactive	≥ 0.03	≥ 0.04	≥ 0.05

3.3.1 Concrete prism test at 38°C (CPT)

Expansion measurements of CPT mixes containing varying alkali contents were taken at monthly intervals after 7 and 28 days until 12 months test duration. The expansion data captured for the fine aggregate blends assessed at varying alkali contents are shown in Figure 2. It is evident that the CPT mixes assessed for expansion show signs of shrinkage. As the alkali content was increased to 5.25 kg/m³ Na₂O_e, the expansion of CPT mixes was seen to increase. However, even though an increase in expansion was observed with an increase in alkali content, the 0.03% expansion limit for classifying reactivity in accordance to AS 1141.60.2 was not yet reached. Therefore, from these results, the fine aggregate blends were inferred to be non-reactive. Consequently, this finding suggests that these aggregate blends may perform well at alkali contents lifted from the current stipulated limit of 2.5 kg/m³ Na₂O_e (set out in CCANZ Technical Report TR 3). Overall, the CPT mixes containing NZ-B_f aggregate showed no expansion. This behaviour is consistent with the petrographic and AMBT classification of slowly reactive assigned to NZ-B_f aggregate. At 12 months, no discernible expansion was observed in CPT mixes for the fine aggregate blends containing up to and including 4.0 kg/m³ Na₂O_e alkali content. However, a minimal amount of expansion was noted for the fine aggregate blend containing non-reactive aggregate at 5.25 kg/m³ Na₂O_e.

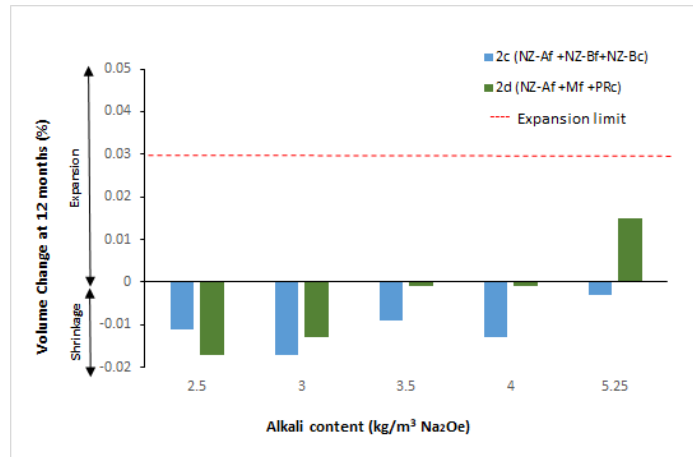


Figure 2. 12-month CPT expansion data for aggregate blends of varying alkali content

RILEM AAR-3.2 (comparable to AS 1141.60.2) proposes an effective method for determining the alkali threshold of an aggregate or aggregate combination for use in concrete. Used in conjunction with RILEM AAR-7.1, a safety margin ($-1.0 \text{ kg/m}^3 \text{ Na}_2\text{O}_e$) is applied to the alkali threshold of the aggregate or aggregate blend under evaluation to establish a safe alkali limit at which potentially reactive aggregates can be used (Nixon & Sims 2016a). The alkali threshold is defined as the highest alkali content that is found to not induce significant expansion in an aggregate or aggregate blend. As discussed, the results in this study show no evidence of expansion for the fine aggregate blends assessed at alkali contents up to $4.0 \text{ kg/m}^3 \text{ Na}_2\text{O}_e$. Although further testing is recommended, this finding suggests that with the implementation of a safety margin the current alkali limit in New Zealand ($2.5 \text{ kg/m}^3 \text{ Na}_2\text{O}_e$) may be lifted to $3.0\text{-}3.5 \text{ kg/m}^3 \text{ Na}_2\text{O}_e$ to incorporate the fine aggregate blends evaluated in this study. A similar approach can thus be adopted to determine the alkali thresholds that apply to other aggregates or aggregate combinations intended for use in concrete.

The effect of age on the rate of expansion of CPT mixes was also considered. For the highest alkali content assessed in this study ($5.25 \text{ kg/m}^3 \text{ Na}_2\text{O}_e$), this data is shown in Figure 3. The rate of expansion of both fine aggregate blends evaluated is noted to increase with age. Although the trends in the rate of expansion appeared to be increasing with age, the 0.03% expansion limit was not reached. This finding suggests that monitoring expansion up to 12 months, and beyond, is beneficial in establishing the rate of expansion that applies for classifying the reactivity status of aggregates as a function of age.

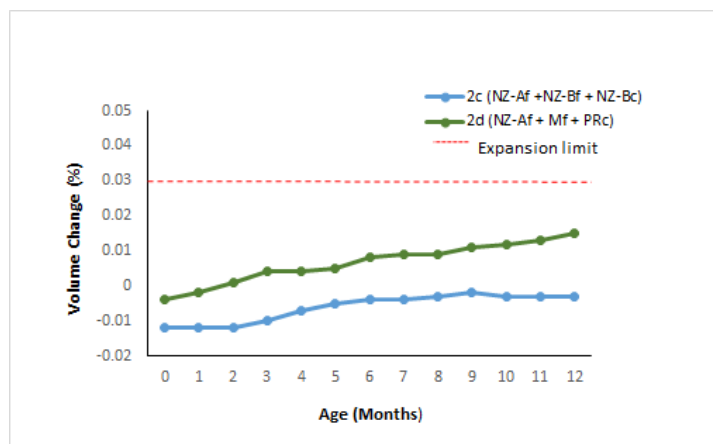


Figure 3. CPT expansion data of aggregate blends at 38°C and 5.25 kg/m^3 alkali content

3.3.2 Concrete prism test at 60°C (ACPT)

The reactivity classification of fine aggregate blends assessed under ACPT conditions have also been interpreted using the CPT expansion limit of 0.03% applied at 3 months (Thomas et al. 2006). This expansion data is shown in Figure 4. From both fine aggregate blends evaluated, neither was found to reach the 0.03% expansion limit. Therefore, following the reactivity classification nomenclature used in AS 1141.60.2 both fine aggregate blends are inferred to be non-reactive. It is interesting to note that like in the CPT studies, the ACPT mixes containing slowly reactive aggregate (Mix 2c) were again observed to exhibit shrinkage for all the alkali contents evaluated up to 4.0 kg/m³ Na₂O_e. In terms of expansion, the fine aggregate blend containing the non-reactive aggregate was found to expand more. A similar observation was noted for this aggregate blend in the CPT studies conducted at 38°C for 12 months.

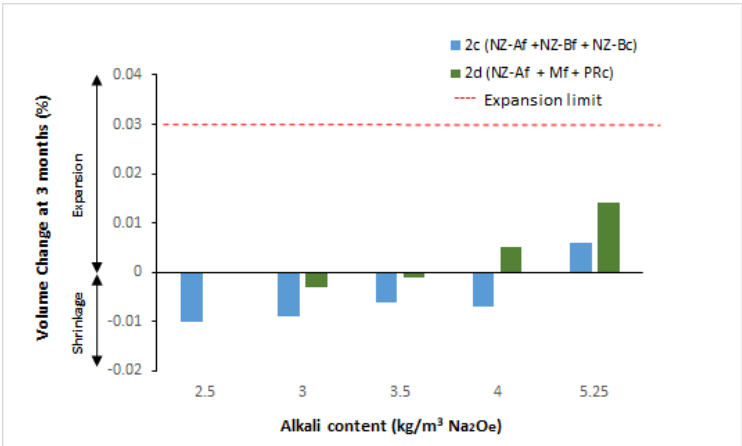


Figure 4. 3-month ACPT expansion data for aggregate blends of varying alkali content

The rate of expansion with age of the fine aggregate blends evaluated in this study was also considered at the maximum alkali content (5.25 kg/m³ Na₂O_e). This data is reflected in Figure 5. In general, an increase in the rate of expansion was observed with age for both fine aggregate blends assessed. However, the rates of expansion differed significantly between both blends. For Mix 2c, the increase in reactivity with age was attributed to the slowly reactive nature of the aggregate NZ-B_f. In comparison, a steep increase in the rate of expansion was observed for Mix 2d with distinct changes noted in the slope at both 3 and 7 months. A similar behaviour in the rate of expansion was also observed at 5 and 8 months for the CPT study conducted on the same fine aggregate blend evaluated at 38°C. However, the higher expansion noted under ACPT conditions suggests that this blend exhibits a tendency to cause deleterious ASR with age. Therefore, careful consideration is required to determine the reactivity classification that applies at any given age when ACPT is considered as an alternative method for screening the reactivity potential of aggregates.

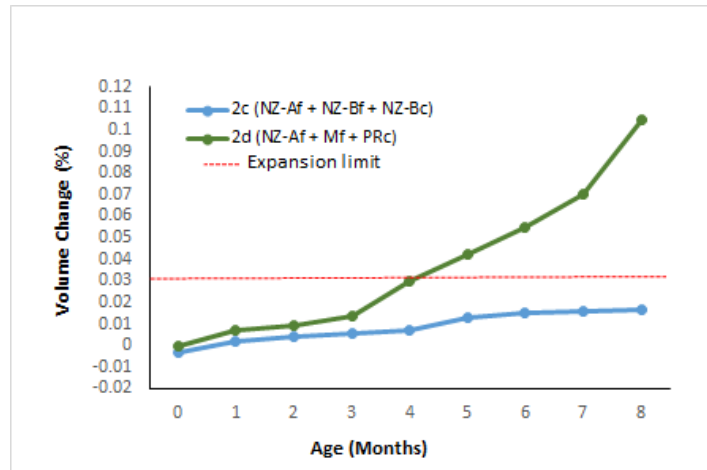


Figure 5. ACPT expansion data of aggregate blends at 60°C and 5.25 kg/m³ alkali content

From the CPT and ACPT studies that have been undertaken, the trends observed in expansion for changes in the alkali content and age appear to be similar in behaviour with the exception that ACPT data shows significantly higher expansion. Elevating the temperature in the ACPT method to 60°C is the most probable cause for the observed increase in expansion. However, a positive correlation can still be established between the expansion data obtained from ACPT studies at 3 months and the expansion data obtained from CPT studies at 12 months.

4.0 Conclusions

In this investigation, AMBT, CPT, ACPT and petrographic examination have been utilised as screening tools in establishing the alkali thresholds that apply in the safe use of potentially reactive aggregates in concrete. The alkali thresholds determined for the fine aggregate blends used in this investigation have been derived following the guidelines specified under RILEM AAR-3.2 and AAR-7.1.

From the results obtained, the following conclusions can be drawn:

- AMBT is limited in its ability in screening the effectiveness of fine aggregate blends in reducing the potential to expansion by ASR.
- Although the fine aggregate blends assessed have shown expansion below the CPT expansion limit of 0.03%, an increase in expansion with increasing alkali content, age and elevated temperature is evident. As age is therefore a critical factor in determining the reactivity potential of aggregates including those that are non-reactive after standard testing periods, it is recommended that CPT should be extended up to 2 years duration. This will allow for investigations to be undertaken in the long-term to establish changes in the reactivity potential of aggregates. Subsequent petrographic examination on CPT mixes is also encouraged to ascertain the presence of ASR.
- The maximum alkali content that will not induce ASR is dependent on the reactivity level of the aggregate used in the concrete. It can therefore be concluded that the potential exists for the revision of the current alkali limits set for concretes in New Zealand to accommodate the safe use of potentially reactive aggregates with increased alkali contents in concrete production. The current alkali limit set of 2.5 kg/m³ is a conservative limit and there is the potential for it to be reviewed upon a comprehensive study that also includes additional aggregates sourced from other locations in New Zealand. This recommendation can be further applied to codes of practice in other countries.

- A strong correlation in expansion data between CPT and ACPT exists. The reactivity status of the aggregates determined from CPT expansion data at 12 months corroborates to ACPT expansion data at 3 months.

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