Evaluation of Western Australian Aggregates for Alkali-Reactivity in Concrete

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ABSTRACT

Nine aggregate sources from Western Australia have been assessed for use in concrete with particular reference to dimensional stability and alkali-reactivity. The aggregates include siliceous river gravel, metamorphosed basalts and dolerite, sandstone, granite, limestone, and amphibolite schist. Petrological examination, X-ray powder diffraction, quick chemical test, mortar bar test, concrete prism tests, and dimensional stability measurement of aggregate and concrete have been used in the evaluation of these sources. Two levels of cement alkali, 0.84% and 1.38% (equivalent Na_2O) were used in the mortar bar and concrete prism tests. The applicability of each test method is discussed. Two river gravels and a metadolerite were judged as potentially reactive when used with high alkali cement, and other aggregates as innocuous even at the high alkali content employed.

INTRODUCTION

Alkali-aggregate reaction (AAR) in concrete is relatively uncommon in Australia. Cole et al. (1981) and Shayan and Lancucki (1986) have reported AAR in a dam in Victoria and in a bridge in Western Australia respectively. A confirmed occurrence of AAR exists in north Queensland and a fourth occurrence, allegedly exists in a major bridge in Queensland. The two aggregate types (largely quartzite and crypto-crystalline chert) used in major concrete structures in Queensland were found innocuous (Carse 1984). However, in view of the experimental conditions employed this conclusion needs verification.

Inadequate testing, by using the quick chemical test (Australian Standard 1141, Section 39 1974) and the standard mortar bar test (Australian Standard 1141, Section 38 1974) only, may be responsible for the slowly expanding Australian aggregates not being identified as potentially reactive. These tests are known to be unsatisfactory for some aggregates (Grattan-Bellew and Litvan 1976, Nixon and Bollinghaus 1983).

In view of the confirmed AAR in a large bridge in Western Australia containing metadolerite, this material and eight other aggregate sources proposed for the construction of new bridges have been evaluated in this work for AAR, using the quick chemical test, the mortar bar test, non-standard concrete prism tests, and petrographic and X-ray diffraction techniques. Moisture sensitivity and the related dimensional changes of aggregate which affect the concrete (Roper 1960, Snowden and Edwards 1962, Cole 1979) were also investigated.

EXPERIMENTAL

The Aggregates

Most of the quarried rock in Western Australia is Precambrian and may have been exposed to several metamorphic events. The rocks are either granitic or mafic, with large variations in each category (Key 1977). A brief mineralogical and petrological description of the rock types used follows.

TKA river gravel: Minerals present (XRD) were quartz with minor amounts of feldspar, kaolinite, mica, and iron oxide. Petrologically the gravel was heterogeneous, varying from very fine to medium in texture and red to black in colour. It contains sandstone, jasper, and quartzite. Some sandstone contains secondary quartz, some amorphous silica and some iron oxide cement. Undulatory extinction is present in most quartz grains, although the angle varied from as high as 54^{o} to as low as $8\text{-}10^{o}$.

HC river gravel: Mineralogical composition (XRD) varied from pure hematite, goethite, and quartz to a mixture of these with minor mica, feldspar, kaolinite, and chlorite. Iron oxide particles are dense and some are banded. Siliceous particles contain crypto-crystalline quartz sometimes with iron oxide bands and staining. Some cherty particles may contain amorphous silica. Quartzite and feldspatic quartzite particles are also present. Quartz grains usually show undulatory extinction angles above 15^{o}.

SPK metabasalt, RMX metabasalt, and TR amphibolite schist: These were very similar in mineralogy (XRD), containing tremolite/actinolite, plagioclase, K-feldspar, chlorite, and quartz. They are all fine to medium grain green rock mottled with white feldspar and quartz. Some quartz veins are present and a large degree of orientation is seen in thin sections. Quartz is fine grained and appears corroded, some with undulatory extinction angles of $15\text{-}20^{o}$.

GSN metadolerite: This rock consists of chlorite, hornblende, quartz, feldspar, and mica (XRD). It is a very fine to fine grey/green rock with recrystallized fine quartz grains which show undulatory extinction angles generally below 20^{o}. A trace amount of iron sulfide may be present.

NBB sandstone: This consists largely of quartz with minor kaolinite with amorphous silica (hump in the XRD pattern). The rock is a fine to medium-grained quartz sand cemented with amorphous silica, estimated at about 20-30% of the rock. Some quartz grains show undulatory extinction from $<15^{o}$ to $25\text{-}30^{o}$.

LR granite: Minerals present (XRD) were plagioclase, K-feldspar, quartz, and minor chlorite and mica. It is a granite with perthitic and graphic texture with some overgrowth on plagioclase which show sericitic alterations. Chlorite appears primary and as an early replacement of biotite.

NGM limestone: This is composed of calcite with a trace of quartz. The calcite is fine grained with occasional oolites and some euhedral crystals. The fine quartz is spread throughout the rock.

The presence of strained quartz, amorphous and crypto-crystalline silica, indicates that some of these rocks could be potentially reactive to the alkali in cement.

The siltstone that caused AAR in an Australian dam (Cole et al. 1981) had a movement of 0.06 to 0.14% on wetting/drying, sufficient to produce distress and cracking in the concrete. The measured wetting/drying length change of the nine rock types used in the present study ranged from 0.001 to 0.011% with an average of 0.005% indicating the lack of moisture sensitivity of the rocks tested.

Testing for Potential Alkali-reactivity

The potential alkali-reactivity of aggregates was tested according to the Australian Standard 1141, Section 39 (1974), which is the same as ASTM C289. All the rocks were classified as innocuous, except NBB sandstone which contains large amounts of amorphous silica. The two river gravels, classed as innocuous, contain large amounts of crypto-crystalline quartz which could be reactive when used in concrete. Further, the metadolerite which has shown reaction in service was passed as innocuous. Generally, in this test, aggregates having an S_c (dissolved silica) value below 100 mmoles/L are considered non-reactive (Vivian 1983), although some authorities require less than 50 mmoles/L for non-reactive aggregate (Grattan-Bellew 1983a).

Cement and Aggregate Combinations

Mortar bar and concrete samples were prepared using plain cement and cement with added alkali. The cement contained 0.62% Na_2O and 0.41% K_2O, i.e., 0.89% Na_2O equivalent based on total alkali content. The amount of active alkali (Brandt et al. 1981) was 0.61% Na_2O and 0.35% K_2O, giving 0.84% Na_2O equivalent. To provide a higher level of alkali, sufficient KOH was added in the mixing water to produce an extra 0.54% Na_2O equivalent, making a total soluble alkali of 1.38% Na_2O equivalent.

Mortar bar test: Mortar bars were made using both the plain cement and that with added alkali. The mortar bars had a wet density of 2343 kg/m^3 and a cement content of 636 kg/m^3, with alkali contents of 5.34 and 8.78 kg/m^3 as Na_2O for the plain cement and cement with added alkali, respectively. Table 1 shows the mortar bar expansion for the cement with 1.38% Na_2O equivalent. None of the aggregates could be classed as reactive according to the standard mortar bar method (6-months expansion <0.1%). Expansion of HC river gravel and GSN metadolerite mortar bars reached 0.1% after 12 months, but TKA river gravel mortar bars expanded by only 0.051% even at 18 months. The TKA river gravel mortar bar surfaces showed large amounts of gel formation, and the aggregate particles appeared to have reacted with the alkali. To avoid classifying a potentially reactive aggregate as non-reactive, the recommended expansion of 0.1% at 6 months has been lowered by various researchers (e.g. Heck 1983 (0.075%), US Army Corps of Engineers 1983 (0.1% at 12 months), Vivian 1983 (0.05%)).

TABLE 1 - Mortar bar expansion (%) for cement of 1.38% Na_2O equivalent

Rock	3 months	6 months	12 months	18 months	Remarks
TKA river gravel	0.018	0.037	0.048	0.051	Extensive gel formation
HC river gravel	0.016	0.042	0.102	0.123	Gel formation
SPK metabasalt	0.015	0.016	0.024	0.030	No gel
RMX metabasalt	0.014	0.014	0.019	0.024	No gel
TR amphibolite schist	0.011	0.015	0.014	0.017	No gel
GSN metadolerite	0.018	0.055	0.097	0.121	Gel formation
NBB sandstone	0.012	0.016	0.014	0.016	Some white spots
LR granite	0.014	0.023	0.033	0.038	No gel
NGM limestone	0.005	0.007	0.009	0.009	No gel

The rate of expansion (day$^{-½}$ x 10^3) were calculated as in Grattan-Bellew (1981). Values of 10.3, 8.5, and 4.4 were obtained for HC gravel, GSN metadolerite and TKA gravel, respectively, when used with the 1.38% alkali cement, and 5.6, 5.0, and 0.5, respectively, when used with the 0.84% alkali cement. Values greater than 6.4 are considered deleterious.

Because of continued mortar bar expansion (HC river gravel and GSN metadolerite) and extensive gel formation (TKA river gravel), these rocks have been ranked potentially reactive with high alkali cement. The exudation of large amounts of gel from the latter mortar bars may have been the reason for the lack of a large expansion.

Concrete tests: The concrete mix used for both the 0.84% and the 1.38% alkali cements was a coarse aggregate:sand:cement:water ratio of 2.62:1.55:1:0.46, and the aggregate was largely of 10-20 mm size. The cement content of 407 kg/m^3 gives alkali contents of 3.42 and 5.62 kg/m^3 as Na_2O for the two levels of alkali, which are sufficient to produce deleterious expansions (Oberholster 1983).

The results of expansion measurement on concrete prisms (Australian Standards 1012, Part 13-1970) made with the 1.38% alkali cement and kept in a humidity cabinet at 38-40°C are given in Table 2. The humidity in the cabinet was unsatisfactory (~ 90%) in the first six months because some prisms showed a shrinkage rather than an expansion and, depending on their position in the cabinet, were noticeably drier than others. After the first six months the prisms were transferred to a fog room at 23°C for three months and then returned to the cabinet which was modified to increase the humidity. Afterwards the prisms were wet uniformly throughout the cabinet, and the conditions were favourable for any potential expansion to take place. Despite the small initial shrinkage of some of the prisms, that occurred because of small water losses (0.18 to 1.0%), the remaining amount of mixing water was probably sufficient for any potential reaction to take place. The reaction product, however, would need additional water to cause expansion.

TABLE 2 - Expansion of concrete prisms* (%) made with the 1.38% alkali cement

Rock	3 months	6 months	12 months	24 months	Remarks
TKA river gravel	0.007	0.004	0.017	0.031	Prisms cracked, white exudation and dark wet appearance
HC river gravel	-0.012	-0.010	-0.005	+0.001	Wet-looking patches and a few white spots. No obvious cracking
SPK metabasalt	0.002	0.005	0.005	0.007	-
RMX metabasalt	-0.006	-0.005	-0.003	0.0001	-
TR amphibolite schist	0.006	0.002	0.010	0.010	-
GSN metadolerite	-0.003	0.001	0.006	0.007	A few wet-looking patches - no sign of cracking
NBB sandstone	-0.019	-0.012	-0.009	-0.004	A few white spots
LR granite	-0.014	-0.006	-0.004	-0.002	-
NGM limestone	-0.007	-0.003	-0.001	+0.003	-

* Humidity was unsatisfactory in the first 6 months.

After two years, the increase in the mass of the concrete prisms was 0.98 to 1.2%, similar to that for concrete prisms made with TKA gravel (0.98%) which had expanded and cracked. Therefore, the slight initial drying was probably not responsible for the lack of expansion at two years. Only the 0.031% expansion reached by TKA gravel could be classed as a deleterious expansion according to the Canadian Standards (Grattan-Bellew 1983b). The observed reaction of GSN metadolerite in the bridge (Shayan and Lancucki 1986) was not reflected in the results of the concrete prism test. However, subjecting other concrete prisms made with GSN metadolerite and TKA and HC river gravels (with both the 0.84% and the 1.38% alkali cements) to cyclic wetting/drying, resulted in microcrack formation, whereas concrete prisms made with other aggregates were not affected by cycling.

Comparison of mortar bar and concrete prism tests: Discrepancy between the results of mortar bar and concrete prism tests, has been observed elsewhere (Oberholster 1981, Grattan-Bellew 1981, Nixon and Bollinghaus 1983).

Possible reasons for the discrepancy observed for the Western Australian aggregates are:

(1) TKA river gravel may show a pessimum effect when used as fine aggregate in mortar bars, therefore not expanding fully when used at 100% of total aggregate, but when used as coarse aggregate (much smaller surface area) in concrete prisms showed a deleterious expansion.

(2) The amount of reactive component in HC river gravel and GSN metadolerite is probably small and dispersed in the matrix and not readily accessible when the aggregate is coarse (concrete prisms) but more readily available when the aggregate is fine (mortar bars). Cyclic wetting/drying seems to enhance the reaction with the coarse aggregates.

(3) The concrete prisms may have shown larger expansions had a continuous aggregate grading been used instead of the approximately 10-20 mm size range. This would be in agreement with the argument in (2) above.

(4) The cement and alkali contents (per m^3) of the mortar bars were much higher than those of the concrete prisms, and consistent with larger expansions for the former.

CONCLUSIONS

(1) The quick chemical test (AS 1141, Section 39-1974) is unreliable, whereas petrographic examination for identifying alkali-reactive aggregate was helpful but not always conclusive.

(2) The results of this work show that the standard mortar bar test (AS 1141, Section 38 1974) does not always predict reactivity. A separate interpretation of longer term results and visual inspection of the specimens was needed for deciding on the potential reactivity of the aggregates.

(3) This work shows that both mortar bar and concrete prism tests (using high alkali cement) should be used together for evaluation of reactivity of aggregate with alkali. If mortar bar expansion at 6 months is less than 0.03% and there is no gel formation, the aggregate is likely to be innocuous. If expansion at 6 months is greater than 0.03% or there is gel formation, concrete prisms should also be tested. If concrete prism expansion exceeds 0.03%, the aggregate is likely to be reactive, and if it is below 0.03%, the aggregate is probably innocuous. It is important to consider the shape of the expansion curve and judge whether the expansion has ceased or is continuing.

(4) The two river gravels and the metadolerite are judged as potentially reactive when used in combination with high alkali cement, but may be innocuous with low alkali cements provided no alkali is added to the concrete from extraneous sources. All other aggregates are judged innocuous even at the high level of alkali used (1.38%).

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REFERENCES

Brandt, M.P., Oberholster, R.E., and Westra, W.B. 1981. In Proc. 5th Int. Conf. on Alkali-Aggregate Reaction in Concrete, ed. R.E. Oberholster, Capetown, S252/10, 6 pp.

Carse, A. 1984. In Proc. 12th Aust. Rd. Res. Board Conf., Part 2, Hobart, 1-9.

Cole, W.F. 1979. Cem. and Conc. Res. 9:425-430.

Cole, W.F., Lancucki, C.J., and Sandy, M.J. 1981. Cem. and Conc. Res. 11:443-454.

Grattan-Bellew, P.E., and Litvan, G.G. 1976. In Proc. Symposium on the Effect of Alkali on the Properties of Concrete, London, 227-242.
Grattan-Bellew, P.E. 1981. In Proc. 5th Int. Conf. on Alkali-Aggregate Reaction in Concrete, ed. R.E. Oberholster, Capetown, S252/9, 13 pp.
Grattan-Bellew, P.E. 1983a. In Proc. 6th Int. Conf. on Alkalis in Concrete, eds G.M. Idorn and S. Rostam, Copenhagen, 303-314.
Grattan-Bellew, P.E. 1983b. Materials and Construction/Research and Testing, No. 94, 243-250.
Heck, W.J. 1983. Cement, Concrete and Aggregates, CCAGDP 5:47-53.
Key, C.A. 1977. In Workshop on the Geology of Quarries, ed. L.J. Wylde, Aust. Road Res. Report ARR80, 33-41.
Nixon, P.J., and Bollinghaus, R. 1983. In Proc. 6th Int. Conf. on Alkalis in Concrete, eds G.M. Idorn and S. Rostam, Copenhagen, 329-336.
Oberholster, R.E. 1981. In Proc. 5th Int. Conf. on Alkali-Aggregate Reaction in Concrete, ed. R.E. Oberholster, Capetown, S252/8, 11 p.
Oberholster, R.E. 1983. In Proc. 6th Int. Conf. on Alkalis in Concrete, eds G.M. Idorn and S. Rostam, Copenhagen, 419-433.
Roper, H. 1960. Journal of the PCA Res. and Develop. Labs. 2:13-19.
Shayan, A., and Lancucki, C.J. 1986. In Proc. 7th Int. Conf. on Alkali-Aggregate Reaction, Ottawa (this volume).
Snowden, L.C., and Edwards, A.G. 1962. Mag. Conc. Res. 14:109-116.
Standards Association of Australia 1970. Australian Standard AS 1012, Part 13. Method for the determination of drying shrinkage of concrete.
Standards Association of Australia 1974. Australian Standard AS 1141, Section 38. Potential alkali reactivity by mortar bar.
Standards Association of Australia 1974. Australian Standard AS 1141, Section 39. Potential reactivity of aggregates (chemical method).
United States Corps of Engineers 1971. Department of the Army, Office of the Chief Engineers, Engineer Manual EM1110-2-2000, B2-B6.
Vivian, H.E. 1983. In Proc. 6th Int. Conf. on Alkali in Concrete, eds G.M. Idorn and S. Rostam, Copenhagen, 365-368.