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Evaluation of laboratory test method for determining the potential alkali contribution from aggregate and the ASR safety of the Three-Gorges dam concrete

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Abstract

The releasable alkali from granite, which was used in the Three-Gorges concrete dam project in China, and from gneiss and feldspar was estimated by extraction in distilled water and super-saturated $Ca(OH)_2$ solution. Results show that: i) the finer the particles and the higher the temperature, the greater and faster the release of alkali; ii) compared with extraction by distilled water, super-saturated $Ca(OH)_2$ solution had a stronger activation on feldspar than on granite and gneiss; iii) for the three rocks tested, thermal activation had the largest effect on gneiss and a lower and similar effect on granite and feldspar. For very fine particles, temperature had a similar effect on the release of alkali by all three rocks.

Because the aggregate used in the Three-Gorges dam concrete is non-reactive and a low calcium fly ash was used in the concrete, ASR would not be an issue for the dam, despite the release of alkali from the aggregate into the concrete.

Keywords: Alkali aggregate reaction (C); Alkali release; Pore solution (B); Granite; Feldspar; Gneiss; Three-Gorges dam

1. Introduction

The Three-Gorges concrete dam, which is being built on the Yangtze River in China, is one of the largest hydraulic projects in the world. Assuring the long-term durability of the concrete and especially preventing the risk of premature concrete deterioration due to alkali-silica reaction (ASR) is of paramount importance in the development of the project. The comprehensive testing program developed for mitigating the risk of ASR in the Three-Gorges dam project included the evaluation of the potential alkali-reactivity of the aggregate using conventional methods, but also the determination of the potential contribution of alkali to the concrete pore solution from the aggregate. The diorite-plagioclase granite used in the concrete for the project contains plagioclase (feldspar) and biotite (mica), which belong to the minerals susceptible to contribute alkali to concrete pore solution, thus raising some concerns about the its effect on the long-term stability of the silica mineral (quartz) present in the granite. This paper reports the results of the alkali release investigations performed in the Three-Gorges testing program for ASR mitigation.

1.1. Alkali contribution from aggregate

Many field and laboratory investigations on concrete, mortar or aggregate samples have shown, or at least suggested, that given enough time, some aggregates (or mineral phases present within aggregate particles) can supply significant amount of alkali to the concrete pore solution [1–10]. Excluding unwashed marine sands and gravels and some artificial materials (expanded shale, artificial glass), the most susceptible mineral phases comprise volcanic glass, nepheline, feldspars, micas, clay minerals, and dawsonite. Feldspars and micas are the mineral phases most susceptible to contribute alkali to the concrete pore solution. In the deterioration of Chambon dam in France, significant amount of alkalis are thought to have been supplied to the concrete pore solution by the micas and

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feldspars present in aggregate particles of the gneiss, mica-schist and granite [11].

Based on laboratory investigations, Bérubé et al. found that the amount of alkali that could be supplied to the concrete pore solution by aggregates could vary from <0.1 to 12.7 kg/m^3 Na_2Oe in the very long term, depending on the rock type [8]. If the aggregate is potentially alkali-reactive, due to its large volume, the release of even small amounts of alkali from the aggregates, could, over time, have a significant impact on the durability of concrete. In fact, ASR deterioration in some concrete structures constructed with low-alkali cement or with cement supplying less than 3 kg/m^3 Na_2Oe was attributed to, or could be explained by the leaching of alkali from certain kinds of alkali-bearing phases within the aggregates [6–13].

1.2. Test procedure for evaluating the alkali contribution by aggregates

A number of different experimental procedures have been used in the past to estimate the alkali contribution by aggregates to the concrete pore solution [8,9]. Most of them involve immersion in a lime-saturated solution, with or without solid lime in excess, or in alkaline solutions (NaOH or KOH). Some other procedures are based on immersion in other types of solutions (e.g. EDTA). The amount of releasable alkali from aggregate varies depending on the different type and proportion of alkali-bearing mineral phases within the aggregate, as well as the testing conditions used, such as the aggregate fineness, the type of extraction solution, the aggregate/solution ratio, the temperature and the test duration. There is still no consensus on the absolute amount of alkali that can be derived from the aggregate and no standard test procedure is yet available to estimate the amount of releasable alkali. Immersion in a saturated or super-saturated lime solution has been and is still the most commonly used procedure for assessing the alkali contribution by aggregates.

In order to assess the laboratory immersion test for releasable alkali from aggregate and the possible alkali contribution by the granite used in the Three-Gorges concrete project, the effects of aggregate fineness, the composition of solution used to extract the alkali, and solution temperature were studied. The study investigated the granite used in the Three-Gorges and, for comparison, a gneiss and a feldspar.

2. Materials and methods

2.1. Mineralogical and chemical composition of aggregates

Three aggregates were used in this study, namely, the pre-Sinian granite used in the Three-Gorges project, a locally quarried pre-Sinian gneiss and a quarried K-feldspar from Jinchun, Hubei province. The mineral phases and their textures were described previously [14–16]. The granite contained mainly plagioclase feldspar (60%) and quartz (25%), with smaller amounts of biotite (10%) and hornblende (5%). The grain size of quartz is 0.3∼2.0 mm; no microcrystalline quartz was observed. Strained quartz showing undulatory extinction was common in the granite, but the extinction angles were small, i.e. about 4°. Some altered plagioclase particles were also observed. The gneiss contained mainly plagioclase (61%) and quartz (16%), with smaller amounts of biotite (10%) and sericite (7%); it was described as a biotite-plagioclase gneiss. The grain size of plagioclase, quartz and biotite were similar to that in granite. The extinction angles of quartz grains varied from 1° to 3°. Some altered plagioclase grains were present in the gneiss. The main phase in the K-feldspar, was sanidine (>80%), with smaller amounts of microcline (<10%) and quartz (<10%). The chemical compositions of the aggregates are listed in Table 1.

2.2. Test procedure used in this study

In this study, rock particles were immersed in super-saturated $Ca(OH)_2$ solution and, for comparison purposes, in distilled water. The aggregates were crushed and sieved to obtain the size fractions of 10–12, 5–10, 1.25–5, 0.63–1.25, 0.15–0.63 and 0.08–0.15 mm. Each size fraction was washed in distilled water to eliminate crushing dust covering the particles. Five oven-dried sub-samples of 25 g each were prepared for each of the size fractions of the selected aggregates. Four of them were put into polyethylene bottles with 50 ml of saturated $Ca(OH)_2$ solution with 1 g of excess solid. The bottles were then sealed and stored in separate water baths maintained at 20, 40, 60 and 80 °C. The fifth sub-sample was placed into a polyethylene bottle with 50 ml of distilled water and stored in the water bath at 80 °C as a control.

After 3, 7, 14, 21 and 28 days, the bottles were shaken and after the aggregate settled, 10 ml of solution was then removed from each bottle each time. This solution was filtered and analyzed for Na_2O and K_2O by flame photometry. The bottles were then refilled with 10 ml of blank solution (saturated $Ca(OH)_2$ solution or distilled water) and stored in the water baths until the next measurement. This was done to maintain the aggregate to solution ratio and the “strength” of the storage solution. This procedure may, however, have disturbed the equilibrium established between solid and solution phases, thus contributing to higher alkali release, and in retrospect it would

Table 1
Chemical composition of the aggregates (%)

	Gneiss	Granite	K-feldspar
SiO_2	49.70	60.18	72.10
TiO_2	0.39	0.63	
Al_2O_3	15.49	17.16	14.97
Fe_2O_3	3.35	0.86	0.40
FeO	5.37	4.12	
MnO	0.12	0.09	
MgO	5.04	3.14	0.49
CaO	13.36	4.50	0.92
Na_2O	3.04	4.74	3.44
K_2O	1.26	2.21	6.40
Na_2O_{eq}	3.87	6.19	7.65
P_2O_5	0.07	0.14	
LOI	2.71	1.78	
Total	99.90	99.95	98.72

Table 2
Alkali released at 80 °C, % of total Na_2Oe in aggregate

Rock	Size (mm)	Time (days) in H_2O					Time (days) in super-saturated $Ca(OH)_2$ solution					
		3	7	14	21	28	3	7	14	21	28	56
Granite	10–12	0.018	0.023	0.025	0.028	0.033	0.026	0.037	0.041	0.047	0.059	0.097
	5–10	0.021	0.026	0.029	0.032	0.037	0.029	0.041	0.049	0.055	0.067	0.120
	1.25–5	0.028	0.035	0.039	0.046	0.051	0.040	0.055	0.064	0.079	0.091	0.170
	0.63–1.25	0.039	0.045	0.056	0.063	0.082	0.060	0.072	0.084	0.092	0.126	0.237
	0.15–0.63	0.064	0.074	0.081	0.101	0.107	0.107	0.118	0.133	0.154	0.185	0.359
	0.08–0.15	0.128	0.143	0.153	0.177	0.191	0.232	0.254	0.307	0.370	0.457	0.829
Gneiss	10–12	0.033	0.043	0.059	0.071	0.084	0.070	0.091	0.126	0.144	0.225	0.423
	5–10	0.041	0.069	0.101	0.128	0.200	0.091	0.148	0.189	0.262	0.383	0.763
	1.25–5	0.069	0.137	0.192	0.250	0.304	0.217	0.314	0.368	0.450	0.529	0.955
	0.63–1.25	0.118	0.184	0.266	0.334	0.382	0.313	0.440	0.486	0.560	0.735	1.192
	0.15–0.63	0.168	0.302	0.369	0.404	0.567	0.438	0.572	0.647	0.747	0.989	1.648
	0.08–0.15	0.386	0.461	0.557	0.643	0.897	0.874	1.040	1.112	1.322	1.663	2.889
K-feldspar	10–12	0.010	0.012	0.014	0.016	0.018	0.043	0.056	0.067	0.079	0.091	0.165
	5–10	0.011	0.014	0.016	0.018	0.022	0.054	0.064	0.077	0.093	0.112	0.198
	1.25–5	0.012	0.016	0.021	0.025	0.028	0.061	0.078	0.098	0.114	0.134	0.252
	0.63–1.25	0.014	0.020	0.025	0.029	0.035	0.079	0.104	0.128	0.148	0.191	0.353
	0.15–0.63	0.022	0.028	0.032	0.036	0.048	0.108	0.138	0.161	0.195	0.246	0.417
	0.08–0.15	0.046	0.061	0.072	0.083	0.095	0.250	0.302	0.370	0.424	0.519	0.981

have been better to remove 10 ml portions of the suspension without replacing it with fresh solution. For the particles stored in the super-saturated $Ca(OH)_2$ solutions, alkali released at 56 d was also determined. The results were expressed as Na_2Oe% by mass of total alkali in aggregate.

3. Results and discussion

3.1. Effect of solution used for alkali extraction

Table 2 shows the alkali released with time at 80 °C by the various size fractions of granite, gneiss and feldspar particles in water and super-saturated $Ca(OH)_2$ solution. It shows that in both the super-saturated $Ca(OH)_2$ solution and distilled water, some alkali was released from all size fractions of the three aggregates; the amount increased with time. Comparison of alkali released in water with that in super-saturated $Ca(OH)_2$ solution shows that a significantly higher percentage of alkali was released in the super-saturated $Ca(OH)_2$ solution than that in distilled water. At 28 days, for all size fractions of granite and gneiss, the amount of alkali released in super-saturated $Ca(OH)_2$ solution was almost double that released in distilled water. The amount of alkali released by the K-feldspar in saturated $Ca(OH)_2$ solution was about five times that in water for the same exposure duration.

Interestingly, although gneiss had the lowest alkali content among the three rock samples tested, it gave the highest values for both the absolute amount and the percentage of released alkali both in distilled water and in super-saturated $Ca(OH)_2$ solution. K-feldspar, with the highest alkali content of 7.65% as Na_2Oe, had the smallest absolute amount and percentage of alkali released into water, but in super-saturated $Ca(OH)_2$ solution, it had a higher amount of released alkali than the granite. The difference is probably due to the differences in the

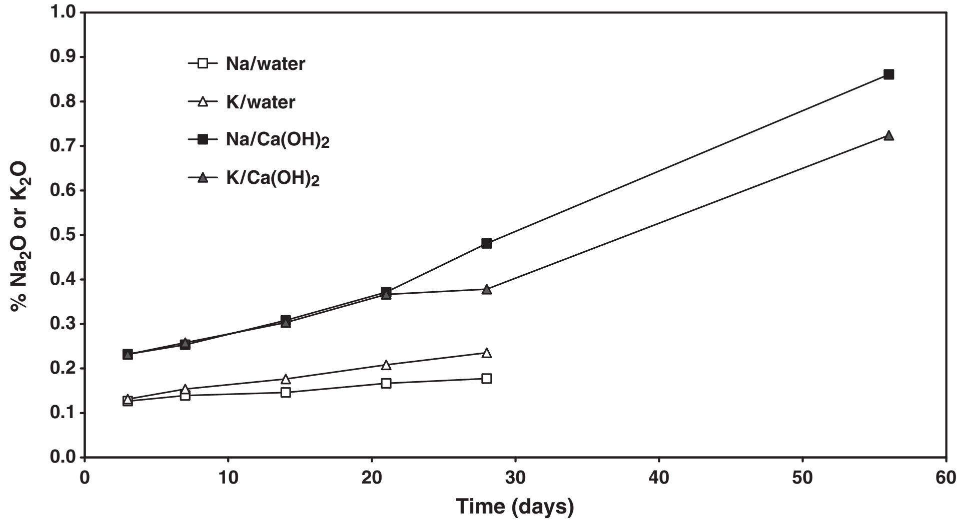

Fig. 1. Na_2O and K_2O released by granite with size fraction 0.15~0.08 mm at 80 °C in distilled water and in super-saturated $Ca(OH)_2$ solution.

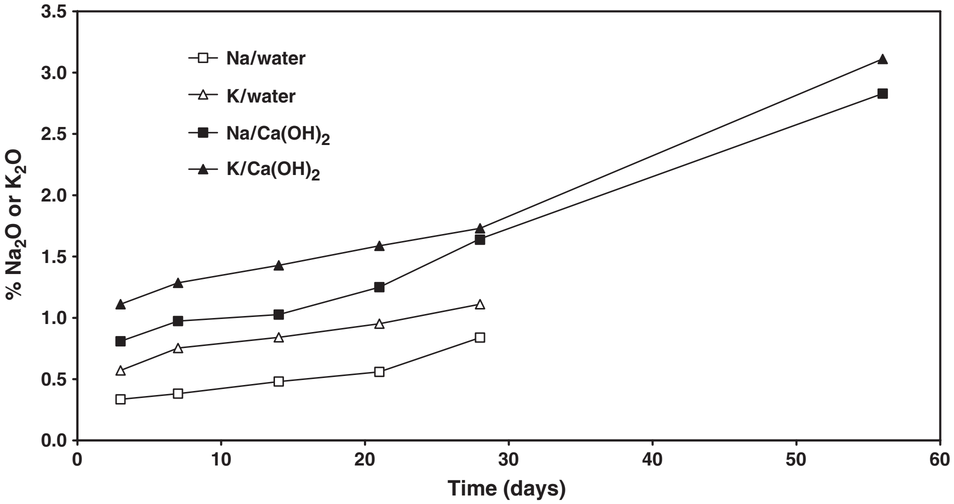

Fig. 2. Na_2O and K_2O released by gneiss with size fraction 0.15~0.08 mm at 80 °C in distilled water and in super-saturated $Ca(OH)_2$ solution.

type of alkali-bearing components as well as the extent of their metamorphic alteration. The gneiss and granite contain similar amounts of plagioclase, silica and biotite. The main difference in mineral composition between them is that gneiss contains a small amount of sericite while granite contains small amount of hornblende. However, metamorphic processes that produce gneiss can cause significant alterations in the mineral phases, their crystal size and their distribution. The stronger effect of $Ca(OH)_2$ solution on alkali extraction from K-feldspar seems to suggest that the potash feldspars (sanidine and microcline) are very sensitive to the pH value in alkali leaching.

The above results suggest that the ability of aggregates to release alkali varies from one type of rock to another, and that it is strongly influenced by the nature of the solution used. Compared to extraction by water, super-saturated $Ca(OH)_2$ solution had a stronger influence on feldspar than on granite and gneiss. The alkali extraction from rocks is also closely related to the particle size of the specimen used, content and distribution of alkali-bearing components in the rocks.

3.2. Extractability of Na and K from aggregate

Figs. 1, 2 and 3 show the amount of Na_2O and K_2O released at 80 °C in distilled water and super-saturated $Ca(OH)_2$ solution for the 0.15~0.08 mm size fraction of the three rocks. More alkali was released into the lime solution than into water. Fig. 1 indicates that the nature of the solution has no significant influence on the extraction of alkali species from the granite. For both extraction solutions, similar amounts of Na and K were released.

The gneiss released a higher proportion of K_2O than Na_2O both in distilled water and saturated $Ca(OH)_2$ solution (Fig. 2), whereas the K-feldspar released a higher proportion of Na_2O (Fig. 3). Bérubé et al. [8] reported that for most of the seventeen aggregates they subjected to alkali extraction in water, lime solution and alkaline solution, the higher the mass proportion of K_2O or Na_2O in the bulk aggregate, the higher the percentage of that species released in the test solution. This trend was not seen in the three rocks tested here. It is possible that the type and

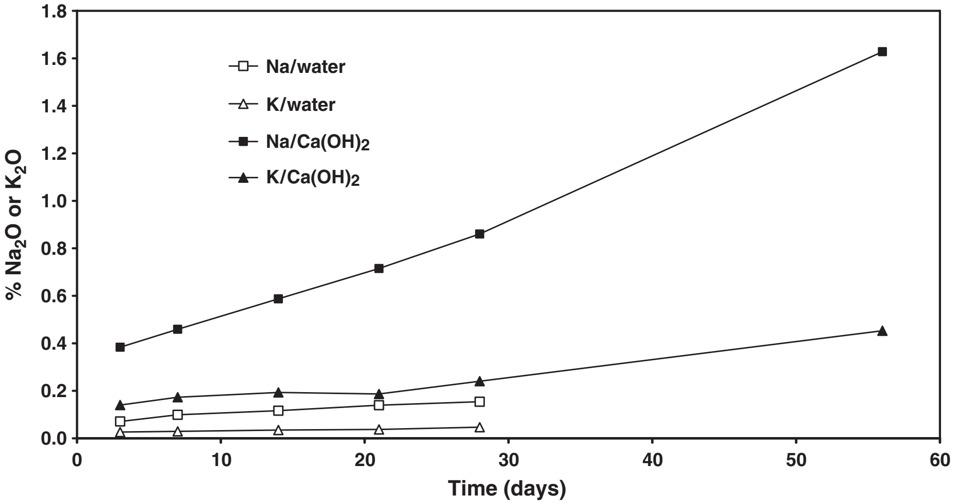

Fig. 3. Na_2O and K_2O released by K-feldspar with size fraction 0.15~0.08 mm at 80 °C in distilled water and in super-saturated $Ca(OH)_2$ solution.

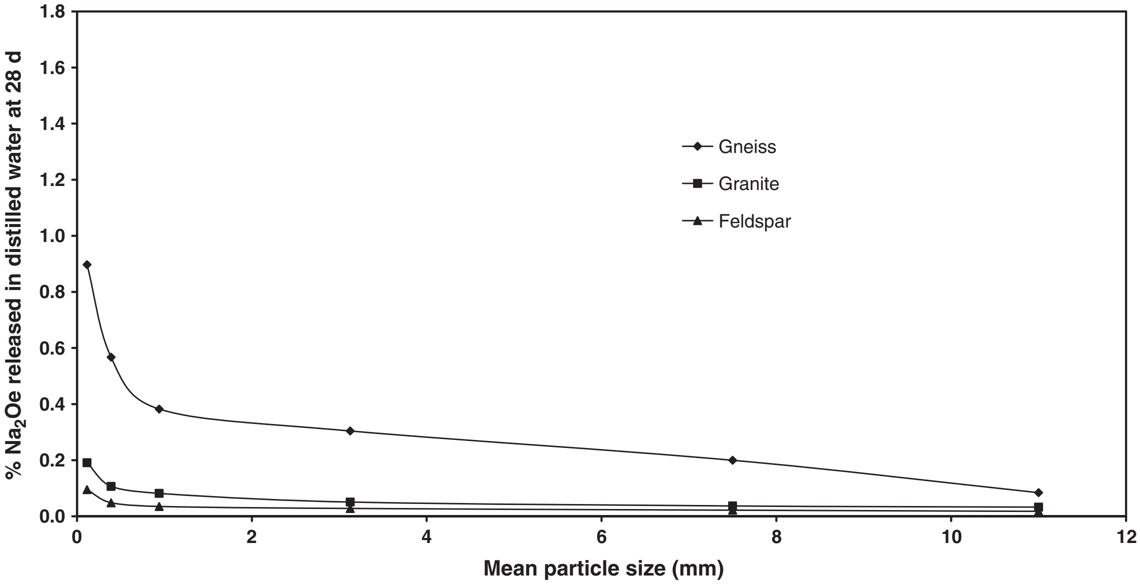

Fig. 4. 28-day alkali extraction in distilled water from three rocks with different size fractions at 80 °C.

grain size of the mineral phases in which the alkali species are combined, their distribution in the rock particles, and the degree of alteration, may be more important than its content in alkali extractability.

3.3. Effect of fineness of aggregate particles on alkali extraction

For the three rock types tested, both in super-saturated Ca $(OH)_2$ solution and in distilled water, the finer the rock particles the higher the proportion of alkali released (Table 2). The relationship between the alkali released at 28 days and the fineness of particles is shown in Figs. 4 and 5 for the water and super-saturated $Ca(OH)_2$ solution, respectively, using the mean particle size of each fraction as *x*-axis. These figures show that all the three rocks have similarly shaped curves in both distilled water and super-saturated $Ca(OH)_2$ solution, regardless of the absolute amount of alkali released. There is a linear area between 1.0 and 11 mm, with a dramatic increase in alkali release when the particles were finer than 1.0 mm. However, for the three rock types, the sensitivity of alkali extraction to the particle fineness is different, especially when the particles were coarser than 1.0 mm. The amount of alkali released by gneiss increased with increasing fineness in the particle size range of 1 to 10 mm, whereas for the granite and K-feldspar, the particle fineness did not have much effect on the amount of released alkali when the particles were coarser than 1.0 mm. The sensitivity of alkali extraction to particle size was greater for

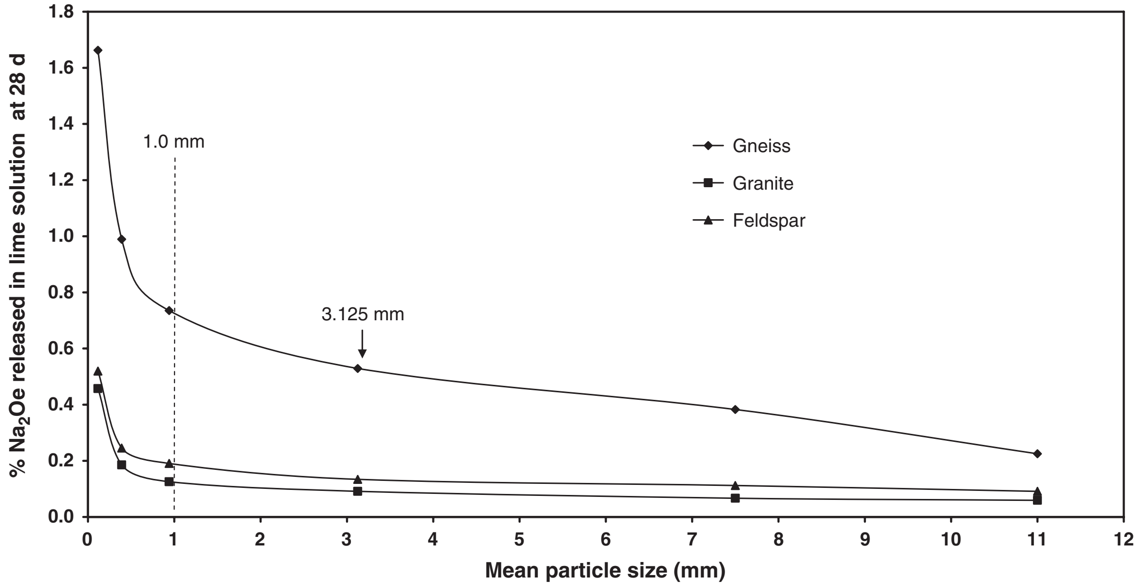

Fig. 5. 28-day alkali extraction in super-saturated $Ca(OH)_2$ solution from three rocks with different size fractions at 80 °C.

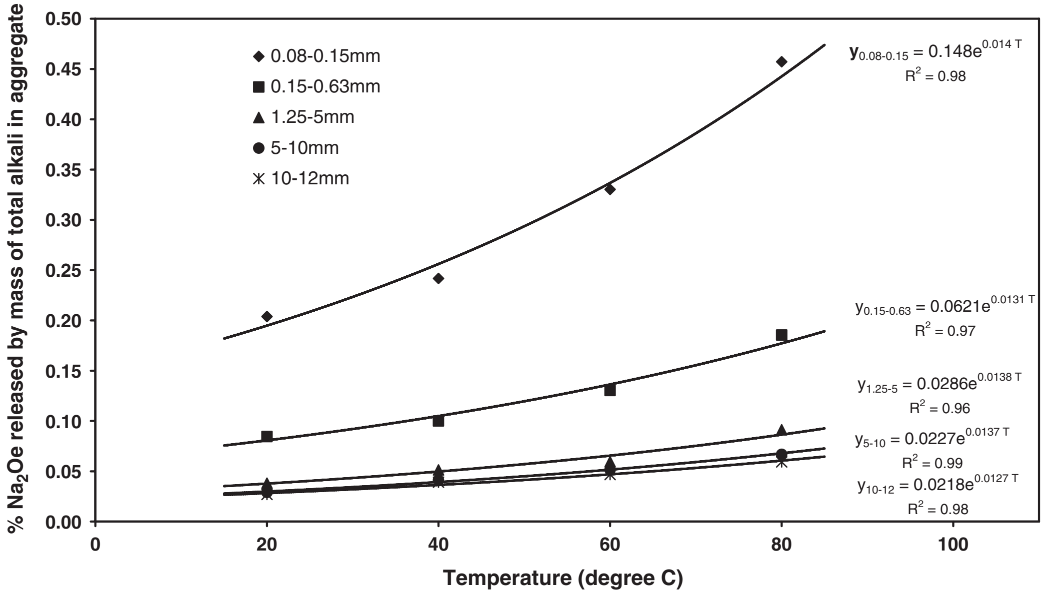

Fig. 6. Effect of temperature on the alkali released from granite at 28 d in saturated $Ca(OH)_2$ solution with solid lime in excess at 80 °C.

the gneiss than for the granite and K-feldspar. For the latter, the effect of the particle size is slightly larger in the super-saturated $Ca(OH)_2$ solution than in distilled water.

These results suggest that, in different particle size ranges, the fineness of particle has different effects on the amount of alkali released by different rock types. This would probably depend on the type and relative proportion of alkali-bearing minerals which they contained, consequently, the alkali release mechanisms dominated in different rock types in different size ranges. The alkali-bearing phase in the granite and the feldspar is largely feldspar which would likely release alkali through dissolution, whereas the gneiss contains both feldspar, which releases alkali through dissolution, and layer-silicate, (e.g. mica, sericite), which would likely participate in cation-exchange reactions. When the particles are coarse, e.g. over 1.0 to 2.0 mm, the granite and feldspar have behaved in a very similar manner, the fineness did not have much influence on alkali release, because the alkali-bearing phase is largely feldspar in both, whereas the gneiss has released much more alkali (and more K than Na) with decreasing the particle size because of the exchange reaction, where K is released from mica and sericite, as well as dissolution of feldspar where both Na and K are released. When the particles are finer than 1.0 mm, the three rocks have behaved in a similar manner, alkali release increased dramatically with decreasing particle size. This may suggest that when the particles are finer than a certain size, the release

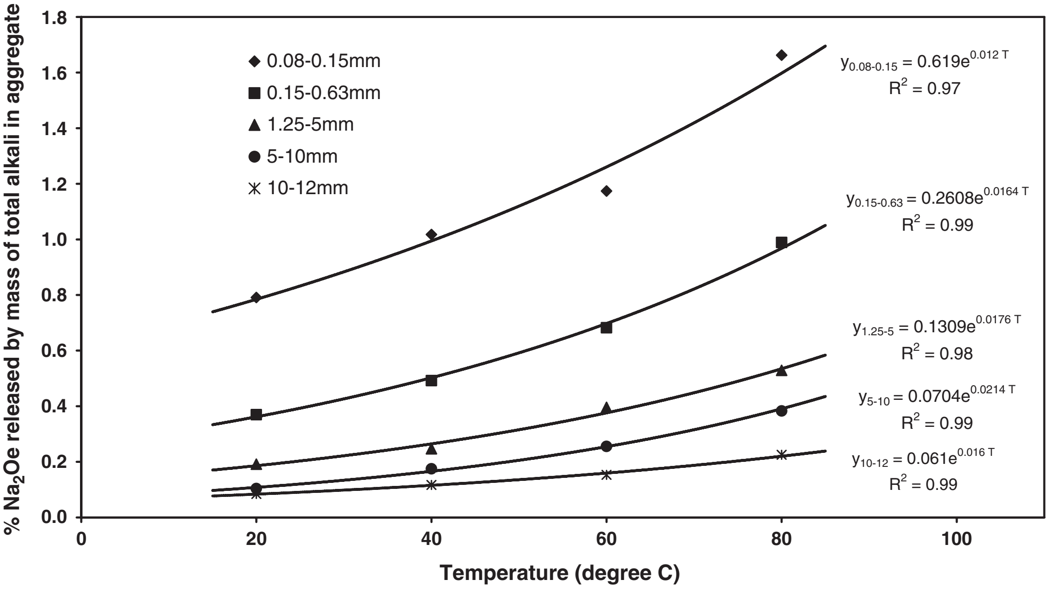

Fig. 7. Effect of temperature on the alkali released from gneiss at 28 d in saturated $Ca(OH)_2$ solution with solid lime in excess at 80 °C.

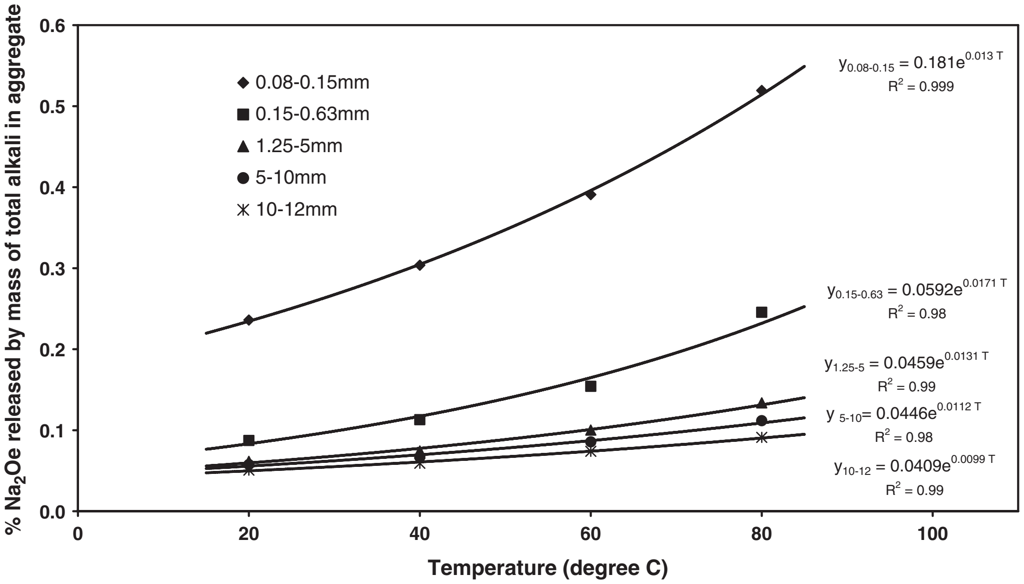

Fig. 8. Effect of temperature on the alkali released from feldspar at 28 d in saturated $Ca(OH)_2$ solution with solid lime in excess at 80°C.

mechanism has no significant influence on the amount of alkali release or the three rocks have similar alkali release mechanisms.

In terms of laboratory testing for the potential alkali released by coarse aggregates, the above results indicate that using particles finer than 1.0 mm could overestimate the contribution. Shayan and Quick [17] also showed that particles of granites passing 75 μm sieve released 0.77–0.93% of their weight as Na_2O_e in $Ca(OH)_2$ solution, which was a gross overestimation because coarse aggregate and not rock powder was used in the concrete. It is recommended to use either 1.25–2.50 mm or 2.5–5.0 mm particle sizes for future laboratory testing since these fractions could ideally maintain the microstructure and texture characteristic of coarse aggregate and gave a reasonable acceleration of alkali extraction.

3.4. Effect of temperature on alkali extraction

The effects of temperature on the amount of alkali released in super-saturated $Ca(OH)_2$ solution at 28 days by various size fractions of granite, gneiss and feldspar are shown in Figs. 6, 7 and 8, respectively. The trend lines and their equations are also given in the figures. The amount of alkali released seems to correlate well with temperature, i.e. for all the size fractions of these three rocks, in the temperature range investigated, the amount of released alkali increased exponentially with increasing temperature. As expected, the granite and the feldspar have behaved in a very similar manner regarding the released alkali per specific size fraction, while the gneiss behaved somewhat differently. This is most likely because of the metamorphic alterations and mineralogical differences, explained earlier in this paper.

To some extent, the value of the temperature coefficient in the trend line equation can represent the effect of thermal activation on the alkali extraction. However, by comparing the temperature coefficients in the trend line equations, the thermal activation on alkali extraction can be shown to vary with the rock types and the fineness of rock particles. Globally, a stronger thermal activation is observed for the gneiss than for feldspar and granite.

Although the thermal activation of alkali extraction varied with the rock types as well as the fineness of rock particles, it is quite similar (0.014, 0.012 and 0.013) for the size fraction 0.08–0.15 mm of the three rock types tested. It suggests further that using the very fine particles could not reflect the real behaviors of coarse particles and might not be suitable for a laboratory alkali extraction test.

Table 3
Concrete mix proportions in the Three-Gorges dam project (kg/m^3)

Water	Cement	Fly ash	Fine agg.	Coarse agg.
82	96.9	52.2	631.4	1920.6
84	149.3	37.3	607.6	1615.1

Superplasticizer, 0.7% by mass of cementitious materials was used.

4. Possible alkali contribution from the granite and the ASR safety of concrete in the Three-Gorges dam

4.1. Possible alkali contribution from the granite

The results presented here and those found in the literature confirm that feldspars and other alkali-bearing minerals in aggregates can release alkali into distilled water, saturated Ca $(OH)_2$ solution as well as alkali hydroxide solutions, and that for some rock types, the alkali contribution can be significant [8,9]. It has been shown that alkali released by aggregate contributed to ASR when alkali-silica reactive aggregate was present [18,19]. However, since leaching is a long-term process and the mechanisms involved are not well understood, there is no standard test procedure to accurately assess alkali contribution by aggregate to the pore solution in concrete.

Because suspensions made with aggregate for alkali extraction in the laboratory are clearly different from the environment prevailing in mortar or concrete, predicting the actual alkali contribution from aggregate in real concrete over several decades is very difficult. However, the results obtained from suspension tests can provide information on the potential alkali contribution from alkali-bearing aggregates. This is especially important when studying ASR-affected concrete structures in which the concrete alkali content had originally been limited by using low-alkali cements. It is also important in the assessment of the possibility of alkali contribution from alkali-bearing aggregates to ASR in new concrete.

According to the concrete mix proportions used in the Three-Gorges dam concrete (Table 3), the amount of granite aggregate used in the different parts of the dam varied from 1615 to 1920 kg/m^3, and the granite aggregate size varied from 5 to 150 mm, with most of the aggregate coarser than 20 mm. Based on the 56 day value of alkali released in $Ca(OH)_2$ solution at 80 °C, the alkali extraction is 0.12% of total alkali for the 5–10 mm size fraction of granite and it is 0.83% for 0.08–0.15 mm fraction, so the possible alkali contributions by 5–10 and 0.08–0.15 mm granite are 0.12–0.14 and 0.83–0.98 kg/m^3, respectively.

In the actual concrete, a number of factors, such as the time, the temperature and the release control process, would affect the amount and process of alkali release. In the concrete, the ambient temperature is less than 80 °C. The grains of granite aggregate in the concrete were much coarser than those tested in suspension and the aggregate/solution ratio was also much smaller than in suspension. Furthermore, the system is static and the release would be diffusion controlled, which is much slower than the dissolution process in the extraction method. The overall influence of these factors determines that the alkali release in actual concrete would be a very slow and long-term process. Also, the presence of fly ash used in the cementitious system would mostly likely contribute to reduce the rate of alkali release/diffusion process in the concrete.

4.2. *ASR safety of the Three-Gorges dam concrete*

Potentially reactive aggregate, sufficiently high alkali concentration in the concrete pore solution and available moisture are three essential conditions needed to initiate and sustain ASR in concrete. The use of a non-reactive aggregate, limiting the concrete alkali content and using a sufficient amount of good quality supplementary cementing materials (SCMs) are widely accepted measures to prevent ASR in concrete. The use of 20∼25% low-alkali, low-calcium fly ash as cement replacement in concrete can eliminate or at least greatly suppress the initiation of ASR even for most alkali-reactive aggregates. Studies have effectively shown that the use of a sufficient amount of a good quality fly ash can control expansion due to ASR even in high-alkali concrete systems [21–24], although there are some exceptions [25].

The non-reactive character of the granite used in the concrete was suggested by using different laboratory testing procedures, including petrographic examination, ASTM C1260 (0.044% at 14 d), ASTM C1293 (0.0081% at 1 y) and the Chinese autoclave method [14–16]. In order to prevent thermal cracking, a medium-heat, low-alkali cement combined with low-alkali, low-calcium fly ash were used; the total alkali content of the concrete was limited to <2.5 kg/m^3 even in the structural parts [20]. All these measures assure sufficient protection against potential ASR in the concrete.

Considering the granite and sand used in the concrete are non-reactive and that the strict measures mentioned above were adopted in designing and making concrete, based on the current state of knowledge on ASR, it is most unlikely that the Three-Gorges dam concrete would be affected by ASR even though the granite could contribute some alkali into the concrete pore solution in the long term.

5. Concluding remarks

Some alkali in granite, gneiss and feldspar can be released into distilled water or $Ca(OH)_2$ solution; the rate and amount of which are strongly affected by the type of solution, the fineness of particles and temperature. The finer the particles and the higher the temperatures, the larger and faster the release of alkali.

Gneiss, which is of metamorphic origin, and contains altered feldspar and micaceous minerals, released more alkali than the granite and feldspar.

The type of solution used has a strong effect on extracting alkali from aggregates; the effect varied with the type of rock. Compared with distilled water, super-saturated $Ca(OH)_2$ solution has a stronger activation on K-feldspar than on granite and gneiss.

The effect of temperature on alkali extraction varied with the type of rocks as well as the fineness of rock particles. For the three rocks tested, the largest thermal activation was with gneiss; similar activations occur with granite and feldspar. For very fine particles, all the three rocks showed the same thermal activation for the release of alkali.

In the long term, there would be some alkali contribution to the pore solution in the Three-Gorges dam concrete by the granite aggregate used. However, since the granite coarse aggregate and sand used in the concrete are non-reactive in standard tests, the occurrence of ASR would not be an issue.

In the design of massive concrete structures incorporating reactive aggregate, alkali contribution by aggregate should be considered. Further study to establish reliable test procedure to estimate the contribution and elucidate the mechanisms involved is required.

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