DIAGNOSIS OF ASR IN AIRPORT PAVEMENTS IN JAPAN – EARLY-EXPANSIVE SAND AGGREGATE MISSED BY CONVENTIONAL TEST

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Abstract

This paper provides ASR diagnosis in a series of concrete pavement of a Japanese airport, based on petrographic examination, accelerated concrete core expansion test, and estimation of alkali contents in concrete. The pavement was built at a region free from freezing and thawing ranging in age from 20 to 4 years ago according to JIS specification (cement alkali Na₂Oeq <3.0kg/m³), but showed D-cracking and map-cracking. Highly reactive opaline mudstone in the coarse sand produced pop-outs and gel-filled cracks. Alkali contents in concrete indicated that total alkalis of cement was lower than Na₂Oeq 2.5kg/m³ with total concrete alkali content over 3.2kg/m³, due to supply of water-soluble alkali from aggregates. Older concretes with late-expansive chert coarse aggregate presented small expansion in the accelerated test due to dissolution into alkali solution. Combination of blast furnace slag sand and fine sand in younger concretes reduced water-soluble alkali (about 30%) with negligible external signs of ASR but a potential for expansion in the accelerated test. D-cracking seems to be an effect of ASR with possible association of thermal stress.

Keywords: airport pavement, alkali-budgets, D-cracking, early-expansive aggregate, petrography

1 INTRODUCTION

From 2011 to 2013, the authors investigated concrete pavements of several airports in Japan showing signs of both D-cracking and map-cracking due to alkali-silica reaction (ASR). Preliminary results from pavements in an airport at a region free from freezing and thawing, and without damage from repeated/cyclic loads, indicated that ASR had contributed to the distress [1]. Subsequently, wider areas of concrete aprons of the same airport ranging 4 to 20 years old were studied thoroughly, based on petrography coupled with supplementary methods. Preventive measures of ASR and all the reacted aggregates used were those that had passed JIS standards on ASR, hence it was decided to confirm the nature and extent of ASR in concrete. This paper discusses the results of the research.

2 MATERIALS AND METHODS

2.1 Materials

Concrete core specimens (dia.10cm x L40cm) representing the type of deterioration, environmental conditions (i.e. high or low humidity) and construction age of concrete slabs, were sampled from the concrete pavements in the apron in 2011 (sound: Nos. K1, K2, cracked: Nos. K7-K9) and in 2012 (Nos. 1.1-6.2) (Table 1). D-cracking was generally confined to the narrow area of the slabs, typically within 50cm from the joints. To avoid possible damage to embedded dowel bars, core samples were taken at locations fairly distant from the joints, meaning the core samples do not necessarily represent the most deteriorated portion in the slabs.

2.2 Methods

Concrete pavements were visually inspected to classify the severity of damage. Concrete core specimens were scanned on their lateral surface (360°), then subjected to stereomicroscopy to examine the presence of pop-outs. Polished thin sections of concrete (25mm by 35mm, thickness $15-20\mu$ m) were prepared for polarizing microscopy to evaluate ASR progress in five stages following the criteria after Katayama [2] (Table 2). ASR progress was also verified in terms of compositions of ASR gel and CSH gel in concrete on the [Ca/Si]-[Ca]/[Na+K] diagram developed by Katayama [3] (Figure 4), after conducting SEM observation and quantitative EDS analysis of reaction products on polished thin section (JEOL JSM 5310LV/JED 2140: 15kV, mainly 0.12nA, ZAF correction).

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Alkali contents in concrete were examined by measuring water-soluble alkalis of bulk concrete and separated coarse aggregate, following the condition of General Project Method (<0.3mm, sample : water=1:10, 40°C, extraction with shaking 30 min.) [4]. In estimating contribution from fine aggregate, the ratio of the separated coarse aggregate to the bulk concrete was used, which is subject to error. A complete set of analyses (K-series) including minimum amount of alkali of unhydrated cement particles (alite, belite, aluminate and ferrite) measured by the first author was cited from Kawamura et al. [1,5]. Distinction of contributions of alkalis from each material in concrete (addition, moving, leaching, etc.) should be called "alkali-budgets" [2] but is simply called here "alkali contents" following Prof. Leandro Sanchez. An accelerated expansion test was performed over 28 days (80°C 1N NaOH solution) using slender core specimens (dia. 5cm x L13cm) [2] extracted from the larger cores (dia. 10cm) in laboratory.

3 RESULTS

3.1 Field and macroscopic

D-cracking appeared on concrete slabs within 2m from the joint corner (exceeding the reach of dowel bars beneath), or along a transverse crack that had formed through subsidence of the subgrade soil. Scanned core image of the damaged slab showed parallel horizontal cracks along to the dowel bars (Figure 2A). Highly reactive sand particles produced pop-outs on the lateral surface of the core within a few days after sampling (Figure 2B). They swelled about 1mm, i.e. 25% linear expansion (length change: 1mm/4mm) (Figure 2C). Crushed chert coarse aggregate in early construction prior to 1996 produced ASR (Figure 2D), while limestone and sandstone in later construction from 2006 were inert (Table 2). No correlation was noted between the grade of deterioration and accessibility of water.

3.2 Polarizing microscopy

Various rock types in both the coarse and mixed coarse/fine sand aggregate reacted in concrete (Table 3). Opaline mudstone in the coarse sand aggregate was most reactive, exhibiting an entire process of ASR (Table 1), ranging from i) formation of reaction rim (Figure 3A), through ii) exudation/rimming of sol/gel (Figure 3B), iii) cracking of aggregate (Figures 3C, D) and iv) pro-pagation of gel-filled crack into cement paste (Figures 3E, F), to v) filling of ASR gel into air voids distant from the reacted aggregate (Figures 3G, H). Intensely reacted opaline aggregate had an internal void space formed by dissolution (Figure 3G). Radial expansion cracks of the aggregate were connected with horizontal cracks, formed possibly by thermal stress (Figure 3H). Opal was pseudomorphic after radiolarian fossils. Andesite particles produced a crack filled with ASR gel from cristobalite that converted to rosette crystals (Figure 2F). Blast furnace slag sand (Figure 2G) was found in younger concretes, while ferro-nickel slag sand (Figure 2H) occurred in blocks of pavement.

3.3 SEM-EDS analysis

Opaline radiolarian fossils in the mudstone left oval-shaped moulds indicative of dissolution in concrete (Figure 4A). In this aggregate, rich in solution pits, ASR gel in the matrix of the rock was accumulated to form a lining along expansion crack (Figure 4B).

Compositional trend line of ASR gel

On the [Ca/Si]-[Ca]/[Na+K] diagram, compositional trend line of ASR gel in the sound pavement (Figure 5A, No. K1) was shorter than that in the damaged pavement (Figure 5B, No. K7), extending on a half way to the "convergent point", i.e. the terminal point of ASR where ASR gel reaches a composition of typical CSH gel (Katayama [3]).

Rosette crystals

Rosette crystals filling a crack in the andesite particle had a composition around [Ca/Si]=1/4, [Ca]/[Na+K]=1.0 (Figure 5B). Their compositions ranged from $(Ca_{2.13})(Na_{1.25}, K_{1.67}, Mn_{0.04})_{2.96}$ (Si_{7.88},Al_{0.05},S_{0.05})_{7.98} O_{19.5} nH₂O to (Ca_{1.97})(Na_{0.31}, K_{1.75}, Mn_{0.02})_{2.07} (Si_{7.97}, S_{0.02})_{7.99} O₁₉ nH₂O (Table 4). When analytical loss from a total of 100% (i.e. water content and count loss due to ultra-thin bladed crystals) and alkali balance are ignored, this corresponds to mountainite Ca₂(K, Na₂)₃ Si₈O_{19.5} 6.5H₂O to shlykovite Ca₂(K, Na)₂ Si₈O₁₉.7H₂O, respectively, of the same mineral family.

3.4 Alkali contents in concrete

The amount of water-soluble alkalis of concrete with and without blastfurnace slag yielded Na₂Oeq 1.2-1.4kg/m³ and 1.8-2.2kg/m³, respectively. This suggests that the slag reduced 35% of water-soluble alkalis (Table 5). Matrix mortar, with and without blastfurnace slag, presented water-soluble alkalis of 0.9-1.0kg/m³ and 1.0-1.8kg/m³, respectively, suggestive of a 30% loss of water-soluble alkali. Total cement alkalis of unhydrated cement particles in both sound (K1) and cracked concrete (K7) as estimated by the first author by EDS analysis [1,5] ranged 2.3-2.5kg/m³, which meets the specification of JIS standard (<Na₂Oeq 3kg/m³) from the time of construction.

3.5 Expansion tests

Poor correlation was noted between the rock types of aggregate and expansion. However, older concretes containing chert coarse aggregate and opaline sand (Figure 6A) generally presented smaller expansion than those without them (Figure 6B). Younger concretes with limestone coarse aggregate and less reactive fine sand containing volcanic rocks (No. 4, No. 6-2), and concretes with opaline sand (No. 3-2, No. 6-1) produced large expansion.

4 DISCUSSION

4.1 Field and macroscopic

The cause of D-cracking is discussed. The concrete pavements in this airport showed compressive strengths of around $60N/mm^2$, with a 10% increase in the sound portions that produced pop-outs after coring [1]. Hence, their tensile strength in the sound portions is expected to be around $6N/mm^2$, assuming 1/10 that of the compressive strength, whereas cracked portions would no longer keep such tensile strength. It has generally been accepted when the thermal difference reaches a maximum in the vertical section of pavement, i.e. between the upper and lower portions of the slab, concrete slab undergoes thermal stress to warp and crack it horizontally. According to Hachiya et al. [6], combination of thermal stress and counteractive confinement stress in high-strength airport concrete pavements (bending strength: $>5N/mm^2$) produces a bending stress component and overall tensile stress up to $5N/mm^2$ and $2N/mm^2$, respectively. These are marginal values but ASR adds enough strain to crack concrete slab, depending on the content of the ASR gel.

4.2 Polarizing microscopy

Unlike cryptocrystalline quartz in the chert aggregate, both opal and cristobalite in the coarse sand that was used without caution are well-known highly reactive minerals with small pessimum proportions and capable of reaction in low alkali conditions (e.g.Na₂Oeq 2.2kg/m³). It is likely that their reactivity was missed when the coarse sand was subjected to chemical tests after mixing with a marginally reactive fine sand. Reaction of the opal may have already been completed in older concretes.

Several aggregates in the pavements seemed to have been supplied from sources over 500km away, including the reactive coarse sand, non-reactive metamorphic limestone aggregates and ferro-nickel slag. This coarse sand was marginally innocuous in the JIS mortar bar test and was used for 5 years in other structures to adjust the grain size distribution of a local fine sand (Hirono [7][8] unpublished data). However, it was later replaced by the crushed limestone fine aggregate and blast furnace slag sand, the latter having been mixed without being reported. Although the slag sand absorbed water-soluble alkali of cement, it was not enough to completely suppress ASR.

4.3 SEM-EDS analysis

Compositional trend line of ASR gel

It has been accepted that during evolution of ASR, alkali-rich ASR gel absorbs Ca ions from cement paste and loses alkalis, approaching a "convergent point" at which apparent chemical equilibrium is reached with CSH gel in the cement paste (e.g. Katayama [3]). Thus, the expansion potential of ASR gel is lost during this process. The range of the compositional trend of ASR gel from the sound slab (K1) was narrower than that of the damaged slab (K7); only halfway to the convergent point. This means that ASR is at an initial stage in the sound area. The absence of cracks on the surface of the pavement is probably a result of constraint on the expansive ASR forces.

Compositions of rosette crystals

When compositions of rosette crystals are recalculated ignoring water content, counting loss and alkali balance, they range from mountainite $Na_2O \cdot 0.5K_2O \cdot 2CaO \cdot 8SiO_2 \cdot 6.5H_2O$ to shlykovite (K, $Na)_2O \cdot 2CaO \cdot 8SiO_2 \cdot 7H_2O$). These were common crystalline counterparts of ASR gel in field deteriorated concretes (Katayama [9][10]). The availability of Ca ions from cement paste and the degree of alkali replacement by calcium before crystallization of the ASR gel probably determines what type of the above minerals is formed [9].

4.4 Alkali contents in concrete

The ratio of water-soluble alkalis to total alkalis of concrete was 0.67-0.68, according to a complete set of data for series K (Table 5). This ratio (0.7) gave a rough estimation of the total alkali content of concretes without slag, i.e. Na₂Oeq 2.6-3.2kg/m³. A few concretes exceeded the total concrete alkali (Na₂Oeq 3.0kg/m³) of JIS specification. Extra water-soluble alkali came chiefly from coarse aggregate, because contribution from fine aggregate was negligible and deicing salt is not applied in the airport. The total cement alkali condition. Blastfurnace slag in the fine aggregate reduced about 30% of water-soluble alkali of concrete, possibly adsorbing this in slag hydrates. A simple calculation indicates that the content of the slag corresponds to 15% in the fine aggregate, or was equivalent to 30% of cement (e.g. assumption in kg/m³: cement 340, coarse aggregate 1200, fine aggregate 650 (natural 550, slag 100), water 136 (w/c=0.40), total 2326). The content of 15% seems to fit the petrographic examination.

4.5 Expansion tests

The poor correlation obtained is due partly to the inhomogeneity of the concrete specimens (large size of the coarse aggregate vs. core size), but mostly to the complexity of the combination of the materials in concrete. In general, larger expansion suggests a potential for further reaction of the aggregate in concrete, i.e. crypto- and microcrystalline quartz persisting in concrete will produce late-expansion even though highly reactive opal was consumed fast. On the other hand, most reactive aggregates (e.g. volcanics and opaline rock) produce expansion >0.10% at 21 days (Katayama et al. [2]), whereas reactive chert produces a small expansion because it dissolves into NaOH solution, e.g. 0.04% at 21 days (unpublished data). It is therefore assumed that late-expansive ASR will continue in concretes that produced large expansion have a potential to develop ASR of volcanics in the fine sand.

Expansion force

The reason why even sound concrete in the field produced pop-out is because expansion force of ASR gel is liberated by coring. The minimum pressure to crack ASR-affected concrete is possibly equal to the tensile strength of concrete but could be about twice that (e.g. Krogh [12]), since many textures allow the expansion pressure of ASR gel to escape, including voids and cracks within aggregate and cement paste. Hence the expansion pressure liberated by opaline aggregate on the core surface might attain 12N/mm². This value is reasonable because hydrostatic pressure caused by ASR gel during wetting is expected to be on the order of 10N/mm² (e.g. from RH 93% to 100%, [9]) or larger. Because this is likely to occur in outdoor conditions, repeated drying and wetting of concrete slab and moisture movement along the joints will add to fatigue by repeated generation of expansion pressure. This suggests that the D-cracking in the airport pavements was a combined effect of expansion due to ASR and thermal stress, and that other fatigues by freeze/thaw cycles and dynamic load are not necessary.

In the first author's experience, the similar association of D-cracking with ASR in the concrete pavements with gel-filled horizontal cracks along with the dowel bars or rebar suggestive of thermal stress, is not rare in concrete slabs of roads in Japan. In the past, however, D-cracking was simply attributed to the result of combined freezing/thawing and fatigue of slabs, without assessing ASR via petrography.

5 CONCLUSIONS

• The formation of D-cracks with internal horizontal cracks around the joint (over dowel bars) of concrete aprons is a combined effect of expansion by ASR and associated thermal stress.

- In early concretes, prior to 1996, ASR was caused by crushed chert coarse aggregate and opaline mudstone in the coarse sand used to adjust the grain size distribution of the local fine sand.
- New concrete pavements, since 2006, contained non-reactive limestone and/or sandstone coarse aggregate, with blast furnace slag sand partly replacing the local fine sand which is also reactive.
- Sound field pavement contained opaline mudstone particles which produced internal ASR. This sand produced numerous pop-outs and gel-exudation after coring due to liberation of strain.
- The estimated alkali content of cement (Na₂Oeq 2.3-2.5kg/m³) met JIS standard (<3.0kg kg/m³) but was not effective in preventing ASR, because opal was highly reactive. The amount of total alkali of concrete (Na₂Oeq 2.6-3.3kg/m³) over the 3kg/m³ limit was due to supply of water-soluble alkali from the aggregates contained in the concrete pavements.

6. ACKNOWLEDGEMENTS

This study was conducted while the first author was working at Kawasaki Geological Engineering Co., Ltd. in Japan. Dr. Shin'ichi Hirono of Taiheiyo Consultant Co., Ltd. is acknowledged for providing information on the reactive coarse sand aggregate. Thanks are also due to Dr.Yuichiro Kawabata of the Port and Airport Research Institute for his help in initiating this study.

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stage	process	remarks
1	formation of reaction rim within aggregate	inner periphery of the aggregate
2	exudation of ASR sol/gel around aggregate	darkening of cement paste in transmitted light
3	cracking of aggregate	ASR gel may fill or line the crack
4	propagation of crack into cement paste	ASR gel may fill or line the crack, crack width grows
5	filling/lining of ASR gel into distant air voids	crack width should be noted for advanced damage

TABLE 1: Progress of ASR of opaline aggregate as observed by thin section petrography

pavement field deterioration							coarse (crusł	aggregate	:	fine aggregate					
	year	cracking			pop-		and	limes	stone	hill sa	ınd	lime- stone	slag		
No.		D- crackin g*	Paral- lel	map- like	out after coring	chert	stone	non- meta- morphic	Meta- morphic	coarse F1	fine F2	Meta- morphic	Blast furnace	ferro- nickel	
1-1	1993	х			х	XXX				х	XX				
6-1	1995	Х			Х	XXX				х	XX				
K1	1006					XXX				х	XX				
K7	1770	XX			Х	XXX				х	XX				
1-2	1006				Х	XXX				х	XX				
5	1770	XX			Х	XXX				х	XX				
2-1	1006	XXX			Х	XXX				х	XX			+	
2-2	1770	XXX			Х	XXX				х	XX			+	
3-1	1006	х				XXX					XX	Х		+	
3-2	1770	х			Х	XXX				х	XX			+	
4	2006		х				х	XX			XX		Х		
6-2	2009**			Х					XXX		XX		Х		

TABLE 2: Aggregates in concrete pavements as identified by polarizing microscopy

xxx: conspicuous, xx: moderate; x: minor; +: rare * concentric corner cracks, ** overlay on the 1995 concrete slab

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I ABLE 3. Intensity and	nrogrees of A	ANK in the concrete r	navements based a	A DOLARIZING MICROSCODY
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	_	1993			1996			1996								2006		1996		1995		2009			
	rock type	lo	w	10	w	dı	cy 🗌	W	et	hi	gh	lo	W	lo	w	hi	gh	<u>lo</u>	w	lo	w	lo	W	hi	gh
		1.	-1	1.	-2	K	.1	K	.7	2-	-1	2.	-2	3.	-1	3-	·2	4	4	ч,	5	6-	-1	6.	-2
С	chert					+	1	+	1-3	+	1	х	3-4	х	3-5	+	1-4			х	1-2	+	1		
	tuff							XX	1-5																
	tuffaceous sandstone	х	3			X	1-5			XX	1-4			+	2			Х	1-2						
D.	tuffaceous mudstone			XX	3	X	1-4	XX	1-4	XX	1-5	XX	1-4			XX	1-5					XX	1-3	х	1-4
Г 1	radiol. sil. mudstone	XX	1-5	X	2-4	XX	1 - 5	XX	1 - 5	XX	1-4					XX	1-5					XX	1-4		
1	siliceous mudstone	XX	1-4	XX	1-4							XX	<u>3-4</u>			X	1-4	+	3-4	XX	1-4	XX	1-4		
	calcareous mudstone							XX	1-5																
	mudstone							X	1-5			х	1-3			х	1			х	1-4				
	chert	X	1			х	1	х	1-3	х	3-4	х	1-2	+	1			х	1	х	1	Х	1	+	1
	radiolarian chert					+	1																		
	radiolarian shale																	х	1						
	siliceous shale																			х	1-4	Х	3		
	sandstone													х	1-2										
	carbonif. mudstone	X	3																						
	andesite	XX	1-2	х	1-2	х	2	х	1-4	х	1-2	х	1-4	+	1-2	+	1-4	+	2	х	1-2	+	2	х	1-2
-	glassy andesite											+	1	XX	1-2					+	1			х	1
F	altered andesite							х	2-5	х	1-2			х	1-2			+	2						
1	andesitic welded tuff											х	3-5												
	dacite					х	1	XX	1-2							х	1			+	1			х	1-2
T	dacitic tuff	X	1-3																						
F	dacitic welded tuff	X	2					х	1									х	1						
2	rhyolite	х	1					х	1-2							+	1					Х	1	х	1
-	glassy rhyolite							XX	1-5							х	1-4			х	1-2	XX	1-3	+	1-2
	rhyolitic tuff			х	1-3							х	1-4					х	3-4	х	1-4	+	1		
	rhyolitic welded tuff	XX	1-3			х	1			х	1-2			Х	1-2	х	1			х	1	+	1	+	1-2
	rhyolitic pumice			х	2					х	2	XX	1-2	Х	1-2	х	1-2			+	2	Х	1-2	х	1-2
	meta-chert											+	1												
	meta-mudstone			+	1																				
	meta-glassy rhyolite																			+	1				
	meta-rhy welded tuff											+	1							+	1				
sev	verity petrographic(1)	1	2	1.	-2	2		3	3	2	2	2.	-3		1	2-	-3		1	1.	-2	1.	-2	1	1
of	ASK field(2)	I	Ι		[]	[I	Π	III	-IV	III	-IV	Ι	Ι	I	Ι	I	Ι	I	Ι	Ι	Ι	Ι	*
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C: coarse aggregate, F1: coarse sand, F2: fine sand, <u>underlined</u>: pop-out after coring * drying shrinkage Intensity of ASR: xx conspicuous, x present, + trace Progress of ASR: 1 formation of reaction rim, 2 exudation of sol/gel along aggregate, 3 cracking of aggregate, 4 propagation of crack into cement paste, 5 migration of gel along crack in cement paste into distant voids Severity of ASR: (1) petrographic: 1 minor, 3 moderate, 3 severe (2) field : 1 cryptic stage (no external crack, sound), II developing stage (minor), III accelerating stage (moderate), IV deterioration stage (severe)

TABLE 4: Compositions of reaction products as determined by EDS on polished thin section

			-		-						1				
	position		material	SiO_2	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	$\mathrm{K}_{2}\mathrm{O}$	SO3	Total	
127	andesite	crack	rosette 1)	43.04	0.00	0.22	0.00	0.28	0.00	10.85	3.50	7.13	0.37	65.39	
К/			rosette 2)	53.83	0.01	0.00	0.00	0.14	0.00	12.38	1.07	9.24	0.16	76.83	

1) (Ca2.13) (Na1.25,K1.67, Mn0.04) 2.96 (Si7.88,Al0.05,S0.05) 7.98 O 19.5 nH2O cf. mountainite: Ca2(K, Na2) 3 Si8 O 19.5 6.5 H2O

 $2) \ (Ca_{1.97}) (Na_{0.31}, K_{1.75}, Mn_{0.02})_{2.07} (Si_{7.97}, S_{0.02})_{7.99} O_{19} \cdot nH_2 O \quad cf. \ shlykovite: Ca_2(K, Na)_2 Si_8 O_{19} \cdot 7H_2 O = 100 \cdot 1$

Pave	ment	it Clinker Cement Concrete Coarse aggregate separated							Fine **	Matrix mortar							
No.		Mini ł	mum a oy ED	alkali S	Total alkali	Water- sol. alk.	Wa	ater-sol	uble alk	ali	Total alkali		Water	alkali		Water sol. alk	
	vear	m	easure	ed	estin	nated	n	neasure	d	estin	nated	r.	neasure	d	estin	nated	estim
	year	% (wt)			Na2Oeq kg/m ³		% (wt)			Na2Oeq kg/m ³			% (wt)		Na2 kg/	Na2Oeq kg/m ³	
		Na2O	$\mathrm{K}_2\mathrm{O}$	(1)	(2)	(3)	Na ₂ O	K_2O	Na2Oeq	(4)	(5)	Na ₂ O	$\rm K_2O$	Na ₂ O _{eq}	(6)	(7)	(8)
1-1	1993						0.061	0.054	0.096	2.23	3.2*	0.028	0.034	0.050	0.43		1.80
K1	1006	0.43	0.21	0.56	2.28	1.37					2.72					0.01	
K2	1990						0.051	0.041	0.078	1.82	2.75	0.022	0.030	0.042	0.44	0.01	1.38
K7	1006	0.42	0.29	0.61	2.49	1.49					3 1 4					0.11	
K9	1990						0.062	0.046	0.092	2.14	5.14	0.028	0.029	0.047	0.54	0.11	1.60
1-2	1996						0.055	0.042	0.083	1.93	2.8*	0.051	0.053	0.086	0.91		1.02
2-1	1006						0.053	0.049	0.085	1.99	2.8*	0.034	0.035	0.057	0.55		1.44
2-2	1990						0.058	0.044	0.087	2.02	2.9*	0.038	0.028	0.056	0.54		1.48
3-1	1006						0.048	0.048	0.080	1.85	2.6*	0.032	0.045	0.062	0.73		1.12
3-2	1990						0.062	0.051	0.096	2.23	3.2*	0.059	0.050	0.092	0.85		1.38
5	1996						0.058	0.038	0.083	1.93	2.8*	0.031	0.031	0.051	0.52		1.41
6-1	1995						0.051	0.040	0.077	1.80	2.6*	0.020	0.020	0.033	0.29		1.51
4	2006						0.032	0.043	0.060	1.40	2.0*	0.019	0.042	0.047	0.39		1.01
6-2	2009						0.025	0.040	0.051	1.20	1.7*	0.015	0.025	0.031	0.25		0.95

TABLE 5: Alkali-budgets of concrete pavements in the airport without use of deicing salt

(1): Na₂Oeq=Na₂O+0.658K₂O is sound concrete in outdoor ** fine aggregate and admixture (2): 1.2 x ((1)/100) x 340 kg/m³, 1.2 = 1.3 (total alkali/minimum alkali) x 0.97 (dilution by gypsum) x 0.96 (dilution by additive) (3): 0.6 x (2), 0.6= water-soluble alkali ratio, (4): as 2330kg/m³, (5): total alkali of concrete = (2)+ (6) + (7) = (2) + (4) - (3), or *: (4)/0.7 where cement data is unavailable (6): water-soluble alkali of fine aggregate and chemical admixture = (4) - (3) - (6) total of water-soluble alkali of fine aggregate and chemical admixture = (6) + (7) = (4) (3)

total water-soluble alkali of coarse aggregate, fine aggregate and chemical mixture = (4) - (4) - (4) - (3)(8): water-soluble alkali of matrix mortar = (4) - (6); "separated coarse aggregate/concrete" ratio was used





FIGURE 1: Type of deterioration in concrete pavements: (A) dense parallel cracks near the control joint (No. 4); (B) map-cracks near the drainage ditch (near No .2-2); (C)D-cracking with concentric corner cracks (near No. 2); and (D) sparse map-cracks on the overlying slab (No. 6-2).

FIGURE 2: (A) scanned core surface of D-cracked slab with internal horizontal cracks (No. 2-2); (B) pop-out formed on the lateral surface after coring (No. 2-1); (C) swelling of mudstone sand particle on the core surface after sampling (No. K); (D) (E) ASR of chert coarse aggregate exuding ASR gel (No. 2-2); (F) crack-filling ASR gel converting to rosette crystals within andesite sand; (G) drying shrinkage crack and blast furnace slag sand (No. 6-2); (H) ferro-nickel slag sand in concrete (No. 2-2).

FIGURE 3: Development of ASR in opaline mudstones in the airport pavements. (A) stage 1: reaction rim (No. 5); (B) stage 2: exudation of ASR sol/gel (arrows) (No. K1); (C) (D)stage 3: cracking within reacted aggregate (arrows): (C) (No. 2-1), (D) (No. 1-2); (E) (F) stage 4: radial expansion cracks running into cement paste (arrows) (No. 3-2); (G) (H) stage 5: migration of ASR gel along cracks in cement paste into distant air voids (arrows) (No. K7). (G) note the dissolution of the interior of the aggregate.

FIGURE 4: (A) molds of reacted radiolarian fossils (No. K7) and (B) crack-lining ASR gel (No. K1), both in opaline mudstone; (C) rosette crystals in andesite (No. K7); and (D) cement particle (No. K7).

FIGURE 5: Compositions of ASR gel and CSH gels in concrete slabs.as determined by EDS analysis on polished thin sections. A: sound dry area (No. K1), B: moderately deteriorated wet area (No. K7).

FIGURE 6: Accelerated expansion test of concrete core specimens (80°C 1N NaOH). A: less expansive group containing chert coarse aggregate, B: expansive group, some (No.4, No.6-2) containing limestone coarse aggregate instead of chert.