Durability and Sustainability of Pavement Quality Concrete in Airfields

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ABSTRACT: Specification and design documents for pavement quality concrete (PQC) in airfields currently limit the use of GGBS to a maximum level of 35%. Operational considerations demand durability characteristics of airfield pavements in respect of preventing scaling. Preventing even small concrete fragments from impacting airframes or being ingested by engines ('FOD' - Foreign Object Damage) especially demands mitigation of ASR risk and high freeze-thaw resistance in the presence of de-icing agents. Irish Standard I.S. EN 206 requirements limit the use of GGBS to a maximum level of 50% in freeze-thaw exposure but airfield PQC specification documents currently limit the use of GGBS to a maximum level of 35%. Increasing GGBS content above this limit would enhance the sustainability credentials of the aviation industry, assuming that concrete strength and durability requirements for pavements were satisfied. Direct emissions from the aviation industry accounts for 2% of global CO_2 emissions, while cement manufacture accounts for around 8%. Replacing Portland cement with 70% GGBS in concrete can reduce the embodied carbon footprint by 65% and play a major role in reducing global CO_2. An experimental programme was developed to produce PQC specimens with 35%, 50% and 70% GGBS cement replacement level for testing against EN standards and aviation-industry specified requirements. Compression and flexural strength requirements were met for all mixes. Specified 28-day flexural strength was met at 7 days. The 70% GGBS mix registered 28-day flexural strength 48% higher than the requirement. Less scaling took place during freeze-thaw testing with potassium acetate, typical of airfield practice, compared with sodium chloride, typical of highway practice. The 70% GGBS mix showed less scaling after 28 cycles in potassium acetate compared to 50% GGBS mix in sodium chloride. Calculations show that by using 70% GGBS there is a 67% reduction in the risk of ASR. The study has demonstrated that 50% and 70% GGBS can be used PQC to meet strength and durability requirements. The reduction in embodied CO_2 by using GGBS at 50% or 70% in PQC offers an immediate contribution to enhance the sustainability credentials of the aviation industry during its most challenging economic period ever, in the decade following the Covid-19 pandemic of 2020.

KEY WORDS: CERI 2020; Concrete durability; GGBS; PQC; sustainability.

1 INTRODUCTION

Direct emissions from the aviation industry accounts for 3% of CO_2 emissions in the EU and more than 2% of global emissions [1]. Concrete is the second most consumed resource in the world but its key ingredient – cement - has a significant carbon footprint. The cement industry contributes about four times the CO_2 emissions of the aviation industry. In 2010 global cement manufacture released 3270 million metric tonnes of CO_2 into the atmosphere. Currently that amount is estimated to be 4370 million metric tonnes of CO_2, and in 2030 it is projected to be 4830 million metric tonnes as global usage of cement continues to increase [2].

Guidance manuals for pavement quality concrete (PQC) in airfields [3] consider both strength and serviceability. Operational considerations demand onerous durability characteristics of airfield pavements to minimise the risk of scaled concrete fragments impacting the airframes of taxying aircraft or being ingested by engines ('FOD' - Foreign Object Damage). Typical specification documents for pavement quality concrete (PQC) in airfields [4] requires a minimum cement content of 350kg/m^3 and maximum w/c ratio of 0.45. Practice in Ireland, exemplified by the Dublin Airport Authority, is 380 kg/m^3 of cement with a maximum w/c ratio of 0.43. Aviation industry pavement design in the UK and Ireland targets a design life of concrete of 20 to 30 years, in comparison with concrete specified to I.S. EN 206 [5] which provides durability guidance based on a minimum life cycle of 50 years. Nevertheless, PQC requirements are in line with the longer-term EN 206 requirements for freeze-thaw resistance.

The worldwide use of GGBS to enhance the strength and durability of concrete is well documented [6]. The use of GGBS significantly enhances the sustainability of concrete through the recovery of an industrial waste material that would otherwise go to landfill. Although high replacement levels are not uncommon, Irish Standard I.S. EN 206 requirements limit the use of GGBS to a maximum level of 50% in freeze-thaw exposure and airfield PQC specification documents currently limit the use of GGBS to a maximum level of 35%.

There are three pillars to sustainability: social, economic and environmental. They are also sometimes referred to as 'people, profit and planet' [7]. Through concrete constituents there is an obvious opportunity to affect environmental sustainability. The aviation industry will need to demonstrate sustainability across the social and environmental pillars in the post Covid-19 pandemic period to achieve economic survival. The working hypothesis of the research reported in this paper was that the aviation industry would benefit from using higher levels of GGBS in PQC for greater long term strength and durability, while enhancing the industry's sustainability credentials through the reduced embodied CO_2 of its global infrastructure.

2 FREEZE-THAW RESISTANCE OF AIRFIELD PAVEMENTS

2.1 Recommendations to mitigate freeze thaw

Air entrainment of concrete is commonly used in exposure conditions subject to freeze-thaw but a primary concern is to reduce the risk of water penetration into concrete. Therefore concrete with a low w/c ratio - low in permeability – is successful in mitigating scaling and cyclical damage due to freezing and thawing [8]. Nevertheless, some researchers [9, 10] favour the inclusion of air entrainment as the single most important factor in freeze thaw resistance. I.S.EN 206 provides recommendations for concrete composition in the case of exposure classes XF1- XF4. Air entrainment as an option allows for a reduction in total cement content and w/c ratio constraints. International specification and national design manuals for PQC include air entrainment advice.

Regarding secondary cementitious materials, the Ministry of Defence [4] specification for PQC permits the use of PFA to a maximum of 25% total cement content and 35% for GGBS total cement content. The Dublin Airport Authority allows for a maximum PFA percentage of 30% total cement content but does not currently include the use of GGBS in its specification.

The use of recycled aggregates is an option but currently only crushed limestone aggregates are permitted under the UK and Irish specifications.

2.2 De-icing agents

Sodium chloride (NaCl) is a commonly used de-icer on highways in the UK and Ireland. Potassium acetate (KAc), a mixture of acetate acid and potassium hydroxide, is mostly used at airports because of its high performance and it is deemed to be less aggressive.

Xie [11] found that KAc had a higher melting capacity than NaCl and that NaCl induced more mass loss through scaling than KAc. Ghajar-Khosravi [12] found little scaling had taken place on mortar bars exposed to KAc. Tsang et al. [13], testing with equal concentration by mass at 4% with $CaCl_2$, NaCl, MgCl, KAc and Na acetate de-icers, found that KAc produced the least mass loss.

3 EXPERIMENTAL PROGRAMME

3.1 Research Objectives

The primary aim of the study was to investigate the strength and durability performance of GGBS concretes, up to 70% replacement level, against the benchmark of performance targets in international and national best practice for airfield pavement quality concrete.

The study also investigated the use of CEM II A-L (42.5N) cement and GGBS combinations in meeting PQC strength and durability exposure class requirements.

The alkali loading of suitable concretes was monitored to ensure compliance with measures to control the risk of alkali-silica reaction.

The benchmarks used were determined from the Ministry of Defence Specification 033 [4] and the Dublin Airport Authority specification, summarised in Table 1.

Table 1. Concrete performance requirements and composition limitations

Requirements	Ministry of Defence Spec 033	Dublin Airport Authority
28 day flexural strength	4.5 MPa	5.0MPa
7 day mean compressive strength	45MPa	---
7 day individual minimum compressive strength	34MPa	---
28 day compressive strength	---	40MPa
Permissible Cements	CEM I	CEM I CEM II
Combination limitation	PFA 25% GGBS 35%	PFA 30% GGBS 0%
Minimum Cement Content	350 kg/m³	380 kg/m³
Maximum w/c ratio	0.45	0.43

3.2 Materials and Methods

3.2.1 Materials

Concrete specimens were prepared with 0% (control), 35%, 50% and 70% GGBS conforming to EN 15167-1 manufactured by Ecocem Ireland Limited. The Blaine value of the GGBS was 440 m²/kg and a D50 value was 11.59 μm.

The cement was CEM II A-L 42.5N, a Portland limestone cement, conforming to EN 197-1. Cement was supplied by Irish Cement Limited in Platin. The CEM II A-L used has a Blaine value of 374 m²/kg and a D50 value of 10.96 μm.

Fine aggregate was natural concrete sand. Coarse aggregate was 10mm and 20mm crushed limestone. The aggregates, supplied by Kilsaran International from their Millennium Park plant, were representative of aggregates being used at the time in concrete being supplied to Dublin Airport Authority works.

Admixtures were GCP applied technologies MIRA 53, a mid-range water reducer and DAREX AEA, an air entraining admixture. These were obtained from Kilsaran International Millennium Park ready mixed concrete plant, which was supplying concrete to works at Dublin Airport.

An approved mix design for PQC works in Dublin Airport was used as the control in the research. Details of the mix designs are presented in Table 2.

Table 2. Concrete trial mix detail - SSD weights (kg/m³)

	Control	35% GGBS	50% GGBS	70% GGBS
Cement	420	273	210	126
GGBS	0	147	210	294
20mm	730	730	730	730
10mm	400	400	400	400
Sand	635	635	635	635
Water	180	180	180	180
MRWRA	2.52	2.52	2.52	2.52
AEA	0.6	0.6	0.6	0.6

The three replacement levels of GGBS were adopted from the 35% GGBS limited as per Specification 033; the 50% GGBS limited by I.S. EN 206 for XF exposure classes and 70% GGBS as the maximum practical level presumed for simultaneously meeting strength, durability and sustainability requirements.

3.2.2 Methods

Six batches of each mix were required to produce 12 no. 100mm cubes; 4 no. beams and 2 no. 150mm cubes test specimens required for compressive, flexural and freeze thaw testing. The EN 480-1 mixing technique for reference concrete was adopted to ensure repeatability of results and consistency in batching method. All specimens were made to EN 12390-2, with consistence measured to EN 12350-1 Part 2 and air content measured to EN 12350-7.

Concrete specimens were tested to:

- EN 12390-3:2009, Testing Hardened Concrete – Part 3: compressive strength of test specimens. Twelve 100mm cubes were made for each mix allowing three cubes for each of four test ages: 2, 7, 28 and 56 days;
- EN 12390-5:2009 Testing Hardened Concrete - Part 5: Flexural strength of test specimens. Four 500*100*100mm beams were cast for each mix allowing two beams to be tested at both 7 and 28 days;
- EN 12390-9 section 7.3, CDF test method using de-icing salts. Pairs of freeze thaw specimens were constructed in 150mm cube moulds with a PTFE (polytetrafluoroethylene) plate in the centre. The plate had a thickness less than 5mm. There were four equally sized thin rectangular plates placed on two opposite faces of these cubes. Two 150mm cubes were cast for each mix, each then yielding two specimens;
- EN 12390-9 methodology but using potassium acetate as a de-icer.

For the purpose of this work the CDF method was chosen for testing of freeze thaw resistance. The first round was carried out with the standard solution of 3% NaCl. The second round of freeze-thaw testing was carried out using potassium acetate to simulate airfield exposure conditions.

An evaluation of alkali loading was calculated using both the UK method described in Specification 033 [4] and the Irish method described in Irish Concrete Society/IEI guidance document for control of alkali silica reaction [14].

4 RESULTS AND DISCUSSION

4.1 Results

The plastic density, air content and slump of the four mixes are presented in Table 3.

The flexural and compressive strength trends over 28 & 56 days are presented in Figure 1 and Figure 2 respectively.

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Table 3. Plastic density, air content and slump

	Control	35% GGBS	50% GGBS	70% GGBS
Plastic Density (kg/m³)	2380	2380	2370	2380
Air Content (%)	4.5	4.3	4.5	4.2
Measured Sump (mm)	50	50	50	50

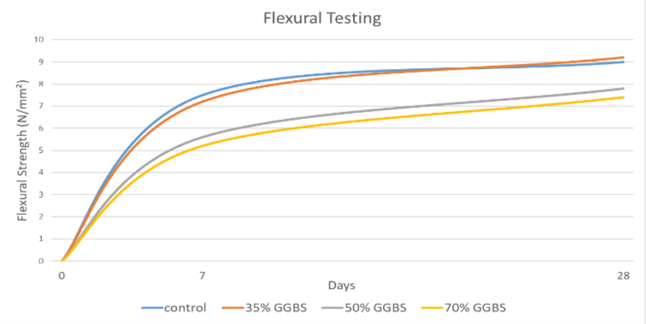

Figure 1. Flexural strength results up to 28 days.

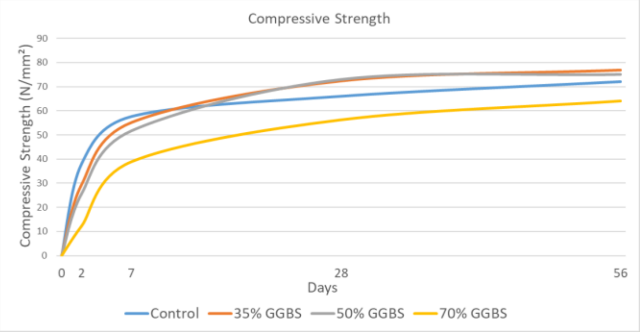

Figure 2. Compressive strength results up to 56 days.

Figure 3 illustrates the amount of scaling for each test specimen measured at 4, 6, 14 and 28 cycles in the tests with NaCl. The cumulative amount of scaled material (Ms,n) is calculated after 28 cycles have been completed. Cumulative mass loss shows the progression of the four mix over the 28 cycles of testing. The difference in the amount of material lost from the samples in comparison to the control ranges from 2 to 6 to 10 times that lost by the 35, 50 and 70% GGBS mixes, respectively.

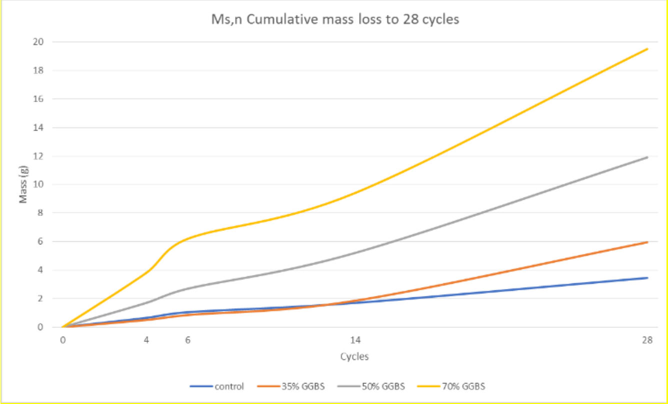

Figure 3 Cumulative mass loss in freeze thaw tests (NaCl)

Figure 4 illustrates the mass of scaled material per unit area in the tests with NaCl. As the percentage of GGBS increases the level of scaling increased. 70% GGBS is five times that of the control mix. However 70% GGBS is 60% of maximum allowable level of mass loss per unit area.

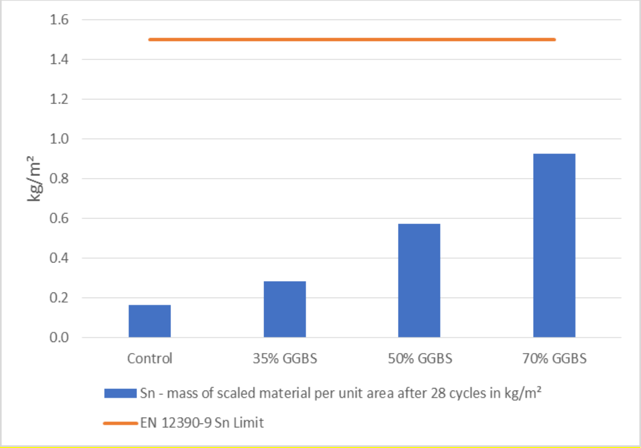

Figure 4. Sn - Mass of scaled material per unit area – FT - NaCl – after 28 cycles

Figure 5 illustrates the amount of scaling for each test specimen measured at 4, 6, 14 and 28 cycles in the tests with KAc. The difference in the amount of material lost from the samples in comparison to the control sample ranging from 4 to 7 to 10 times more than the 35, 50 and 70% GGBS specimens respectively.

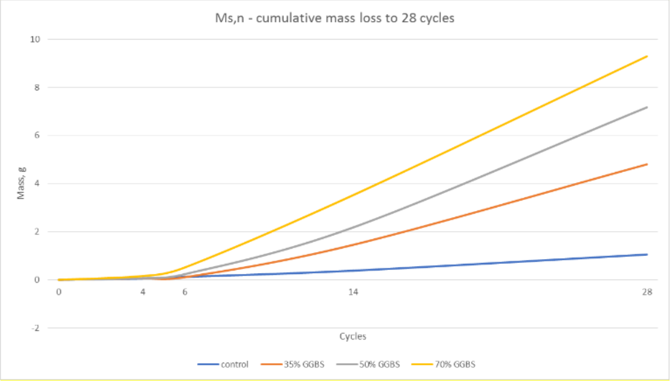

Figure 5. Cumulative mass loss in freeze thaw tests (KAc)

Figure 6 illustrates the mass of scaled material per unit area in the tests with KAc. A trend may be observed whereby the Sn calculated with 70% GGBS is up to ten times more scaled material per unit area than the control mix.

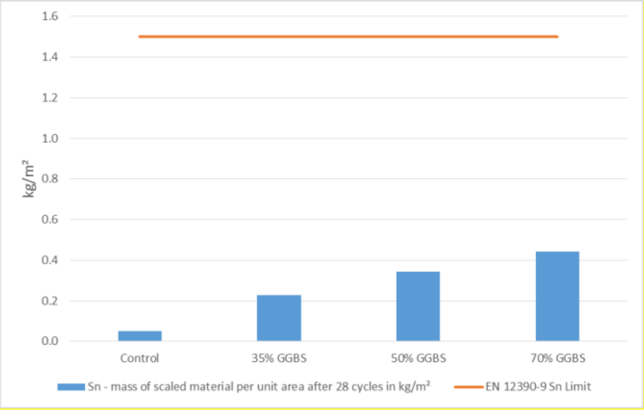

Figure 6. Sn - Mass of scaled material per unit area – FT - KAc – after 28 cycles

However when exposed to FT cycles using KAc 70% GGBS displays scaling at 30% of the allowable limit given in EN 12390-9.

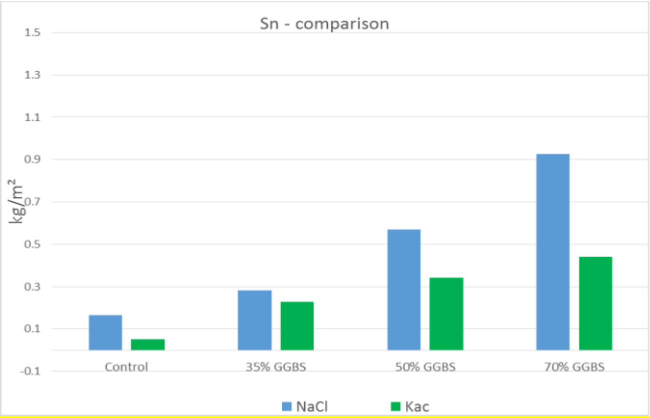

Figure 7. Sn – comparison between NaCl and KAc after 28 cycles

Table 4 presents alkali loading calculation with Specification 033 / BS 8500 method giving a higher level of ASR risk reduction at all trialled levels of GGBS addition when compared to the approved control mix.

The use of GGBS aids in producing a less permeable concrete, reduced the alkali loading of a concrete mix and reduces the risk of ASR occurring.

Table 4. Alkali loading calculation comparison

	Control	35% GGBS	50% GGBS	70% GGBS
IEI Calculation	2.94	2.91	2.20	1.91
ASR Risk Reduction		1%	25%	35%
BS 8500	2.55	2.10	1.33	0.84
ASR Risk Reduction		18%	48%	67%

Standard / guidance document maximum limit for alkali load Specification 033 - 3.25 Na2Oeq kg/m³.
IEI guidance document - 4.5 Na2Oeq kg/m³.

4.2 Discussion

4.2.1 Compressive and flexural strength

Compressive and flexural strength requirements of pavement quality concrete at 28 days were met using CEM II A-L 42.5N The Dublin Airport Authority 28 day requirement of 40MPa for pavement quality concrete was exceeded by 35%, 50% and 70% GGBS mixes.

The Ministry of Defence Specification 033 – Pavement Quality Concrete in Airfields [4] specifies a 7 day, rather than a 28 day, mean compressive strength requirement of 45MPa. This was achieved by 35% and 50% GGBS mixes. 70% GGBS mix did not meet compressive mean strength requirement at 7 days, however it reached 56.3MPa at 28 days. This mix also gives the lowest compressive strength at 28 days. Early age performance could be enhanced with the use of a hardening accelerating admixture. There is a well-established difference in performance between 100% cement and GGBS concrete in early age testing [15, 16]. The 7-day results indicate that the control and 35% GGBS concrete mixes performed satisfactorily, with the 50% GGBS concrete approximately 10% behind. The performance of 50% GGBS is as expected at 7 day testing when compared to others work that has been carried out using GGBS as a replacement for OPC [17]. The 7 day strength performance is aided by the low w/c ratio. Control 35% and 50% have achieved the 45MPa mean compressive strength requirement at 7 days. Arivalagan [17] shows a similar trend to results achieved in flexural testing with samples at 30% and 40% GGBS achieving similar results to a CEM I at 7 days, while showing a slight increase in compressive strength at 28 days.

Testing out to 56 days showed continued increases for all mixes in compressive strength.

Standard deviation for sets of cubes at 2 days returned a maximum of 0.5, 7 days 1.0, 28 days 1.9 and 56 days 2.1. These results were in line with testing expectations

All combinations resulted in higher flexural strength than required by DAA and the MOD. 35% GGBS mix achieved greater flexural strength at 28 days than the control mix. 50% GGBS and 70% GGBS mixes achieved a lower flexural strength than control mix.

4.2.2 Freeze-thaw resistance

All mixes were under the required EN 12390-9 limit of 1.5kg/m² for scaling after freeze thaw testing at 28 cycles. However, it was found that the level of scaling increased as the percentage of GGBS increased. It was observed that less scaling took place during freeze thaw with potassium acetate (KAc) when compared to sodium chloride (NaCl). The 70% GGBS mix showed less scaling after 28 cycles in KAc compared to 50% GGBS mix in NaCl.

I.S EN 206 recommends limiting use of GGBS to 50% in areas subjected to XF expose. In testing it was observed that 70% GGBS did not perform as well as control mix. However it was within industry limits for allowable amount of scaling when exposes to both NaCl and KAc.

The difference between the two different test runs with the two different solution has shown there to be a larger amount of scaling in total mass lost and mass lost per unit area when using the 3% NaCl solution when compared to the KAc application. This indicates that the use of KAc as a de-icing and anti-icing agent has less impact on concrete. In turn when considering the exposure to freeze-thaw and preventative measures used, KAc will allow for a longer life cycle when compared to the degradation caused by NaCl over the same period of time.

However a revision of freeze thaw testing to incorporate different di-icing agents and curing conditions for GGBS sample preparation is needed. EN 12390-9 does not facilitate the use of alternative de-icing agents in its standard test method. Currently there is no industry standard test method for the use of KAc or alternative de-icing agents in freeze thaw testing of PQC. Also the sample preparation for freeze thaw testing to EN 12390-9 calls for water curing up to 7 days and air curing to 28 days for CDF testing. This method of curing weighs in favour of OPC over GGBS because OPC gains a higher proportion of its overall strength up to 7 days.

4.2.2 Alkali-silica reaction

ASR more commonly known as "concrete cancer", is a swelling reaction that occurs over time in concrete between the highly alkaline cement paste and the reactive non-crystalline (amorphous) silica found in many common aggregates, given sufficient moisture. The risk of alkali-silica reaction is reduced using GGBS. Alkali loading calculation with Specification 033 / BS 8500 method gives 18%, 48%, 67% risk reduction for 35%, 50% and 70% GGBS respectively. Alkali loading calculation with IS EN 206:2013 NA: 2015 NA.5.3 / IEI/ICS report method gives 1%, 25%, 35% risk reduction for 35%, 50% and 70% GGBS respectively. Alkali loading calculation with Specification 033 / BS 8500 method gives a higher level of ASR risk reduction at all trialled levels of GGBS addition when compared to the approved control mix. The use of GGBS aids in producing a less permeable concrete, reduced the alkali loading of a concrete mix and reduces the risk of ASR occurring.

5 CONCLUSIONS

The performance of concretes with up to 70% GGBS were found to meet strength and durability requirements for PQC.

It is recommended that consideration be given to amending airfield pavement specifications in the context of further reducing embodied CO_2 by permitting the use of GGBS at levels considerably greater than the current limit of 35%.

It is further recommended that standard EN 12390-9 be revised to include testing with alternative de-icing agents to permit an aviation industry standard test method for the use of KAc or alternative de-icing agents in freeze thaw testing of PQC.

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