Effect of GU vs. GUL Cement on AAR Testing of Concrete Aggregates

Principal Author:
Zhiyong Jiang, M.A.Sc., P.Eng.
Senior Soils and Aggregates Engineer
Soils and Aggregates Section
Ontario Ministry of Transportation
95 Arrow Road, Toronto, ON M9M 2L4
Email: Zhiyong.Jiang@ontario.ca

Co-Authors:
Athanasios Verros
Master's Candidate
Faculty of Engineering and Architectural Science
Toronto Metropolitan University
350 Victoria St, Toronto, ON M5B 2K3
Email: averros@torontomu.ca

Dr. Medhat Shehata
Professor of Civil Engineering
Associate Dean, Teaching and Outreach
Faculty of Engineering and Architectural Science
350 Victoria St, Toronto, ON M5B 2K3
Email: mshehata@torontomu.ca

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Abstract

Alkali-Aggregate Reaction (AAR) is a severe deterioration affecting concrete infrastructures worldwide. AAR occurs when the aggregates react with the alkalis in cement used for the concrete, thereby producing pressure within the concrete that causes expansion, deterioration and cracking. The Ministry of Transportation (MTO) evaluates the reactivity of concrete aggregates using the MTO laboratory methods, Accelerated Mortar Bar Test (LS-620) and Concrete Prism Test (LS-635), demanding the use of Portland Cement (GU). The introduction of Portland-limestone (GUL) cement calls for an investigation of the aggregate reactivity with GUL cement using the two test methods. The findings would support the ministry's understanding of the difference in expansion with the use of GU and GUL cements and any impact of using GUL cement on the two test methods.

This paper reports on the LS-620 test data on four MTO reference aggregates (two quarried siliceous limestones (ASR CA3 and CA6) from Ottawa area, a quarried dolomitic limestone (ACR CA1) from Kingston area, and a crushed siliceous gravel (ASR CA5) from Sudbury area) using both GU and GUL cements from cement suppliers in Canada. The data were produced through MTO Aggregate and Soil Proficiency Program and MTO-Toronto Metropolitan University partnering program. Multi-stage statistical methods were used to analyze the data.

The precision estimates calculated for ASR CA6 suggested that for expansion of more than 0.3%, the variations in expansion with GUL cement are comparable to the variations obtained for GU cement from the same supplier. It was also found that the difference in expansion between GU and GUL was comparable to the difference in expansion with GU cement from different suppliers.

In comparing the expansions between the use of GU and GUL cements from the same supplier, ANOVA analysis of ASR CA3 expansion data showed no significant difference, while the analysis of ASR CA6 expansion data showed a significant difference.

A calculation of Percent Within Limits (PWL) using the ASR CA6 expansion data suggested that 94% to 95% of the expansion results using GUL cement will fall within the expansion range obtained by using GU cement from the same supplier. This showed that the significant difference in expansion suggested by ANOVA for ASR CA6 was masked by the current variability of the test method LS-620 and that the use of GUL cement may not have a significant impact on the test method.

Introduction

Alkali-Aggregate Reaction (AAR) is a severe deterioration that affects the durability and serviceability of concrete infrastructure worldwide [1]. Affected infrastructure may suffer from premature deterioration, leading to costly repairs or replacements. To avoid this deterioration and the associated economic and serviceability loss, MTO and many agencies established programs to test aggregates before being used in concrete. MTO maintains a robust oversight program to prevent alkali reactive aggregates from being used in concrete infrastructure, through the implementation of MTO Concrete Aggregate Sources List (CASL) and the requirements of OPSS 1002 Specification for Concrete Aggregates [2] which includes AAR screening tests.

AAR is a reaction between certain aggregates and the alkalis (Na_2O and K_2O) in cement used in concrete. The reaction produces an expansive product that creates internal pressure on the concrete causing it to expand and crack [3] [4] [5] [6]. MTO SSP110S17 [7], which amends OPSS 1002 [2], specifies two tests to evaluate the reactivity of concrete aggregates: the Accelerated Mortar Bar Test and Concrete Prism Test, which follow MTO Laboratory Standard test methods LS-620 and LS-635, respectively. Both test methods mandate the use of General Use (GU) Portland cement in the preparation of the test samples containing the aggregates. MTO quality assurance protocol requires that for assessment of an unknown aggregate against the acceptance limits in OPSS 1002 [2], the test methods must be strictly followed.

The two test methods mandate the use of type GU cement with total alkali content of 0.9 ± 0.10%. However, in recent years, type GU cement has been increasingly replaced by Portland-limestone (GUL) cement as a greener alternative, with type GU cement being phased out. GUL cement is manufactured by intergrinding Portland cement clinker with up to 15% limestone, whereas only up to 5% limestone is ground with clinker to produce GU cement [8]. It has been suggested by industry to revise the two test methods correspondingly to allow both GU and GUL cement types. It is imperative that MTO evaluate the effect of the GUL cement on the results from the two tests mentioned above and whether the use of GUL cement in the tests has any impact.

This paper discusses a comparison of the effect of GU cement and GUL cement on potentially reactive aggregates using LS-620 Accelerated Mortar Bar Test. Findings from three programs: a consultant testing program, 2021 MTO Aggregate & Soil Proficiency Program and a project under Highway Infrastructure Innovations Funding Program (HIIFP) are discussed. Test data from these programs are reported elsewhere [9].

Laboratory Testing Programs

The paper discusses the findings of the following programs in this order:

- A testing program by external consultants in 2020.
- 2021 MTO LS-620 proficiency sample testing program
- HIIFP project in 2022

Description of MTO LS-620 - Accelerated Mortar Bar (AMBT)

MTO LS-620 is a laboratory standard test method used by the ministry and the industry to evaluate the potential of aggregates to produce deleterious expansion in concrete mainly as a result of alkali-silica reaction.

The test involves preparation of a test sample to a specified grading, washing and drying individual fractions prior to mixing. The dry aggregates are mixed with cements and water in one batch to cast three mortar bars for subsequent immersion of the bars in a sodium hydroxide solution at 80°C and measurements of the expansion of the bars on days 1, 7 and 14.

Preparation of Materials for the 2020 and 2021 Programs

The testing program by external consultants and MTO Aggregate & Soil Proficiency Program were based on testing random samples of duplicate by the participating laboratories with experience in the testing. The test samples supplied for the programs are nearly identical and the test data are representative of the testing practices of the industry. Each laboratory (or firm) received pairs of aggregate samples, cement samples, and forms for recording expansion data.

To supply nearly identical samples to the laboratories, aggregates were first crushed at the MTO laboratory with a jaw crusher down to P4.75mm according to LS-633 Rev. 33 [10]. MTO staff homogenized the crushed aggregate accordingly to ASTM C702-18 Method C [11], and placed the aggregate in aggregate pans. MTO staff then successively took one scoop of aggregate from each pan into a hopper so that the hopper contains material from all the pans, followed by riffling to produce the required aggregate sample mass that meets the requirements of the test methods. These samples were bagged and distributed to the participating firms.

MTO staff prepared cement samples by successively placing about 200 g of cement scooped from each plastic barrel of the same cement type in a plastic bag with a sealing closure. This preparation process was repeated for GU and GUL cement types separately until a bag of about 2.6 kg GU cement and a bag of about 2.6 kg GUL cement were prepared for each firm. The bags were sealed and distributed to the firms within 2 months of preparation of the cement materials.

Details of Laboratory Testing Program by External Consultant in 2020

Four consulting firms were engaged by MTO in 2020 to study the impact of GU vs. GUL cement on LS-620 Rev. 33 [10] Accelerated Mortar Bar Test. These selected firms were recognized by MTO to have consistently demonstrated satisfactory proficiency in LS-620 over the years in MTO Aggregate & Soil Proficiency Program. Each firm was asked to perform LS-620 on pairs of samples using both GU cement and GUL cement for comparison.

Aggregates

MTO RM ASR CA3 (ASR CA3) was supplied by MTO for the study. ASR CA3 is a siliceous limestone from a quarry near Ottawa, Ontario, known to develop AAR and currently being used as an MTO reference material for LS-620 [12] / CSA A23.2-25A-14 Accelerated Mortar Bar Test [13] and LS-635 [12] / CSA A23.2-14A Concrete Prism Expansion Test [13]. As one of the most expansive alkali-silica aggregates in Canada, ASR CA3 has an expansion range from 0.28-0.49 at 14 days of LS-620 [14].

Cement Materials

MTO obtained GU and GUL cements with alkali content of 0.9 ± 0.10% from a cement supplier in Ontario for the study. The cement materials were held in respective plastic barrels with airtight lids, stored in a dry building in summer prior to being prepared into bags and distributed to the firms.

LS-620 Test Results

The firms reported expansion of the individual mortar bars and the average expansion of three bars at 1, 7 and 14 days. For the purpose of this study, only the average expansion at 14 days was analyzed and shown in Table 1 below. All the reported mortar bar expansions fall within the range of 0.28 to 0.49 at 14 days established for ASR CA3 used as a reference material for LS 602, regardless of the cement materials used.

The difference between the expansion results of two mixes made with the same aggregate was calculated and expressed as a percentage of their mean expansion. Table 1 showed the difference in expansions between the use of GU and GUL cement type.

For the difference in the 14-day expansion between the use of GU and GUL cements from the same firm, it was found that only Firm 2 shows the difference of 16.1% of the mean, while in all other incidences, the difference is less than the single laboratory precision of 8.3% published in LS-620 for mortars showing average expansions after 14 days in solution of more than 0.1%. The maximum difference in the expansion between the use of GU and GUL cement types from a different laboratory is 0.097% which is 24% of the mean of the two results 0.453 and 0.356; 24% is less than the multi-laboratory precision (43%) published in LS-620. In general, the variability of the data in this study is within the variability of the test method, except for one incidence of 16.1% in Firm 2, which is larger than the single laboratory precision of the test method.

Table 1. 2020 Accelerated Mortar Bar Test – Average Expansion at 14 Days

Consulting Firm	1.20 GUL	2.20 GUL	1.20 GU	2.20 GU	% Difference of the Mean
1	0.407	0.392	0.393	0.394	3.6
2	0.453	0.425	0.386	0.394	16.1
3	0.369	0.379	0.372	0.360	5.1
4	0.360	0.368	0.370	0.356	3.9
Mean	0.397	0.391	0.380	0.376	N/A
Standard Deviation	0.042	0.025	0.011	0.021	N/A

The scatter diagram described by Youden [15] is used to show the data in Figure 1. For each type of cement, the test value for the first sample of the pair (1.20) on the horizontal axis is plotted against the test value for the second sample (2.20) on the vertical axis. The horizontal and vertical axes are of equal length and are scaled to give an informative display of the plotted points. The vertical and horizontal crosshairs on the plots represent the mean values for all the valid results on the first sample (1.20) and the second sample (2.20), respectively. Test results for GU and GUL cements are plotted on the same scatter diagram. Considering the limited number of observations, no outlier was removed.

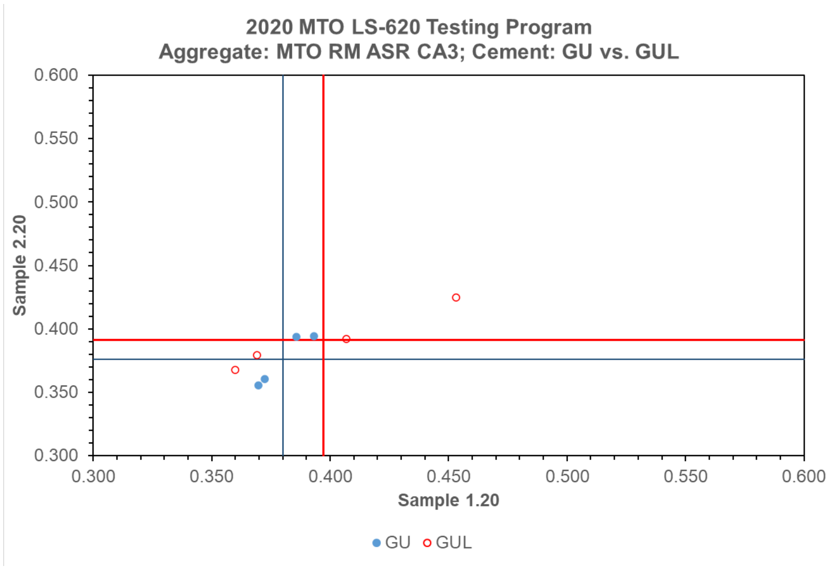

Figure 1. 2020 Accelerated Mortar Bar Test – Average Expansion at 14 Days

ANOVA Analysis

The test results were analyzed using a statistical analysis tool called Analysis of Variance or ANOVA [11] [16]. ANOVA provides evidence whether the means for multiple groups of data are significantly different or not. It compares the variance of the data between the groups with the variance within the data groups. The ANOVA analysis (Figure 2) of the test results showed that the calculated F statistic of 0.5067 is much less than Fcrit of 3.4903, and the calculated P-Value of 68.5% is much greater than the 5% significance level. Hence, there is no significant evidence to reject the Null hypothesis that the mean expansions produced by GU and GUL cements with ASR CA3 are equal.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1.20 GUL	4	1.589	0.3972	0.0018
2.20 GUL	4	1.564	0.3911	0.0006
1.20 GU	4	1.521	0.3802	0.0001
2.20 GU	4	1.504	0.3761	0.0004

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0011289	3	0.0004	0.5067	0.685	3.4903
Within Groups	0.008912	12	0.0007			
Total	0.0100409	15				

Figure 2. ANOVA Analysis of 2020 Accelerated Mortar Bar Test Results

2021 MTO LS-620 Proficiency Sample Testing Program

ASTM C802-14 recommends that testing of two duplicate samples by more than 15 laboratories will provide statistically adequate information to determine a meaningful estimate of single-operator precision [17].

Thirty (30) laboratories voluntarily participated in 2021 MTO LS-620 Proficiency Sample Testing Program. Each laboratory was asked to perform LS-620 Rev. 35 [18] on pairs of nearly identical samples, using both GU cement and GUL cement for comparison.

Aggregates

In 2021, MTO secured a new stockpile of material, MTO RM ASR CA6 (ASR CA6) to replace the current depleting stockpile of ASR CA3 aggregate for control and calibration of LS-620 Accelerated Mortar Bar Test [12] and LS-635 Concrete Prism Expansion Test [12], as well as AAR-related laboratory investigations. ASR CA6 is a quarried siliceous limestone from Eastern Ontario, expected to develop AAR similar to ASR CA3. This paper discuss a preliminary mortar bar expansion range at 14 days for ASR CA6.

Cement Materials

MTO obtained GU and GUL cements with alkali content of 0.9 ± 0.10% from a cement supplier in Ontario for the study. The cement materials were held in respective plastic barrels with airtight lids, stored in a dry building in summer prior to being prepared into bags and distributed to the firms.

LS-620 Test Results

The participants reported expansion of the individual mortar bars and the average expansion of three bars at 1, 7 and 14 days. The Youden scatter diagram is shown in Figure 3. Test results for GU and GUL cement types are plotted on the same scatter diagram. A majority of the test results concentrate in the upper right corner (quadrant 1) and the lower left corner (quadrant 3) on the scatter diagram, with some laboratories obtaining either consistently low expansion or consistently high expansion, showing pronounced between laboratory bias and equal variation for each material. The number of laboratories shown on the diagram was removed by the AMRL technique from analysis of precision estimates as discussed in the next section.

Statistical Analysis to Determine Precision Estimates

Outlying test data that do not belong to the data population may mislead the calculation of the normal test method variability and precision values. Statistically, the probability to include the outlying data in the data set is very small. For the purpose of this study, outlying data were identifed using the statistical criteria provided below.

Precision estimates of the LS-620 proficiency sample test results were analyzed to compare the variations in expansion with the use of GU cement and the values with the use of GUL cement from the same cement supplier. A technique designed by AMRL was used to extract the core of the data from the MTO proficiency test results as explained later in the section [19]. The core data were analyzed to determine single operator precision, single-operator, multi-batch precision (2 batches in this study) and multi-laboratory precision as defined in ASTM C802-14. The AMRL technique uses the cut-off limits based on the range of inner 75% of the data set.

The following steps were employed to determine the precision estimates. Detailed explaination of the process was reported elsewhere [9].

Step 1. Remove test data for any non-compliance of test procedure.

Step 2. Remove invalid data that fall beyond 4.725 times the standard deviation of the median [20] [21]. The probability is approximately twenty-four in ten million that the invalid data should be included in the data set [20].

Step 3. Remove outliers that fall beyond 2.7 times the standard deviation of the median. The probability is approximately seven in one thousand that the outlying data should be included in the data set [20].

Step 4. Analyze the remaining core data to determine the mean and standard deviation of each data set, after the elimination of invalid data and outliers.

Step 5. Determine precision estimates [17].

The precision estimates summarized in Table 2 below suggested that for mortar bars with average expansions (after 14 days in NaOH solution) of more than 0.3%, the variations in expansion with the use of GU cement are comparable to the values with the use of GUL cement from the same cement supplier.

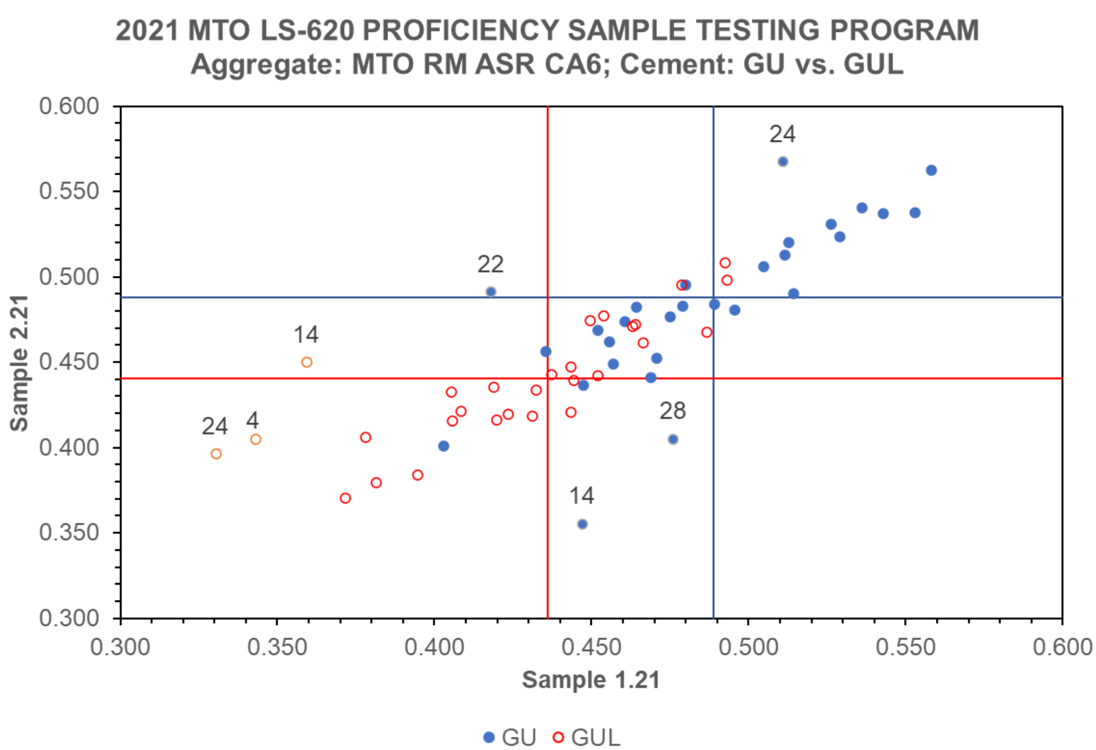

Figure 3. 2021 Accelerated Mortar Bar Test – Average Expansion at 14 Days

Table 2. Summary of Precision Estimates for 2021 Study with ASR CA6

Precision Estimate	2021 GU Cement	2021 GUL Cement
Single Operator CV%, 1s%	2.5	2.5
Single Operator CV%, d2s%	8.2	8.2
Single Operator, Multi-batch Precision, 1s%	2.1	2.3
Single Operator, Multi-batch Precision, d2s%	5.8	6.4
Multi-laboratory CV%, 1s%	8.0	8.1
Multi-laboratory CV%, d2s%	22.5	22.6

ANOVA Analysis

The ANOVA analysis of the core test results is showed in Figure 4 below. The calculated F statistic of 15.528 is higher than F crit of 2.6974 (critical value), and the calculated P-Value is much smaller than the 5% significance level. Hence, there is significant evidence to reject the Null hypothesis that the mean expansions produced by GU and GUL cements with ASR CA6 are equal.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1.21 GU	25	12.222	0.4889	0.0015
2.21 GU	25	12.201	0.488	0.0015
1.21 GUL	26	11.339	0.4361	0.0012
2.21 GUL	26	11.45	0.4404	0.0013

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0645	3	0.0215	15.528	2.44365E-08	2.6974
Within Groups	0.1357	98	0.0014			
Total	0.2002	101				

Figure 4. ANOVA Analysis of 2021 Accelerated Mortar Bar Test Results

Percent Within Limits (PWL) Analysis

The multi-laboratory precision of LS-620 Accelerated Mortar Bar Test Method states that the results of two properly conducted tests in different laboratories on specimens of a sample of aggregate should not differ by more than 43% of the mean expansion [18]. This multi-laboratory precision of 43% is much higher than the multi-laboratory precision estimate in Table 2 for 2021 GU cement and ASR CA6. In addition to supply of nearly identical aggregate samples, the supply of standard cement by MTO to all participating laboratories would have contributed to the improvement of multi-laboratory variation to some extent.

Based on the core test results, the mean expansion of the mortar bars using 2021 GU cement is 0.488%. Hence, by applying the inherent multi-laboratory precision of test method, the following statement is possible:

Statement 1: the average expansion of ASR CA6 mortar bars using 2021 GU cement at 14 days should not fall beyond the range of 0.38% - 0.59%, 19 times in twenty (95%).

MTO LS-100 Rev.16 [18] provides a procedure to calculate Percent Within Limits (PWL) which is frequently used as a statistical tool to estimate the percentage of a given volume of material or tests that is within acceptable limits in a specification as part of MTO statistically based quality assurance program. To assess the acceptability of the expansion test results, LS-100 was followed to estimate the percentage of expansion results with GUL cement that was within the upper expansion limit with GU cement (UL=0.59%) and the lower expansion limit with GU cement (LL=0.38%), based on calculation of Quality Index using the mean and standard deviation of the core data with GUL cement. It was found that PWL of 1.21GUL expansions is 94% and PWL of 2.21GUL expansions is 95%. Therefore, the following statement is possible:

Statement 2: 94% to 95% of the expansion results using GUL cement will fall within the expansion range produced by using GU cement from the same cement supplier.

The statistics in Statement 2 matched the 95% confidence level in Statement 1 for which the inherent multi-laboratory precision of test method was valid. Although the foregoing ANOVA analysis showed significant difference in expansions produced by GU and GUL cements with ASR CA6, it may be concluded that such difference was masked by the current variability of the test method that requires use of GU cement. In testing the same reactive aggregate with both GU and GUL cements, the expansion range produced by using GU cement may only be exceeded one time in twenty when GUL cement of the same supplier is used for the test. This incidence of exceedance is considered a very small probability.

HIIFP Project in 2022

In 2022, MTO launched an HIIFP project with Toronto Metropolitan University (TMU) to evaluate the effect of using GU and GUL cements from five cement suppliers on the expansion results of the mortar bar test. TMU performed LS-620 Rev. 36 [12] on the aggregates and cements supplied by MTO, as described below.

Aggregates

Four aggregates were supplied by MTO for this project including ASR CA3 and ASR CA6 as described in the foregoing programs, as well as MTO RM ACR CA1 (ACR CA1) and MTO RM ASR CA5 (ASR CA5). MTO maintained a stockpile of ACR CA1 that was a quarried dolomitic limestone near Kingston, Ontario. This aggregate is well known as being alkali-carbonate reactive (Rogers, 1986). The major element oxides of ACR CA1 determined by fusion XRF analysis are listed in Table 1 of LS-615 Rev. 35 [18]. ASR CA5 was a crushed siliceous gravel from a pit near Sudbury area, Ontario. The ASR CA5 exhibited alkali-silica reactivity [22]. All aggregates used for this program was also crushed at the MTO laboratory with a jaw crusher down to P4.75mm according to LS-633 Rev. 33 [10].

Cement

MTO supplied high alkali GU and GUL cements obtained from five cement suppliers in Canada for the study. This paper only included the available data for four cement suppliers (suppliers 1, 2, 4 and 5) received by MTO by February 14, 2023.

LS-620 Test Results

Expansion of the individual mortar bars and the average expansion of three mortar bars were reported at 1, 7, 14 and 28 days. For the purpose of this study, only the average expansions at 7, 14 and 28 days were shown in Table 1below.

ANOVA Analysis

Each group of expansion data is produced with the use of the same type of cement from 3 different suppliers. The data for cement supplier 5 was excluded in the ANOVA analysis because the alkali content of the cement from supplier 5 is lower than the minimum of 0.8% required by LS-620 test method. However, the data for cement supplier 5 was included in the analysis of single laboratory variation as discussed later.

Given the limited number of data, ANOVA analysis was only performed on the test results for ASR CA3, ASR CA5 and ASR CA6, as shown in Figure 5 through Figure 7 respectively. For each of the 3 aggregates, the calculated F statistic is much less than F crit, and the calculated P-Value is much greater than the 5% significance level. Hence, there is no significant evidence to reject the Null hypothesis that the mean expansions produced by GU and GUL cements for each of the 3 aggregates are equal.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
GU and ASR CA3	3	1.1845	0.394844667	0.001005116
GUL and ASR CA3	3	1.2075	0.402489	0.000672021

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8.76537E-05	1	8.76537E-05	0.104527792	0.7627	7.7086
Within Groups	0.003354275	4	0.000838569			
Total	0.003441929	5				

Figure 5. ANOVA Analysis of HIIFP Mortar Bar Expansion for ASR CA3

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
GU and ASR CA5	3	0.9489	0.316289	0.00088199
GUL and ASR CA5	3	0.9887	0.329555667	0.000428918

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000264007	1	0.000264007	0.402784475	0.5601	7.7086
Within Groups	0.002621816	4	0.000655454			
Total	0.002885822	5				

Figure 6. ANOVA Analysis of HIIFP Mortar Bar Expansion for ASR CA5

SUMMARY

Groups	Count	Sum	Average	Variance
GU and ASR CA6	3	1.1085	0.369489	8.75804E-05
GUL and ASR CA6	3	1.1413	0.380444333	4.95923E-05

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.000180029	1	0.000180029	2.624852409	0.1805	7.7086
Within Groups	0.000274345	4	6.85863E-05			
Total	0.000454374	5				

Figure 7. ANOVA Analysis of HIIFP Mortar Bar Expansion for ASR CA6

Analysis of Single Laboratory Variation

LS-620 Rev. 36 provides a single laboratory precision of 8.3%, meaning that two results obtained in the same laboratory, by the same operator testing the same material and using the same equipment should not differ by more than 8.3% of the mean expansion [12].

Because different cements were used for each mixture in the study, the LS-620 Rev. 36 single laboratory precision cannot be properly applied and hence was used as a reference for comparison only.

The difference between the expansion results of two mixes made with the same aggregate was calculated and expressed as a percentage of their mean expansion. Table 3 to Table 5 showed the difference in expansions between the use of GU and GUL cements from the same cement supplier and the difference in expansions with the same type of cements from different suppliers. Table 5 shows the difference in expansions between the use of GU and GUL cements from the same supplier 5 only, because the alkali content of the cements from supplier 5 is lower than the minimum of 0.8% required by LS-620 test method.

In terms of the difference in the 14-day expansion between the use of GU and GUL cements (from the same cement supplier), it was found that there is only one incidence where the difference for ASR CA5 was 17.2% of the mean, while all other incidences are either close to or less than 8.3%. A comparison between the expansion with GU cement from one supplier and the expansion with GUL cement from a different supplier shows that the difference is from 7.4% of the mean for ASR CA6, 15.2% for ASR CA3, up to 20.7% for ASR CA5.

For the same aggregate, the difference in the 14-day expansion with same type of cement (from different cement suppliers) was up to 16.4% for the GU cement and up to 12.5% for the GUL. Hence, the difference in expansion within the same cement type (either GU or GUL) from different suppliers is already larger than 8.3%, with the GU being larger (16.4%) which is comparable to the 17.2% (GU and GUL from the same supplier) and the 20.7% (GU and GUL from a different supplier) as described above.

Table 3. HIIFP LS-620 Accelerated Mortar Bar Test Results for ASR CA3

Days in NaOH	7 days	7 days	% Difference of the mean	14 days	14 days	% Difference of the mean	28 days	28 days	% Difference of the mean
Cement Supplier	**GU**	**GUL**		**GU**	**GUL**		**GU**	**GUL**	
Supplier 1	0.247	0.253	**2.4**	0.370	0.395	**6.5**	0.556	0.591	**6.1**
Supplier 2	0.302	0.303	**0.3**	0.431	0.431	**0**	0.678	0.658	**3.0**
Supplier 4	0.241	0.246	**2.0**	0.383	0.381	**0.7**	0.634	0.633	**0.2**
Standard Deviation	**0.033**	**0.031**	**N/A**	**0.032**	**0.026**	**N/A**	**0.062**	**0.034**	**N/A**
% Difference of the mean	**23.1**	**21.5**	**N/A**	**15.3**	**12.5**	**N/A**	**19.6**	**10.8**	**N/A**

Table 4. HIIFP LS-620 Accelerated Mortar Bar Test Results for ASR CA5

Days in NaOH	7 days	7 days	% Difference of the mean	14 days	14 days	% Difference of the mean	28 days	28 days	% Difference of the mean
Cement Supplier	**GU**	**GUL**		**GU**	**GUL**		**GU**	**GUL**	
Supplier 1	0.080	0.110	**31.6**	0.282	0.335	**17.2**	0.575	0.592	**2.9**
Supplier 2	0.137	0.162	**16.7**	0.333	0.347	**4.1**	0.602	0.581	**3.6**
Supplier 4	0.146	0.142	**2.8**	0.334	0.307	**8.5**	0.572	0.536	**6.5**
Standard Deviation	**0.036**	**0.026**	**N/A**	**0.030**	**0.021**	**N/A**	**0.016**	**0.030**	**N/A**
% Difference of the mean	**54.5**	**37.7**	**N/A**	**16.4**	**12.2**	**N/A**	**5.1**	**9.9**	**N/A**

Table 5. HIIFP LS-620 Accelerated Mortar Bar Test Results for ASR CA6

Days in NaOH	7 days	7 days	% Difference of the mean	14 days	14 days	% Difference of the mean	28 days	28 days	% Difference of the mean
Cement Supplier	**GU**	**GUL**		**GU**	**GUL**		**GU**	**GUL**	
Supplier 1	0.275	0.278	**1.1**	0.378	0.387	**2.4**	0.544	0.582	**6.7**
Supplier 2	0.259	0.267	**3.0**	0.371	0.373	**0.5**	0.646	0.622	**3.8**
Supplier 4	0.234	0.246	**5.1**	0.359	0.381	**5.9**	0.677	0.693	**2.3**
Standard Deviation	**0.021**	**0.016**	**N/A**	**0.009**	**0.007**	**N/A**	**0.069**	**0.056**	**N/A**
% Difference of the mean	**16.1**	**12.1**	**N/A**	**5.0**	**3.7**	**N/A**	**21.3**	**17.5**	**N/A**

Table 6. HIIFP LS-620 Accelerated Mortar Bar Test Results for ACR CA1

Days in NaOH	7 days	7 days	% Difference of the mean	14 days	14 days	% Difference of the mean	28 days	28 days	% Difference of the mean
Cement Supplier	**GU**	**GUL**		**GU**	**GUL**		**GU**	**GUL**	
Supplier 2	0.092	0.083	**10.3**	0.126	0.116	**8.2**	0.168	0.151	**10.7**

Table 7. HIIFP LS-620 Accelerated Mortar Bar Test Results for Cement Supplier 5 with alkali content < 0.8%

Days in NaOH	7 days	7 days	% Difference of the mean	14 days	14 days	% Difference of the mean	28 days	28 days	% Difference of the mean
Aggregates	**GU**	**GUL**		**GU**	**GUL**		**GU**	**GUL**	
ASR CA3	0.269	0.261	**3.0**	0.412	0.400	**3.0**	0.626	0.584	**6.9**
ASR CA5	0.139	0.140	**0.7**	0.303	0.312	**2.9**	0.544	0.535	**1.7**
ASR CA6	0.278	0.273	**1.8**	0.414	0.409	**1.2**	0.770	0.727	**5.7**
ACR CA1	0.050	0.049	**2.0**	0.091	0.088	**3.4**	0.129	0.124	**4.0**

Summary and Conclusions

This paper discussed the LS-620 test data on four MTO reference aggregates (ASR CA3, ASR CA5, ASR CA6 and ACR CA1) using both GU and GUL cement types from cement suppliers in Canada. The data were produced through 2020 consultant testing program, 2021 MTO Aggregate and Soil Proficiency Program and the HIIFP project at TMU.

ANOVA statistical analyses of ASR CA3 expansion data showed that the use of GU and GUL cements (from the same cement supplier) did not cause significant difference in expansions. For GU and GUL cements, each from different suppliers, the ANOVA analysis of the HIIFP data from TMU also showed that the use of GU and GUL cements did not cause significant difference in expansions.

In 2021 MTO Aggregate & Soil Proficiency Program with ASR CA6, it was found that the average expansion range at 14 days was 0.43% - 0.55% for mortar bars made with GU cement, and 0.39% - 0.49% for mortar bars made with GUL cement from the same cement supplier. The ANOVA statistical analysis suggested that use of GU and GUL cements (from the same cement supplier) did cause significant difference in expansions in this case. Applying the inherent variability (multi-laboratory precision) of the test method, a calculation of PWL revealed that in testing the same reactive aggregate with both GU and GUL cements, the expansion range produced by using GU cement may only be exceeded one time in twenty when GUL cement of the same supplier is used for the test. This incidence of exceedance is considered a very small probability. This conclusion is based on the standard deviation of the mortar bar data 1.21 GUL and 2.21 GUL being 0.035 and 0.036 respectively, as calculated from the core data of 2021 Proficiency Program.

The inherent multi-laboratory variability of 43% was not applied to the expansion data produced by the GUL cement, because the variability was developed based on GU cement [23] and hence may not be appliable to GUL cement. An interlaboratory study is forthcoming to determine the variability in accelerated mortar bar test with GUL cements from different suppliers. The available limited data from the HIIFP project indicated that the variability produced by GUL cement from different suppliers is less than that produced by GU cement from different suppliers (as indicated by the standard deviations in

Table 3 to Table 5). It is expected that the forthcoming interlaboratory study would provide a representative statistical means to further review this conclusion.

The precision estimates summarized in Table 2 suggested that for mortar bars with average expansions (after 14 days in NaOH solution) of more than 0.3%, the variations in expansion with the use of GU cement are comparable to the values with the use of GUL cement from the same cement supplier.

Based on the studies, there is not sufficient justification to support that the use of GUL cement has significant impact on the results of LS-620 Accelerated Mortar Bar Test, which currently mandates the use of GU cement.

Future Directions

Consideration is being given to studying the variation in expansion with the use of GUL cements from different cement suppliers, provided that the cement contains a total alkali content of 0.9 ± 0.10% as required by the two AAR screening test methods LS-620 and LS-635. It is also suggested that precision should be estimated by requesting the participating laboratories in the proficiency sample testing program to crush and prepare the aggregate for the tests. This approach closely follows the normal testing procedure in which a laboratory prepares its own test samples from field samples. It is expected that the data from such study would provide a representative statistical means to complement the analysis in this report. A separate precision estimate for the use of GUL cement may be considered.

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