Laboratory Assessment on Effects of Blended Cements on Strength and Durability of Full-Depth Reclaimed Pavement Materials

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Abstract

In North America, chemical stabilizer that is commonly used in the full-depth reclamation process is General Use (GU) cement. Blended cements that contain substantial amount of supplementary cementitious materials, however, could be plausible alternatives that can help reduce the carbon footprint and improve certain properties, like shrinkage, of the stabilized materials. In this paper, the effects of blended cements, also known as Hydraulic Road Binder (HRB), on the strength and durability of full-depth reclaimed pavement materials were assessed based on laboratory investigations. The assessment was conducted using two types of reclaimed pavement materials and three types of blended cements. In addition, GU cement was used to produce control mixes. The strength of the stabilized materials was evaluated using unconfined compressive strength (UCS) test. The UCS test was performed on compacted specimens that had been prepared with different binder contents and moist cured for 7-days and 28-days. The durability assessment was carried out with freeze-thaw test. This test was done on compacted specimens that had been made with optimum binder contents. The results of UCS and freeze-thaw tests were analyzed with ANOVA, Fisher's test and Dunnett's test to identify the effects of the blended cements on the strength and durability of the full-depth reclaimed pavement materials. The analyses outputs indicated that blended cements can provide equivalent or even better strength and durability than GU cement if applied in full-depth reclamation process.

Key words: blended cement, hydraulic road binders, full-depth reclamation, soil stabilization, unconfined compressive strength, freeze-thaw test

INTRODUCTION

Full-depth reclamation (FDR) is a type of cold in-place recycling in which the existing old and deteriorated pavement is pulverised, treated with appropriate binder, and compacted to form a strong base layer. In this process, the most commonly used chemical stabilizer is GU cement. Blended cements that contain substantial amounts of supplementary cementitious materials (SCMs) could be plausible alternatives to straight GU cement that can help reduce the carbon footprint and improve certain properties such as shrinkage of the stabilized materials.

This paper presents the effects of blended cement on the strength and durability of FDR pavement materials.

Blended Cement

Blended cement is defined by various standards in different ways but with almost similar meaning. The Canadian CSA A 3000-13 defines blended cement as:

> ‘*a single manufactured product obtained by*
>
> *a) blending Portland cement or Portland-limestone cement and up to three supplementary cementing materials; or*
>
> b) *integrinding Portland cement clinker and up to three supplementary cementing materials or two supplementary cementing materials and granulated blast-furnace slag, to which the forms of calcium sulphate, limestone, water, and processing additions may be added at the option of the manufacturer.*’

Similarly, ASTM C219 defines blended cement as:

> ‘*hydraulic cement consisting of two or more inorganic constituents (at least one of which is not Portland cement or Portland cement clinker) which separately or in combination contribute to the strength gaining properties of the cement, (made with or without other constituents, processing additions and functional additions, by intergrinding or other blending.*’

In the context of these definitions, blended cements can be considered as families of hydraulic road binders (HRBs) specified in European Standard, EN-13282. Similar to blended cements, HRBs are also factory made hydraulic binders that are composed of a blend of various constituents of which the main ones are the following:

- Portland cement clinker,
- granulated blastfurnace slag,
- pozzolans,
- fly ash,
- burnt shale, and
- limestone

EN 13282 defines hydraulic road binder as:

> *'a factory produced hydraulic binder, supplied ready for use, having properties specifically suitable for treatment of materials for bases, sub-bases and capping layers as well as earthworks, in road, railway, airport and other types of infrastructures.'*

The specifications for some of the basic properties of blended cements and hydraulic road binders are shown in Table-1 and Table-2. Comparing these specifications, it can be observed that blended cements can be subgroups of hydraulic binders. This is because blended cements that fulfill the requirements of CSA A-3000-13 and ASTM C 595-17 could also meet the requirements of EN 13282. Based on this premise, blended cements can be suitable binders to treat bases, sub-bases, capping layers and embankments in road, railway, airport and other similar infrastructure constructions.

Table 1 Comparison of the Canadian and ASTM Specifications for blended cement

Specification	**Fineness: 45µm sieve, [% retained]**	**Autoclave Expansion [% expansion]**	**Time of initial set (minutes)**	**Compressive Strength (MPa)**			
				1-day	3-day	7-day	28-day
CSA A-3000-13	Max[#]. 24	Max. 0.8	Min[#]. 45-90 Max. 250-480	Min. 13.5[1]	Min. 14.5[2]	Min. 20.0[3]	Min 26.5[4]
ASTM C 595-17	-	Max. 0.8	Min. 45 Max. 420	-	Min. 10-13	Min. 5-20	Min. 11-28

#- Max. = maximum; Min. = minimum.
1- is applicable only for high-early strength blended cements.
2- for high-early strength blended cement, it is 24.0 MPa.
3- for low-heat of hydration cements, it is 8.5 MPa.
4- for low-heat of hydration cements, it is 24 MPa.

Table 2 European Specification for Hydraulic Road Binders

Specification	**Fineness: 90µm sieve, [% residue]**	**Expansion [mm]**	**Time of initial set (minutes)**	**Compressive Strength (MPa)**		
				7-day	28-day	56-day
EN 13282-1	Max. 15	Max. 10	Min. 90[1]	Min. 5-16	Min. 12-32.5 Max. 32.5-52.5	-
EN 13282-2	Max. 15	Max. 30	Min. 150	-	-	Min. 2.5-32.5 Max. 22.5-52.5

1- for rapid setting binders the specified value is maximum time set, which is 90 minutes.

The Canadian CSA A-3000-13 categorizes blended cements as binary, ternary, and quaternary depending on the number of constituents they are made from. ASTM C 595-17 also has the similar classification scheme. However, in ASTM C 595-17, there are only binary and ternary cements (there are no quaternary cements). All of these types contain Portland cement as a common ingredient along with one or more supplementary cementitious materials. As the name suggests, binary blended cements consist of two constituents, of which one is Portland cement and the other supplementary cementing material. Similarly, ternary and quaternary blended cements consist of two and three SCMs, respectively, in addition to Portland cement.

Various studies indicated that the use of blended cements have significant impact in reducing CO_2 emissions. E. Worrell et al., (2001) estimated that the global CO_2 emission potential can be reduced by 5%-20% by using blended cements. A study made for California Climate Action Registry showed at least 25% reduction in greenhouse gas emissions can be achieved in U.S. by using blended cement (The Loreti Group, 2008). The environmental friendliness of blended cements compared to the Portland cement is also supported by the Environmental Product Declarations (EPD) of Portland Cement Association (PCA). In its EPD, PCA provided the results of life cycle assessment (LCA) that were conducted based on the U.S. industry average composition of blended cement and Portland cement. These compositions are shown in Table 3 and the results of the life cycle assessment is shown in Table 4. From Table 4, it can be seen that production of blended cement has lower environmental impact, consumes less energy and material resources, and generates fewer hazardous wastes as compared to Portland cement.

Table 3 U.S. Industry Average Composition (PCA, 2016a, 2016b)

Cement Ingredients	**Portion of Cement Product (% by weight per mass of cement product)**	
	Portland cement	**Blended cement**
Clinker	92.2	77.1
Slag		11.0
Gypsum	4.63	5.4
Uncalcined limestone	1.86	4.69
Fly ash		1.30
Other	< 1.0	< 1.0

Despite their environmental friendliness, the use of blended cements in U.S. and Canada is not prevalent. In 1995, Malhotra and Hammings (1995) stated that there were only two plants in Canada and one plant in U.S. that had been producing blended cements up until then. The Canadian plants, which were located in Brookfield, Nova Scotia and St Constant, Quebec, had been annually producing a total amount of 80, 000 tonnes silica fume blended cement. The single U.S. plant, which was located at Dundee, Michigan, had been annually producing 50,000 – 200,000 tonnes of fly ash blended cement (Malhotra and Hammings, 1995). According to the data from Statistics Canada (Government of Canada, 2017), the blended cement production has not shown significant change during the periods after 1995. The Canadian cement production over a period of 13-years, 2004-2016, is shown in Figure 1.

Table 4 LCA Results of Portland and Blended Cement Productions (PCA, 2016a, 2016b)

Impact Categories	Unit	Cradle-to-gate total per metric tonne of production	
		Portland cement	**Blended cement**
Environmental Impact			
Global warming potential (100 years)	kg CO_2-eq.	1040	892
Acidification potential	kg CO_2-eq.	2.45	2.26
Eutrophication potential	kg N-eq.	1.22	1.11
Formation potential of tropospheric ozone	kg O_3-eq.	48.8	42.3
Ozone depletion potential	kg CFC 11-eq.	2.61E-05	2.48E-05
Total Primary Energy Consumption			
Non-renewable primary energy: Fossil	MJ	5250	4660
Non-renewable primary energy: Nuclear	MJ	345	411
Renewable primary energy: Solar, wind, hydroelectric, geothermal	MJ	127	95.5
Renewable primary energy: Biomass	MJ	165	76.9
Material Resources Consumption			
Non-renewable material resources	kg	1420	1240
Renewable material resources	kg	7.64	3.42
Net fresh water withdrawal	L	9700	9240
Total Waste Generation			
Non-hazardous waste generated	kg	8.99	10.5
Hazardous waste generated	kg	0.0518	0.0511

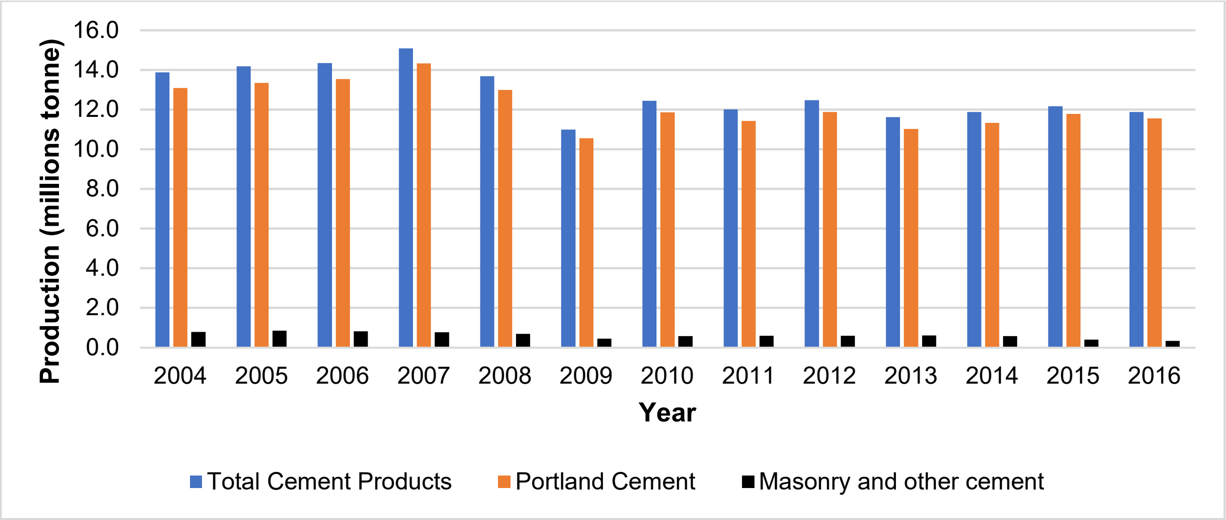

Figure 1 13-years cement production in Canada

Scope and Objective

In this research, three types of HRBs were used to stabilize two types of materials acquired from different FDR projects. The HRBs consist of blast furnace slag as a supplementary cementing material.

The objective of the research is to assess the effects of blended cements on the strength and durability of full-depth reclaimed pavement materials. For this purpose, comparative assessment was performed using GU cement as a control binder.

MATERIALS AND METHODOLOGY

Full-depth reclaimed materials

Full-depth reclaimed pavement material samples were collected from Line 8 Road at Niagara-on-the-Lake and County Road 1 at Bruce County. The pavement of Line 8 Road was composed of granular base and sub-base with chip seal surfacing while the pavement of County Road 1 was composed of granular base and sub-base layer with high float surface treatment and micro-surfacing surface layer. The two sample locations are shown in Figure 2 and Figure 3.

Figure 2 Reclaimed materials sample locations

Index property tests like Atterberg limits, particle size analysis and other tests like Methylene Blue Value of Clays and micro-deval abrasion resistance were conducted on both material samples. The test results are shown in Figure 4 and Table 5. For the sake of simplicity, the Niagara-on-the-Lake materials are designated as ‘NL’ and the Bruce County materials are designated as ‘BC’.

Figure 3 Partly pulverized pavement sections (*left: Niagara-on-the-Lake, right: Bruce County*)

Particle size analysis was performed according to AASHTO T-88 using different sieve sizes. As can be seen from the grading curves, both materials are well-graded with particle size distributions falling on the finer side of the maximum density line (0.45-power curve). The Niagara-on-the-Lake material have denser packing arrangement and coarser fractions than Bruce County material on most of sieve sizes.

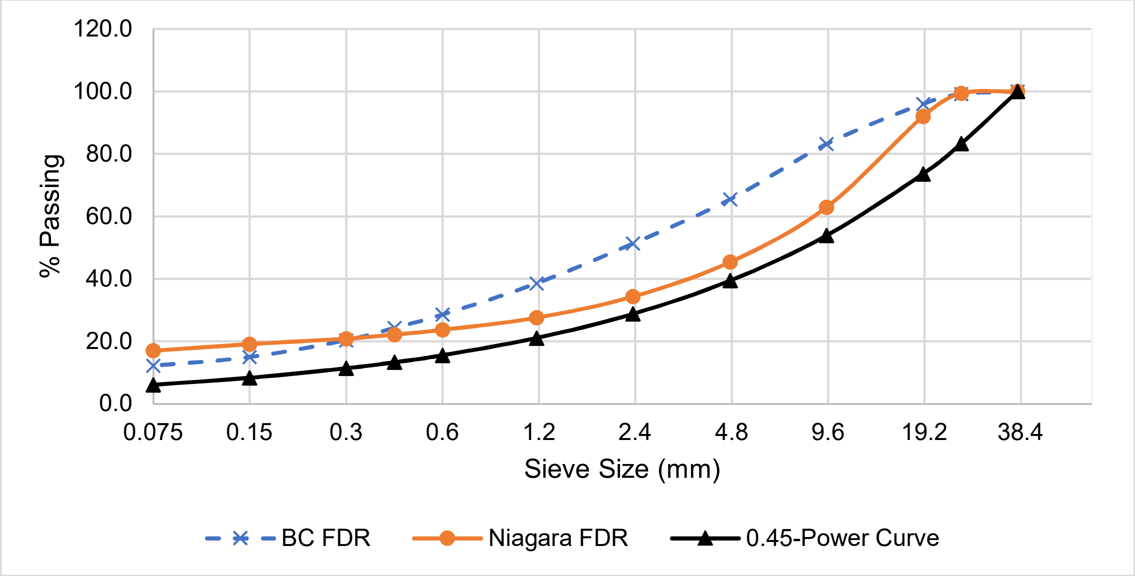

Figure 4 Particle size distribution of reclaimed materials

Consistency index tests show that NL material have liquid limit of 22% and plasticity index of 5, whereas the BC material is non-plastic. The micro-deval abrasion loss of NL material is by far higher than that of BC material. This indicates that coarse aggregates of NL material are weaker than coarse aggregates of BC material. Similarly, the Methylene Blue Value of NL material by far exceeds the corresponding value for BC material. This shows that NL material contains larger amount of harmful clays than BC material.

Overall, even if NL material have the denser particle size distribution, quality wise BC material is better. As would be seen later, this difference in the quality of the materials affects the strength and durability of the stabilized materials. That means, if the two materials have to be stabilized to attain the same level of strength, the one with the inferior quality will demand higher binder content.

Table 5 Results of Laboratory Tests on Reclaimed Materials

Test Description	Test Method	Test Results	
		Niagara-on-the-Lake	Bruce County
Liquid Limit (%)	AASHTO T 89	22	Non-plastic
Plasticity Index	AASHTO T 90	5	Non-plastic
Micro-Deval Abrasion Loss (%)	ASTM D 6928	45.6	10.8
Methylene Blue Value (mg/g)	AASHTO TP 57	8.7	1.3
AASHTO Soil Class	AAHTO M 145	A-1-b	A-1-a

Binders

The three hydraulic road binders used in this research are designated as HRB-1, HRB-2, and HRB-3. As mentioned earlier, in addition to the three hydraulic road binders, GU cement was used in this research to make control specimens. The physical properties and chemical composition of the binders are presented in Table 6 and Table 7 respectively.

Table 6 Physical Properties of Binders

Physical Properties	GU	HRB-1	HRB-2	HRB-3
Blaine Fineness, m^2/kg	383	497	389	465
Fineness 45µm sieve, % retained	4	1.9	4.1	5.0
Autoclave, % Expansion	0.05	0.0	0.0	0.0
Compressive Strength at 28-days, MPa	40.5	41.5	35.0	34.8
Initial time of set, minutes	90	173	153	161
Sulphate Resistance, % expansion at 6 months	0.014	0.005	0.04	-

Table 7 Chemical Composition of Binders

Chemical Components	GU	HRB-1	HRB-2	HRB-3
SiO_2 (%)	19.6	22.3	26.2	28.4
Al_2O_3 (%)	5.0	5.7	7.0	7.6
Fe_2O_3 (%)	3.3	2.3	2.3	2.1
CaO (%)	62.2	55.4	53.4	49.4
MgO (%)	2.5	4.7	5.9	7.2
SO_3 (%)	3.9	3.7	3.6	3.3
Loss on ignition @ 950 (%)	2.3	4.3	1.7	1.5
Equivalent alkalis, % (as Sodium Oxide)	0.66	0.7	0.6	0.6

Methodology

The research was conducted according to the following approach:

- Step-1: Standard proctor test was done, per ASTM D 558, on soil-cement mixture to determine optimum moisture content (OMC);

- Step-2: Unconfined compressive strength (UCS) specimens were prepared and tested, per ASTM D 1633-Method A, with different binder content. At each binder content duplicate or triplicate specimens were produced for each of NL and BC material. UCS tests were conducted after 7-days of moist curing. To assess the effect of the various binders on the early strength, ANOVA, and Fisher's and Dunnett's tests were performed on 7-days UCS test data.

- Step-3: The lowest binder content for which UCS of 2.1 MPa – 2.8 MPa attained were selected as optimum. This range of UCS is recommended as optimum range by PCA (Luhr et al., 2008).

- Step-4: Triplicate UCS specimens were prepared with optimum binder content from Step-3 and moist cured for 28-days. UCS tests were conducted on the 28-days cured specimens to assess the effect of blended cements on long-term strength. Statistical analyses the same as Step-2 were performed on the 28-days UCS test data.

- Step-5: Duplicate freeze-thaw specimens were prepared for each binder with optimum binder content and freeze-thaw test was conducted per ASTM D 560. Again, the effect of the various binders on durability was evaluated using ANOVA, and Fisher's and Dunnett's tests.

RESULTS AND DISCUSSION

Standard proctor test

Standard proctor test was conducted to determine the maximum dry density (MDD) and optimum moisture content (MDD) of the FDR-cement mixture. The test was performed for each of the eight FDR-cement combinations with an initial cement contents of 5-6%. This range of initial cement content is recommended in PCA's Soil-Cement Laboratory Handbook (PCA, 1992) for AASHTO A-1 soil group. The test results are shown in Figure 5 and Table 8.

Reeder et al. (2017) stated MDD and OMC of FDR-cement mixtures with different cement contents will not vary significantly from those obtained with initial cement content. Similarly, Luhr et al. (2008) mentioned cement contents within 1% - 2% of initial cement content will not substantially deviate OMC. Thus, OMCs in Table 8 are used to prepare the UCS specimens with varying cement contents.

As can be seen in Table 8, the MDD and OMC do not show significant variation with cement type. The lowest MDD is about 98% of the highest MDD for both of NL and BC materials. Similarly, the largest variation among the OMCs is only 0.4% for both of NL and BC materials.

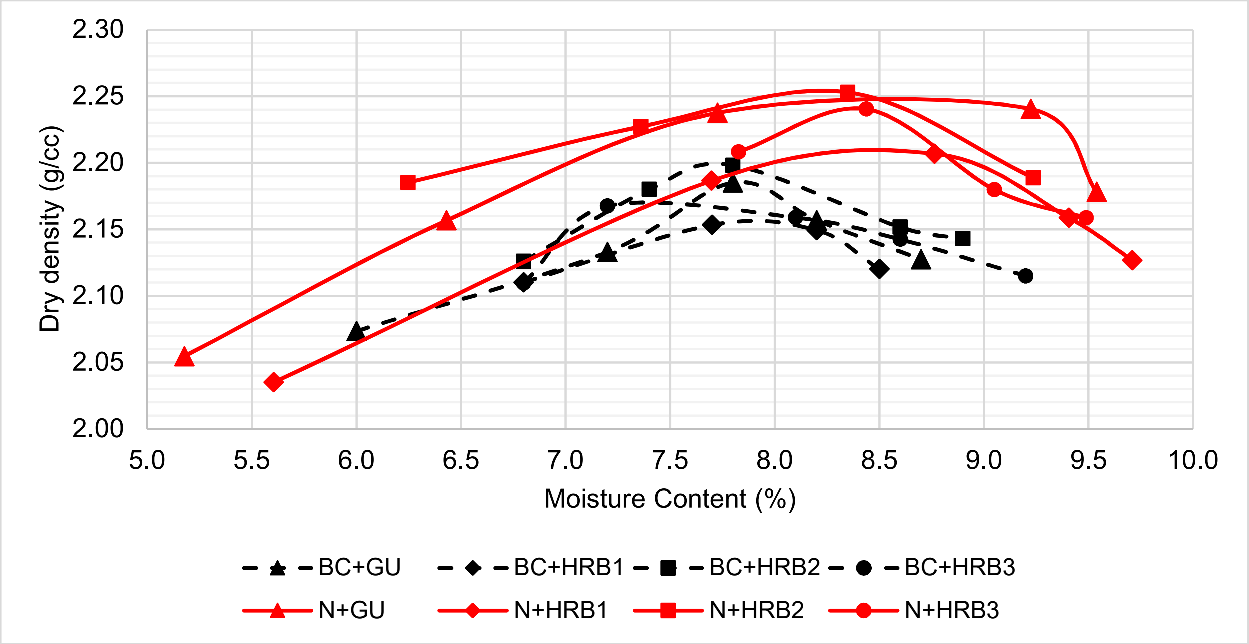

Figure 5 Moisture-density relation curves for the eight mixes

Table 8 Maximum Dry Density and Optimum Moisture Content of FDR-Cement Mixtures

FDR Material Source	Cement Type	MDD (g/cc)	OMC (%)
NL	GU	2.25	8.6
	HRB1	2.21	8.5
	HRB2	2.26	8.2
	HRB3	2.24	8.4
BC	GU	2.19	7.8
	HRB1	2.16	7.9
	HRB2	2.20	7.7
	HRB3	2.17	7.4

Unconfined compressive strength

In this study, sixty 7-days and twenty-four 28-days, totally eighty-four UCS tests were conducted. Out of the eighty-four tests, forty-seven were done on NL specimens and the remaining thirty-seven tests were conducted on BC specimens. NL 7-days specimens were made with 3.5, 4.0, 5.0, and 6.0% cement contents while BC specimens were made with 2.0%, 2.5% and 3.0% cement contents. These cement contents were selected to come up with UCS values within (at least fairly close to) the recommended limits of 2.1 – 2.8 MPa. Here, it should be noted that BC material required less cement compared to NL material to attain equivalent strength. This is due to the difference in the quality of the two reclaimed materials as was discussed before. The 7-days UCS test results are shown in Table 9.

Table 9 Seven days Unconfined Compressive Strength Test Results

FDR Material Source	Cement Type	Unconfined Compressive Strength (MPa)						
		Cement Content (%)						
		2.0	2.5	3.0	3.5	4.0	5.0	6.0
NL	GU					2.0	2.6	3.1
						1.8	2.5	3.3
							3.0	
	HRB1					1.8	2.3	2.5
						1.9	2.2	2.7
						2.1	2.4	3.0
	HRB2					2.4	2.8	3.0
						2.5	3.0	3.1
						2.2	3.2	3.1
							3.3	
	HRB3				2.3	3.0	4.0	
					2.7	2.9	3.5	
					2.5	2.9		
BC	GU	1.9	2.2	2.8				
		2.0	2.4	2.6				
			2.1					
	HRB1		2.0	2.3				
			2.0	2.3				
			1.9	2.4				
	HRB2	2.0	2.3					
		2.1	2.2					
		2.0	2.2					
	HRB3	1.8	2.5					
		2.0	2.3					
		1.7	2.0					

The boxplots of these data are shown in Figure 6 and Figure 7. It can be observed from these figures that materials treated with hydraulic road binders gained strength fairly close to or even more than the strength gained using GU cement after 7-days of moist curing. This is clearly depicted in Figure 8 based the average 7-days UCS values.

To assess whether these effects of the hydraulic road binder are statistically significant, single factor fixed effects model ANOVA test was run using Minitab 18 with significance level, $\alpha = 0.05$. In this test, the null hypothesis was ‘use of hydraulic road binders do not have any effect on the strength of the treated reclaimed materials’ whereas the alternative hypothesis was the opposite. The null hypothesis implied all the measured UCS values are the family of a normal distribution with the same mean and standard deviation. ANOVA test was done with all UCS data of each FDR material (with all cement contents) and with UCS values specific to individual cement content for each cement and FDR material type.

In the ANOVA test rejection of the null hypothesis merely indicates some of the treatment or factor level means are different. It does not tell which means are different (Douglas Montgomery and George Runger, 2003). It also does not show which mean is greater or which one is lesser. Thus, it is often important to support ANOVA test with multiple comparisons methods. In this paper, Dunnett’s test and Fisher’s least significant difference (LSD) methods were used for multiple comparison of means.

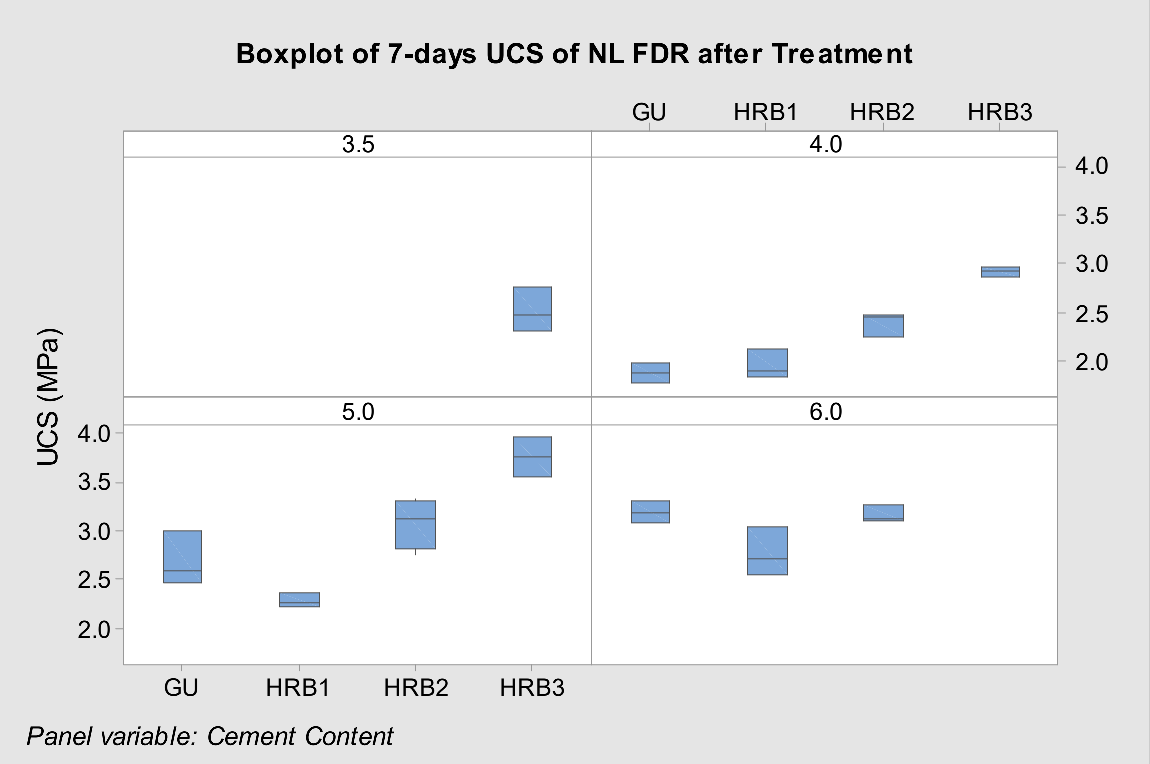

Figure 6 Boxplots of 7-days UCS of NL FDR materials treated with various cements

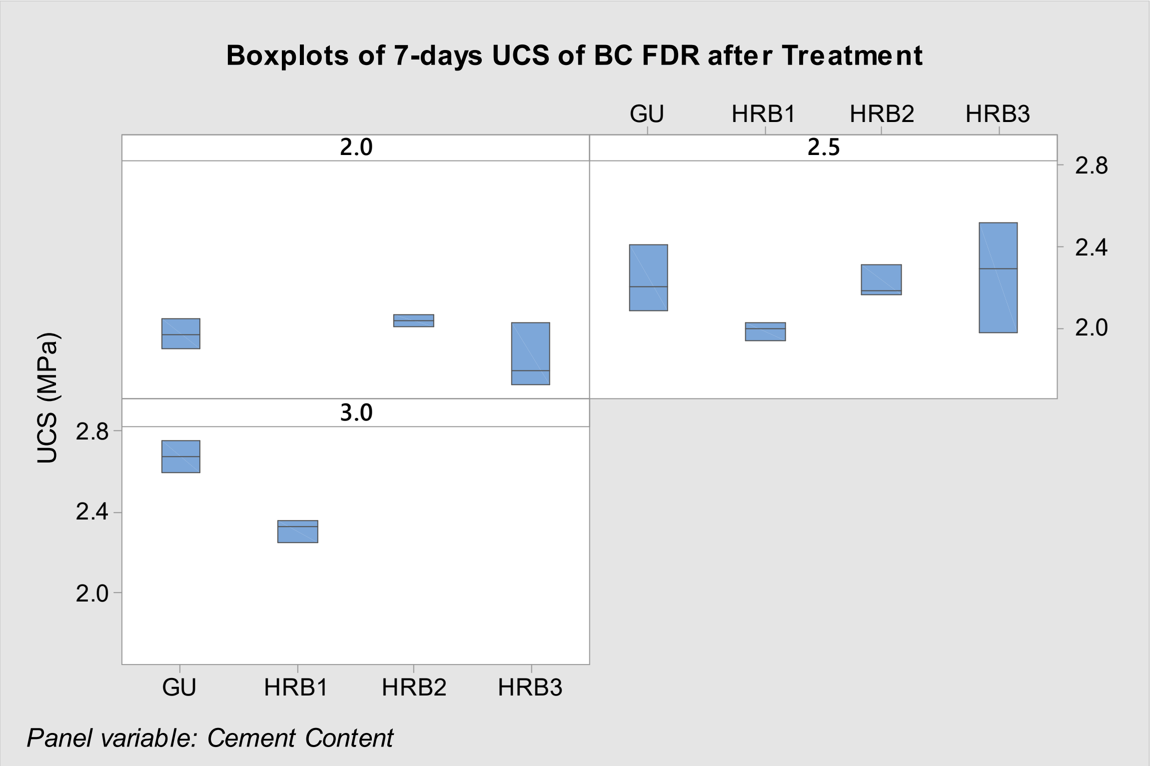

Figure 7 Boxplots of 7-days UCS of BC FDR materials treated with various cements

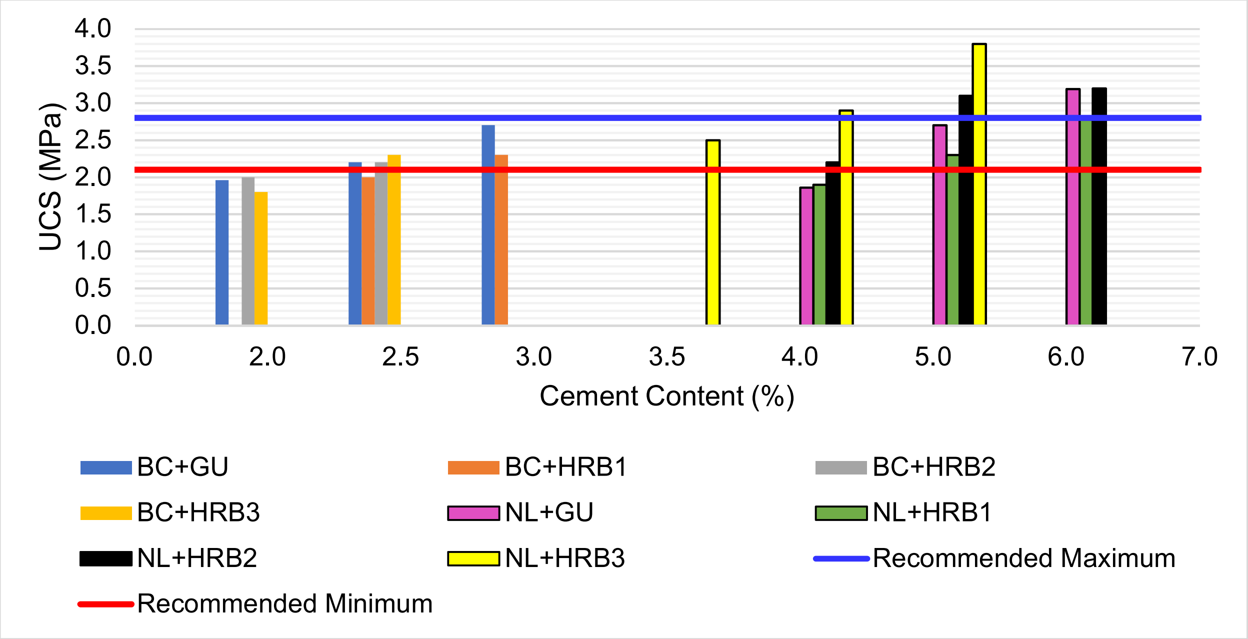

Figure 8 Average of 7-days UCS values

The results of these analyses are shown in Table 10, Table 11 and Figure 9. The ANOVA in Table 10 indicates there is strong evidence to reject the null hypothesis for NL material since the P-value of 0.031 is less than the significance level 0.05. This implies that the means of the UCS of NL material treated with different cement types are different. This is supported by Fisher's pairwise comparison, shown in Table 11, since simultaneous 95% confidence interval (CI) for differences of means HRB2 – HRB1 and HRB3 – HRB1 do not contain zero. This is interpreted as the strength of NL mix with HRB1 cement is different from the corresponding mixes with HRB2 and HRB3 cements. However, both Fisher's LSD test and Dunnett's test show that the 7-days strength of the mixes with hydraulic road binders are not significantly different from the strength of mixes with GU cement, which is the control mix for NL material.

The ANOVA output in Table 10 also shows that for BC material there is no strong evidence to reject the null hypothesis as the P-value of 0.330 is greater than the significance level of 0.05. The multiple comparisons with Fisher's and Dunnett's methods also show that there is no significant difference among the strengths of mixes with various cement types including the control mix with GU cement.

Table 10 Summary of ANOVA for UCS with Individual Cement Contents

FDR Material	Cement Content (%)	F-Value	P-Value
NL	All	3.37	0.031
	4.0	45.52	0.000
	5.0	17.10	0.001
	6.0	4.35	0.081
BC	All	1.20	0.330
	2.0	2.68	0.148
	2.5	1.75	0.234
	3.0	39.62	0.003

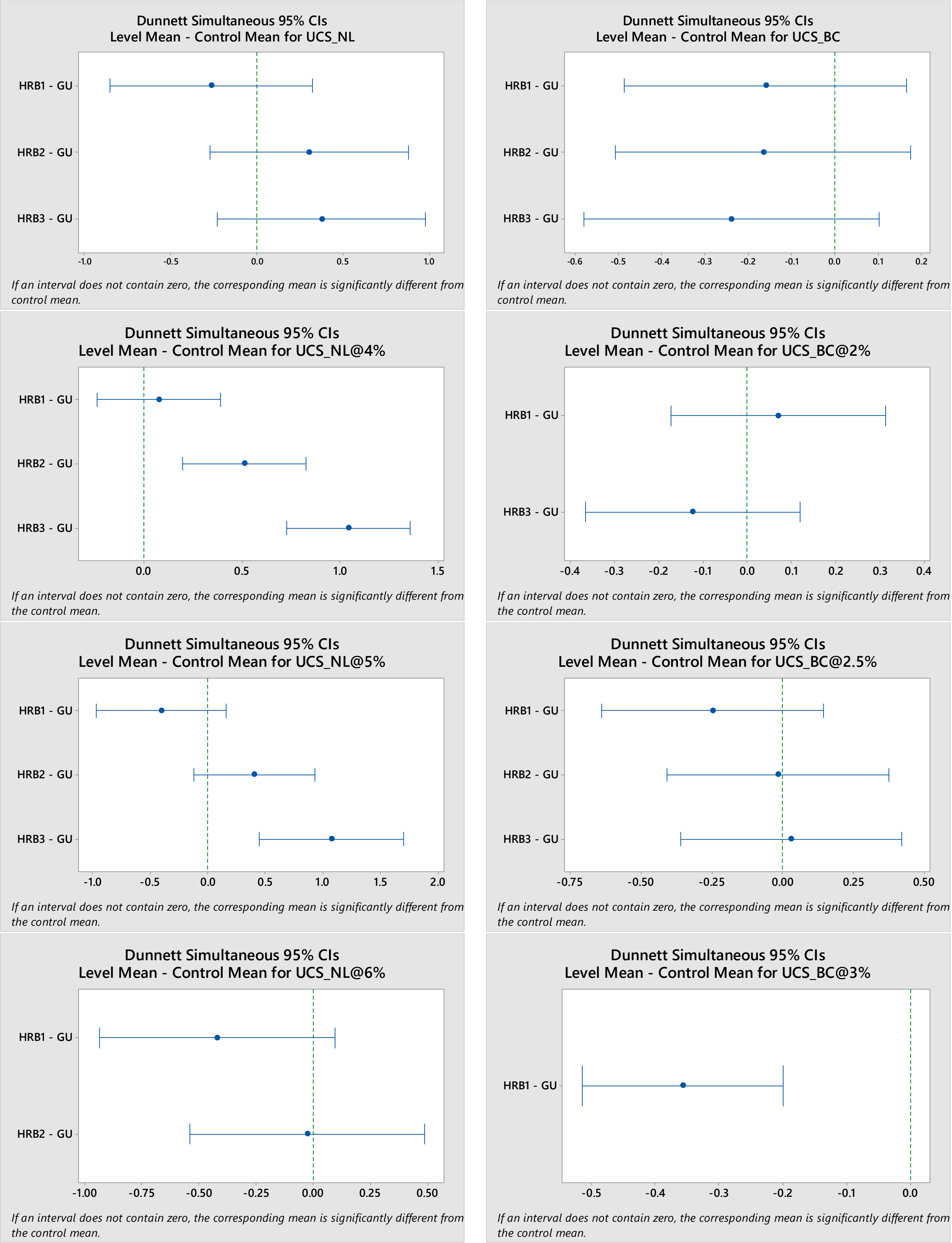

Figure 9 Dunnett's multiple comparisons with simultaneous 95% CI for 7-days UCS

Table 11 Fisher Pairwise Comparisons

Difference of Levels	NL		BC	
	95% CI	Adjusted P-Value	95% CI	Adjusted P-Value
HRB1 – GU	(-0.752,0.224)	0.278	(-0.426,0.107)	0.228
HRB2 – GU	(-0.174,0.780)	0.204	(-0.444,0.113)	0.232
HRB3 – GU	(-0.128,0.875)	0.139	(-0.518,0.040)	0.090
HRB2 – HRB1	(0.122,1.012)	0.014	(-0.300,0.288)	0.968
HRB3 – HRB1	(0.167,1.108)	0.010	(-0.373,0.215)	0.584
HRB3 – HRB2	(-0.389,0.530)	0.757	(-0.379,0.232)	0.625

The analysis based on individual cement contents indicates, the means of the UCS of NL material with 4% and 5% cement contents are different for different cement types. However, there is no strong evidence to reject the null hypothesis in the case of NL UCS with 6% cement content. The Dunnett's multiple comparison test result, shown in Figure 9 (first column), indicates for NL material:

- with 4% cement content, the means of the UCS of mixes with HRB2 and HRB3 cement are greater than the mean UCS of control mix with GU cement, whereas the mean UCS of the mix with HRB1 cement does not have significant difference from the mean UCS of the control mix;

- with 5% cement content, the means of the UCS of mixes with HRB1 and HRB2 cement do not have significant difference from the mean UCS of GU mix, whereas the mean of UCS of the mix with HRB3 cement is greater than the mean UCS of GU mix;

- with 6% cement content, the mean UCS of mixes with both HRB1 and HRB2 cement do not have significant difference from the mean UCS of control GU mix.

For BC material with 2% and 2.5% cement content there is no strong evidence to reject the null hypothesis. However, with 3% cement content the null hypothesis can be rejected as P-value of 0.003 is less than the significance level, $\alpha = 0.05$. The Dunnett's multiple comparison test result for BC material, which is shown in Figure 9 (second column), indicates:

- with 2% and 2.5% cement content, there is no significant difference between the mean UCS of the control mix with GU cement and the other mixes with hydraulic road binder;

- with 3% cement content, however, the mean UCS of the control mix significantly exceeds the mean UCS of HRB1 mix.

The two BC material mixes with 3% cement content have average 7-days UCS greater than 2.1 MPa but less than 2.8 MPa, which are the recommended strength thresholds, as shown in Figure 8. Thus, the strength of the mix with HRB1 cement is still acceptable even if it is lower than the strength of the mix with GU cement.

Overall, it can be inferred from the statistical analysis on the 7-days UCS test data that hydraulic road binders used in this research can provide early strength as good as or better than the General Use cement in most instances.

The effect of the cements on the long-term strength was assessed using 28-days UCS data. Twenty-eight days UCS specimens were prepared with the minimum cement content that provides 7-days UCS above the minimum recommended threshold of 2.1 MPa. Accordingly, NL specimens were prepared with 5% GU and HRB1, 4% HRB2, and 3.5% HRB3 cements; while BC specimens were produced with 2.5% GU, HRB2, and HRB3, and 3% HRB1 cements. The test results are shown in Table 12.

Taking a closer look at the data in Table 12, one can observe that the 28-days UCS for all of NL mixes are fairly similar. This consistency is also confirmed by ANOVA and Dunnett's tests. However, for BC mixes UCS of HRB2 and HRB3 mixes are significantly lower than GU and HRB1 mixes. The main reason for this variation is the change in the testing machine. The test machine which had been used for the other UCS tests went down before the HRB2 and HRB3 specimens were tested. As a result, these specimens were tested with the heavy-duty machine with 1500kN capacity and higher noise level by setting the loading rate to the same level, 1.3mm/min. Thus, the 28-days UCS for HRB2 and HRB3 specimens were not used for ANOVA test. The difference between 7-days and 28-days strength can be shown in Figure 10. From Table 9, Table 12, and Figure 10, it can be observed that the 7-day strength is approximately 60% of 28-days strength.

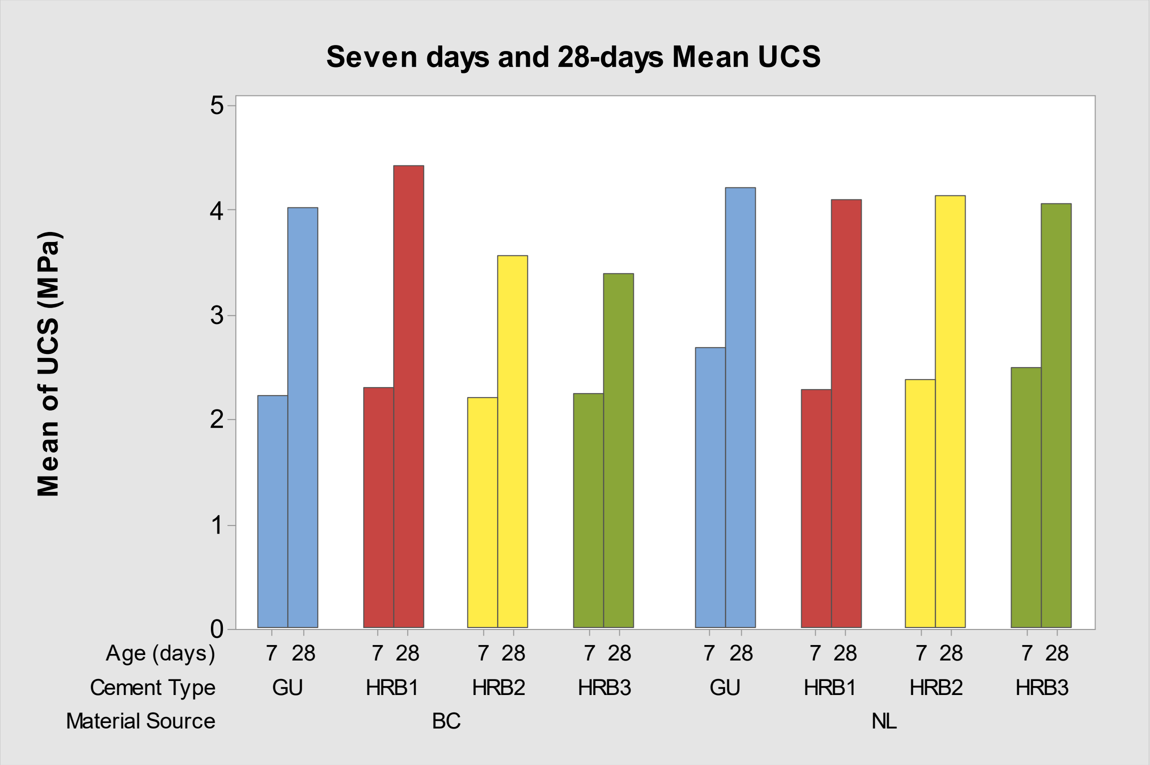

Figure 10 Early strength and long-term strength of stabilized FDR pavement materials

Table 12 Twenty-Eight Days Unconfined Compressive Strength Test Results

FDR Material Source	28-days Unconfined Compressive Strength (MPa)			
	Cement Type			
	GU	HRB1	HRB2	HRB3
NL	4.1	4.5	4.0	4.0
	4.4	3.9	4.0	4.1
	4.2	3.9	4.4	4.1
BC	3.9	4.6	3.5	3.3
	4.2	4.4	3.5	3.6
	4.0	4.3	3.7	3.3

Freeze-thaw test

Freeze-thaw test was performed on triplicate specimens which were prepared for each of the eight reclaimed material-cement compositions. These specimens were prepared with the same cement content as the 28-days UCS specimens. One of each triplicate specimen was control specimen which was used to correct oven dry weight of the test specimens at the end of the 12 freeze-thaw cycles. The test results, which are soil-cement loss percentages, are shown in Figure 11 and Table 13.

As shown in Table 5, the AASHTO soil classes for NL and BC materials is A-1-b and A-1-a, respectively. For these types of soil, the maximum allowable soil-cement loss after 12-cycles of freezing and thawing is 14% (PCA, 1992). Based on this requirement, all of the eight mixtures are durable and hence the cement contents used to produce the specimens can be considered as optimum from both strength and durability requirements.

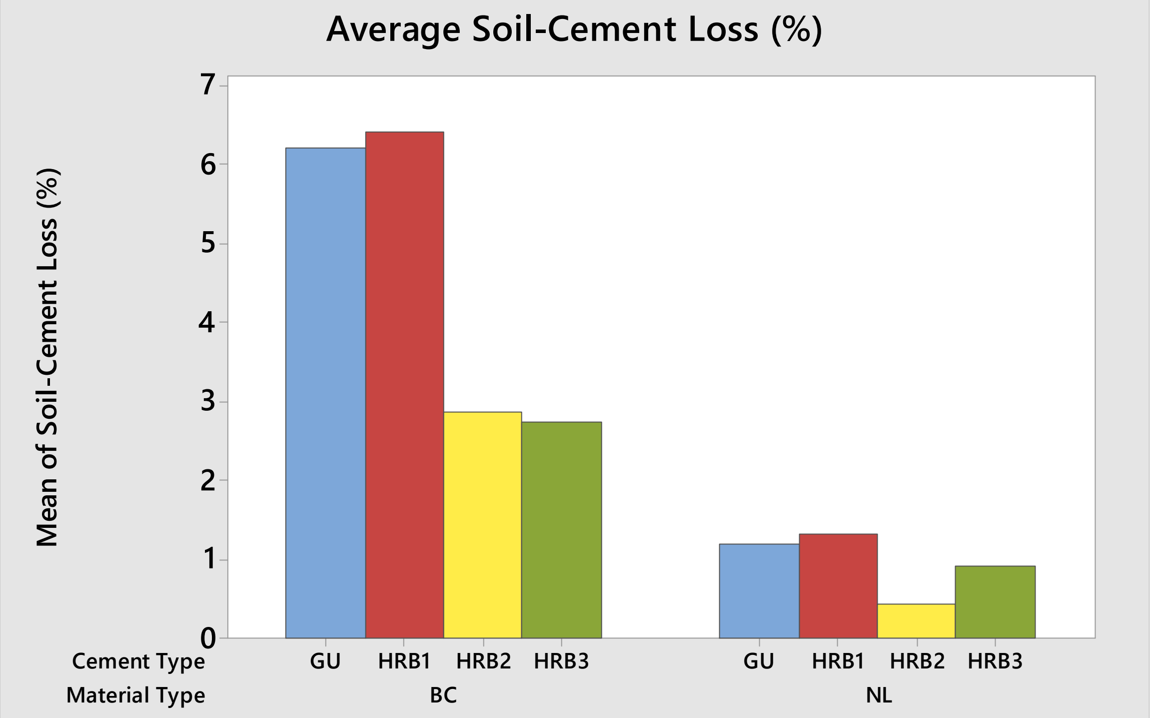

Figure 11 Average soil-cement loss after 12-cycles of freezing and thawing

Table 13 Freeze-thaw Test Results

FDR Material Source	Soil-Cement Loss after Freeze-Thaw Test (%)			
	Cement Type			
	GU	HRB1	HRB2	HRB3
NL	1.03	1.22	0.59	0.51
	1.35	1.42	0.28	1.34
BC	5.40	6.00	2.98	2.83
	7.00	6.80	2.76	2.68

To evaluate the impact of hydraulic road binders on durability of the mixes, again ANOVA and Dunnett's tests were performed. The test on NL material mixes showed that hydraulic road binder mixes have equivalent soil-cement losses as the control GU mix. The test on BC mixes, on the other hand, indicated HRB2 and HRB3 mixes have significantly lower soil-cement loss than the control mix, whereas HRB1 mix has equivalent loss. Dunnett's multiple comparisons of the soil-cement losses are shown in Figure 12.

Overall, the results of the statistical analysis once again indicated that hydraulic road binder mixtures have the same or even better durability than the control mix with GU cement.

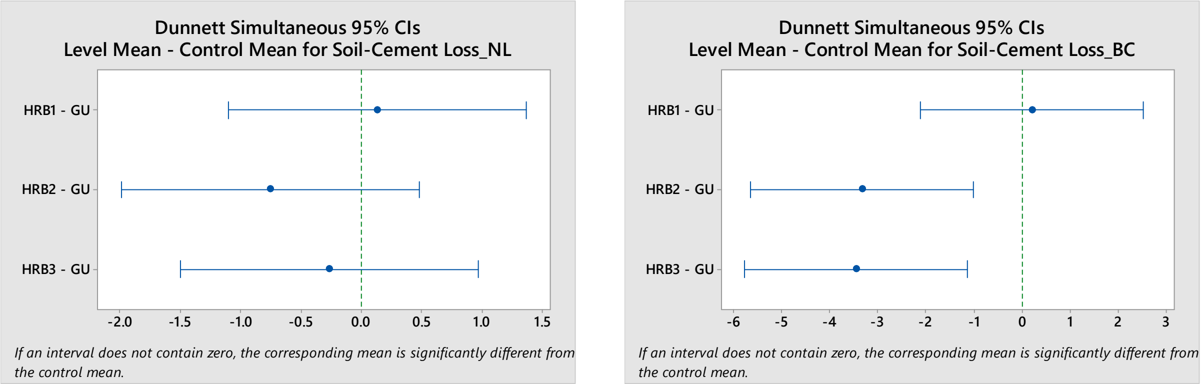

Figure 12 Dunnett's multiple comparisons with simultaneous 95% CIs for soil-cement losses

SUMMARY AND CONCLUSION

This study was conducted with the aim of assessing the effects of hydraulic road binders on the strength and durability of full-depth reclaimed pavement materials. For this purpose, two types of full-depth reclaimed pavement materials and four types of cements (including the control GU cement) were used. Unconfined compressive strength test and freeze-thaw test were conducted to assess the strength and durability of the reclaimed materials-cement mixtures. These tests were performed in laboratory on eight reclaimed materials-cement mixtures, which were composed of the two reclaimed materials and four cement types.

Both strength and durability test results were analysed with ANOVA, Fisher's test and Dunnett's test. The analyses results revealed that compared to General Use cement, hydraulic road binders used in this research can make mixes with equivalent or better strength and durability.

The research findings indicate that hydraulic road binders can replace GU cement in full-depth reclamation process without compromising strength and durability. This, however, be verified through further full-scale research on field trial sections.

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