

DEVELOPMENT OF HIGH-PERFORMANCE CONCRETE MIXTURES FOR DURABLE BRIDGE DECKS IN MONTANA USING LOCALLY AVAILABLE MATERIALS

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April 2005

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RESEARCH PROGRAMS

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Development of High-Performance Concrete Mixtures for Durable Bridge Decks in Montana Using Locally Available Materials

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16. Abstract The Montana Department of Transportation (MDT) is performing research to develop a cost-effective, indigenous high-performance concrete (HPC) for use in bridge deck applications. The investigation was divided into two tasks: 1) identification of the optimum cementitious matrix for the HPC and 2) evaluation of the performance of this matrix in combination with aggregates readily available in Montana. The work focused on the use of binary, ternary, and quaternary blends of portland cement with fly ash (Class C and F), slag, calcined clay, metakaolin, and silica fume, in combination with Yellowstone River and Western Montana aggregate sources. Testing included plastic properties, setting characteristics, air-void system parameters, electrical conductivity, strength, chloride diffusion, freezing and thawing resistance, scaling resistance, and drying shrinkage. The paper discusses the process required to test and implement HPC specifically for bridge deck applications and presents the test results for this MDT study. The supplementary cementitious material combinations that produced the best performance were silica fume alone, silica fume and slag, Class F fly ash, silica fume and slag-blended cement, and silica fume and calcined clay-blended cement. The importance of raw material testing and the practical reproducibility of the concrete mixture are also considered.			
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EXECUTIVE SUMMARY

Concrete bridge decks in Montana are subjected to severe service conditions. Potential deterioration mechanisms include corrosion of the reinforcing steel and scaling of the concrete surface resulting from deicing salt applications, freezing and thawing distress, cracking due to thermal and humidity extremes during and after construction, and materials-related problems. To maximize the useful life of the structure, the concrete used in bridge decks constructed in Montana must be durable and impart durability to the bridge deck structure. The investigation reported in this document was conducted to determine how best to achieve this objective, through the development of a high-performance concrete (HPC) based on locally available materials.

The following essential tasks in the HPC development process were conducted: 1) definition of performance objectives, 2) selection of the locally-available raw materials determined to be most likely consistent with the objectives, and 3) evaluation of possible combinations of raw materials.

The performance objectives for durable concrete were used to design an experimental program based on standardized tests. The intent of this program was to estimate performance of the concrete relative to these mechanisms. Testing included plastic properties, slump loss, setting characteristics, air-void system parameters, electrical conductivity, strength, chloride diffusion, freezing and thawing resistance, scaling resistance, and drying shrinkage.

The raw materials included aggregates and a Type I/II portland cement from Montana and the following supplementary cementitious materials (SCMs): Class C and Class F fly ashes, ground granulated blast furnace slag (slag), high-reactivity metakaolin, and silica fume. Also examined were blended cements that pre-combined portland cement and SCMs. These blends included a slag blend, a Class C fly ash blend and a calcined-clay blend. To ensure that the aggregates do not pose a potential limit on the concrete durability, aggregates from four sources throughout the State were evaluated for the potential for developing alkali-silica reaction. The aggregate test program was conducted in parallel to the HPC mixture design investigation.

Three rounds of HPC testing were conducted. The first examined combinations that have historically demonstrated good performance as reported in the literature and based on the experience of the investigators. Since the mixes in the first round that performed best were complex (containing three SCMs), the second round quantified the performance of pre-combined blended cements that enabled similar combinations. The third round examined easy-to-produce mixtures. The first two rounds were conducted using an aggregate from Billings, while the third tested an aggregate source from Missoula.

In evaluating which mixture is the best performer, judgments must be made about the relative importance of desired properties in the actual concrete and about how well the laboratory results from the testing procedures represent the expected in-place concrete behavior. The greatest cause of deterioration in Montana bridge decks is expected to be corrosion of embedded steel initiated by the intrusion of chloride ions from deicers. Therefore, given reasonable or better performance in the other tested properties, the highest emphasis was placed on chloride ponding testing results since improvements in penetration resistance can be directly measured and will almost certainly translate into more durable structures.

Based on the 14 mixtures evaluated and for the specific set of raw materials tested, the combinations of SCMs that produced the best overall results were 5% silica fume alone (denoted Mixtures B and M), 7% silica fume and 20% slag (Mixture N), the slag-blended cement with 10% Class F fly ash and 5.5% silica fume (Mixture J) and the calcined clay-blend with 4% silica fume (Mixture L). In this test program, concretes produced using the Missoula aggregate (mainly quartzite and sandstone) demonstrated better performance in terms of strength, resistance to chloride penetration and scaling resistance than that measured with the Billings aggregate (mainly granite and basalt). The influence of the raw materials and the importance of testing each mix containing specific materials was clearly demonstrated. In addition, the importance of the character of the paste-aggregate interfacial transition zone for high performance concrete as determined by aggregate type and batching procedures was highlighted.

To ensure the ultimate success of HPC projects in Montana using these mixtures in the future, it would be highly valuable to conduct trial batches using the local production batching procedures and equipment. In addition, the construction demands of HPC beyond typical construction, such as increased curing and quality control, must be considered. However, this study has provided a solid foundation for constructing highly durable concrete bridge decks in Montana, using locally available materials.

INTRODUCTION

Concrete bridge decks in the state of Montana are subjected to one of the most severe service environments in the United States, experiencing some of the largest temperature extremes and the greatest number of freeze thaw cycles (Visher 1945). Mountain roads are subjected to abrasion from tire chains and bridge decks throughout the state are treated with de-icing salts. As a result, the durability of the concrete used in such projects must be as great as possible. Therefore, a rigorous program was conducted to develop a cost-effective, indigenous high-performance concrete (HPC) for use in bridge deck applications that would stand up to these conditions.

High-performance concrete (HPC), as defined by ACI, is “concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing and curing practices” (Russell 1999). Long-term durability of a bridge structure is perhaps the most common performance requirement to which HPC is targeted. While there may be similarities between HPC for durability and high strength concrete, such as the use of high cement contents, supplementary cementitious materials (SCMs) and low water-cementitious materials ratios (w/cm), experience over the past 20 years has shown that high strength concrete is not likely to be as durable as concrete in which long-term performance has been optimized and these high strength mixes may introduce additional construction challenges that actually reduce its durability. As the definition of HPC suggests, meeting increased durability requirements requires a non-standard effort beyond that for “normal” concrete.

Design and implementation of an HPC for durability poses some specific challenges since optimizing HPC for durability typically requires the use of SCMs, which improve workability and beneficially modify the structure of the cementitious paste. Despite these benefits, the number of materials involved increases the complexity of batching, mixing, and placing the final concrete. Also, since some of these supplementary cementitious materials are byproducts of other industries, there is inherent variability in their properties resulting from the limited production control effort involved in their generation. Therefore, generalizations about the best combination of SCMs cannot be made for each application, and the appropriate solution must be determined separately based on locally available materials. A parallel goal of this study is to suggest HPC mixes and materials that will provide the most consistent and trouble free performance in the field.

TEST PROGRAM

The investigation reported here was conducted with two objectives: (1) identification of the optimum cementitious and concrete mix design and (2) evaluation of the performance of this mix in combination with aggregates readily available in Montana. Before the performance of the concrete is evaluated, the individual properties of the available raw materials must be evaluated to restrict materials that may not be durable. The available cementitious materials were examined and based on their mill test reports determined to be consistent with the goal of high durability. To verify that the aggregates were also likely to result in durable concrete, a parallel study to identify the alkali-silica reactivity of the aggregates was also conducted. Once appropriate materials were selected, testing to determine the optimum combination of materials was initiated.

Cementitious Materials and Admixtures

Maximizing the durability of a given HPC requires that the raw materials be evaluated and those most likely to produce the best results be selected. Materials for consideration in the testing program were selected from candidates from around the state based on the raw material properties and availability.

An ASTM C150 Type I/II portland cement with one of the lowest alkali contents (Na_2O eq. = 0.31%) of the possible sources was selected to form the basis for testing. Low-alkali cement was selected to reduce the risk of alkali-silica reactions. The Type II cement may be less prone to cracking and may have lower heat of hydration. Class C and F

fly ashes with low loss on ignition values (low carbon contents) were chosen to minimize the impact of the fly ash on the process of entraining air into the concrete, necessary for cyclic freezing resistance. Ground granulated blast furnace slag and silica fume have seen limited use in Montana; however, because of the well-known possible benefits of these materials, out-of-state sources of Grade 100 slag and silica fume meeting ASTM specifications were identified and included in the test program. For the second round of testing, blended cements combining portland cement with slag (22% by weight), with Class C fly ash (18% by weight) and with calcined clay (17.5% by weight) that could be obtained in Montana, were included. A high-reactivity metakaolin was also introduced in this round as a possible alternative to silica fume.

Throughout the test program, a vinsol resin-based air-entraining admixture, a mid-range water-reducing agent (MRWR) and a naphthalene sulfonate-based high-range water-reducing agent (HRWR) commonly available in Montana were used. These admixtures generally produce consistent results and have been widely used. The material sources used in this study are identified in Appendix A.

Aggregates

Four aggregate sources, from pits geographically distributed around the state, were proposed for testing. One of these, from the Yellowstone River Valley (Billings), was selected based on experience of good performance with the aggregate, and was used in the first and second round of testing. A second aggregate source, from Western Montana (Missoula), was used in the third round of testing. The Yellowstone River aggregate consisted of basaltic and granitic particles with additional fractions of rhyolite, dacite and andesite, while the Western Montana aggregate were mostly quartzite and sandstone with argillite. Both fine and coarse aggregates came from the same source. The coarse aggregate gradations were within the limits of ASTM C33 aggregate size #67 and the nominal maximum size of the coarse aggregates for each of these sources was 3/4 in. (19mm).

Investigation of Alkali-Silica Reactivity in Aggregates

Since the objective of this project is to produce the most durable concrete possible, the potential for developing the Alkali-Silica Reaction (ASR) was evaluated for the fine and coarse aggregate sources proposed for use in the HPC. ASR, a reaction between active forms of silica that are present in certain kinds of natural aggregate and the alkali environment resulting in concrete from the use of portland cement, is harmful to concrete since the alkali-silicate gel that is produced over time will swell and may produce cracking in the concrete. Repair of structures affected with ASR cracking is very difficult. ASR is a potential limiting factor in the long-term performance of the concrete, and so should be considered in the overall selection of materials.

The aggregate sources tested for ASR reactivity were selected to geographically cover the State and are from Billings, Missoula, Great Falls and Glasgow. This study was initiated because little information was available regarding the reactivity of these aggregates.

This testing was conducted in a preliminary phase and then, when this preliminary data suggested more work was needed, in an in-depth phase. Preliminary testing was performed to determine the potential for the selected Montana aggregates to develop ASR using ASTM C1260 “Standard Test Method for Potential Alkali Silica Reactivity of Aggregates (Mortar Bar Method).” The initial phase of this testing indicated potentially deleterious expansion may occur with some Montana aggregate sources. The C1260 mortar-bar test is very severe and may result in aggregate incorrectly being classed as potentially reactive but is of use as an inexpensive, rapid and definitive test to determine whether an aggregate is unreactive. The reason this test was performed was because if the aggregate was shown to be innocuous further testing would have been unnecessary.

Because all of the aggregates tested by ASTM C1260 demonstrated potential for deleterious behavior, a second evaluation phase was initiated that included a petrographic examination (ASTM C295) of the fine and coarse aggregate samples individually to identify the reactive materials in the aggregate and testing according to ASTM C1293 “Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction”. The C1293 test method calls for performing testing on concrete containing the fine and coarse aggregates but with artificially high alkali content.

In addition to this method which tests the aggregates alone, a modified ASTM C1293 test, substituting the cementitious matrix combinations considered in the mixture optimization phase of this study was also conducted to assess the impact of the SCMs on this reaction. The aggregate that has appeared most susceptible to ASR based on ASTM C1260 testing and petrographic analysis is that supplied from Billings and so this aggregate was selected for testing in this manner. Four cementitious matrices are being tested and are based on the mixture designs examined in the durability testing program detailed above (5% silica fume only, 7% silica fume and 20% slag, and 7% silica fume and 20% Class C fly ash) and with an additional mix containing 5% silica fume and 20% Class F fly ash. These mixtures were cast on October 23, 2003 and will be tested over the next two years.

Identification of HPC Mixture Proportions

For an “optimum” combination of materials to be determined, the project objectives had to be defined both in terms of in-service performance and in terms of performance that can be quantified using accepted test procedures. Based on the service conditions expected for Montana bridge decks, the following durability-related properties were identified for evaluation and optimization: freezing and thawing resistance, air-void system parameters, salt scaling resistance, chloride diffusion, electrical conductivity, and drying shrinkage. To ensure the constructability and serviceability of the structure, the plastic properties, setting characteristics, and strength were also examined. The test methods to measure these characteristics and the target test results for each category expected to coincide with ease of constructability and durable in-place performance in a severe environment, where appropriate, were selected and are listed in Table 1.

Table 1. Test Program and Recommended Test Performance

Property Tested	Standard Method	Recommended Target
Air content of fresh concrete	AASHTO T152	5.5 to 8.5%
Slump, initial and after 45 minutes	AASHTO T119	4 to 8 in. (100 to 200 mm) initially, less than 4 in. (100 mm) loss after 45 min.
Set time, initial and final	AASHTO T197	greater than 3 hour initial set
Compressive strength at 3, 7, 28 days and 6 months	AASHTO T22	5000 to 9000 psi (34.5 to 62 MPa) at 28 days
Modulus of Elasticity, 7 and 28 days	ASTM C469	-
Air content of hardened concrete	ASTM C457	5.5 to 8.5%
Rapid chloride permeability at 28 and 90 days	AASHTO T277	less than 2000 C at 28 days
Chloride penetration resistance at 90 days, 6 months and 1 year* (* for Round 3)	AASHTO T259/T260	less than 0.030 % chloride in slice from 1/2 to 1 in. (13 to 25 mm) depth at 90 days
Freezing and thawing resistance	AASHTO T161 (Procedure A)	durability factor greater than 90% after 300 cycles and greater than 85% after 500 cycles
Scaling resistance	ASTM C672	Scaling rating less than 1
Shrinkage	AASHTO T197	less than 0.0600% at 90 days

These target values were selected as general guidelines and may be more or less stringent than required to ensure maximum durability for a specific job or conditions. For example, the recommendation of a maximum drying shrinkage of 0.06% at 90 days was chosen to select mixtures exhibiting drying shrinkage at the low end of the range typically seen in HPC. However, for a specific bridge deck design, the restraint and curing conditions may dictate that less shrinkage at earlier ages is necessary to prevent cracking.

Testing to identify the best cementitious matrix was conducted in three rounds. The first focused on the use of binary, ternary, and quaternary blends of portland cement with SCMs based on mixtures that have proven effective in the past. However, since the practical considerations of using up to four different cementitious materials may make their combined use too difficult for some Montana ready-mix plants, mixtures based on blended cements,

which pre-combine a SCM with portland cement, were considered in the second round of testing. To further increase the practicality of an HPC mixture, Round 3 focused on simple mixtures with the widest possible applicability.

Mixture Evaluation

The mixtures that were examined are detailed in Table 2 and Table 3, which give the percentage replacements of cement with SCM and the mixture proportions for standard volumes, respectively. All mixtures were based on a cement-only mixture containing 720 lbs./cu. yd. (427 kg/m^3) of cement and cement replacement was performed by volume. Therefore, mixtures that were based on the same water-cementitious materials ratio for the cement-only mixture contained the same weight of water and aggregates. The weight of the cementitious materials varied depending on the density of SCMs. Rounds 1, 2 and 3 consisted of Mixtures A to E, F to L, and M to O, respectively.

The mixing procedure was as follows: the water and air-entraining admixtures were added to the pre-mixed aggregates and cement in a pan-mixer along with the mid-range water reducing admixture and a sufficient amount of high-range water reducer to produce an approximately 4-in. slump. The concrete was mixed for three minutes and then allowed to rest for three minutes. The remaining superplasticizer was then added and the concrete mixed for an additional four minutes. The concrete was placed in a wheelbarrow while the plastic tests were performed and test specimens were made. It was then mixed by hand before the slump was re-measured 45 minutes after the start of batching.

Table 2. Percent cement replacement by volume and other proportioning details of mixtures tested

Material/Property		Mixture ID													
		A	B	C	D	E	F	G	H	J	K	L	M	N	O
Replacement of cement	Fly Ash (Class C) Blend							92.5	92.5						
	Slag Blend									84.5	92.5				
	Calcined-Clay Blend											96			
	Fly Ash (Class C)	22		22	10										20
	Fly Ash (Class F)					10				10					
	Slag				12	12									20
	Silica Fume		5	5	5	5		7.5		5.5	7.5	4	5	7	7
	HR Metakaolin								7.5						
SCM equivalent replacement of cement	Fly Ash - Class C	22		22	10			18.6	18.6						
	Fly Ash - Class F					10				10	17.1				
	Slag				12	12				15.6					
	Silica Fume		5	5	5	5		7.5		5.5	7.5	4			
	HR Metakaolin								7.5						
	Calcined Clay											19.8			
Basis w/cm (for cement-only mixture)		0.37	0.37	0.37	0.37	0.37	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Aggregate Source		YR	YR	YR	YR	YR	YR	YR	YR	YR	YR	YR	WM	WM	WM

YR=Yellowstone River
WM = Western Montana

Table 3. Mixture proportions as batched

Material per cubic yard	Mixture ID													
	A	B	C	D	E	F	G	H	J	K	L	M	N	O
Cement or blend (lbs.)	562	684	526	526	526	720	649*	649*	575 [†]	629 [†]	654 [‡]	685	526	526
Water (lbs.)	266	266	266	266	266	252	252	252	252	252	252	252	252	252
Fly Ash - Class C (lbs.)	138	0	138	63	0	0	0	0	0	0	0	0	0	125
Fly Ash - Class F (lbs.)	0	0	0	0	54	0	0	0	54	0	0	0	0	0
Silica Fume (lbs.)	0	25	25	25	25	0	38	0	28	38	20	25	35	35
Slag (lbs.)	0	0	0	80	80	0	0	0	0	0	0	0	133	0
HR Metakaolin (lbs.)	0	0	0	0	0	0	0	45	0	0	0	0	0	0
Fine Aggregate (lbs.)	1284	1284	1284	1284	1284	1300	1300	1300	1300	1300	1300	1296	1296	1296
Coarse Aggregate (lbs.)	1572	1572	1572	1572	1572	1593	1593	1593	1593	1593	1593	1573	1573	1573
AEA (fl. oz./cwt.)	2.5	1.8	2.6	2.6	2.2	1.5	1.8	2.9	2.3	2.0	1.8	1.9	2.4	4.2
MRWR (fl. oz./cwt.)	2.4	2.0	2.5	2.5	1.7	4.0	7.0	2.6	2.5	2.6	2.5	2.5	2.5	2.5
HRWR (fl. oz./cwt.)	4.4	4.3	3.7	6.1	7.1	8.0	6.4	11.7	16.3	11.8	17.1	14.1	20.2	18.4

* = Class C fly ash blend, [†]=Slag blended cement, [‡]= Calcined clay blended cement

RESULTS

Table 4 lists the fresh properties of the concrete mixtures, and the air content and air-void parameters of the hardened concrete measured on one cylinder. This table also gives the initial and final setting times. Figure 1 presents the average compressive strength calculated from three 4-in. (100-mm) diameter cylinders tested for each mixture at each age.

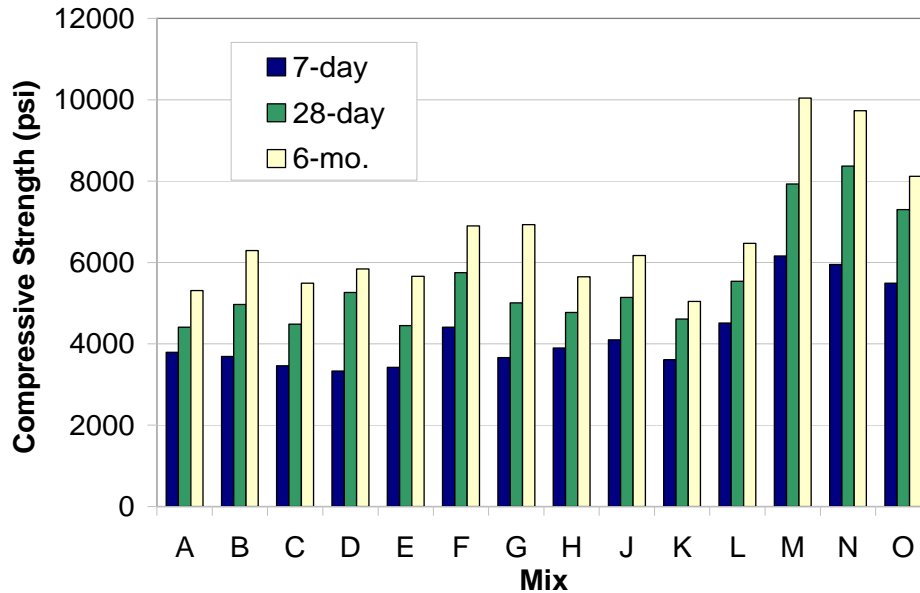


Figure 1. Compressive Strength

The scaling resistance (ASTM C672) of the surface of these concretes when exposed to deicing salts is presented in Figure 2, in terms of the visual rating, which ranges between 0 for no scaling to 5 for severe scaling. This is the average visual rating assigned to three slabs of each mixture subjected to 50 cycles of freezing and thawing, while ponded with a 4% calcium chloride solution.

The resistance to freezing and thawing (AASHTO T672-A) is displayed in terms of the durability factor (the dynamic modulus after the given number of cycles as a percentage of the initial dynamic modulus) and the weight loss after 300 and 500 cycles between 0 and 40°F (-17.8 to 4.4°C) while submerged in water, in Figure 3. This is the average of three 3 x 4 x 15-in. (75 x 100 x 380-mm) prisms.

Table 4. Fresh properties and air void network parameters in hardened concrete

Mix	SCM contents	Slump (in.)	Slump loss @ 45 min. (in. lost)	Air content, fresh concrete (%)	Air content, hardened concrete (%)	Specific surface (in ² /in ³)	Spacing factor (in.)	Initial set (hr:min)	Final set (hr:min)
A	22% FAC	8.75	2.5	8.6	5.1	1147	0.0041	8:30	10:35
B	5% SF	5	1.25	7.5	5.8	724	0.0061	4:40	6:10
C	22% FAC + 5% SF	4.5	2.5	7.9	7.9	920	0.0021	7:25	9:15
D	10% FAC + 12% Slag + 5% SF	6.25	3	7	6.1	812	0.0053	5:40	7:20
E	10% FAF + 12% Slag + 5% SF	7.5	2.25	7.4	6.8	889	0.0044	6:11	7:46
F	Cement only	7.25	4.25	8.2	9.4	546	0.0054	9:10	11:05
G	92.5% FAC Blend + 7.5% SF	8	2.5	8.7	9.9	652	0.0042	14:10	18:10
H	92.5% FAC Blend + 7.5% HRM	8	4	7.6	5.9	838	0.0050	10:00	12:55
J	84.5% Slag Blend + 10% FAF + 5.5% SF	8.25	4.5	7.8	8.0	501	0.0062	5:10	6:30
K	92.5% Slag Blend + 7.5% SF	6	3.5	7.6	7.7	596	0.0053	5:15	6:45
L	96% CC Blend + 4% SF	7.75	2.5	7.9	6.7	598	0.0062	5:35	8:30
M	5% SF	6.5	2.25	6.4	5.0	535	0.0093	7:05	9:10
N	20% Slag + 5% SF	7.5	3	6	5.4	524	0.0088	7:00	9:05
O	20% FAC + 5% SF	4.75	2	6.5	5.3	700	0.0068	9:00	10:40
Recommended target		< 8	< 4	5.5-8.5	5.5-8.5	> 500	< 0.010	> 3:00	-

FAC = Class C fly ash, FAF = Class F fly ash, SF = Silica fume, HRM = High reactivity metakaolin, CC = calcined clay

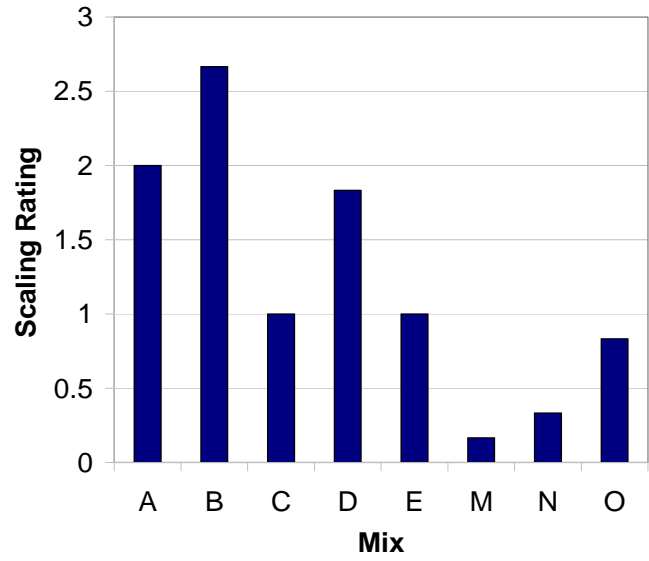


Figure 2. Visual rating of scaling resistance

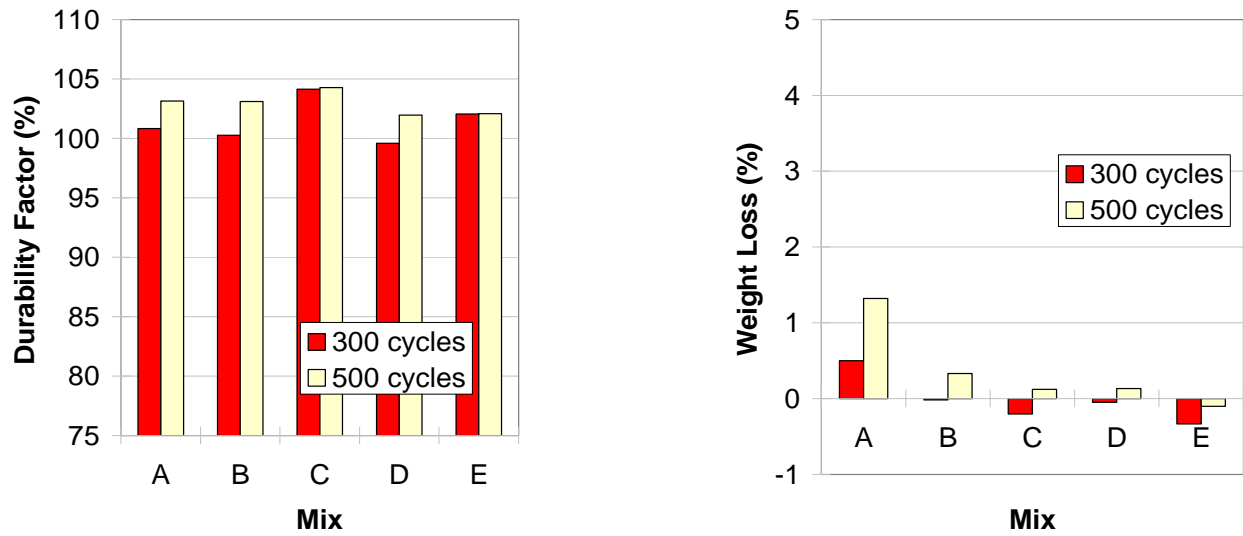


Figure 3. Resistance to Freezing and Thawing as measured via Durability Factor (left) and Weight Loss (right) after 300 and 500 cycles (Note: a negative weight loss means that the specimen gained weight.)

Figure 4 gives the average amount of charge passed in six hours across two 2-in (50-mm) thick, 4-in. (100-mm) diameter disks of concrete with sodium chloride solution on one side and sodium hydroxide on the other under a 60 V potential difference (AASHTO T277).

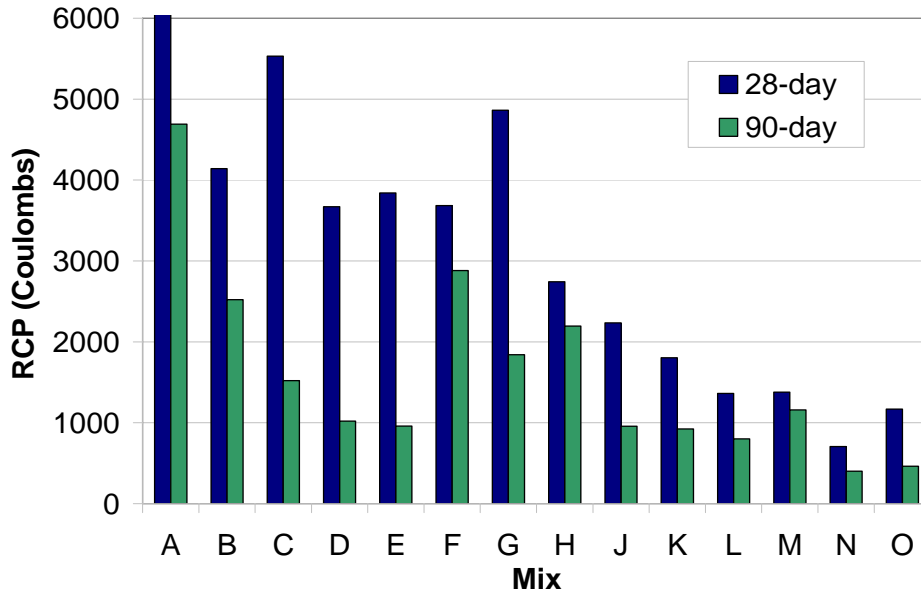


Figure 4. Rapid Chloride Permeability (RCP)

Figure 5 and Figure 6 show the average acid-soluble chloride content (measured according to AASTHTO T260) of three slices taken from depths of 1/16 to 1/2 in. (1.6 to 13 mm) and from 1/2 to 1 in. (13 to 25 mm), respectively, of concrete cores taken from slabs which had been constantly ponded with 3% NaCl solution for the lengths of time listed. (The six-month chloride contents of Mixtures H and K were measured at 227 days.)

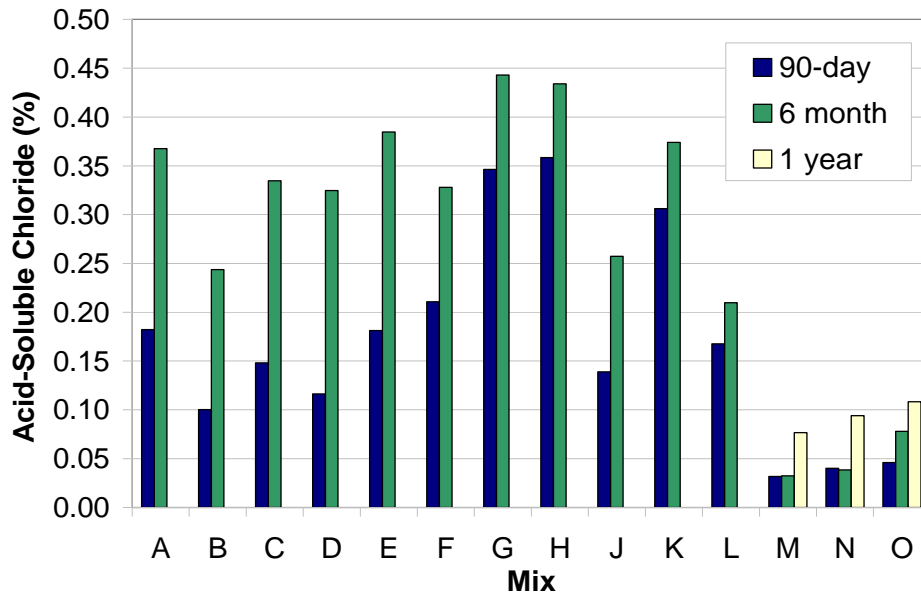


Figure 5. Chloride Content in upper slice (1/16 to 1/2 in. [1.6 to 13 mm]) of core from chloride penetration resistance test

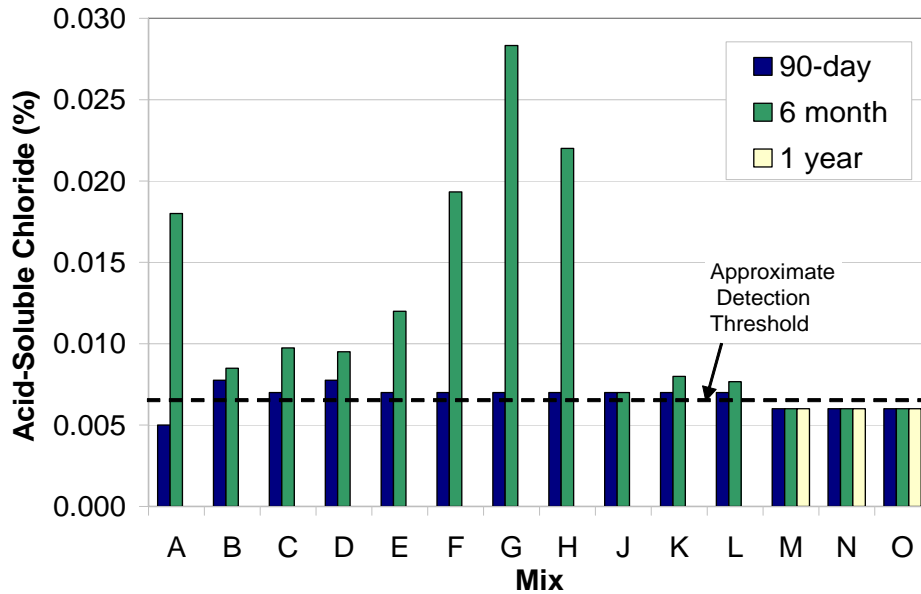


Figure 6. Chloride Content in lower slice (1/2 to 1 in. [13 to 25 mm]) of core from chloride penetration resistance test

Finally, Figure 7 gives the average shrinkage strain of three prisms with a 3 x 3-in. (75 x 75-mm) cross-section subjected to drying in a 50% RH, 73°F (23°C) environment (AASHTO T197).

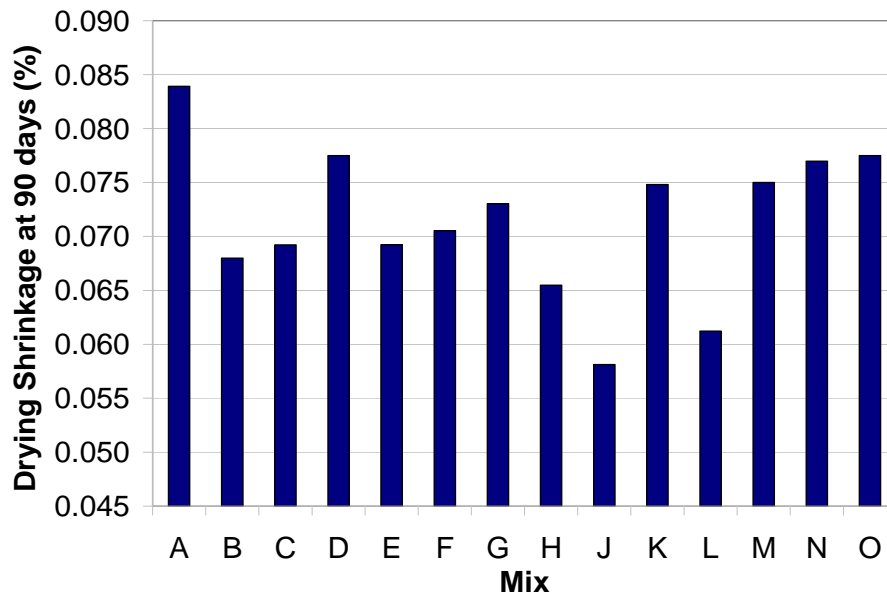


Figure 7. Drying shrinkage at 90 days

All data obtained during this test program is presented in Table form in Appendix B. Since subsequent rounds of testing were performed based on results of the previous rounds, each round is discussed separately below.

Round 1

In general, the concretes produced in Round 1 all demonstrated adequate plastic concrete properties. Often a discrepancy was observed between the air contents of the fresh concrete, measured with the pressure method, and the air voids measured in the hardened concrete, measured using the modified point-count method (Table 4). Nevertheless, the air void parameters in the hardened concrete, namely spacing factor and specific surface, were all significantly better than typically recommended for imparting good freezing and thawing resistance to concrete. The effectiveness of this entrained air was evident in the good scaling resistance and excellent freeze/thaw performance that was observed (Figure 2 and Figure 3). Essentially no freezing and thawing degradation was observed.

The strength of the mixtures in Round 1 up to 28 days was similar (between 4400-5300 psi [30.3-36.5 MPa]) and is considered adequate but lower than normally expected by us for concretes with this low a w/cm (Figure 1). These mixtures gained strength through six months, particularly Mixture B with 5% silica fume, due to hydration of the SCMs, which occurs at a slower rate than for straight portland cement. The generally lower strength is also likely aggravated by the high air void content requirements.

The Rapid Chloride Permeability (RCP) of all the mixtures in Round 1 was over 3500 Coulombs after 28 days, which is also higher than expected for concretes having a low w/cm and for similar mixtures containing SCMs (Figure 4). After 90 days, most mixtures displayed a significantly lower RCP as the influence of the SCMs became apparent. The chloride penetration resistance of all mixtures was below the target value of 0.03% in the 1/2 to 1 in. (13 to 25 mm) slice at 90 days (Figure 5 and Figure 6). The chloride content in the slices taken at the two depths examined was lowest in Mixture B, with only a slightly greater amount of chloride than the detectible limit found between 1/2 and 1 in. (13 and 25 mm) in Mixtures B, C, and D after six months.

In all cases, shrinkage was higher than typically desired (Figure 7). This reflects the high cementitious content of the mixtures and the moderately small maximum aggregate size.

Evaluating overall mixture performance, Mixture A, containing 22% of Class C fly ash, exhibited long setting times, the highest shrinkage, and the highest RCP and chloride penetration of the mixtures tested in Round 1. Mixture B with 5% silica fume, was rated the worst in terms of scaling resistance after 50 cycles and did not experience as large a drop in RCP at 90 days as the other Round 1 mixtures did, ending with higher RCP than Mixtures C through E. A potential drawback of this mixture is related to constructability - concretes containing silica fume only are known to be more difficult to finish and prone to early age cracking. Nevertheless, strength was highest after 6 months and the chloride penetration resistance and shrinkage was lowest. The chloride penetration result from the ponding test is a much more reliable indicator of field performance than RCP which only measures the concrete electrical conductivity.

The mixture containing a blend of 22% Class C fly ash and 5% silica fume, Mixture C, exhibited long setting times and higher RCP than mixtures D and E. However, the overall performance was generally good. Mixtures D and E combining 5% silica fume and 12% slag with 10% Class C fly ash or 10% Class F fly ash, respectively, produced the best overall performance, demonstrating good setting characteristics, good strength gain, and low RCP and chloride penetration values. In addition to its slightly better performance in terms of shrinkage and scaling, from a performance point of view, Mixture E is more desirable than Mixture D since it contains Class F fly ash, which may help to mitigate ASR. Despite this advantage, the Class F fly ash is less readily available in Montana and must be imported from a neighboring state, which may limit the applicability of such a mixture.

Survey of Montana Ready-mix Suppliers

As discussed above, the Round 1 results indicate that the highest durability can be achieved using a quaternary blend of mineral admixtures including silica fume, fly ash and slag. To gain some sense of the feasibility of producing HPC containing multiple mineral admixtures, telephone interviews were conducted with several ready-mix suppliers throughout the State of Montana in the summer of 2002. The plants and the contact information of the suppliers that were contacted are listed in Table 5.

Table 5. Montana ready-mix suppliers

Supplier	Location	Contact	Contact Number
Empire Sand and Gravel	Billings, MT	Bob Kober	406-252-8465
JTL-Billings	Billings, MT	Kevin McGovern	406-655-2005
Missoula Ready Mix	Missoula, MT	John Young	406-549-2385
United Materials	Great Falls, MT	Basil Jacobson	406-453-7692

All plants contacted had some experience using fly ash, with Class C being more common than Class F. Such mixes made up between 15 and 60 % of their current business. One plant had used silica fume in bagged form, which had been truck mixed, and had found this to be extremely difficult. However, all the suppliers stated they were willing to consider using additional mineral admixtures or fume.

When questioned whether replacing the typical Type I cement with a blended cement containing fly ash for use on all jobs was possible, all said they were open to it but that the decision would be dependant on the price of the blend and the cost of redesigning mixes to work with the new blended cement.

Two of the plants had two silos while the other two plants had three. In all cases the second silo was currently being used to store fly ash while the third, if available, contained a second cement, either a different brand for the sake of pricing and availability or a different type. The second type of cement, Type V, was being used only when no fly ash was included in the mix.

One concern expressed by a supplier was that the payment schedule for producing the materials should recognize the slower hydration rates of concretes containing mineral admixtures. Specifically, final strength for payment purposes should be determined at 56 or more days instead of 28 days.

Based on the input from the ready-mix suppliers, the least disruptive option for producing a quaternary mix (cement, slag, fly ash and silica fume) appears to be the use of blended cements containing pre-mixed portland cement and a mineral admixture. This will alleviate the need of the suppliers for four separate silos or tanks to produce a quaternary mix. However, replacing the current Type I cement with blended cement would probably require that the supplier use the blended cement for other jobs.

A portland-slag blended cement, in combination Class C or F fly ash and silica fume appears to be the easiest means achieving a quaternary mix. Such a combination has particular advantages because the portland-slag blended cement, when used alone, will likely produce performance very similar to common Type I cement and would allow the producer to continue to keep fly ash in their second silo. This also allows the use of Class F ash. An alternate is to use portland-fly ash blended cement, in conjunction with slag in the second silo and silica fume. However, this may impact the producers' other work, since the portland-fly ash blend is likely to hydrate more slowly than Type I cement or the portland-slag blended cement. In both of these alternatives, only silica fume would require special handling procedures. Switching to a Class F fly ash should not greatly impact operations during warm weather, and is preferred and may be essential if the aggregate is found to be potentially alkali-reactive.

Round 2

The practical considerations of using four different cementitious materials may make their combined use unrealistic by some Montana ready-mix plants. As a result, blended cements that pre-combine a SCM with portland cement were examined in Round 2. In addition to this modification, two other changes were made in this round: to eliminate the possibility of negative interaction with other admixtures, the mid-range water-reducer was changed to one that does not contain sodium thiocyanate and to increase strength, the water content was based on a portland cement-only mixture with a w/cm of 0.35 instead of 0.37.

To maximize the effective use of available resources and since the mixtures in Round 1 all produced excellent freezing and thawing durability, the cyclic freezing and scaling testing procedures were not included in this round. Instead, the freezing and thawing resistance of the mixtures was indirectly evaluated based on the parameters of the air-void networks measured in the hardened concrete. It was assumed that if a specific surface of greater than

500 in.²/in.³ (20 mm²/mm³) and a spacing factor of less than 0.01 in. (0.254 mm) could be achieved, than the freezing and thawing deterioration of the tested specimens would be less than could be detected after 500 cycles. Elastic modulus testing was also eliminated.

In general, the Round 2 concretes demonstrated good plastic performance but the first two mixtures (Mixture F and G) had long setting times. This may have been influenced by the high contents of mid-range water reducer which were needed to produce an approximately 4-in. (100 mm) slump after the first three minutes of mixing. As a result, the dose of the mid-range was set to 2.5 fl. oz. (74 ml) per 100 lbs. (45.4 kg) of cement and the mixture procedure was adjusted so that the amount of superplasticizer required to get a 4-in. (100 mm) slump was initially added with the other admixtures. This modification produced more favorable setting results, with the exception of Mixture H containing the Class C fly ash blend and metakaolin. However, the slump loss after 45 minutes was more pronounced and was typically about 4 in. (100 mm). The one exception to this trend of rapid slump loss was Mixture L with silica fume and calcined clay which lost only 2.5 in. (63 mm).

The air content of the fresh concrete mixtures was at the higher end of the acceptable range but within about a 1% wide band. The air content measured in the hardened concrete was more variable, ranging between 5.9 and 9.9%. Despite this variation, which may be related to the interaction between the air entraining admixture and the SCMs, the spacing factors for these mixtures were acceptable (less than 0.0062 in. (0.16 mm)) and the specific surfaces were greater than 500 in.²/in.³ (20 mm²/mm³) indicating good cyclic freezing resistance.

The strength of the mixtures in Round 2 up to 28 days is similar and slightly higher than measured for the first round of mixtures as a result of the slightly lowered w/cm (Table 2). The results are considered adequate.

The cement-only mixture (Mixture F) set slowly, which may have been the result of the high content of mid-range water reducer, but demonstrated some of the fastest strength gain. This mixture exhibited moderate RCP (Figure 4) at 28 days compared to other mixtures but the second worst RCP at 90 days, as the RCP dropped less with additional curing than the mixtures containing SCMs. The chloride penetration and shrinkage was comparable to the mixtures in Round 1 (Figures 5-7).

The mixtures containing Class C fly ash-blended cement combined with 7.5% silica fume (G) or with 7.5% metakaolin (H) both set slowly. The content of the mid-range water reducer may have played a role in this for Mixture G, but the mid-range water reducer content was lowered significantly for H. Based on these results and those from Mixtures A and C from Round 1, it appears that the presence of the Class C fly ash may be a factor in causing the long setting times. The workability and ease of finishing of the mixture containing metakaolin was excellent. Mixture G had a high RCP at 28 days that dropped significantly by 90 days while Mixture H started with a moderate 28-day RCP and did not show much improvement through 90 days. The drying shrinkage of G was significantly higher than H. Both G and H demonstrated poor chloride penetration resistance and were the only two mixtures that permitted an acid-soluble chloride content of over 0.02% at six months in the deepest test slice.

Mixtures J (84.5% slag blend, 10% Class F fly ash and 5.5% silica fume), K (92.5% slag blend and 7.5% silica fume) and L (96% calcined clay blend and 4% silica fume) produced more reasonable setting times and excellent 90-day RCP results. Mixture K displayed high shrinkage and exhibited poor chloride penetration resistance after 90 days at the 1/16 to 1/2 in. (1.3 to 13 mm) depth, although did better through six months in the 1/2 to 1 in. (13 to 25 mm) slice. Mixture L appeared to hydrate most quickly and achieved the highest 7-day strength and the lowest 28-day RCP of all mixtures tested in Rounds 1 and 2. Both Mixture J and L had very low chloride penetration and low shrinkage, with Mixture J outperforming Mixture L slightly in both categories.

Mix J would require that the blended cement and the Class F fly ash be shipped in from Washington and handling of three cementitious materials. It is likely that the slag blend could serve as a replacement for ordinary portland cement in ready-mix producers' silos; however based on price and their other project requirements, it may be difficult to convince them that this is the case. Nevertheless, this mix gave excellent performance across the board and would be expected to deal well with potential alkali-silica reactivity. Finally, Mix L gave excellent performance but is a more uncertain option since the calcined-clay material tested is similar but not exactly the same as would be produced for Montana construction. A representative of Ashgrove Cement, the manufacturer of the calcined-clay blended cement, suggested that it would be possible to produce this material in its Montana City plant with locally produced cement and calcined clay shipped in from Nebraska. The actual availability and cost of the material will

depend on demand for the material in Montana and on the transportation costs. Prior research, conducted by Ashgrove, suggests that the calcined clay blend is effective at mitigating ASR and performed well in freeze-thaw and scaling testing. However, testing of these properties should be conducted to confirm this material performance since the material is somewhat new and without widespread use or testing.

Round 3

Round 3 focused on “simple” mixtures with the widest possible applicability. While Mixture J and L tested in Round 2 performed very well, they are not simple mixtures and their production could result in logistical difficulties for most plants. With the goal of simplifying the final mixture in mind, the Round 3 testing was performed using the Western Montana aggregate source not tested previously. To establish that the different aggregate would not negatively impact the scaling performance of the concrete, this property was tested in this round. The same basis for the water content and the same admixtures used in Round 2 were used in Round 3. Also, in an attempt to produce strengths and RCP in the range expected for the w/cm employed, the air contents as mixed were targeted at the lower portion of the acceptable range selected at the start of this project, compared to the previous rounds where the air contents were targeted at the higher end of the range.

The fresh property targets were met with only a slight problem with Mixture O. A high total dose of air-entraining admixture in Mixture O was necessary because an additional dose of admixture after the initial three minute mixing period was needed. While the total air content of all of the concrete mixtures examined was at the lower limit of the recommended range (and approximately one percent less than the air content measured when the concrete was tested in a fresh condition), the specific surface areas and spacing factors met the recommended values. This suggests that all of these concretes would perform well in a freezing and thawing environment.

Mixture O, containing 20% Class C fly ash and 7% silica fume, exhibited a longer setting time than the other mixtures. Previous rounds of testing have indicated that this Class C fly ash source may have a retarding effect and this trend was repeated in this round of testing.

All three mixtures in Round 3 achieved higher strengths than those obtained in Rounds 1 and 2, with 7-day strengths over 5000 psi (34.5 MPa) and 28-day strengths of over 7000 psi (48.3 MPa) (Figure 1). The mixtures containing 5% silica fume (Mixture M) and a combination of 20% slag and 5% silica fume (Mixture N) were strongest.

All of these mixtures demonstrated very low chloride penetration rates with chloride contents less than 0.012% in the upper slice through one year (Figure 5 and Figure 6). The chloride permeability of these mixtures compares very favorably with the other mixtures tested in this investigation. The chloride content at depths greater than 1/2 in. was below detectable limits in all three cases throughout the test period.

The RCP at 28 days of Mixtures M and O were higher than that of Mixture N (Figure 4). By 90 days, however, the RCP of all mixtures had dropped, with Mixture O (silica fume and Class C fly ash) falling further than Mixture M (silica fume alone) to a value similar to that achieved with the silica fume and slag blend (Mixture N).

All mixtures in Round 3 performed well in the scaling test, with the fly ash and silica fume combination (Mixture O) exhibiting slightly more deterioration after 50 cycles (Figure 2). The scaling ratings in Round 3 were significantly better than in Round 1, even though the air content was slightly lower and likely reflecting the increase in strength and reduced permeability. The three mixtures demonstrated similar free drying shrinkage to mixtures from Rounds 1 and 2, at a magnitude still above preferred values for bridge deck applications (Figure 7).

Aggregate Testing for Alkali-Silica Reaction

The investigation of the potential for alkali silica reactivity consisted of two phases. The first used only the mortar bar test described in ASTM C1260. The second phase included a petrographic examination of the aggregates and testing according to ASTM C1293, which was conducted both using the cement alone and replacing cement with the SCM materials.

Phase 1 - Preliminary Investigation

The aggregate potential for ASR is classified based on the percent length change at 14 days according to the criteria given in Table 6, which was developed based on test results obtained using this method and the field performance of actual concretes.

Table 6. ASTM C1260 (Mortar Bar) criteria

Percent length change at 14 days	ASTM C1260 classification of aggregate
Less than 0.1 %	Innocuous in most cases
Between 0.1 and 0.2 %	Innocuous or deleterious
Greater than 0.2 %	Potentially deleterious

The expansion of the aggregate types tested is presented in Figure 8 and Figure 9. As can be seen in these graphs, only the Glasgow - Coarse aggregate did not exceed the potentially deleterious threshold of 0.2 % at 14 days. However, the Glasgow - Coarse aggregate specimens expanded more than 0.1% at 14 days, and maintained a steady rate of expansion though 28 days suggesting that, despite “passing” the ASTM test guidelines, this aggregate may also be susceptible to long-term ASR.

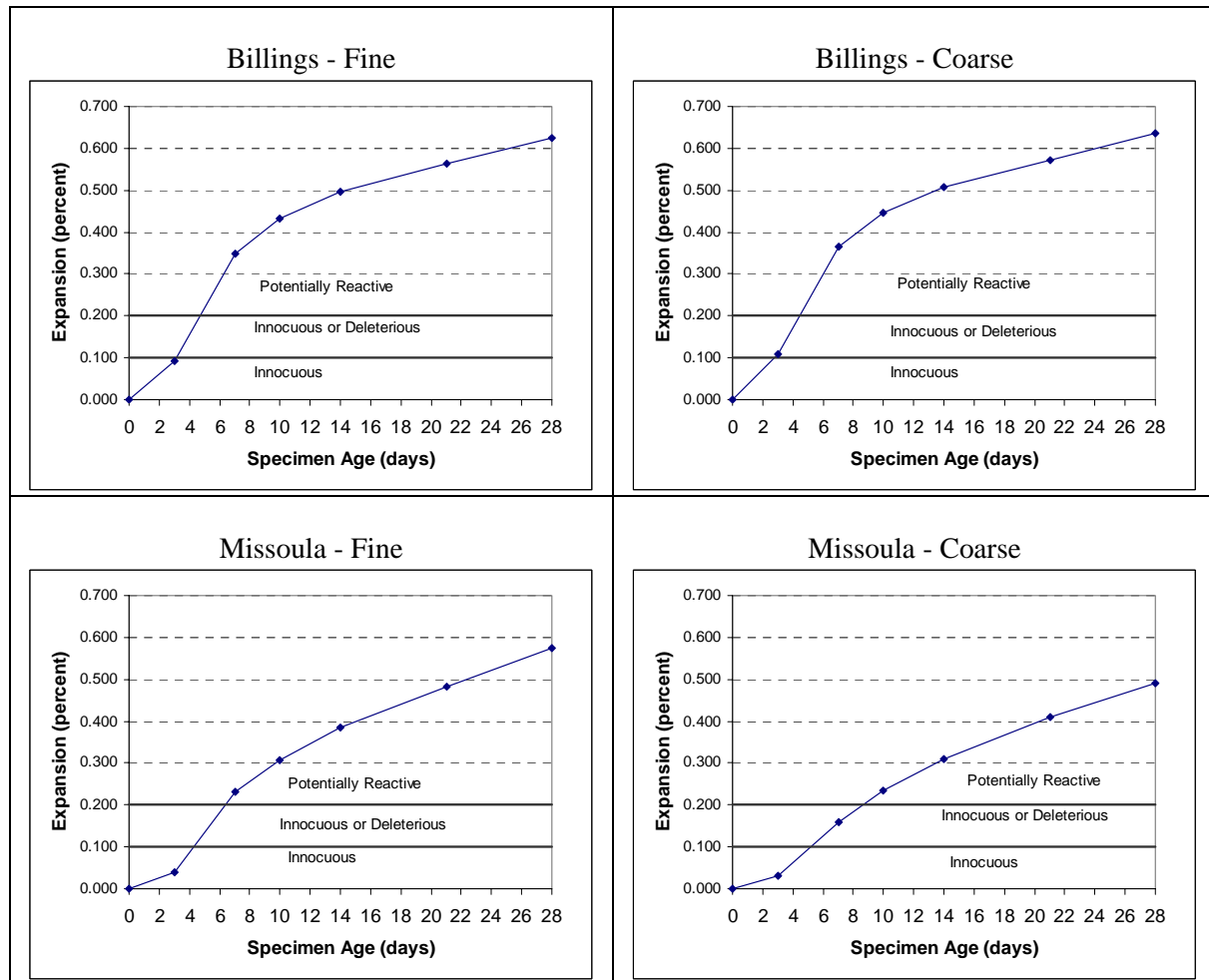


Figure 8. C1260 Results for Billings and Missoula Sources

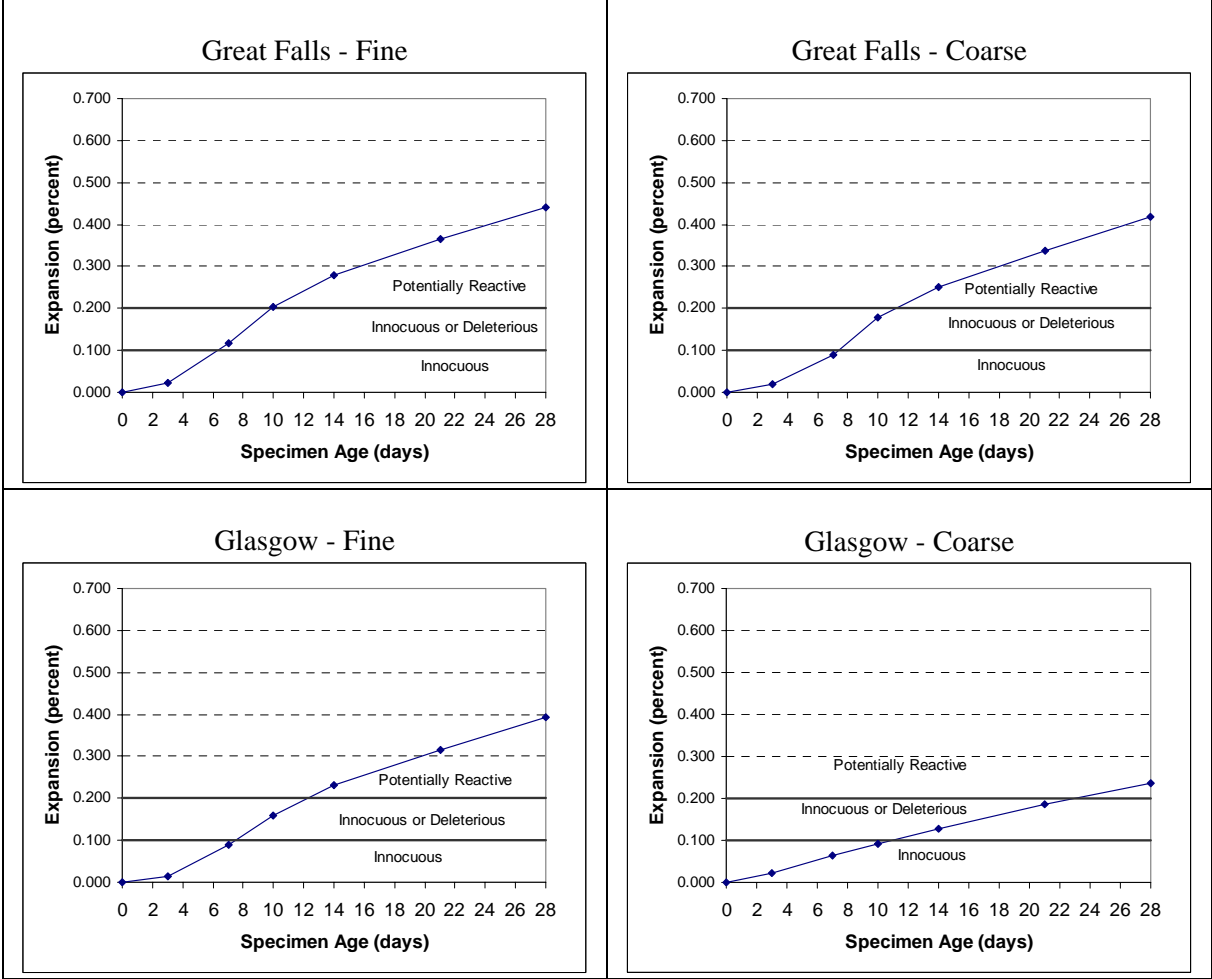


Figure 9. C1260 Results for Great Falls and Glasgow Sources

As discussed, the C1260 test method is a harsh simulation of the conditions that an aggregate might see in practice and may identify aggregate which could be used safely in concrete as reactive.

Phase 2 - In-depth Investigation

The results of the petrographic examinations of the materials are summarized in Table 7, which shows the percentage of potentially deleterious materials in each source. This table also lists the percentage of potentially deleterious materials in each source that are readily available. Readily available particles are those in which the potentially reactive silica in the particle interior is more available to participate in expansive reactions because the particles may be weaker, more porous or less dense. Most potentially deleterious particles from the Billings source typically contain high proportions of known reactive components. Therefore, a differentiation between readily and non-readily available reactive silica could not be easily made. The complete reports are attached as Appendix C.

Table 7. Potentially deleterious materials in aggregate sources

Sample	Total potentially deleterious, %			Potentially deleterious in readily available form, %		
	Coarse	Fine	Combined	Coarse	Fine	Combined
Missoula	24.4	10.9	35.3	4.7	1.4	6.1
Billings	35.0	22.3	57.3	<35.0	<22.3	<57.3
Glasgow	19.7	9.8	29.5	4.8	5.7	10.5
Great Falls	25.1	16.0	41.1	7.2	6.1	13.3

The C1293 testing is still ongoing. The results of this testing will be issued as an addendum to this report.

DISCUSSION

Round 3 Performance Variation

A clear difference in performance, specifically in terms of strength, RCP and chloride penetration resistance, was observed between the first two rounds and the third round of mixtures. The Round 3 mixes had a lower air content and different aggregate source and this lower air content is a contributing factor to these trends. However, since air content reduces concrete strength about 5% for every 1% of increase in air and the air contents in Rounds 1 and 2 were less than 3% greater than Round 3, this is not sufficient to fully explain the 30% difference in strength between similar mixtures, nor the large differences in permeability that were observed. Instead, it appears that significant differences in the properties of the paste-aggregate interfacial zone, as identified by subsequent petrographic examination, played a large role in modifying the overall concrete performance.

Microscopic examination of the aggregate sockets in the concretes from Round 3 with Western Montana aggregates showed a dense, smooth region of lower w/cm, while the surface of the sockets in the Rounds 1 and 2 with Yellowstone River aggregate was comparatively soft and friable, indicative of locally higher w/cm. Adjustments to the batch weights of water and aggregates were made based on the aggregate moisture contents so that the overall water content of the mixtures were constant. It appears, however, that characteristics of the Yellowstone River aggregates resulted in more porosity within the aggregate-paste contact zone than for the Western Montana source.

This interfacial zone is where cracks typically initiate in concrete under load, and weakening this “weak-link” in the internal structure of concrete through introduction of even small amounts of additional water or porosity may significantly reduce the strength of the material. This is especially true for concrete of this low w/cm. This interfacial zone also plays a determining role in the permeability of concretes since the interfacial zone provides a pathway for chloride ions to penetrate through the concrete, especially if the zone is weak and porous.

Coarse aggregate particles exposed on the fresh fracture surfaces of these concretes exhibited a greater tendency to fracture in the concretes from Round 3 than in the prior two rounds, suggesting that the interfacial bond between the aggregate and paste matrix was stronger. In addition, some of the Western Montana aggregate particles used in Round 3 exhibited greater surface roughness than the Yellowstone River aggregate and this was likely a factor in increasing the bond strength of the interfacial zone and so also contributed to the greater strength and impermeability of the concrete.

Performance Evaluation

In evaluating which mixture is the best performer, judgments must be made about the relative importance of desired properties in the actual concrete and about how well the laboratory results from the employed testing procedures represent the expected in-place concrete behavior. Since this mixture is intended to produce highly durable bridge decks in Montana, the end result must be concrete that has low deicer permeable and is resistant to cracking and cyclic freezing and thawing. However, before durability can be evaluated, this mixture must demonstrate plastic properties that suggest it will be consistent and easy to place and finish. The test results that characterize this type of property include slump, slump loss, setting time, and plastic air content.

Once the utility of the concrete has been verified, durability can be considered. Typically, the greatest cause of deterioration in Montana bridge decks is corrosion of embedded steel initiated by the intrusion of chloride ions. Concrete impermeability is most realistically estimated using the chloride penetration resistance (ponding) test since this most closely simulates chloride ingress of de-icing salts. However, this is a slow test and the most useful data is obtained after 6 months or longer though initial measurements are made at 90 days. The RCP Test is a much faster but imperfect test since concrete electrical conductivity is measured by an applied electrical voltage and the results of this test may be confused by non-chloride ions introduced into the concrete by supplementary cementitious materials.

Regardless of how impermeable the concrete is, if the concrete cracks chloride will have access to the interior of the deck and reinforcing steel. Therefore, moderate to low drying shrinkage in combination with a low elastic modulus is highly desirable. In addition, adequate freeze-thaw resistance, which is directly related to the quality of the hardened air network, as described in terms of air content, specific surface area and spacing factor, is essential. Finally, scaling, which deteriorates concrete surfaces exposed to de-icing salts and undergoing freezing, must be assessed for a traffic bearing surface in a cold climate. While shrinkage, scaling and freeze-thaw resistance are important properties, as long as they meet minimum levels of performance, the concrete should be acceptable. Therefore, given a workable mixture, the highest emphasis should be placed on the chloride solution ponding results since improvements in penetration resistance can be directly measured and will almost certainly translate into more durable structures. The strength, shrinkage and other durability test results should receive secondary consideration, as long as minimum acceptable values are obtained.

One other item for consideration in the interpretation of the chloride penetration results should be mentioned: the slabs for chloride penetration were wet cured for 14 days and then dried for 14 more days before ponding began. This is a relatively short curing period for supplementary materials and chloride penetration may occur in the SCM-rich mixtures during the first 90 days while they continue to hydrate and their permeability continues to decrease as demonstrated in the later-age RCP tests. This is in contrast to the cement-only mixture where more hydration will have occurred by 28 days. It is likely that if the ponding was not initiated until a later time, for example 56 or 90 days, the concretes containing large amounts of SCM would perform significantly better while those containing only small amounts of SCM would expect only marginally improved performance to the results presented here.

Despite the variation in air content and distribution, all the mixtures tested demonstrated negligible amounts of chloride at depths greater than 1/2 in. (13 mm) after 90 days and chloride resistance consistent with what is typically expected of HPC. To select the best performer, however, the chloride content after 6 months or more of ponding gives the strongest basis for differentiating these mixtures. To differentiate the Round 3 mixtures, examination of the one-year data is necessary.

For the specific set of raw materials evaluated, the combinations of SCMs that produced the best results were 5% silica fume alone (Mixtures B and M), 7% silica fume and 20% slag (Mixture N), the slag-blended cement with 10% Class F fly ash and 5.5% silica fume (Mixture J) and the calcined clay-blend with 4% silica fume (Mixture L).

A silica fume-only mixture may be more difficult to finish and displays somewhat higher shrinkage and given the limited amount of SCM may not have as much ASR-compensating effect as some of the other mixtures. However, it displayed excellent chloride penetration resistance and would be the simplest of the four options to produce. Prevention of deck cracking is also a potential concern with this mixture. The silica fume and slag combination mix exhibited well-rounded performance across the test program. This would be more complex to produce but could be simplified by the use of the slag cement blend, though this blend is produced by an out-of-state supplier. It is likely that the slag blend could easily serve as a replacement for ordinary portland cement in ready-mix producers' silos; however based on price and their other project requirements, it may be difficult to institute. The combination of the slag-blended cement, Class F fly ash and silica fume also gave excellent performance across all tests, standing out particularly for low drying shrinkage, and would be expected to be the best option to mitigate alkali-silica reactivity. However, the cement blend and fly ash would have to be shipped in from out of state and production would require handling three cementitious materials. Finally, the calcined-clay combination gave excellent performance, including low drying shrinkage, but is a more uncertain option since the materials tested are similar but not exactly the same as would be produced for Montana construction. Also, the material has seen less widespread use and testing than the

other SCMs evaluated. The actual availability and cost of the material will depend on demand in Montana and on the transportation costs.

One property shared by all mixtures tested was higher drying shrinkage levels at 90 days than the recommended target of 0.06%. This is influenced by the mixture proportions and also by characteristics of the cement and the other raw materials. Therefore, when HPC mixtures based on this testing program are used, this property of these mixes should be considered during design, restraint should be minimized where possible, and early wet curing should be scrupulously applied.

While not evaluated directly, based on the durability of the concretes tested, the aggregate from Western Montana appeared to provide better performance than that from the Yellowstone River.

CONCLUSIONS AND RECOMMENDATIONS

To maximize the durability-related performance of concrete for use in bridge deck applications for the state of Montana, the following essential steps in successful implementation of HPC were completed: 1) based on the desired function of the structure, the project objectives were defined in a manner that could be quantified, 2) the highest quality raw materials available were selected, and 3) trial batches using the local materials were conducted.

This program gave an indication of what combination of locally available materials would likely produce the best concrete for the application considered. Based on the 14 mixtures evaluated and for the specific set of raw materials tested, the best supplemental materials combinations included silica fume alone, silica fume and slag, a slag-blended cement with Class F fly ash and silica fume and a calcined clay-blend with silica fume. The influence of the raw materials, including the aggregate, and the importance of testing each was clearly demonstrated. In addition, the importance of the character of the paste-aggregate interfacial transition zone for high performance concrete as determined by aggregate type and batching procedures was highlighted.

To ensure the ultimate success of HPC projects in Montana using these mixtures in the future, it would be highly valuable to conduct trial batches using the local production procedures and comparing results of tests to the results obtained in this study. In addition, the construction demands of HPC beyond typical construction, such as increased curing and quality control testing, must be considered and enforced in specifications. However, this study has provided a solid foundation for constructing highly durable concrete bridge decks in Montana using locally available materials.

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APPENDIX A - MATERIAL SOURCES

The material sources investigated are given in Table A1. The mid-range water reducing admixture was changed during the program from Polyheed 997 to Pozzolith 322N, at the start of Round 2, to minimize the potential for admixture-cement reactions.

Table A1. Materials Investigated

Material	Supplier	Location of Supplier/Plant
Type I/II Cement	Holcim Ltd.	Trident, MT
Cement-Fly Ash Blend (Class C - Corrette)	Holcim Ltd.	Trident, MT
Cement-Slag Blend	LaFarge Corp.	Seattle, WA
Cement-Calcined Clay Blend	AshGrove Cement Co.	Louisville, NE
Fly Ash (Class C)	ISG Resources, Inc.	Corette, MT
Fly Ash (Class F)	ISG Resources, Inc.	Centralia, WA
Silica Fume	Master Builders, Inc.	Chicago, IL
Slag grade 100	Holcim Ltd.	Dundee, MI
High-Reactivity Metakaolin	Advanced Cem. Tech.	Stockton, CA
Air Entraining Agent (MB-VR)	Master Builders, Inc.	Chicago, IL
Mid-Range Water Reducer (Polyheed 997)	Master Builders, Inc.	Chicago, IL
Mid-Range Water Reducer (Pozzolith 322N)	Master Builders, Inc.	Chicago, IL
High Range Water Reducer (Rhebuild 1000)	Master Builders, Inc.	Chicago, IL
Billings Aggregate	JTL Group, Inc.	Billings, MT
Missoula Aggregate	JTL Group, Inc.	Missoula, MT
Glasgow Aggregate	Fossum Ready Mix	Glasgow, MT
Great Falls Aggregate	United Materials	Great Falls, MT

APPENDIX B - TEST RESULTS

Mix	SCM contents	Rapid Chloride Permeability (Coulombs)		Percent acid soluble chloride @ 90 days		Percent acid soluble chloride @ 6 mos.		Percent acid soluble chloride @ 1 yr.	
		28 days	90 days	1/16 - 1/2 in.	1/2 - 1 in.	1/16 - 1/2 in.	1/2 - 1 in.	1/16 - 1/2 in.	1/2 - 1 in.
A	22% FAC	8980	4690	0.182	0.005	0.368	0.018	0.395	0.062
B	5% SF	4140	2520	0.100	0.008	0.244	0.009	0.207	0.015
C	22% FAC + 5% SF	5530	1520	0.148	0.007	0.335	0.010	0.287	0.008
D	10% FAC + 12% Slag + 5% SF	3670	1020	0.116	0.008	0.325	0.010	0.355	0.011
E	10% FAF + 12% Slag + 5% SF	3840	960	0.181	0.007	0.385	0.012	0.407	0.037
F	Cement only	3684	2880	0.211	0.007	0.328	0.019		
G	92.5% FAC Blend + 7.5% SF	4861	1842	0.346	0.007	0.443	0.028		
H	92.5% FAC Blend + 7.5% HRM	2744	2195	0.358	0.007	0.434*	0.022*		
J	84.5% Slag Blend + 10% FAF + 5.5% SF	2234	958	0.139	0.007	0.257	0.007		
K	92.5% Slag Blend + 7.5% SF	1804	924	0.306	0.007	0.374*	0.008*		
L	96% CC Blend + 4% SF	1362	800	0.168	0.007	0.210	0.008		
M	5% SF	1378	1158	0.032	0.006	0.032	0.006	0.077	0.006
N	20% Slag + 5% SF	705	403	0.040	0.006	0.038	0.006	0.094	0.006
O	20% FAC + 5% SF	1168	462	0.046	0.006	0.078	0.006	0.108	0.006
Recommended target		< 2000	-	-	-	-	< 0.030	-	-

FAC = Class C fly ash, FAF = Class F fly ash, SF = Silica fume, HRM = High reactivity metakaolin, CC = calcined clay

* Measured at 222 days

Mix	SCM contents	Comp. strength @ 3 days (psi)	Comp. strength @ 7 days (psi)	Comp. strength @ 28 days (psi)	Comp. strength @ 6 mos. (psi)	Modulus of Elasticity @ 7 days (Msi)	Modulus of Elasticity @ 28 days (Msi)
A	22% FAC	2680	3790	4410	5310	3.24	3.96
B	5% SF	3590	3690	4970	6290	3.49	4.22
C	22% FAC + 5% SF	2520	3460	4480	5490	3.14	3.68
D	10% FAC + 12% Slag + 5% SF	2680	3330	5260	5840	3.32	3.62
E	10% FAF + 12% Slag + 5% SF	2390	3420	4450	5660	2.92	4.21
F	Cement only		4410	5750	6900		
G	92.5% FAC Blend + 7.5% SF		3660	5010	6930		
H	92.5% FAC Blend + 7.5% HRM		3900	4770	5650		
J	84.5% Slag Blend + 10% FAF + 5.5% SF		4100	5140	6170		
K	92.5% Slag Blend + 7.5% SF		3610	4610	5040		
L	96% CC Blend + 4% SF		4510	5540	6470		
M	5% SF	5250	6160	7930	10040		
N	20% Slag + 5% SF	4380	5950	8370	9730		
O	20% FAC + 5% SF	3830	5490	7300	8120		
Recommended target		-	-	5000-9000	-	-	-

FAC = Class C fly ash, FAF = Class F fly ash, SF = Silica fume, HRM = High reactivity metakaolin, CC = calcined clay

Mix	SCM contents	Ave. scaling rating after 50 cyc.	Ave. number of pop outs	F/T: mass loss after 300 cyc. (%)	F/T: mass loss after 500 cyc. (%)	F/T: DF after 300 cyc. (%)	F/T: DF after 500 cyc. (%)	Drying Shrinkage at 90 days (%)
A	22% FAC	2.0	9	0.50	1.32	100.8	103.1	0.0839
B	5% SF	2.7	28	-0.02	0.33	100.3	103.1	0.0680
C	22% FAC + 5% SF	1.0	12	-0.20	0.12	104.1	104.3	0.0692
D	10% FAC + 12% Slag + 5% SF	1.8	14	-0.05	0.13	99.6	101.9	0.0775
E	10% FAF + 12% Slag + 5% SF	1.0	7	-0.33	-0.10	102.1	102.1	0.0692
F	Cement only							0.0705
G	92.5% FAC Blend + 7.5% SF							0.0730
H	92.5% FAC Blend + 7.5% HRM							0.0655
J	84.5% Slag Blend + 10% FAF + 5.5% SF							0.0581
K	92.5% Slag Blend + 7.5% SF							0.0748
L	96% CC Blend + 4% SF							0.0612
M	5% SF	0.2						0.075
N	20% Slag + 5% SF	0.3						0.077
O	20% FAC + 5% SF	0.8						0.077
Recommended target		0-1	-	-	-	-> 90	>85	< 0.0600

FAC = Class C fly ash, FAF = Class F fly ash, SF = Silica fume, HRM = High reactivity metakaolin, CC = calcined clay

APPENDIX C - PETROGRAPHIC STUDIES OF AGGREGATE SOURCES

Source: Missoula

Coarse Aggregate: The Missoula coarse aggregate is a geologically mature gravel, possibly partially crushed, as there are a large number of very well rounded particles, but numerous recently fractured and angular particles. All rock and mineral types present are hard, firmly indurated, and dense. They show little evidence of chemical weathering. Occasional particles have a partial coating of calcareous caliche material that is very firmly attached to the particles. Additionally, many particles have a slight, partial, but very tenacious coating of clay-sized material.

The coarse aggregate contains a total 24.4 weighted percent materials that are considered potentially deleterious because they contain forms of silica known to be reactive with the alkalis in portland cement. However, of that amount, only 4.7 weighted percent occurs in particles in which the potentially reactive silica can be considered readily available. Even in this amount, probably only half is easily available. This is because all of the particles in this aggregate are extremely hard and dense, and most particles contain only small amounts of potentially reactive silica. The results of the Missoula coarse aggregate analysis are given in Table C1.

Fine Aggregate: The Missoula fine aggregate is derived from the same source as the coarse aggregate. Particles are generally more frequently angular and irregularly shaped than in the coarse aggregate, but are similarly hard, firm, and dense with little evidence of chemical weathering. Caliche was not observed, but particles continued to have slight, partial, but very tenacious coatings of clay-sized material.

The fine aggregate does not meet the gradation requirements of ASTM C33, as the cumulative percent passing the No. 50 mesh sieve is 34.1.

The fine aggregate contains a total 10.9 weighted percent materials that are considered potentially deleterious because they contain forms of silica known to be reactive with the alkalis in portland cement. However, of that amount, only 1.4 weighted percent occurs in particles in which the potentially reactive silica can be considered readily available. The same considerations as for the coarse aggregate apply to the fine aggregate particles.

The types of materials in the Missoula aggregates (coarse and fine) are as follows:

Dacite: The dacitic rocks in this aggregate are generally porphyritic, gray to brown in color, and exhibit slight to moderate weathering. Dacite is a fine-grained to aphanitic¹, compositionally acidic, shallowly intrusive to extrusive igneous rock. It contains cryptocrystalline quartz, volcanic glass, and devitrified volcanic glass that has optical properties of such materials known to be reactive with the alkalis in portland cement.

Chert, innocuous: This is a green translucent, occasionally sandy rock that contains microcrystalline quartz, none of which has optical properties indicative of potential alkali-silica reactivity.

Chert, deleterious: The type of chert that contains potentially reactive silica is translucent gray to off-white or translucent blue, often iron stained to shades of brown, slightly granular. These particles are largely innocuous, but contain very small amounts of opal. Opal is highly reactive with the alkalis in portland cement paste.

Orthoquartzite: This material is usually very fine grained, reddish to buff or tan. A translucent to white variety is also present in small amounts.

Orthoquartzite, potentially deleterious: These particles are translucent pink, medium fine grained to occasionally fine grained. They contain small amounts of chalcedonic cement that is potentially very deleterious.

¹ Composed of particles too small to discern with the unaided eye.

Metaquartzite: These particles consist of microcrystalline to cryptocrystalline, strained quartz. Particles exhibit a very distinct, microscopic foliation. Because of the very small grain size and strain, they are considered highly deleterious. These particles were included in the classification with deleterious orthoquartzite.

Argillite, innocuous: These are very fine-grained to microcrystalline², hard, very firmly indurated, dense, sedimentary rocks. The varieties present are: gray-brown, sandy; gray-green, occasionally white-speckled, arkosic; light gray, black-speckled; and maroon red to red brown.

Argillaceous sandstone – subgraywacke: these particles are often poorly banded, sandy, and various shades of maroon red. They consist of alternating, poorly developed bands of sand and argillite. Included in argillite count.

Argillite, deleterious: These particles are deep brown with off-white mottling. They contain chalcedonic quartz with a refractive index less than 1.54, characteristic of such material known to be reactive with the alkalis in portland cement paste.

Sandstone: The category includes very fine grained, gray translucent arenites; fine grained, maroon red, ferruginously³ cemented sandstones and subgraywackes⁴; brown, speckled to gray with green inclusions occasionally lithic⁵ or arkosic arenites⁶. Also counted in this category are medium grained, deep pink to gray, occasionally slightly to moderately ferruginous and rarely calcareously cemented arenites.

Sandstone, potentially deleterious: These particles are siliceously cemented, translucent pale pink to off-white, medium to fine grained, and occasionally arkosic. Small amounts of the cement is chalcedonic and has a refractive index well below 1.54.

Basalt: This includes all fine grained to aphanitic, compositionally basic igneous rocks.

Granite: Generally medium grained, slightly to moderately weathered. Diorite is also included in this classification.

Limestones: These particles are usually very dark gray, weathering to buff and tan. Occasionally they are greenish gray to deep gray brown, microscopically speckled or banded. Many particles are slightly to moderately weathered to a depth of a few millimeters.

Quartz: Quartz is present as monomineralic particles only in the No.4 and pan fractions of the coarse aggregate, and in the fine aggregate.

Feldspar: All particles composed predominantly of one or more feldspar minerals. Present only in the fine aggregate.

Mafic minerals: All particles composed predominantly of one or more mafic minerals. These are present only in the fine aggregate.

The results of the Missoula fine aggregate analysis are given in Table C2.

² These particles often grade into more granular varieties (such as siltstones), often within the same particle. Because most of the particles are aphanitic, all have been classified as argillites.

³ The binding matrix is composed predominantly of clay-sized iron oxides.

⁴ A subgraywacke is a sandstone with an abundant, fine-grained, often clay-sized cementing matrix.

⁵ Containing rock fragments.

⁶ An arenite is a sandstone composed predominantly of quartz. Arkoses contain 25 percent or more feldspar. Lithic arenites contain rock fragments. Thus, a lithic arenite is mostly quartz with rock fragments, and an arkosic arenite is mostly quartz with less than 25 percent feldspar.

Table C1—Petrographic Composition of Missoula Coarse Aggregate

Constituents	Weight percent of constituent in sieve fraction					Constituent in Whole Aggregate (weighted percent)
	+ 3/4	+ 1/2	+ 3/8	+ No. 4	Pan (est.)	
Basalt	0.2	1.2	0.8	0.7	Tr.	2.9
Chert, Innocuous	-	0.6	1.0	1.0	Tr.	2.6
Dacite	0.2	0.3	1.1	0.3	Tr.	1.9
Sandstone, Innocuous	0.2	10.0	5.9	3.3	0.2	19.6
Sandstone, Potentially Deleterious	-	4.8	2.1	0.9	Tr.	7.8
Granite	0.2	2.7	1.6	0.2	-	4.7
Chert, Potentially Deleterious	-	0.6	1.1	1.1	Tr.	2.8
Orthoquartzite	0.5	12.4	7.3	4.2	0.2	24.6
Quartzite, Potentially Deleterious	-	4.5	0.6	0.8	Tr.	5.9
Argillite, Potentially Deleterious	0.2	3.3	1.1	1.3	0.1	6.0
Argillite, Innocuous	0.2	6.9	3.4	3.2	0.2	13.9
Limestone	-	3.6	1.6	1.2	0.1	6.5
Quartz	-	-	-	0.7	0.1	0.8
Percent by weight of aggregate in sieve fraction	1.7	50.9	27.6	18.9	0.9	100.0

Table C2—Petrographic Composition of Missoula Fine Aggregate

Constituents	Weight percent of constituent in sieve fraction							Constituent in Whole Aggregate (weighted percent)
	+ No. 4	+ No. 8	+ No. 16	+ No. 30	+ No. 50	+ No. 100	pan	
Basalt	-	0.5	0.3	0.2	0.3	-	0.1	1.3
Chert, Innocuous	-	1.0	1.0	0.6	2.2	1.0	0.4	6.2
Dacite	-	0.2	0.5	0.2	0.2	0.2	0.1	1.4
Sandstone, Innocuous	-	1.2	1.3	0.6	0.3	-	-	3.4
Sandstone, Potentially Deleterious	-	0.4	0.7	0.1	-	-	-	1.2
Granite	-	0.7	1.3	1.2	0.7	0.3	-	4.2
Chert, Potentially Deleterious	-	0.4	0.2	0.1	0.3	0.7	0.2	1.9
Orthoquartzite	-	1.1	1.6	1.5	4.1	3.2	1.0	12.5
Quartzite, Potentially Deleterious	-	0.4	0.4	1.4	1.4	0.9	0.2	4.7
Argillite, Potentially Deleterious	-	0.3	0.2	0.2	0.5	0.3	0.2	1.7
Argillite, Innocuous	0.1	3.5	2.3	2.8	5.3	3.8	1.2	19.0
Quartz	-	0.4	0.6	2.5	11.9	12.1	3.4	30.9
Mafic minerals	-	-	-	0.2	1.0	0.9	0.3	2.4
Limestone	-	0.5	0.6	0.4	1.2	0.5	0.2	3.4
Feldspar	-	Tr.	0.3	0.6	1.9	2.2	0.7	5.7
Percent by weight of aggregate in sieve fraction	0.1	10.6	11.3	12.6	31.3	26.1	8.0	99.9

Source: Billings

Coarse Aggregate—The Billings coarse aggregate is a geologically mature gravel. Particles are generally irregularly shaped to frequently sublenticular and subovoid and well to very well rounded. They are hard, firm, dense, and generally chemically unweathered, although occasional granite particles evince minor decomposition of mica.

Infrequently, particles have a partial, very hard, tenacious, secondary coating of iron oxides and hydroxides. The coating ranges from a moderate stain to a deposit approximately $\frac{3}{32}$ inch thick. No more than one or two particles in a given sieve fraction have a significant coating or stain. The only effect of this coating on concrete made with the aggregate is likely to be infrequent staining of the concrete surface where such a particle is exposed.

The coarse aggregate contains a total of 35.0 weighted percent of particles that contain a form of silica known to be reactive with the alkalis in portland cement paste. In the case of these particles, most of this potentially reactive silica is in the form of devitrified glass that has a refractive index slightly to well below 1.54. The potentially deleterious particles are rhyolites and dacites. Andesites are also a prominent component, but no potentially reactive materials were detected in andesite particles. There is a compositional and textural gradation from rhyolite through dacite to andesite. Rhyolite contains the highest amount of modal silica. It is generally cryptocrystalline to glassy, devitrified, and is potentially the most reactive. Dacite may contain as much modal silica as rhyolite, but is usually better crystallized and thus less potentially reactive. Andesite usually contains only small amounts of potentially reactive silica, if it contains any at all.

As indicated above, rhyolite grades both compositionally and texturally into dacite. In classifying the particles in this aggregate a judgment has to be made on particles that are transitional between the two. Thus, if every particle were examined in detail, the relative proportions of rhyolite and dacite might be slightly different.

The potentially deleterious particles are all very hard, strong, and dense for their types. Thus, the functional reactivity of the uncrushed aggregate may be substantially less than the results of this examination indicate.

The results for the Billings coarse aggregate are summarized in Table C3.

Fine Aggregate—The Billings fine aggregate is derived from the same source as the coarse aggregate of the same name. Particles are more frequently angular and irregularly shaped than in the coarse aggregate, with irregularity and angularity increasing with decreasing particle size.

The fine aggregate does not meet the grading requirements of ASTM C33 because the cumulative percent passing a No. 8 mesh sieve is 78.8 percent by weight.

The fine aggregate contains a total 22.3 weighted percent of material considered to be potentially deleterious. While this is less than in the coarse aggregate, these particles may result in a higher potential expansion because they are smaller and the total surface area is proportionately greater.

The types of materials in the Billings aggregates are as follows:

Basaltic Rocks: These particles are usually dark gray to black, occasionally brick red, occasionally porphyritic and infrequently microporphyritic. Most appear to be diabbases a few are amygdaloidal. Vesicular types are conspicuously absent.

Rhyolite: These are light to occasionally dark gray, or occasionally off white, compositionally acidic, volcanic or shallowly intrusive igneous rocks. They contain major amounts of devitrified glass with a refractive index less than 1.54. They are considered highly potentially deleterious.

Dacite: These are medium to very dark gray particles, often porphyritic to microporphyritic, compositionally intermediate to acidic rocks, usually shallowly intrusive to volcanic. They usually contain moderate amounts of devitrified glass with a refractive index less than 1.54, but may contain as much as is common in rhyolites. They are considered moderately to highly potentially deleterious.

Andesite: These are medium to dark gray or red, generally porphyritic, fine grained, compositionally intermediate to basic, generally shallowly intrusive to occasionally extrusive igneous rocks. They may contain small amounts of several forms of silica that are potentially reactive with the alkalis in portland cement paste. No such materials were detected in these particles, and they are considered non-deleterious in this aggregate.

Chert, innocuous: This is a pale medium buff gray, occasionally fossiliferous rock. It is cryptocrystalline and has no characteristics of chert that is reactive with the alkalis in portland cement paste.

Granite: These particles are predominantly a normative, medium grained, compositionally acidic, intrusive igneous rock. Infrequently, mica grains evince slight to moderate chemical weathering.

Diorite: These are normative, medium to fine grained particles of compositionally intermediate, intrusive igneous rock.

Orthoquartzite: In this aggregate, this includes a very fine grained, relatively pure arenitic quartzite, a very fine grained arkosic arenite, and a fine grained subgraywacke. In the coarse aggregate table, monomineralic quartz is included in this classification.

Quartz: In the fine aggregate, this includes all monomineralic particles of quartz that cannot be classified as orthoquartzite.

Feldspars: In the fine aggregate, this includes all particles consisting predominantly of one or more feldspar crystals, regardless of type.

Mafic minerals: In the fine aggregate, this includes all particles consisting predominantly of one or more crystals of ferroan, magnesian, or ferromagnesian minerals.

The results for the Billings fine aggregate are summarized in Table C4.

Table C3—Petrographic Composition of the Billings Coarse Aggregate

Constituents	Weight percent of constituent in sieve fraction					Constituent in Whole Aggregate (weighted percent)
	+ 3/4 in.	+ 1/2 in.	+ 3/8 in.	+ No. 4	Pan (est.)	
Basaltic rocks	1.5	10.6	5.9	3.8	0.6	22.4
Rhyolite	0.2	7.0	3.8	5.9	1.0	17.9
Dacite	0.7	7.3	3.8	4.6	0.7	17.1
Andesite	1.5	6.7	3.9	3.1	0.5	15.7
Chert, Innocuous	0.2	-	0.1	0.1	Tr.	0.4
Granitic Rocks	1.1	8.5	3.8	4.3	0.7	18.4
Diorite	0.4	1.3	1.4	1.1	0.2	4.4
Orthoquartzite	0.4	1.6	1.0	0.5	0.1	3.6
Percent by weight of aggregate in sieve fraction	6.0	43.0	23.7	23.4	3.8	99.9

Table C4—Petrographic Composition of the Billings Fine Aggregate.

Constituents	Weight percent of constituent in sieve fraction							Constituent in Whole Aggregate (weighted percent)
	+ No. 4	+ No. 8	+ No. 16	+ No. 30	+ No. 50	+ No. 100	pan (est.)	
Quartz	-	0.4	1.0	2.9	19.4	4.9	0.9	29.5
Feldspar	-	0.5	0.5	1.2	2.5	3.0	0.5	8.2
Basaltic Rocks	0.1	3.0	1.0	0.9	1.4	3.0	0.3	9.7
Rhyolite	0.3	3.0	2.8	1.4	3.3	1.3	Tr.	12.1
Dacite	0.1	3.2	1.6	1.1	2.7	1.4	0.1	10.2
Andesite	0.2	2.3	1.1	0.7	1.7	1.9	0.2	8.1
Chert, Innocuous	-	0.3	0.1	0.1	-	-	-	0.5
Granite	0.2	5.0	3.1	1.2	0.6	-	-	10.1
Diorite	-	0.9	0.3	-	-	-	-	1.2
Orthoquartzite	0.1	1.6	1.4	0.6	2.7	-	-	6.4
Mafic Minerals	-	-	0.1	0.1	1.0	2.3	0.5	4.0
Percent by weight of aggregate in sieve fraction	1.0	20.2	13.0	10.2	35.3	17.8	2.5	100.0

Source: Glasgow

Coarse Aggregate: The coarse aggregate is a gravel. Most particles are well rounded, but particle angularity increases with decreasing particle size. Many particles are lenticular to sublenticular in shape, subvoid particles are also moderately frequent. With few exceptions, particles are hard, firm, and dense.

This gravel contains some of the same rock types as found in the Great Falls aggregates, and occasional particles are partially encrusted with a similar caliche deposit, although the amount of caliche material is much less. These features indicate that the two aggregates may be derived from geologically similar source regions. The majority of the particles in this aggregate are also aphanitic⁷, making identification and classification more laborious than usual.

The aggregate contains a total of 19.7 weighted percent of materials that are classified as potentially deleterious because of their potential to react with the alkalis in portland cement paste. While this is very high, actual reactivity in service may be substantially less than expected. This is because 14.9 percent of the potentially reactive material occurs in particles that are very hard, strong, and dense, and many contain relatively small amounts of reactive material for their weight. Because this is a coarse aggregate, the large particles have a relatively low surface area on which reactive silica is exposed, and unless the particles are broken, the potentially reactive silica in their interiors may never be exposed to alkalis.

However, 4.8 weighted percent of the aggregate is not only potentially deleterious, but the particles in which the potentially reactive silica occurs are not exceptionally strong or dense.

Assuming that the submitted sample is representative, this aggregate is considered marginal for use in concrete that will be exposed to moisture unless it can be shown that use of low alkali cement, and possibly other ameliorating measures, will effectively prevent alkali-silica reactions from occurring and disrupting the concrete.

The results for the Glasgow coarse aggregate are summarized in Table C5.

Fine Aggregate: This fine aggregate is a natural sand. It is genetically related and compositionally similar to the coarse aggregate from this location. The largest particles are frequently subvoid and well rounded. Particle shape becomes more irregular with decreasing particle size, and angularity increases. Particles are generally hard, firm, and dense.

The components of this aggregate are the same as for the coarse aggregate, with the addition of quartz, feldspar, and mafic minerals. Mafic minerals are only present in the No. 50 and No. 100, and pan sieve fractions. They were included in the basaltic rock classification.

The fine aggregate contains a total of 9.8 weighted percent materials classified as potentially deleterious. Of this material, 4.1 weighted percent occurs in particles that are quite hard, strong, and dense, and so may react more slowly than the other potentially reactive particles. However, because this is a fine aggregate with a higher surface area than a coarse aggregate, this factor may be minimized. The remaining 5.7 weighted percent of the potentially reactive materials are classified as highly deleterious.

Assuming that the submitted sample is representative, this aggregate is not recommended for use in concrete that will be exposed to moisture unless it can be shown that use of low alkali cement, and possibly other ameliorating measures, will effectively prevent alkali-silica reactions from occurring and disrupting the concrete.

The descriptions of the coarse and fine aggregate components are as follows:

⁷ Made of grains too small to distinguish with the unaided eye.

Basaltic: All fine grained to aphanitic, compositionally basic igneous rocks. Shallowly intrusive and basalts and diabase are the most common types present. Vesicular basalts are rare.

Chert, Innocuous: Varieties of microcrystalline to cryptocrystalline chert that did not contain detectable amounts of potentially reactive silica included: dark gray to black, dense chert; dark gray with brown flecks, dense chert; brown vuggy chert; brown sandy chert; translucent gray chert with ferruginous inclusions; and brown silty chert.

Dacite: Fine grained to porphyritic, extrusive and shallowly intrusive igneous rocks compositionally similar to rhyolites, but containing less alkali feldspar and more plagioclase. These rocks contain devitrified glass and cryptocrystalline silica that has optical properties of such materials known to be reactive with the alkalis in portland cement paste. These particles are classified as potentially deleterious.

Sandstone: All fine to medium grained sedimentary rocks, including arenites⁸, arkoses⁹, subgraywackes¹⁰, and calcareously cemented varieties of these, are included in this classification. The predominant varieties are fine grained quartz arenites. Arenites are occasionally slightly to moderately weathered. Arkoses and subgraywackes are frequently moderately weathered, but are infrequent to rare.

Granitic: All medium to coarse grained igneous rocks of granitic composition. Granites in this sample are often slightly to moderately weathered.

Chert, Potentially Deleterious: This includes all varieties containing microcrystalline to cryptocrystalline and chalcedonic quartz with refractive indices less than 1.54. Varieties included: greenish-brown argillaceous chert; dense red chert; dense concentrically layered chalcedony; brown and white, foliated to poorly banded, chalcedonic chert; brown, dense chert with sponge spicules (the spicules are deleterious). All of these particles are hard and very firmly indurated, and most are dense.

Orthoquartzite: Orthoquartzites are rocks composed predominantly of detrital quartz grains that are so well cemented that induced fractures pass through, rather than around individual grains as they do in arenites.

Limestones: All carbonate rocks. There are very few limestone particles in the sample. Most are fine-grained to aphanitic. A few are fossiliferous.

Argillites, Potentially Deleterious: These are very fine-grained to microcrystalline, hard, very firmly indurated, dense, sedimentary rocks. The dense green, dense olive brown, and deep red varieties in this sample are cemented by cryptocrystalline silica, portions of which have a refractive index less than 1.54, characteristic of potential reactivity with the alkalis in portland cement. The green and olive varieties, in particular, nearly grade into a chert and contain substantial amounts of potentially deleterious material.

Argillites, Innocuous: these argillites grade into chert-like material, but no potentially reactive forms of silica were detected. The varieties include dark gray to black, medium tan, medium brown, and a maroon red to brown, more coarsely granular variety.

Quartz: Particles consisting of one to several large (approximately 1/2 inch or larger) quartz crystals.

Andesite: This is a fine grained, extrusive to shallow intrusive igneous rock intermediate in composition between dacite and basalt. Andesites occasionally contain small amounts of potentially deleterious silica. These appear essentially innocuous and were not included in the total of potentially deleterious materials.

⁸ Arenite is a textural and compositional term describing a sandstone composed almost entirely of quartz.

⁹ An arkose is sandstone containing 25 percent or more detrital feldspar grains.

¹⁰ A subgraywacke is a sandstone with an abundant, fine-grained, often clay-sized cementing matrix.

Rhyolite: These are fine grained to glassy, extrusive igneous rocks, compositionally equivalent to granite. They contain volcanic glass, often partially to completely devitrified, that often has a refractive index below 1.54, and is potentially reactive with the alkalis in portland cement paste. These particles are classified as potentially deleterious.

Feldspar: all monomineralic grains composed of one or more feldspar minerals as the predominant components. These were only identified in the fine aggregate.

The results for the Glasgow fine aggregate are summarized in Table C6.

Table C5—Petrographic Composition of Glasgow Coarse Aggregate

Constituents	Weight percent of constituent in sieve fraction					Constituent in Whole Aggregate (weighted percent)
	+ 3/4 in.	+ 1/2 in.	+ 3/8 in.	+ No. 4	Pan (est.)	
Basaltic Rocks	-	0.5	1.0	1.5	0.1	3.1
Chert, Innocuous	1.8	6.5	6.2	8.6	0.7	23.8
Dacite	-	0.9	0.4	1.7	0.1	3.1
Sandstones	1.2	10.4	5.0	4.6	0.4	21.6
Granitic Rocks	-	0.7	0.7	0.6	Tr.	2.0
Chert, Potentially Deleterious	0.5	2.8	1.8	2.2	0.2	7.5
Orthoquartzite	0.7	0.9	0.8	1.7	0.2	4.3
Limestones	-	0.5	0.6	0.7	Tr.	1.8
Argillites, Potentially Deleterious	0.4	2.5	1.2	3.1	0.2	7.4
Argillites, Innocuous	1.0	5.6	3.3	3.1	0.2	13.2
Quartz	0.2	0.5	0.8	0.7	0.1	2.3
Andesites	0.2	1.9	1.8	4.0	0.3	8.2
Rhyolites	-	0.7	0.1	0.9	Tr.	1.7
Percent by weight of aggregate in sieve fraction	6.0	34.4	23.7	33.4	2.5	100.0

Table C6—Petrographic Composition of Glasgow Fine Aggregate

Constituents	Weight percent of constituent in sieve fraction							Constituent in Whole Aggregate (weighted percent)
	+ No. 4	+ No. 8	+ No. 16	+ No. 30	+ No. 50	+ No. 100	pan (est.)	
Basaltic Rocks	-	0.5	1.6	0.5	1.7	2.8	0.4	7.5
Chert, Innocuous	0.1	2.7	3.7	1.8	3.3	1.9	0.3	13.8
Dacite	-	0.7	1.4	0.7	1.7	0.9	0.1	5.5
Sandstones	-	0.7	0.6	-	-	-	-	1.3
Granitic Rocks	-	1.2	1.6	1.1	-	-	-	3.9
Chert, Potentially Deleterious	-	0.9	0.9	0.3	0.2	0.2	-	2.5
Orthoquartzite	-	0.3	0.7	0.3	-	-	-	1.3
Limestones	-	0.5	0.7	-	0.5	0.2	-	1.9
Argillites, Potentially Deleterious	-	0.4	0.5	0.3	0.4	-	-	1.6
Argillites, Innocuous	Tr.	1.7	0.9	0.9	0.4	0.5	-	4.4
Quartz	-	0.4	2.0	5.9	18.3	13.6	2.7	42.9
Andesites	-	0.6	0.5	1.1	0.7	1.1	0.1	4.1
Rhyolites	-	0.2	-	-	-	-	-	0.2
Feldspars	-	0.3	0.7	1.2	3.3	3.0	0.6	9.1
Percent by weight of aggregate in sieve fraction	0.1	11.1	15.8	14.1	30.5	24.2	4.2	100.0

Source: Great Falls

Coarse Aggregate: This aggregate is a gravel. Particles are usually well rounded in the larger sizes, but particle angularity increases as size decreases. Particles are usually irregularly shaped to sublenticular. Most particles, except as described below, are hard, firm, and generally dense.

Many particles are partially coated to a greater or lesser degree by a hard, firmly indurated, sandy, calcium carbonate caliche. All particles have at least a partial, microscopically thin, very tenacious coating of secondary calcium carbonate. This coating obscures features of the particles, and often must be removed from individual particles before they can be identified. Combined with the aphanitic¹¹ character of many of the rock types present, this made identification of particles unusually laborious. The present of a partial coating may affect paste bond, but because this coating is so hard and tenacious, bond may actually be improved. The caliche becomes a separate component of the aggregate in the pan fraction.

The aggregate contains a total of 25.1 weighted percent materials that are classified as potentially deleterious. While this is very high, actual reactivity in service may be substantially less than expected. This is because 17.9 weighted percent of the potentially reactive particles are very hard, strong, and dense, and many contain relatively small amounts of reactive material for their weight. Because this is a coarse aggregate, the large particles have a relatively low surface area on which reactive silica is exposed, and unless the particles are broken, the potentially reactive silica in their interiors may never be exposed to alkalis.

However, 7.2 weighted percent of the aggregate is not only potentially deleterious, but the particles in which the potentially reactive silica occurs are not exceptionally strong or dense. Assuming that the submitted sample is representative, this aggregate is not recommended for use in concrete that will be exposed to moisture unless it can be shown that use of low alkali cement, and possibly other ameliorating measures, will effectively prevent alkali-silica reactions from occurring and disrupting the concrete.

The results for the Great Falls coarse aggregate are summarized in Table C7.

Fine Aggregate: This aggregate is a natural sand, genetically related, and compositionally similar to the coarse aggregate from the same location. Particles are usually irregularly shaped and frequently well rounded, although particle angularity increases with decreasing particle size. Particles are usually hard, firm, and dense except as described below.

Coating of these particles by a caliche deposit, as described for the coarse aggregate, is less extensive than in the coarse aggregate, but many particles are still at least microscopically coated. The same considerations as described for the coarse aggregate apply to the fine aggregate.

The aggregate contains a total of 16.0 weighted percent materials that are classified as potentially deleterious. While this is quite high, actual reactivity in service may be less than expected. This is because of the 16.0 weighted percent, 9.9 percent of the potentially reactive particles are very hard, strong, and dense, and many contain relatively small amounts of reactive material for their weight. Thus, they may react less and more slowly than suggested by these figures. However, it should also be recognized that the total surface area of a fine aggregate is much higher than for a coarse aggregate, and thus the potential for reactivity is higher.

Additionally, 6.1 weighted percent of the aggregate is not only potentially deleterious, but the particles in which the potentially reactive silica occurs are not exceptionally strong or dense. These particles will react much more readily.

Assuming that the submitted sample is representative, this aggregate is not recommended for use in concrete that will be exposed to moisture unless it can be shown that use of low alkali cement, and possibly other ameliorating measures, will effectively prevent alkali-silica reactions from occurring and disrupting the concrete.

The descriptions of the coarse and fine aggregate components are as follows:

¹¹ Made of grains too small to see with the unaided eye.

Basaltic: All fine grained to aphanitic, compositionally basic igneous rocks. Porphyritic basalts and diabase are the most common types present. Vesicular basalts are rare.

Limestones: All carbonate rocks. The most prevalent type is a deep medium to dark brown, massive textured, and infrequently fossiliferous. Numerous other massive textured limestones are also present, as well as several fossiliferous and oolitic varieties. Calcareously cemented sandstones and caliche were not included in this classification.

Dacite: Fine grained to porphyritic, extrusive and intrusive igneous rocks compositionally similar to rhyolites, but containing less alkali feldspar and more plagioclase. These rocks contain devitrified glass and cryptocrystalline silica that has optical properties of such materials known to be reactive with the alkalies in portland cement paste. These particles are classified as potentially deleterious. The sample contains 4.4 weighted percent dacite.

Sandstone: All fine to medium grained sedimentary rocks, including arenites¹², arkoses¹³, subgraywackes¹⁴, and calcareously cemented varieties of these, are included in this classification. The predominant varieties are fine grained quartz arenites. Arenites are occasionally slightly to moderately weathered. Arkoses and subgraywackes are frequently moderately weathered, and infrequently strongly weathered. A red-brown arkose, cemented by goethite-limonite, is present in trace amounts. This material is not deleterious, but has the potential to cause minor local staining if it is exposed and weathers. A single particle of soft, friable siltstone in the No. 16 sieve fraction is included here.

Dioritic: Dioritic rocks are similar to granites in texture, but contain more plagioclase feldspar and less alkali feldspar than granites. They are the intrusive equivalents of dacites and andesites.

Granitic: All medium to coarse grained igneous rocks of granitic composition. Granites in this sample are often slightly to moderately weathered.

Chert, potentially deleterious: Almost all the chert material in this aggregate is classified as potentially deleterious, and all particles were counted as such. The gray brown chert contains small amounts of cryptocrystalline to finely microcrystalline silica, including small amounts of chalcedony, that have refractive indices less than 1.54, characteristic of silica that is reactive with the alkalies in portland cement paste. Traces of opal are also occasionally present. The red chert is itself innocuous, but contains inclusions of white, soft, porous, opaline chert. The off-white, dense to porous, and occasionally slightly ferruginous chert contains abundant chalcedonic and cryptocrystalline silica with a refractive index less than 1.54. The sample contains 7.2 weighted percent of these particles.

Orthoquartzite: Orthoquartzites are rocks composed predominantly of detrital quartz grains that are so well cemented that induced fractures pass through, rather than around individual grains as they do in arenites

Syenitic rocks: These are medium to coarse grained igneous rocks containing very little quartz and in which alkali feldspars predominate.

Argillites, potentially deleterious: These are very fine-grained to microcrystalline, hard, very firmly indurated, dense, sedimentary rocks. The green and red-brown varieties in this sample are generally innocuous but cemented by cryptocrystalline silica, portions of which have a refractive index less than 1.54, characteristic of potential reactivity with the alkalies in portland cement. The sample contains 10.7 weighted percent potentially deleterious argillites.

Argillite, innocuous: This includes all varieties of dense, gray-brown, gray, light gray to off-white, and arkosic argillites. These particles are fine grained to microcrystalline. No potentially deleterious materials were detected.

¹² Arenite is a textural and compositional term describing a sandstone composed almost entirely of quartz.

¹³ An arkose is sandstone containing 25 percent or more detrital feldspar grains.

¹⁴ A subgraywacke is a sandstone with an abundant, fine-grained, often clay-sized cementing matrix.

Andesite: This is a fine grained, extrusive to shallow intrusive igneous rock intermediate in composition between dacite and basalt. Andesites occasionally contain small amounts of potentially deleterious silica. These appear essentially innocuous and were not included in the total of potentially deleterious materials.

Rhyolite: These are fine grained to glassy, extrusive igneous rocks, compositionally equivalent to granite. They contain volcanic glass, often partially to completely devitrified, that often has a refractive index below 1.54, and is potentially reactive with the alkalis in portland cement paste. These particles are classified as potentially deleterious. The sample contains 2.8 weighted percent rhyolite.

Quartz: These are monocrystalline particles of quartz. They are present only in the pan fraction of the coarse aggregate, but form a major component of the fine aggregate.

Feldspar: These are particles consisting of one or two feldspar crystals. They are present only in the pan fraction of the coarse aggregate. They are a minor component of the fine aggregate.

Caliche: Particles consisting of secondary calcium carbonate formed by evaporation, often encrusting and entrapping aggregate particles. As discrete particles, they are present only in the pan fraction. There, they are essentially a calcareously cemented subgraywacke, entrapping sand-sized particles in a matrix of calcium carbonate.

Mafic Minerals: These include all essentially monomineralic grains of ferromagnesian minerals. They were not detected as discrete species in the coarse aggregate, but are a minor component of the fine aggregate.

The results for the Great Falls fine aggregate are summarized in Table C8.

Table C7—Petrographic Composition of Great Falls Coarse Aggregate

Constituents	Weight percent of constituent in sieve fraction					Constituent in Whole Aggregate (weighted percent)
	+ 3/4 in.	+ 1/2 in.	+ 3/8 in.	No. 4	Pan.	
Basalt	1.2	3.7	3.3	7.7	1.1	17.0
Limestones	0.9	4.7	3.4	5.6	0.9	15.5
Dacite	0.7	0.9	1.2	1.4	0.2	4.4
Sandstones, Arkoses	0.9	3.2	2.2	5.7	1.0	13.0
Dioritic Rocks	0.2	0.5	1.0	0.6	0.1	2.4
Granitic Rocks	0.2	1.9	1.5	1.6	0.8	6.0
Chert, Potentially Deleterious	0.9	1.4	2.0	2.6	0.3	7.2
Orthoquartzite	-	0.7	1.9	2.0	0.4	5.0
Syenitic Rocks	0.5	0.4	0.3	0.4	-	1.6
Argilites, Potentially Deleterious	0.7	2.5	2.4	4.5	0.6	10.7
Argilites, Innocuous	-	1.5	1.6	3.0	0.4	6.5
Andesite	-	1.5	2.0	3.4	0.5	7.4
Rhyolite	-	0.7	0.8	1.0	0.3	2.8
Quartz	-	-	-	-	Tr.	Tr.
Feldspar	-	-	-	-	Tr.	Tr.
Caliche	-	-	-	-	0.2	0.2
Percent by weight of aggregate in sieve fraction	6.2	23.6	23.6	39.5	6.8	99.7

Table C8—Petrographic Composition of Great Falls Fine Aggregate.

Constituents	Weight percent of constituent in sieve fraction							Constituent in Whole Aggregate (weighted percent)
	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	pan (est.)	
Basaltic Rocks	0.1	2.0	2.2	0.8	0.9	0.8	0.1	6.9
Limestones	-	1.6	1.6	1.0	2.2	1.4	-	7.8
Dacite	-	0.9	0.6	0.3	0.7	0.6	-	3.1
Sandstones	-	1.6	1.3	0.9	0.2	-	-	4.0
Dioritic Rocks	-	0.5	0.8	Tr.	0.2	-	-	1.5
Granitic Rocks	Tr.	0.6	2.0	0.9	1.6	1.1	-	6.2
Chert, Potentially Deleterious	-	1.1	0.6	0.5	0.6	0.8	0.1	3.7
Orthoquartzite	Tr.	0.9	0.9	0.6	0.9	-	-	3.3
Agillites, Potentially Deleterious	-	2.2	1.6	0.8	0.7	0.8	0.1	6.2
Argillites, Innocuous	-	1.4	1.2	0.6	0.5	0.1	-	3.8
Andesite	-	1.5	1.3	0.8	0.7	1.1	0.1	5.5
Rhyolite	-	0.4	0.5	0.3	0.5	1.2	0.1	3.0
Quartz	-	0.1	0.5	1.8	15.3	11.4	1.3	30.4
Feldspar	-	0.2	0.2	0.8	4.0	2.3	0.3	7.8
Caliche	-	0.6	0.7	0.2	0.4	0.1	-	2.0
Mafic Minerals	-	-	-	0.2	1.3	2.8	0.4	4.7
Percent by weight of aggregate in sieve fraction	0.1	15.6	16.0	10.5	30.7	24.5	2.5	99.9

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