ENHANCED PRECAST CONCRETE WITH PUMICE BLENDED CEMENTS

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ABSTRACT

Natural pozzolans have been used for more than 3000 years. Natural pozzolans are supplementary cementitious materials that are often volcanic minerals deposited in an amorphous formation. High grade pumice, a volcanic mineral, exists in select locations of the western United States. Its silicates and aluminosilicates are much like that of class F pozzolans in bulk composition however the microstructural phases of these materials are quite different. The pumice has the potential to be both pozzolanic and a hydration nucleation substrate to improve the hydration of ordinary portland cement. The pumice can be used in combination with hydraulic cements to improve the durability of concrete and its environmental sustainability. The precast and architectural concrete industry can especially benefit from pumice materials. In addition to its chemical attributes, it is also white in color and has a Mohs hardness greater than 6, between feldspar and quartz. A battery of standardized tests was conducted to understand the base chemical and physical characteristics of pumice, hydration kinetics of blended cements containing pumice, and the mixture design properties of concrete containing pumice. The results of this research program show the improvement of cementitious systems for precast concrete elements and systems through the reduction the carbon footprint, color acceptance qualities and enhanced durability related to material related distress mechanisms.

Keywords: Pumice, durability, hydration, material characterization, mechanical performance.

INTRODUCTION

Pumice is natural material of volcanic origin produced during volcanic eruption, the rapid cooling of magma composed mainly of aluminosilicates results in the formation of glass or vitreous phases with disordered structure. These aluminosilicates, having disordered structure, will not remain stable when it is exposed to saturated lime which is the basis for pozzolanic property of volcanic glasses[1]. Pumice is white porous volcanic glass, interlocking vitreous fibers filled with tiny air bubbles. These abundant small bubbles give pumice its unique useful qualities. The mining operations crush and process it for use in a wide variety of products and industries.

The pumice used in this project is from the largest producer of finely ground processed pumice located in Southeastern Idaho near the community of Malad City. In the past, it has been found that concrete containing pozzolanic materials exhibited desirable properties like improved workability, lower temperature rise and lower cost[2]. Generally a portion of portland cement is reduced and natural pozzolans are added to not only to reduce cost but also to improve the technical properties. It has been shown that water adsorbed by porous fine aggregate particles are helpful in maintaining a high relative humidity within the concrete, which creates an environment conducive to cement and pozzolan hydration. Due to the lower heat of hydration and other benefits, pozzolans were used in mass construction application such as dams and other huge structures in 1920s and 1930s[2]. Many durability problems can be addressed by the addition of suitable pozzolans to portland cement[3,4]. Pozzolans are able to mitigate alkali silica reaction through the consumption of hydrated lime, eliminate expansions related to sulfate exposures and greatly reduce the permeability of concrete, which assists in resisting the ingress of chlorides and other salt species[5]. Because of its ability to resist sulfate attack from sea water, portland-pozzolan cement was used in many bridge constructions[6]. Despite the above benefits, replacement of pumice in portland cement is limited due to a perceived slower rate of strength gain. The blending of portland cement, slags, fly ash, processes pozzolans and/or natural pozzolans produces ASTM C595[7] and ASTM C1157[8] cements for ready mix and/or precast concrete products. Extensive use of natural pozzolans in multiple projects in the past has been reported in the literature[2,9,10].

This research was conducted to determine pozzolanic activity and complimentary cementitious capability of pumice labeled DS-200, DS-325, and Ultrafine pumice products for use in combination of portland and hydraulic cements. According to ASTM C 618[11], pozzolans are the siliceous and aluminous material in finely divided form and in the presence of moisture, at ordinary temperature chemically react with calcium hydroxide to form compounds possessing cementitious properties. Complimentary cementitious materials are the materials that provide micro substrate materials for the more efficient hydration of other cementitious material. Pumice is characterized by understanding its base chemical and physical characteristics, hydration kinetics and the mixture design properties of concrete with pumice. Five combinations of mixture designs with pumice blended with a Type II/V were examined. A control mixture with 100% cement, three mixtures with 20% cement replaced by DS200, DS325 and Ultrafine (different grade pumice) and one mixture with 30% replacement by DS325.

CHEMICAL AND PHYSICAL MATERIAL CHARACTERIZATION

It is necessary to understand the chemical and physical characteristics of pumice materials to predict and optimize the use of these materials. The materials were evaluated using X-Ray Diffraction (XRD) to determine the mineralogical composition and the chemical composition was determined using X-Ray Fluorescence (XRF). The particle size distribution of each of the products was determined using a laser diffractometer, providing a size spectrum from 0.02-2000µm. Particle shape was characterized by microscopic techniques using a 600x controlled optics microscope and the images from scanning electron microscope (SEM).

MINERALOGICAL COMPOSITION OF PUMICE

X-Ray Diffraction was performed on sample of pumice from a range of 5 to 90 degrees 2Φ. It has been confirmed by XRD analyses that pumice tested are more than 99% amorphous by the halo shaped diffusion band. There is no peak in the signature, which indicates the pumice has no well-defined crystalline minerals. It also shows the vitreous/glassy nature of material. Whereas in cement, well defined peaks were observed along a level baseline. The amorphous nature of pumice is corroborated by XRD results of different grades of pumice. X-ray diffraction patterns of DS-200 pumice and cement is shown in Fig. 1(a) and (b) respectively.

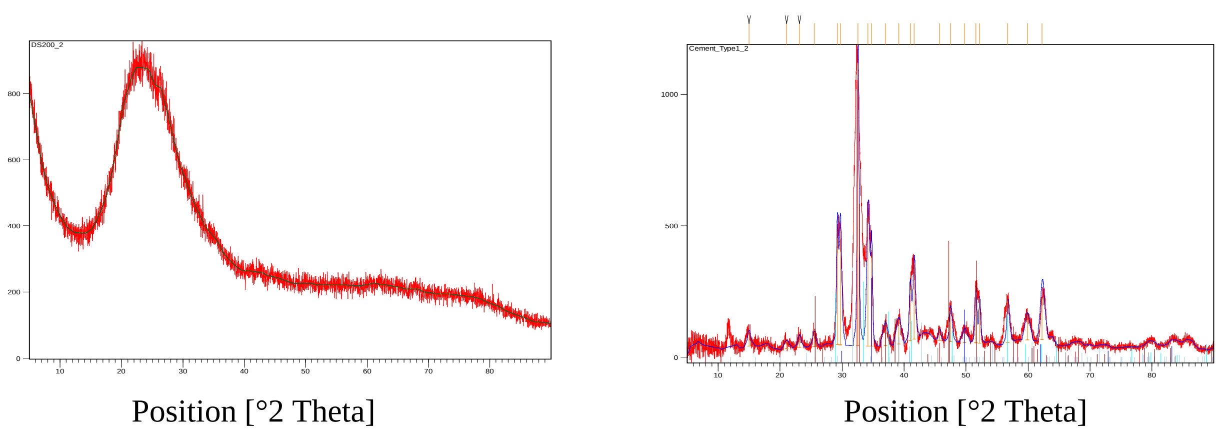


Fig. 1 (a) DS200 Pumice XRD Signature (b) Cement XRD Signature

X-RAY FLUORESCENCE

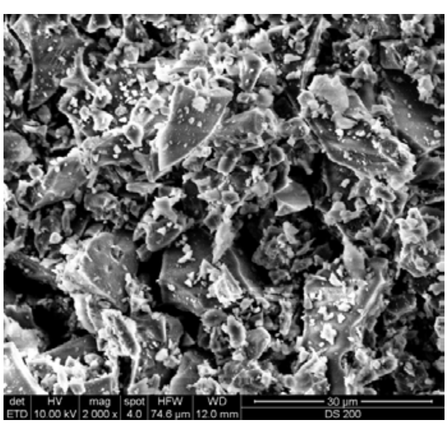
The total chemical composition of different grades of pumice and cement are given in Table 1. Chemical analysis shows that pumice is mainly composed of silica (70%) whereas cement has calcium oxide (62%). ASTM C 618[11] classifies pumice as a Class N pozzolan (for raw or calcined natural pozzolan) if it meets specific physical and chemical requirements. Class N pozzolan should have a minimum of SiO_2+Al_2O_3+Fe_2O_3 content of 70%, pumice has approximately 80% of these materials. Presence of siliceous and aluminous compounds is evident from chemical analysis results of pumice. From the chemical analysis result, it is evident that all grades of pumice composed of more or less same percentage of elements differ only in particle size, which can be inferred from particle size distribution analysis and scanning electron microscopy. From Table 1, it is inferred that pumice has very high silica, very low calcium, more alumina and alkali content compared to Type I and II cement.

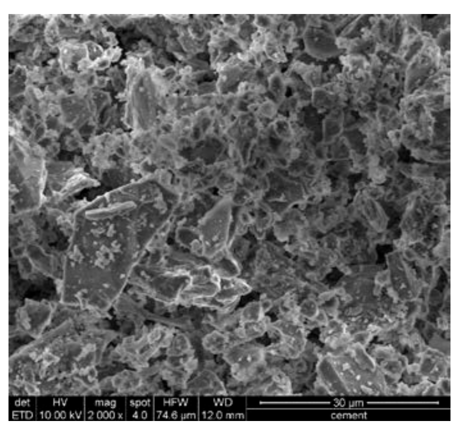
Table 1: Chemical Analysis Result from XRF test

	Type I	Type II	DS200	DS325	Ultrafine
SiO_2	20.02	20.67	69.09	69.16	69.75
Al_2O_3	5.37	3.97	10.63	10.79	11.18
Fe_2O_3	2.35	3.65	1.01	1	1.04
CaO	61.67	63.57	0.93	0.93	0.97
MgO	2.46	1.55	0.09	0.16	0.25
SO_3	3.81	2.81	-0.04	-0.04	-0.04
Na_2O	0.25	0.06	2.49	2.13	2.34
K_2O	1.18	0.72	4.77	5.08	4.79
Cl	0.055	0.018	Nil	Nil	Nil
Total	99.4	98.43	89.12	89.33	90.42

PARTICLE SIZE DISTRIBUTION AND SCANNING ELECTRON MICROSCOPY

Scanning electron micrographs for DS200 and cement with two different magnifications are shown in Fig. 2. From the image, the glassy nature of pumice is evident and it also illustrates the crushed nature of the material. The particle analysis results for different grades of pumice are shown in Fig. 3 and Table 2. It is clear from the mean diameter of particle, the finest is ultrafine and coarsest is DS200. Ultrafine pumice is approximately four times finer than portland cement.





DS200

Cement

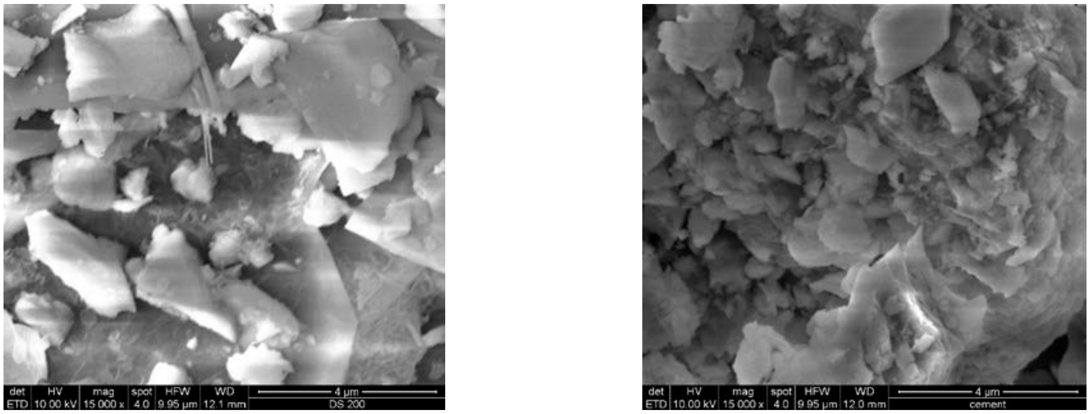


Fig. 2 Scanning Electron Micrograph for DS200 and Cement @ 2000X and 1500X

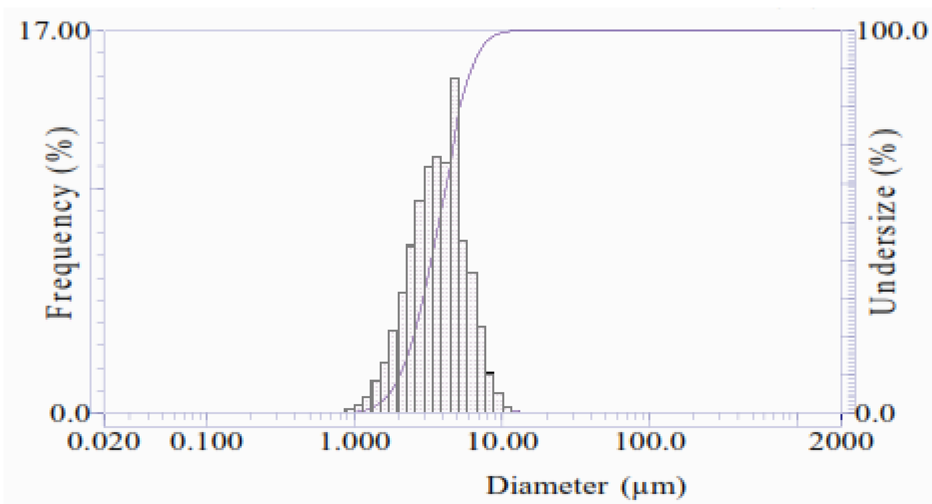


Fig. 3 Particle Size Distribution of "Ultrafine" Pumice

Table 2: Particle Size Details of Pumice

Sample	**Ultrafine**	**DS325**	**DS200**
S.P. Area (cm^2/cm^3)	18093	5921.2	4375.4
Median (µm)	3.755	17.788	31.725
Mean (µm)	3.995	21.292	45.369
S.D. (µm)	1.695	16.158	60.756
Mode (µm)	4.711	24.373	41.895
R.R. Index	1.5	1.5	1.5

HYDRATION KINETICS OF PUMICE BLENDED CEMENTS

Cementitious materials generate heat through exothermic hydration reaction. The kinetics of pozzolanic and cementitious reaction can be measured with an isothermal heat conduction calorimeter. An air isolated heat conduction calorimeter was used to analyze 8 pumice combinations with a control cement. The 8 combinations used were 100% portland cement, ASTM Type II/V; 20 and 30% DS200; 10, 20, 30% DS325; 20 and 30% ultrafine pumice. Each of the tests was conducted at 21° C (70° F) for 30 days, and replacement percentages are done by mass.

A sample of 10 g per ampoule with a reference of 10 g per ampoule was used with w/cm ratio of 0.5. Eight combinations were tested at ambient temperatures for 30 days and the results are shown for the first 225 hours in Fig. 4 and 5.

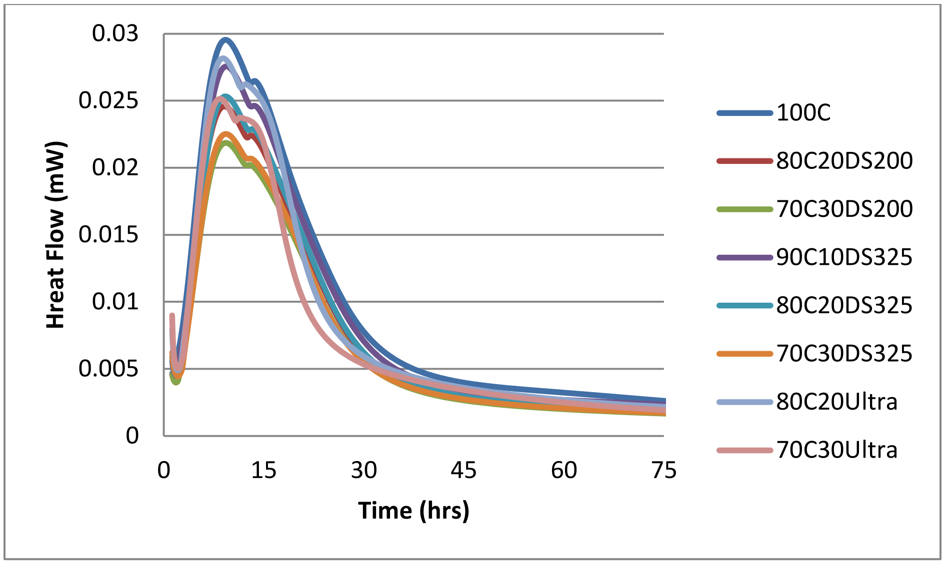


Fig. 4 Heat Flow for different mixture combinations during first 75 hours

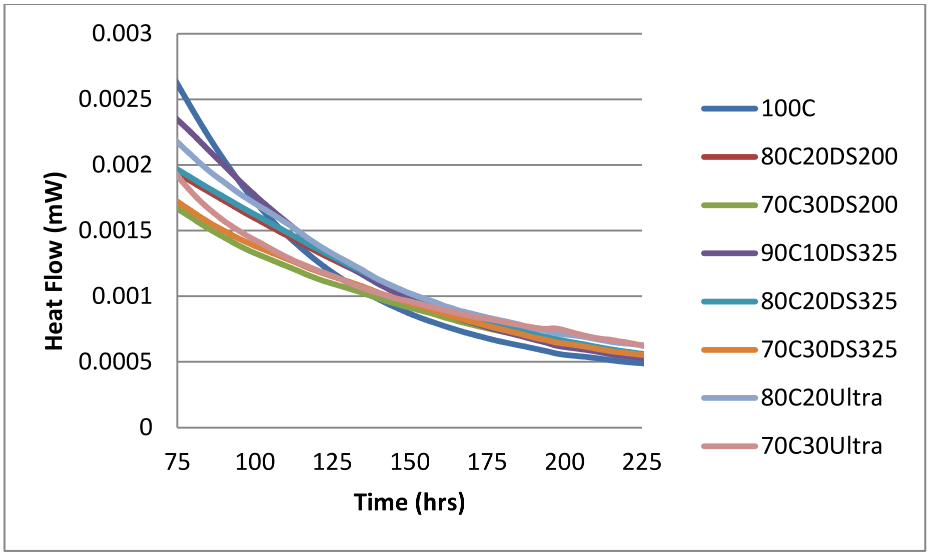


Fig. 5 Heat Flow for different mixture combinations during 75 -225 hours

Fig. 4 shows the heat flow for eight combinations during first seventy five hours and Fig. 5 shows the heat flow between 75 to 225 hours at 70° F. 100% cement mixture produces more heat as compared to the mixtures containing pumice. As the pozzolanic content increases, the main peak of heat flow decreases. Depend on the grades of pumice; the height of main peak varies for same percentage combination of cement and pozzolanic material. 70% cement and 30% DS200 & DS325 produces lowest heat flow respectively among the 8 mixtures whereas 70% cement and 30% ultra produces heat comparable to 80% cement and 20% DS200 & DS325 mixtures. 90% cement and 10% DS325 produces the heat flow comparable to 80% cement and 20% ultra. The calorimeter testing shows that there is no appreciable pozzolanic activity in the first 100 hours for DS200 or DS325. However the ultrafine pumice impacts the early age hydration characteristics. After 100 hours, hydration of 100% cement mixture starts declining whereas for pumice containing mixtures there seems to be continuous hydration. It shows the pozzolanic reaction of different grades of pumice.

CONCRETE MIXTURE DESIGNS WITH PUMICE

By replacing a portion of cement with pumice, many properties of the cementitious system can be influenced, some by physical effects associated with small particles, finer particle size distribution than portland cement and others by pozzolanic and cementitious reactions. Since pozzolans have the ability to influence the durability and strength development properties, it is important to study these properties alongside the kinetics, color and sustainability features.

SETTING TIME

Setting times of five mixtures were determined by Vicat needle test method ASTM C191[12]. The variation of setting time and water requirement for different mixture are presented in Table 3 and Fig. 6. There is an increase in initial and final setting time for the mixtures containing pumice compared to 100% cement (ASTM Type II/V) when tested at a constant flow without admixtures. The increases are well within the limits of ASTM C595[7] specification for blended hydraulic cement is likely attributed to the increased water demand. Water demand is more for mixture containing pumice compared to 100% cement. The percentage increase in water demand is shown in Table 1. The grade of pumice which has very small particles (Ultra) requires more water compared to grades with comparatively larger particles (DS200 and DS325). Also the mixture which has 30% replacement consumed more water due to increase in surface area and also due to porous nature of pumice. The increase in water demand can be addressed by addition of common water reducing admixtures.

Penetration resistance for different mixture combinations over a time period is shown in Fig. 7. Penetration resistance indicates the setting characteristic of cement mixture paste. From Fig. 7 it is clear that 100% cement (100C) mixture has rapid setting characteristic compared to other mixtures and 80% cement with 20% Ultrafine (80C20Ultra) mixture setting characteristic is closer to 100C compared to other pumice mixtures. This indicates 80C20Ultra mixture has the ability to set faster than other pumice mixture combinations.

Table 3: Effect of Pumice on Setting Time and Water Demand

Mixture	Setting Time (min)		Water Used (in g)	% Increase in water
	Initial	Final		
100C	117	242	173	
80C20DS200	143	286	181	4.6
80C20DS325	148	271	195	12.7
70C30DS325	159	315	201	16.2
80C20Ultra	129	323	199	15

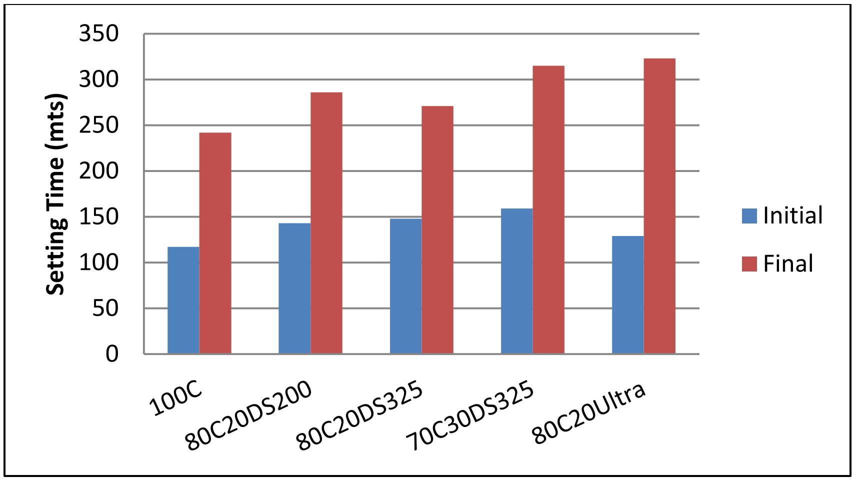


Fig. 6: Effect of Pumice on Setting Time

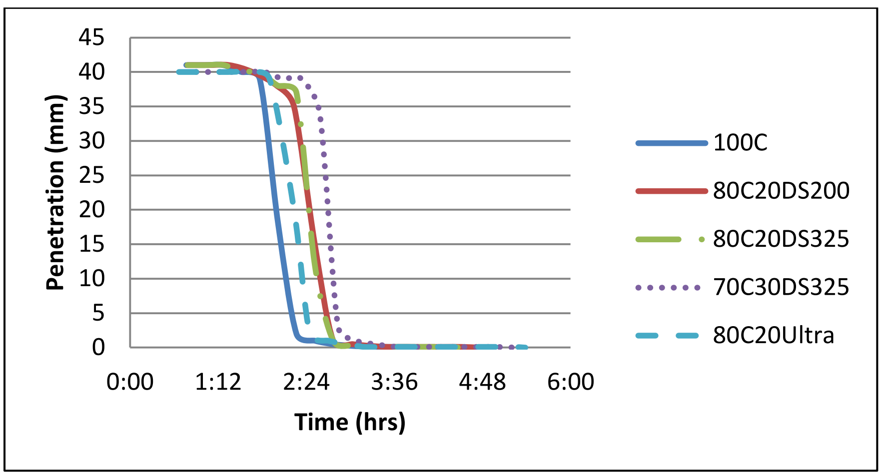


Fig. 7: Penetration resistance of different mixtures

STRENGTH DEVELOPMENT

The compressive strength of concrete is one of the primary considerations in concrete mixture design. Following ASTM C39[13], compressive strength of 4"x8" cylinders were tested with different grades of pumice for five mixtures commonly used for 4 ksi specification. Five mixtures include 100% cement (ASTM Type II/V), 20% of DS200, DS325, ultrafine pumice with 80% cement and 30% DS325 with 70% cement with a w/cm ratio of 0.485. ASTM C192[14] is followed for preparing concrete test specimens and the basic mixture design used to produce 1 cubic feet concrete is shown in Table 4. ASTM Type II/V cement along with different grades of pumice is used as cementitious materials and a polycarboxylate-based mid-range water reducer admixture is used in the mixtures to maintain the slump of 3-5 in. Compressive strength results were shown in Table 5 and Fig. 8.

The mixtures containing pumice reached the compressive strength later than control mixture. However, the minimum strength at age 7 days is greater than 3000 psi and at age 28 days is greater than 4500 psi. Concrete with these qualities is less likely to be subject to early age cracking and has long term strength capability. Mixture containing ultrafine pumice reaches higher early strength compared to mixture containing DS200 and DS325. This trend is supported by the results from hydration behavior of blended cements, in which ultrafine pumice mixture showed rapid hydration characteristics. 80C20DS200 mixture reaches higher strength at 7 and 28 days compared to 80CDS325 mixture which shows the difference in hydration behavior exhibited by different grades of pumice.

Table 4: Basic Mixture Design to Produce 1 Cubic Foot of Concrete

Ingredients	**Mix-1**	**Mix-2**	**Mix-3**	**Mix-4**	**Mix-5**
Cement (lb)	20.9	16.7	16.7	14.6	16.7
Pumice (lb)	0	4.2	4.2	6.3	4.2
Coarse Aggregate (lb)	67	67	67	67	67
Fine Aggregate (lb)	54	53	53	52	53
Water Content (lb)	10	10	10	10	10

Table 5: Compressive strength of 4x8 cylinders

Mixture Design	**Strength at age 7 (psi)**	**Strength at age 28 (psi)**
Cement (C)	5636	7400
80%C+20%DS200 (Mix-2)	4214	5749
80%C+20%DS325 (Mix-3)	3343	4860
70%C+30%DS325 (Mix-4)	3398	5359
80%C+20%Ultrafine (Mix-5)	4648	7083

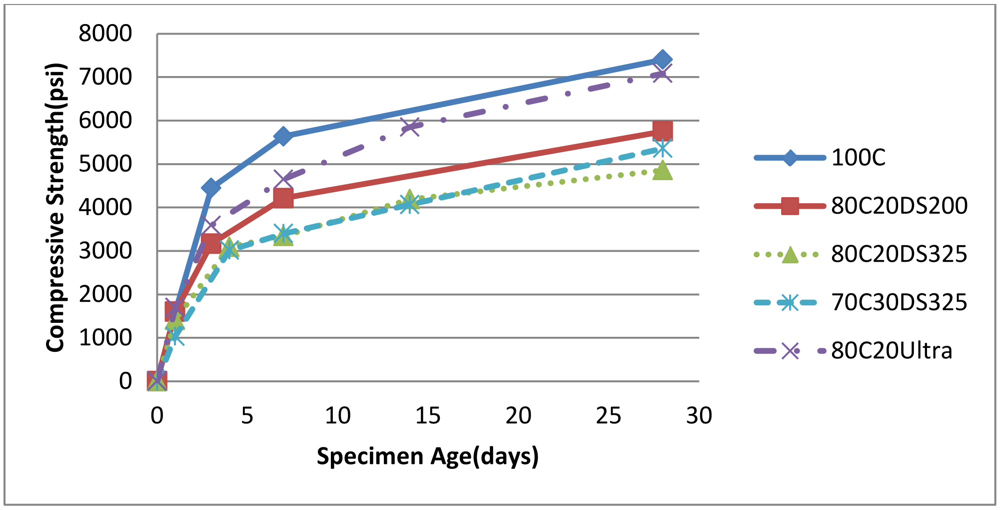


Fig. 8 Compressive strength for 4X8 cylinders

SULFATE MITIGATION

Following the procedures of ASTM C1012[15], five mortar mixture designs were tested for sulfate resistance. The cementitious combinations were same as used in the compressive strength testing. The specimens were tested through 6 months and the percentage length change of mortar specimens for different mixtures is shown in Fig. 9 and Table 6. Test values below 0.05% at 6 months indicate high sulfate resistance and test values below 0.10% at 6 months indicate moderate sulfate resistance. All the pozzolanic mixtures are within the limit of 0.1%, hence qualified to be MS (Moderate Sulfate resistance). Out of five mixtures tested, the four mixtures containing pumice are classified as HS (High sulfate resistant cement) since the length change is less than 0.05% after 26 weeks. Improved performance was seen in the mixtures which have pumice as part of cementitious blend.

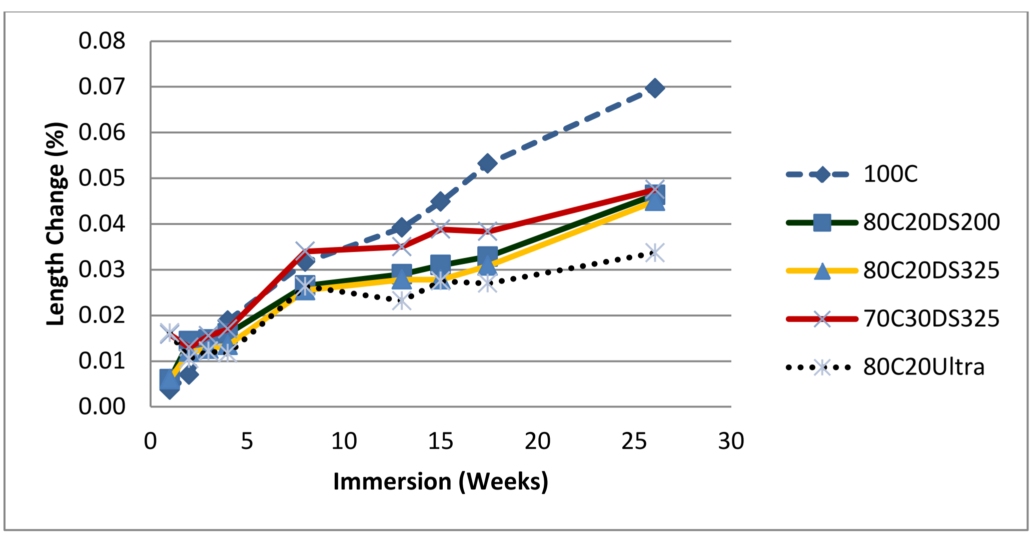


Fig. 9 Length Change (%) of Mortar Specimen due to sulfate

Table 6: Length Change (%) of Mortar Specimen due to sulfate

	Length change (%)				
Weeks	**C**	**Mix-2**	**Mix-3**	**Mix-4**	**Mix-5**
1	0.004	0.006	0.006	0.016	0.016
2	0.007	0.014	0.012	0.013	0.011
3	0.014	0.015	0.013	0.016	0.012
4	0.019	0.016	0.014	0.017	0.012
8	0.032	0.027	0.026	0.034	0.026
13	0.039	0.029	0.028	0.035	0.023
15	0.045	0.031	0.028	0.039	0.028
Month 4	0.053	0.033	0.031	0.038	0.027
Month 6	0.070	0.046	0.045	0.048	0.034

ALKALI SILICA REACTION

Five mortar mixture designs were tested for alkali silica reaction according to a modified ASTM C1567[16] procedure. Mixture proportions used were same as for sulfate resistance except the ASTM Type I cement is used instead of Type II/V cement, along with 25% replacement of fine aggregate with ground cullet glass; ASTM C1567 aggregates gradation was used. The percent length change of mortar specimens for different mixtures was shown in Figure 10 and the summary is given in Table 6. The percent length change for "acceptable expansion" is less than 0.10% at fourteen days with reactive aggregates. Any percent length changeover 0.10% is considered "deleterious expansion". From the result, it is very clear that the usage of pumice is very effective in mitigating the alkali-aggregate expansion.

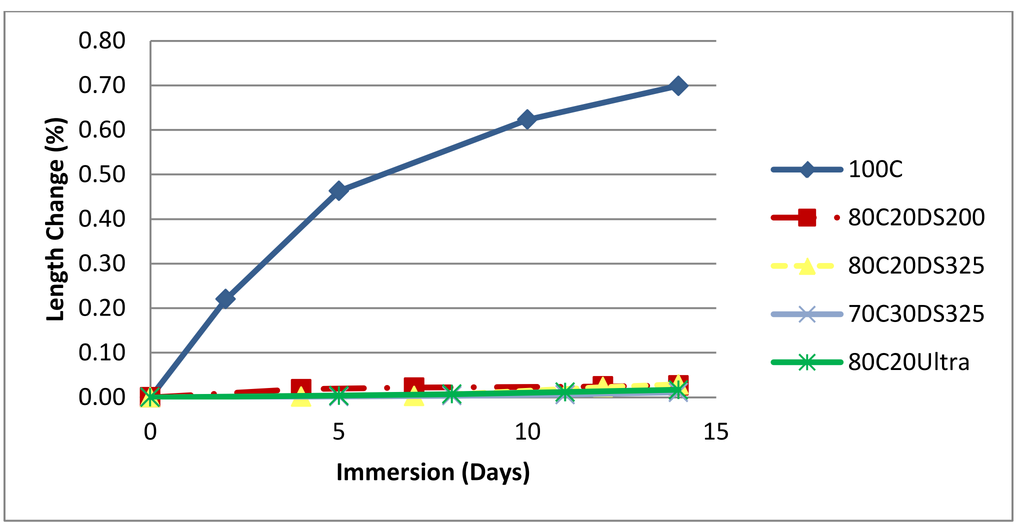


Fig. 10 Length Change (%) of Mortar Specimen due to ASR

Table 7: Summary of ASR Resistance

Mixture	ASR % Length Change	Rating
100C 25%Glass	0.699	Deleterious Expansion
80C20DS200 25%Glass	0.027	Acceptable Expansion
80C20DS325 25%Glass	0.029	Acceptable Expansion
70C30DS325 25%Glass	0.011	Acceptable Expansion
80C20Ultra 25%Glass	0.017	Acceptable Expansion

CONCLUSION

Pumice tested in this research was determined to be pozzolanic and well suited for precast concrete elements and systems. The various grades of pumice behave differently in the hydration characteristic even with the same chemical composition, which may be due to varying particle size distribution. Ultrafine pumice showed improved performance over other grades of pumice in hydration, strength and in durability characteristics such as sulfate resistance and alkali silica reaction (ASR). The greater hydration characteristics of ultrafine pumice are also supported by the compressive strength and the penetration resistance results of the same. Though the water demand is high for the mixtures containing pumice, improved performance in hydration kinetics, strength and durability make it a valuable addition to exposed precast elements. Mid-range water reducer can be used to reduce the water demand which may help in reducing the setting time and makes it probably same as 100% cement mixture. DS200 and DS325 pumice showed improved performance over cement in durability characteristics. If the application requires primarily durability characteristic i.e. high sulfate resistance and high ASR resistant then DS200 and DS325 pumice can be used as a part of cementitious material. If the requirement is both strength and durability, then ultrafine pumice can be used. By producing precast elements with pumice as a part of cementitious material, carbon footprint of building materials can be reduced along with improved technical properties in the precast industry.

The heat produced from mixtures containing pumice is less than that of mixtures with 100 % cement which makes it advantageous in mass concrete placements or large precast elements. Also its white color makes it easier to produce desired colored concrete. Using 20% pumice as a part of total cementitious material produces required strength gain for most applications, and shows excellent performance in durability characteristics. To maintain higher strength, improved durability characteristics and reduced the potential for thermal cracking, ultrafine pumice can be used as a part of cementitious material. When pumice is used as a supplementary cementitious material in precast concrete, it is possible to produce an enhanced concrete with improved technical properties along with environmental benefits.

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