Durability of Concrete Containing Natural Pozzolans

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

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Acronyms and Abbreviations

ASR	Alkali-Silica Reaction
LOI	Loss on Ignition
PI	Principal Investigator
Reclamation	Bureau of Reclamation
SCM	Supplementary Cementitious Materials
TSC	Technical Service Center
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

Contents

Executive Summary

Reclamation has used natural pozzolans for large dams in the past. Trends in the market made fly ash a preferable choice as a supplementary cementitious material for decades. As the future supply of fly ash becomes less predictable, concrete producers are interested in other pozzolans, including natural pozzolans. This report summarizes Reclamation's history with using natural pozzolans and proposes sites to extract cores to assess the long-term durability of concrete made with calcined shales.

Introduction

Supplementary cementitious materials (SCMs) are frequently used in concrete as they can improve durability, strength, and thermal behavior. Reclamation frequently specifies a minimum pozzolan content, usually requiring Class F fly ash or ground granulated blast furnace slag. Fly ash has been the most commonly used supplementary cementitious material for the last several decades. Due to several changes in energy policy, quality fly ash from coal combustion has been increasingly hard to source. Many concrete producers are turning to natural pozzolans as a replacement for fly ash, but some owners are hesitant to specify natural pozzolans due to lack of experience or concerns regarding strength or long-term durability. Although Reclamation has an inventory of facilities that have used natural pozzolans, there have not been any published summaries of the condition of these structures. In addition, future research will provide condition assessment through a concrete coring program aimed at looking at the potential deterioration mechanisms (if any) that the concrete has experienced.

This research will not only benefit Reclamation but will also benefit the entire concrete industry by providing long-term information about how natural pozzolans have been performing over the service life of various concrete structures. Most of the structures that are reviewed in this study were built in the 1950s with one, Friant Dam, constructed from 1939 to 1942. This gives approximately 70 years of service life to see if there have been any adverse effects from using natural pozzolans. There is no other inventory in the United States that could provide the range of environmental conditions and number of facilities that Reclamation can provide.

Project Background

There have been instances in recent Reclamation projects where a consistent supply of fly ash was not available and the contractor proposed the use of a Class N natural pozzolan. Currently, there is not a lot of data in the concrete industry showing if natural pozzolans have long term durability in concrete like Class F fly ash does. This can lead to hesitancy in accepting a Class N pozzolan over a Class F fly ash for certain applications. The Principal Investigator (PI) hypothesizes that the results of this research will show natural pozzolans are durable and are a good substitute for Class F fly ash. If this research hypothesis is proven correct, this will have a huge impact on the concrete community and will open options for other substitutes to fly ash, which is getting harder to find and more expensive to use.

Using natural pozzolans will lead to using resources that are available locally, thereby reducing the cost associated with shipping fly ash to areas where fly ash is not readily available. Natural pozzolans can be a sustainable replacement for Class F fly ash.

This research will benefit Reclamation now because it will give confidence to construction offices that a natural pozzolan is an acceptable replacement to Class F fly ash. In addition, it will likely reduce the cost of the material since there is a current shortage of Class F fly ash. This research is hoping to prove that it will also have long term durability benefits to the structure.

Objectives

The objective of this research is to determine the long-term durability of Reclamation structures that have been built with concrete that used natural pozzolans as a supplementary cementitious material.

Literature Review

The use of natural pozzolans dates back to 2000 BC and they have been used extensively throughout history in Roman, Greek, Indian and Egyptian structures [1]. According to the American Concrete Institute, a pozzolan is "a siliceous or silico-aluminous material that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties" [2]. There are naturally occurring pozzolans and artificial pozzolans such as fly ash or ground granulated blast furnace slag. Natural pozzolans can either be raw or calcined and are usually ground to a sufficiently small particle size to increase pozzolanic activity. Natural pozzolans are generally found in the Western US, although some deposits are located in the Southeast. They are used to improve properties of concrete such as resistance to alkali-silica reaction, decrease heat of hydration in mass concrete, or increase economy of a concrete mixture. Natural pozzolans have been used in the United States as early as the construction of the Golden Gate Bridge (1933 through 1937) and Bonneville Dam (1934 through 1937).

Natural Pozzolans in Reclamation Structures

Early Research and Specifications

Reclamation dams built with various types of natural pozzolans are summarized in Table 1 and shown on a map in Figure 1.

Table 1. Reclamation dams in which natural pozzolan has been used, 1940 to 1970 [3]

Feature Name	Date Completed	State	Type of Pozzolan	Percent Replacement of Cement (%)
Friant	1942	California	Pumice	17 to 20
Altus	1945	Oklahoma	Pumice	22
Davis	1950	Arizona-California	Calcined Shale	17
Glenn Anne	1953	California	Calcined Shale	17 to 27
Bradbury	1953	California	Calcined Shale	20
Trenton	1953	Nebraska	Calcined Silicon-Clay	25
Monticello	1957	California	Calcined Diatomaceous Clay	25 to 30
Twitchell	1958	California	Calcined Shale	varies
Flaming Gorge	1963	Utah	Calcined Shale	20 to 25
Glen Canyon	1964	Arizona	Pumice	30

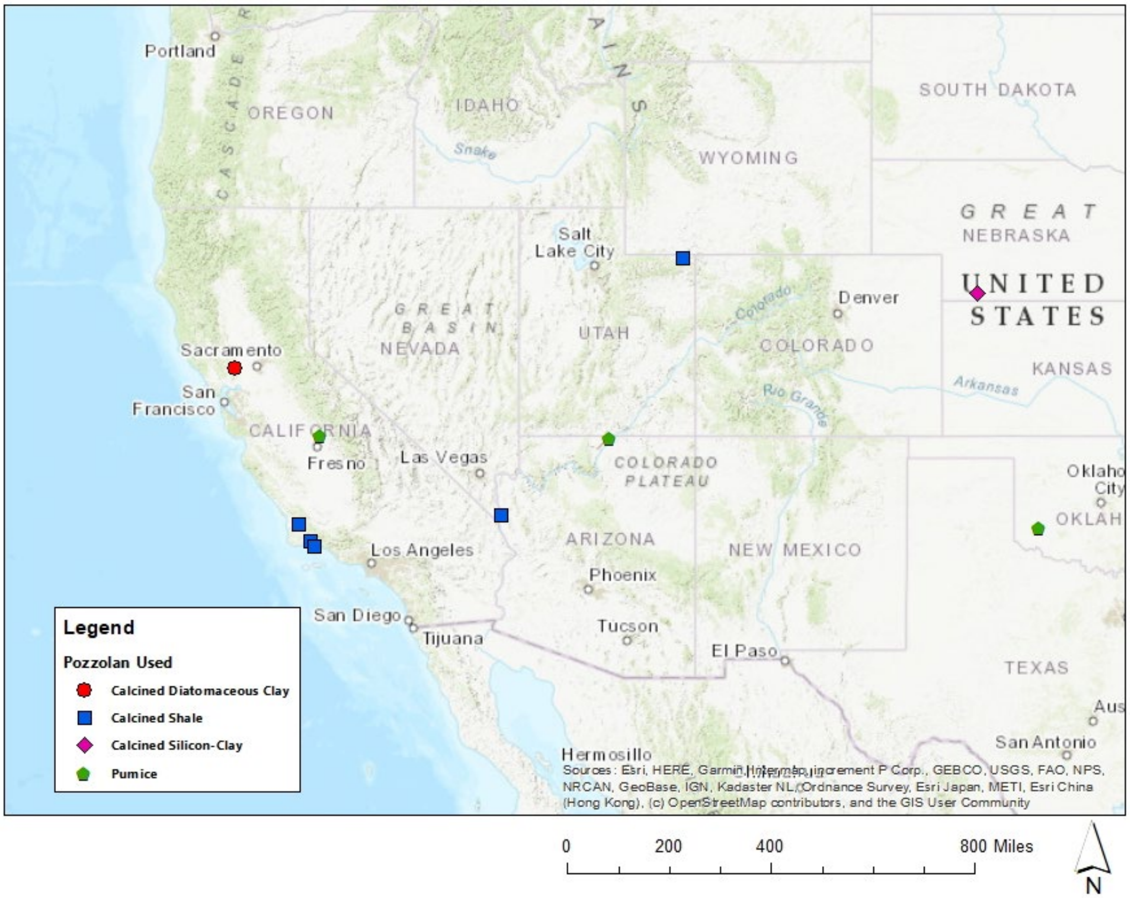

Figure 1. Location of dams constructed with natural pozzolans

In support of concrete mixture designs for projects, Reclamation invested heavily in researching natural pozzolans. In the time between the 1940s and 1970s, Reclamation needed large, consistent supplies of materials for use in mass concrete, many of which are identified in Figure 2. The first major natural pozzolan investigation performed by Reclamation was in support of Grand Coulee Dam [4]. Seventy-five materials were identified and tested as potential pozzolans for use in concrete. At the time, there were no ASTM standard test procedures for "pozzolanic reactivity" so engineers combined data from chemical and physical properties of the powder material itself, chemical activity with lime, and compressive strength of mortar to determine if a given pozzolan was a suitable material.

Early research attempted to correlate the minerology of the pozzolan to the performance in concrete [5]. "Activity Types" were established by Mielenz et al based on mineralogical content and are summarized below [6]:

1. Volcanic Glass
2. Opal
3. Clays
    a. Kaolinite-type clays
    b. Montmorillonite-type clays
    c. Illite-type clays
    d. Mixed clays with altered vermiculite
4. Zeolites
5. Hydrous aluminum oxides

Type I pozzolans owe their reactivity to volcanic glass. This type of pozzolan includes rhyolite tuff and pumicites. The glass content must be over 60 percent in order to gain satisfactory strength in mortar. Additionally, the glass content must be over 90 percent in order to control alkali-aggregate reaction. Some volcanic pozzolans contain a large quantity of alkalis and may increase the rate of alkali-silica reaction (ASR). Most volcanic pozzolans require grinding, but some rhyolitic pumicites are naturally sufficiently fine for use in concrete. For Activity Type I pozzolans, calcination does little to change specific gravity, grindability, water requirement, and setting time.

Type 2 pozzolans include diatomaceous earth and cherts owing their activity to opal. According to Mielenz, Activity Type 2 is "the most active of all natural pozzolans." Diatomaceous earth usually requires a higher water demand which effects the strength, weathering resistance, and drying shrinkage of concrete. The water requirement can be reduced with additional grinding or calcination. Early applications used 1.5 to 3 percent by weight replacement of cement to improve workability and reduce segregation and bleeding of water in concrete. Mortar strength, specific gravity, time of set, and grindability generally increase with calcination. Mielenz notes that diatomaceous earth is "highly reactive with cement alkalis but the high water requirement has precluded use of sufficient pozzolan to effect permanent control of the alkali-aggregate reaction." Opaline cherts are free from the high internal porosity of diatomaceous earth, so they do not have high water demand like diatomaceous earth. Calcined opaline cherts are the most effective pozzolans for control of ASR. Calcined opaline shales are also effective in reducing ASR as well as sulfate attack.

Type 3 pozzolans are clays that must be calcined at temperatures over 1000 °F to induce optimum strength development, ASR control, and reduce water demand. All clayey pozzolans require grinding. Type 3c (Illite-type clays) are inferior for controlling ASR.

Type 4 pozzolans owe their reactivity to zeolites, namely clinoptilolite, ptilolite and analcite. Activity of the altered tuff is improved by calcination to 1400 °F. Some materials tested release alkalis and cause an increase in ASR.

Type 5 pozzolans are not common and are not summarized in this report.

A summary of materials investigated between 1940 and 1970, including activity type, is in Appendix A. A map of materials investigated is shown in Figure 2.

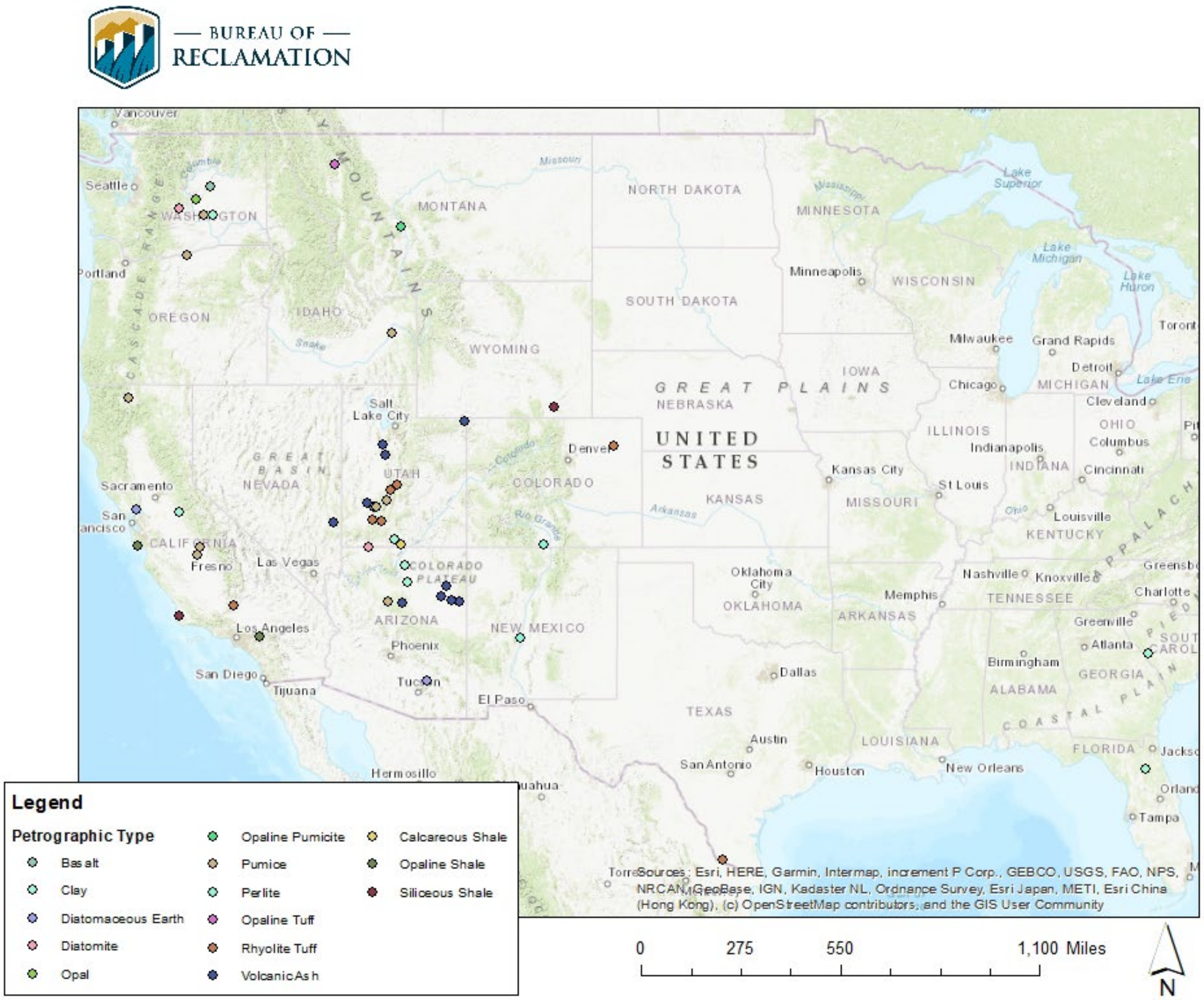

Figure 2. Approximate locations of potential natural pozzolan sources investigated by Reclamation 1935 to 1970.

In general, natural pozzolans were found to increase concrete resistance to deleterious reactions such as sulfate attack or ASR [7, 8, 9, 10]. However, pozzolans do not always increase the durability of concrete. Investigations for both Yellowtail and Flaming Gorge Dam showed that 20% replacements of calcined shale reduced the freeze-thaw durability by up to 30% compared to the control [11, 12]. Other studies showed improvement in freeze-thaw durability with 15% calcined shale compared to control [9].

The first set of chemical and physical specifications written for pozzolans was developed for Davis Dam. The limits are summarized in Table 2 [13]. Generally, specifications included a minimum sum of oxides, maximum available alkalis, maximum loss on ignition, maximum moisture content, and minimum fineness. ASTM C402 was the first ASTM standard specification for raw or calcined natural pozzolans. In 1968, it was replaced by ASTM C618 which includes fly ash as well as natural pozzolans for use in concrete [14].

Table 2. Specification limits for pozzolan used at Davis Dam (Specification No. 1904).

	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Na_2+ K_2O	Total Water Sol. Mat'l	Water Sol. Alkali	LOI	Moisture Content	Specific Surface Area*	Specific Gravity
Limit	+60	+2.0	-15.0	-10.0	-4.0	-4.0	-1.0	-0.10	-7.0	-3.0	+8,000	+2.3

* Blaine Fineness in cm^2/g

Current Condition of Structures

A summary of the general state of dams containing natural pozzolans is summarized in the following section. Information was collected from construction field reports, core reports, comprehensive facility reviews (CFR) and other construction and inspection documentation.

Friant Dam was constructed between 1939 and 1942. Approximately 20 percent pumicite was to be used for all sections of the dam except for the 6-foot layer of concrete on the surface of the crest and the downstream slope of the spillway section. The pumicite was chosen to control the heat of hydration, improve workability and reduce segregation of the lean concrete. The pumicite deposit used is located three miles from the dam on land acquired by the Government. The aggregates used for the concrete are igneous varieties including andesite, syenite, and basalt as well as other sedimentary types including quartzite, which are now known to be susceptible to alkali silica reaction (ASR). In 1942 and 1945, cores were taken from Friant Dam to determine the presence of ASR after early reports of the phenomena were published [15, 16, 17]. The presence of ASR gel was confirmed, but the reaction was not considered significant because low-alkali cement was used. However, engineers at Reclamation noted signs of ASR distress such as displacement between blocks as seen in Figure 3, and wide cracks beginning in 1980 [18]. Cores taken in 1988 revealed deterioration due to ASR is more severe in placements using a high-alkali cement apparently without pozzolan. In placements using the low-alkali cement either with or without pumicite, damage from ASR was negligible [19].

Figure 3. Concrete at Friant Dam with pumicite (left) and without pumicite (right). Arrows pointing to map cracking indicative of ASR.

Altus Dam was constructed between 1941 and 1945. The lean interior concrete contained 30 percent pumicite from approximately 20 miles from the dam site to control temperature and provide cost savings on cement. A rich cement mix was used on the exterior 3-feet of the main dam to provide greater resistance to deterioration. Two core runs through the depth of the structure were taken from the crest for compression and direct tension testing in 2003, and it was noted that "no apparent degradation is shown from these tests" [20].

Davis Dam was constructed between 1942 and 1950. Preliminary aggregate studies noted that some rock types may be susceptible to ASR, prompting the use of a low-alkali cement and pozzolan to mitigate future deterioration. The cement came from four suppliers, and most shipments reported a total alkali content less than 0.60 percent. The concrete contains a calcined shale from the Colton Mill of the California Portland Cement Company. The pozzolan content varied depending on the application of the concrete. Shortly after construction was completed, there was some crazing and cracking on the surface of concrete near the left abutment that was attributed to the hot, arid climate [21]. There are no other records of cores extracted and analyzed from Davis Dam, and according to the most recent 2014 CFR, there is no serious concrete deterioration [22].

Bradbury (originally named Cachuma) Dam was constructed from 1950 to 1953. It is a zoned, rolled earthfill structure with a concrete spillway chute and stilling basin. Calcined shale pozzolan was purchased from the Airox Company in Los Angeles. The pozzolan was produced from a deposit near Casmalia, CA. Initial trial batches produced concrete with low strength and a poor aggregate to paste bond. The pozzolan was ground finer and the strength of the concrete increased "appreciably" [23]. There are no records of cores extracted and analyzed from Bradbury Dam spillway or other appurtenances. In the early 2000s, dam safety modifications were made to the spillway crest structure walls and piers. The most recent 2015 CFR did not note any serious concrete deterioration [24], but a 2019 inspection report describes cracking and small aggregate popouts on the spillway chute slabs in the original portion from the 1950s. Several locations had exposed reinforcing steel as seen in Figure 4. The authors recommended a petrographic examination to confirm presence of ASR [25].

Figure 4. Typical cracking and deterioration along spillway chute at Bradbury Dam.

Trenton Dam was constructed between 1949 and 1953. All original concrete contained a blended cement containing Type II low-alkali cement and 25 percent calcined clay from Ash Grove Lime and Portland Cement Company from Louisville, Nebraska [26]. There are no records of cores extracted and analyzed from Trenton Dam spillway or other appurtenances. The most recent 2018 CFR did not note any serious concrete deterioration, although it did report some deterioration on the floor of the spillway chute, typically near corners of panels where spalling has occurred [27].

Monticello Dam was constructed between 1953 and 1957. The pozzolan is a diatomaceous calcined clay produced by Basalt Rock Company in Napa, CA. The mass concrete in the main dam contained the pozzolan, but the spillway tunnel invert lining was a cement-only mix for increased resistance to abrasion. Ten-inch diameter cores were extracted six months after placement and tested seven months later resulting in a 13-month compressive strength of 4160 psi [28]. A petrographic examination indicated poor bond between the paste and aggregate due to voids around the aggregate [29]. Ten-inch cores were later taken in 1995 and had an average compressive strength of 4710 psi [30]. Additional ten-inch cores were taken in 1998 and had an average compressive strength of 4760 psi [31]. A petrographic examination was also performed because the ratio of tensile to compressive strength was low. The exam concluded that the concrete quality is considered satisfactory and appears to be moderately well consolidated with well distributed aggregate. No evidence of deterioration was observed, however there were pockets of excessive air voids [32]. The most recent 2019 CFR reports that the concrete is in good condition with no deterioration or performance issues noted [33].

Twichell Dam is an earthfill embankment dam with a concrete lined spillway constructed between 1955 and 1958. The concrete contains calcined shale. There are no records of cores extracted and analyzed from Twitchell Dam spillway or other appurtenances. The most recent CFR indicates that concrete surfaces of the inlet, tunnel, discharge portal, and sloping discharge chute are sound with no significant spalling or cracking observed. No significant signs of deterioration, spalling, cracking, or offsets were observed inside the outlet works tunnel. Minor cracks have been observed in the gate chamber concrete wall [34].

Flaming Gorge Dam was constructed between 1958 and 1964. The calcined shale was produced by Idealite Cement Company and used only in the interior mass of the dam due to concerns of freeze-thaw durability of concrete with the pozzolan [35]. Average interior mass concrete strength ranged from 3350 to 5420 psi from 1960 to the end of 1962 [36]. Cores were taken at 1, 3, 5, and 10 years age from both the exterior and interior mixes and results are summarized in Figure 5 [37, 38]. The most recent 2014 CFR reports that the interior concrete with pozzolan is in good condition, but there are areas of the spillway (concrete without pozzolan) that have suffered from freeze-thaw deterioration [39].

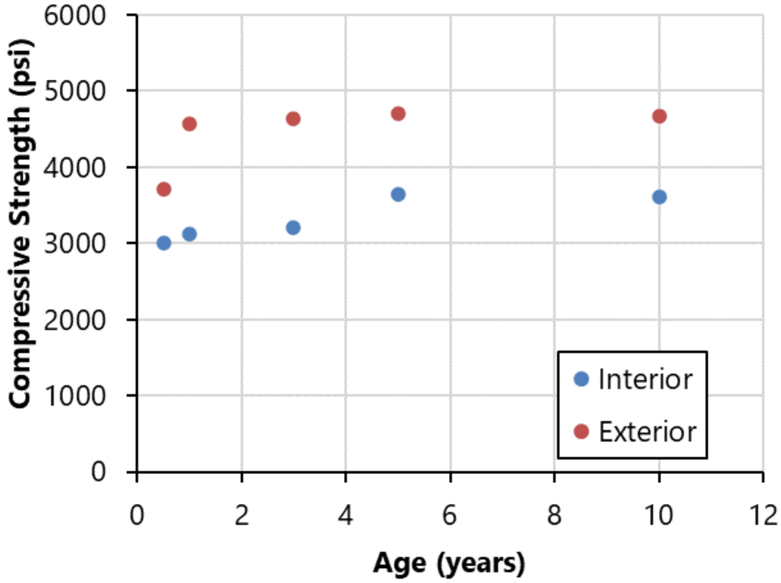

Figure 5. Average compressive strength of concrete cores from Flaming Gorge Dam.

Glen Canyon Dam was constructed between 1957 and 1964. The pozzolan plant was located about 30 miles north of Flagstaff, Arizona. Material from the Bonner deposit was used until it was depleted in 1962. When the Bonner deposit was nearly depleted, the nearby Sugar Loaf deposit was investigated and accepted for use. At times there were insufficient quantities of pumice delivered to the site so the concrete mix was adjusted to contain less pozzolan. There were two primary mass concrete mixtures, one for interior and one for exterior. Both mixtures contained pumice, but the exterior had a higher total cementitious content [40]. A 1984 petrographic examination concluded that the concrete was in good condition with no signs of aging in the interior concrete, but slight signs of aging due to carbonation in the exterior concrete. There were no signs of chemical attack or freeze thaw damage [41]. There was an extensive 20-year core report published in 1986. A summary of the compressive strength results are shown in Figure 6 [42]. According to the most recent CFR, the concrete in the dam has generally performed well. There was an area of spalling on the downstream face of the dam that was repaired in 2001 [43]. Samples taken from the spalled area were examined and there was evidence of minor to moderate deterioration due to carbonation near the exterior surface. There was also very minor deterioration due to ASR. The paste was considered well hydrated with only minor amounts of ettringite and no evidence of sulfate attack or freeze-thaw deterioration. The deterioration appeared to be mechanical and unrelated to concrete quality [44].

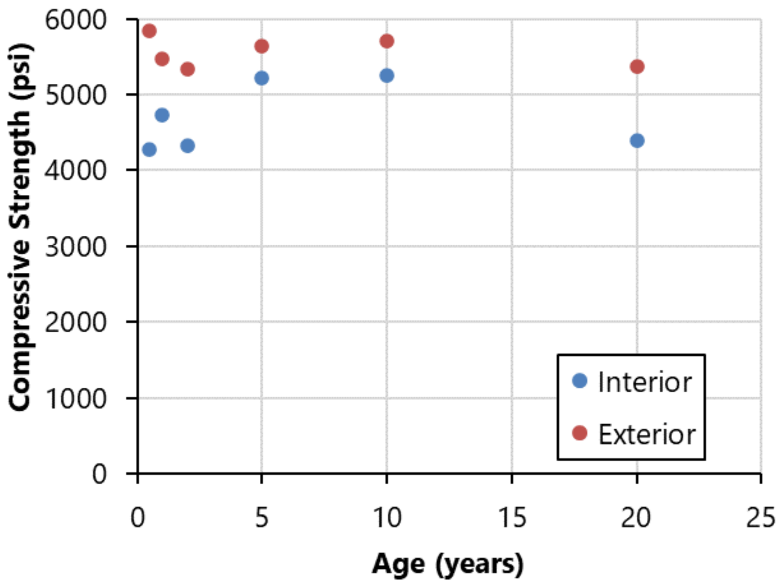

Figure 6. Average compressive strength of concrete cores from Glen Canyon Dam.

The most recent use of natural pozzolans in a Reclamation structure was for a dam safety modification to Stampede Dam near Truckee, CA from 2016 through 2018. The project included reconstructing the spillway crest structure to limit outflows during large floods. During construction, the contractor requested the use of a natural pozzolan due to the lack of Class F fly ash supply in the area. Reclamation performed additional lab testing on the local source of natural pozzolan to determine if it would have similar temperature rise properties as Class F fly ash due to some of the placements being mass concrete. Testing indicated that temperature rise was comparable to concrete mixes with Class F fly ash so the use of the natural pozzolan was approved. The local ready mixed concrete producer selected a commercially available rhyolitic glass from Nevada Cement Company to replace 25 percent of cement in all mixtures. The new structure has been in service for approximately three years with no reported issues or degradation.

Current Trends in the Natural Pozzolan Market

SCMs, including fly ash, slag, and natural pozzolans, are frequently used in concrete to improve workability, increase resistance to sulfate attack or ASR, and decrease cost.

Fly ash and slag are "artificial pozzolans" and are considered industrial waste products. Federal projects require the use of recovered materials for new construction, and fly ash satisfies that requirement [45]. For decades, fly ash was an extremely cost-effective material with a surplus of supply as seen in Figure 7. The more recent lower supply can be attributed to changes in power production. Coal plants are retiring and being replaced by wind and solar as seen as Figure 8.

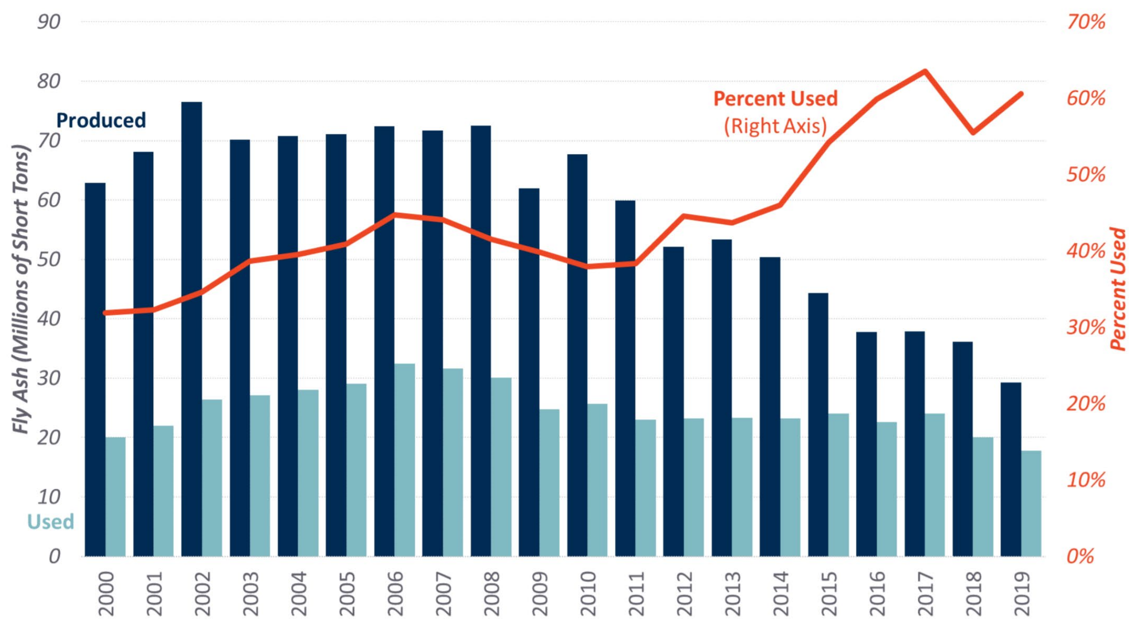

Figure 7. Fly ash production and use. American Coal Ash Association [46]

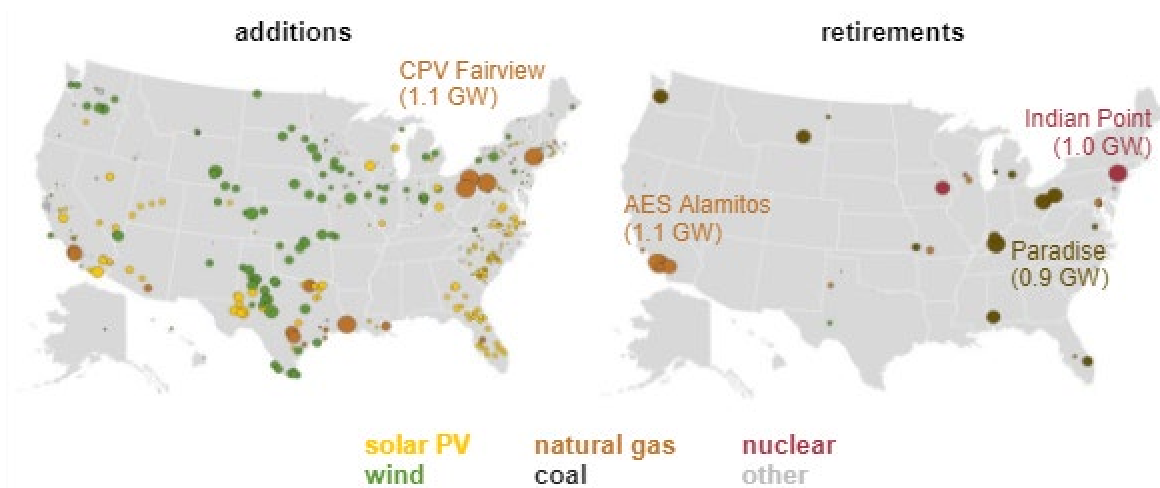

Figure 8. US electric capacity additions and retirements, 2020. US Energy Information Administration [47]

There is still a need to include SCMs in concrete as many state and federal concrete specifications require them for ASR mitigation, temperature rise mitigation in mass concrete, or other benefits to ensure a long service life. Some concrete suppliers are beginning to rely more on natural pozzolans. According to the Natural Pozzolan Association, there are natural pozzolan suppliers in eleven states, primarily in the West, with a few in the Southeast as seen in Figure 9.

The increasing need for an alternative to fly ash has spurred the development of new test methods and specifications for evaluating alternative pozzolans. It is possible to obtain false positive results for some materials using ASTM C618 specifications [48]. ASTM C1897-20 is a new test method to assess the chemical reactivity of an SCM by either measuring the cumulative heat release or bound water content of hydrated pastes composed of the SCM, calcium hydroxide, calcium carbonate, potassium sulfate, and potassium hydroxide [49].

Figure 9. Current and future sites of commercially available natural pozzolans [50]

Proposed Fiscal Year 2022 Coring Plan

The proposed FY2022 coring plan focuses on concrete containing calcined shale. It is the most frequently used natural pozzolan in Reclamation structures and calcined shales are found throughout the US which makes the results of the analysis applicable to several regions outside of Reclamation's purview. Reasonably complete records of materials used during construction and final concrete proportions have been located for the proposed coring sites. The proposed sites range in exposure condition, from interior mass concrete to damaged concrete in a spillway invert.

Several samples of varying diameter and depth will be collected from at least three of the proposed sites. The cores will be analyzed using several methods to assess the condition of the concrete after 70 or more years in service. Larger diameter (6-inch) cores will be tested for compressive strength, modulus of elasticity, and poisson's ratio. Smaller cores will be collected for chemical analysis using x-ray diffraction (XRD) as well as chemical mapping using x-ray fluorescence (XRF). XRD analysis uses a powdered sample obtained from the core to identify phases in the hydrated paste. This information can help assess what type of deterioration the concrete may be experiencing. For example, if the concrete is undergoing sulfate attack, the XRF analysis may show the presence thaumasite and less portlandite than a normally hydrated concrete may exhibit. Micro XRF can be used to see the distribution of various elements along a cross section of the cores. For example, the amount of chloride ions can be mapped to see how deep the ions have penetrated. Other techniques may be utilized such as mercury intrusion porosimetry to analyze the pore size distribution.

Flaming Gorge Dam

Due to concerns of premature scaling and deterioration from the pozzolan, an exterior concrete mix containing only cement was used on the outer 5 to 10 feet. The straight-cement mixture was also used for the powerhouse, spillway, dam parapets, roadways and walkways. In order to obtain cores with natural pozzolan concrete, TSC personnel must drill about 15 feet into the main dam. Alternatively, shallow cores may be taken from inside the gallery.

Twitchell Dam

All concrete for the spillway tunnel contains calcined shale. According to previous CFRs, the concrete is all from original construction. It may be challenging to obtain cores from the tunnel lining or intake structure. It may be easier to obtain cores from the gate chamber or outlet works tunnel wall.

Davis Dam

Both interior and exterior mixtures for the main dam contain calcined shale. shallow cores can be taken. The mixture was designed to contain 17 to 20% pozzolan, but there are areas where excess pozzolan was inadvertently used which caused premature deterioration [20]. Areas of the dam with excess pozzolan include Blocks G-8 and G-10 of the left abutment wall, above the high-water line. The remainder of the dam was proportioned as designed. Shallow cores can be taken to provide the desired samples.

Bradbury Dam

While there have been modifications to the spillway crest and walls, original concrete containing calcined shale is found in the spillway chute, gate chamber, and control house. Additionally, the same source of calcined shale was used in the lining of the Tecolote Tunnel.

The concrete in the spillway chute has some deterioration ranging from minor surface cracking to exposed rebar while other portions of original concrete are in good condition. Cores would be easy to collect from this location and could possibly be collected in conjunction with minor repairs.

Summary

Natural pozzolans have been used in the United States for decades. With uncertainty surrounding the future supply of fly ash, there has been renewed interest in alternative pozzolans. Reclamation has used natural pozzolans in the past for several large projects with success. Quality natural pozzolans increase durability by mitigating expansion due to ASR and sulfate attack, refining the pore structure of the paste, and decreasing heat of hydration which can aid in mitigating cracking due to temperature gradients. Since fly ash dominated the market for decades, its ability to produce concrete with long term service life is well documented. Reclamation owns several facilities with different exposure conditions that have been in service for 70 or more years. There is opportunity to analyze cores and assess the long-term durability of concrete containing natural pozzolans.

References

[1] M. L. Wilson and S. H. Kosmatka, "Supplementary Cementitious Materials," in *Design and Control of Concrete Mixtures, 15th ed*, Skokie, IL, Portland Cement Association, 2011, pp. 58-72.

[2] ACI, "CT-20, Concrete Terminology," American Concrete Institute, Farmington Hills, MI, 2020.

[3] US Bureau of Mines, "Report No. 8421, Pozzolanic Raw Materials Resources in the Central and Western United States," US Department of the Interior, Washington, D.C., 1969.

[4] H. S. Meissner and W. T. Moran, "TM-500, Laboratory Procedure for Determining the Relative Cementitious Value of Pozzolanic Material," US Bureau of Reclamation, Denver, CO, 1935.

[5] E. J. Benton, W. Y. Holland and W. U. Gartska, "PET-128, Investigation of the Correlation of Minerology ofPozzolans with Performance in Concrete," US Bureau of Reclamation, Denver, CO, 1961.

[6] R. C. Meilenz, K. T. Greene and N. C. Schieltz, "Natural Pozzolans for Concrete," *Economic Geology,* vol. 46, no. 3, pp. 311-328, 1951.

[7] S. V. Failor, "C-956, Laboratory Investigations of a Type I Cement, Pumicite, and Portland-Pozzolan Cement Produced to Better the Efficiency of Controlling the Alkali-Aggregate Reaction in Concrete," US Bureau of Reclamation, Denver, CO, 1960.

[8] "C-1047, Investigation of Specification Low-Alkali Cement and Opaline Pozzolans for Controlling Reactive Expansion of Concrete Containing Reactive Aggregates," US Bureau of Reclamation, Denver, CO, 1963.

[9] H. L. Flack, "Five Year Progress Report on Investigation of the Durability of Concretes with Different Types and Percentages of Pozzolans," Concrete Laboratory Report No. C-989, Bureau of Reclamation, Denver, CO, 1961.

[10] W. Y. Holland, E. J. Benton, E. M. Hunter and S. Failor, "PET-123, Summary of Results of a Study of the Alklai Release from Various Combinations of Pozzolans with Hydrated Lime Versus the Expansion Due to the Alklai-Aggregate Reaction in Pyrex Mortar," US Bureau of Reclamation, Denver, CO, 1959.

[11] W. F. Harris, "C-1019, Effect of Various Pozzolanic Replacements and Crushed Aggregate Addition on Resistance of Concrete to Freezing-Thawing Action - Yellowtail Dam," US Bureau of Reclamation, Denver, CO, 1962.

[12] G. O. Biggs, "C-1178, Some Factors Influencing Durability of Concrete - Flaming Gorge Dam," US Bureau of Reclamation, Denver, CO, 1966.

[13] US Bureau of Reclamation, "Final Concrete Report - Davis Dam," 1952.

[14] ACI Committee 232, "ACI 232.1R-12, Report on the Use of Raw or Processed Natural Pozzolans in Concrete," in *ACI Collection*, Farmington Hills, MI, American Concrete Institute, 2012.

[15] B. Tremper, "Further Studies on Alkalis in Cement and Their Effect on Aggregates and Concrete," in *American Association of State Highway Officials*, 1941.

[16] T. E. Stanton, "Influence of cement and aggregate on concrete expansion," *Engineering News-Record,* vol. 124, pp. 171-173, 1940.

[17] "CE-301, Test Results of 6-inch DiameterConcrete Cores Drilled from Friant Dam," US Bureau of Reclamation, Denver, CO, 1946.

[18] J. N. Hartwell, "R-90-05, Alkali-Aggregate Reaction Investigatoins at Friant Dam," US Bureau of Reclamation, Denver, CO, 1990.

[19] J. N. Hartwell, "PET-88-27, Petrographic and Afterbreak Examinations of Concrete Core - Friant Dam," US Bureau of Reclamation, Denver, CO, 1988.

[20] D. W. Harris, "Laboratory Evaluation of Concrete Cores - Altus Dam," US Bureau of Reclamation, Denver, CO, 2004.

[21] E. L. Ore, "C-505, Investigations of Crazing, Cracking, and Excess Pozzolan in Concrete - Davis Dam," US Bureau of Reclamation, Denver, CO, 1950.

[22] "Comprehensive Facility Review - Davis Dam," Technical Service Center, US Bureau of Reclamation, Denver, CO, 2014.

[23] US Bureau of Reclamation, "Concrete Control," in *Technical Record of Design and Construction - Cachuma Dam*, Denver, CO, 1959, pp. 122-129.

[24] "Comprehensive Facility Review - Bradbury Dam," Technical Service Center, US Bureau of Reclamation, Denver, CO, 2015.

[25] W. T. Joy, "8530-2019-05, Bradbury Dam Spillway Concrete Damage Inspection," Technical Service Center, US Bureau of Reclamation, Denver, CO, 2019.

[26] US Bureau of Reclamation, Technical Record of Design and Construction - Trenton Dam, Denver, CO, 1966.

[27] "Comprehensive Facility Review - Trenton Dam," Technical Service Center, US Bureau of Reclamation, Denver, CO, 2018.

[28] US Bureau of Reclamation, "Construction," in *Technical Record of Design and Construction - Monticello Dam*, Denver, CO, 1959, pp. 86-111.

[29] "PET-58-24," US Bureau of Reclamation, Denver, CO, 1958.

[30] T. P. Dolen, "Monticello Dam Core Testing Program," US Bureau of Reclamation, Denver, CO, 1996.

[31] D. W. Harris, "Summary of Material Characteristics - Monticello Dam Core Testing Program," US Bureau of Reclamation, Denver, CO, 1998.

[32] D. R. Hurcomb, "PET-98-22, Cursory Petrographic Examination of Concrete Core - Monticello Dam," US Bureau of Reclamation, Denver, CO, 1998.

[33] "Comprehensive Facility Review - Monticello Dam," Technical Service Center, US Bureau of Reclamation, Denver, CO, 2019.

[34] "Comprehensive Facility Review - Twitchell Dam," Technical Service Center, US Bureau of Reclamation, Denver, CO, 2012.

[35] US Bureau of Reclamation, "Summary of Freeze-Thaw Durability Data for Concrete With and Without Idealite Pozzolan - Flaming Gorge Dam," Denver, CO.

[36] US Bureau of Reclamation, "Concrete," in *Technical Record of Design and Construction - Flaming Gorge Dam*, Denver, CO, 1968, pp. 324-344.

[37] H. C. Rifle, "GR-13-76, Strength and Elastic Properties of Concrete in Flaming Gorge Dam, 10-Year Core Report," US Bureau of Reclamation, Denver, CO, 1976.

[38] T. P. Dolen, "DSO-05-05, Materials Properties Model of Aging Concrete," Dam Safety Technology Development, Bureau of Reclamation, Denver, CO, 2005.

[39] "Comprehensive Facility Review - Flaming Gorge Dam," Technical Service Center, US Bureau of Reclamation, Denver, CO, 2014.

[40] US Bureau of Reclamation, "Concrete Production and Placement," in *Technical Record of Design and Construction - Glen Canyon Dam and Powerplant*, Denver, CO, 1970, pp. 424-446.

[41] C. Bechtold, "PET-84-26, Petrographic Examination of Concrete Core - Glen Canyon Dam," US Bureau of Reclamation, Denver, CO, 1984.

[42] E. Harboe, "GR-85-12, Properties of Concrete in Glen Canyon Dam, 20-Year Core Report," US Bureau of Reclamation, Denver, CO, 1986.

[43] "Comprehensive Facility Review - Glen Canyon Dam," Technical Service Center, US Bureau of Reclamation, Denver, CO, 2017.

[44] D. R. Hurcomb, "PET-00-04, Petrographic Examination of Concrete Core - Glen Canyon Dam," US Bureau of Reclamation, Denver, CO, 2000.

[45] Environmental Protection Agency, "Comprehensive Procurement Guideline (CPG) Program," [Online]. Available: https://www.epa.gov/smm/comprehensive-procurement-guideline-cpg-program.

[46] American Coal Ash Association, "Coal Combustion Products Production & Use Reports," 2021. [Online]. Available: https://acaa-usa.org/wp-content/uploads/coal-combustion-products-use/2019-Charts.pdf. [Accessed 30 June 2021].

[47] US Energy Information Administration, "New electric generating capacity in 2020 will come primarily from wind and solar," 14 January 2020. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=42495. [Accessed 30 June 2021].

[48] R. D. Kalina, S. Al-Shmaisani, R. D. Ferron and M. C. G. Juenger, "False Positives in ASTM C618 Specifications for Natural Pozzolans," *ACI Materials Journal ,* vol. 116, no. 1, pp. 166-172, 2019.

[49] ASTM International, "ASTM C1897-20, Standard Test Methods for Measuring the Reactivity of Supplementary Cementitious Materials by Isothermal Calorimetry and Bound Water Measurements," West Conshohocken, PA, 2020.

[50] J. Thomas, "Ash an Expert...A Prelude to Alternative SCMs," in *Colorado Ready Mixed Concrete Association Webinar*, 2021.

Appendix A

Potential Sources of Natural Pozzolans 1940-1970

USBR Designation	Petrographic Classification	State	Activity Type	Petrographic Description
A-858	Rhyolite Pumice	Alaska	1	Light-gray, friable, fine. Composed of glass (N=1.490) (75 to 80 percent), and essentially inert minerals (20 to 25 percent), chiefly feldspars with some quartz, epidote, amphiboles, and pyroxenes
9126-1	Rhyolite Pumicite	Oregon	1	Light-gray, loose to pulverulent, exceedingly fine grained. Composed of glass (N=1.503) (95 percent), quartz, and sanidine (5 percent)
M-2540	Pumice	Idaho	1	Volcanic glass, rhyolitic, about 90-95 percent. Quartz, feldspars, 5-10 percent
M-2681	Volcanic Ash	Utah	1	Volcanic Glass (index about 1.495) about 95 percent. Feldspars, quartz, and micas about 5 percent. Traces of amphiboles and miscellaneous minerals
M-2858	Volcanic Ash	Utah	1	Volcanic Glass (index about 1.495) about 95 percent. Feldspars, quartz, and micas about 5 percent. Traces of amphiboles and miscellaneous minerals
M-2858F	Volcanic Ash	Utah	1	Ground finer. Volcanic Glass (index about 1.495) about 95 percent. Feldspars, quartz, and micas about 5 percent. Traces of amphiboles and miscellaneous minerals
M-2861	Pumicite	Utah	1	Volcanic glass (index about 1.51) over 90 percent. Quartz, feldspar, calcite, and miscellaneous minerals less than 10 percent
M-2861F	Pumicite	Utah	1	Ground finer. Volcanic glass (index about 1.51) over 90 percent. Quartz, feldspar, calcite, and miscellaneous minerals less than 10 percent
M-2718	Pumice	Utah	1	Volcanic Glass (index about 1.495) about 95 percent. Feldspars and quartz about 5 percent. Traces of miscellaneous minerals
M-2883	Pumice	Utah	1	Volcanic Glass (index about 1.495) approximately 90 percent. Feldspars, quartz, micas and miscellaneous rock and mineral fragments nearly 10 percent

USBR Designation	Petrographic Classification	State	Activity Type	Petrographic Description
M-2883F	Pumice	Utah	1	Ground finer. Volcanic Glass (index about 1.495) approximately 90 percent. Feldspars, quartz, micas and miscellaneous rock and mineral fragments nearly 10 percent
M-2677	Rhyolitic Volcanic Ash	Nevada	1	Volcanic glass (index about 1.50) about 94 percent. Calcium carbonate, feldspars, and quartz about 6 percent
M-2677F	Rhyolitic Volcanic Ash	Nevada	1	Ground finer. Volcanic glass (index about 1.50) about 94 percent. Calcium carbonate, feldspars, and quartz about 6 percent
M-2677F1	Rhyolitic Volcanic Ash	Nevada	1	Ground finer. Volcanic glass (index about 1.50) about 94 percent. Calcium carbonate, feldspars, and quartz about 6 percent
M-2835	Rhyolitic Volcanic Ash	Nevada	1	Volcanic glass (index about 1.50) about 94 percent. Calcium carbonate, feldspars, and quartz about 6 percent
M-2835F	Rhyolitic Volcanic Ash	Nevada	1	Ground finer. Volcanic glass (index about 1.50) about 94 percent. Calcium carbonate, feldspars, and quartz about 6 percent
M-2835C	Rhyolitic Volcanic Ash	Nevada	1	Ground finer and calcined at 1400F for 30 minutes with muffle furnace closed
M-2835C1	Rhyolitic Volcanic Ash	Nevada	1	Ground finer and calcined at 1400F for 1 hour with muffle furnace close
M-2835C2	Rhyolitic Volcanic Ash	Nevada	1	Ground finer and calcined at 1400F for 2 hours with muffle furnace closed
M-3078	Pumice	Utah	1	Rhyolitic volcanic glass about 95 percent. Quartz, feldspars about 5 percent
M-2942	Pumice	Arizona	1	Volcanic glass (index about 1.50) over 90 percent. Small amounts of feldspar, mica, hornblende, quartz, and miscellaneous minerals
M-2942F	Pumice	Arizona	1	Ground Finer. Volcanic glass (index about 1.50) over 90 percent. Small amounts of feldspar, mica, hornblende, quartz, and miscellaneous minerals
M-2909	Rhyolitic Volcanic Ash	Arizona	1	Volcanic glass (index about 1.495) about 95 percent. Small proportions of feldspars, quartz and miscellaneous minerals
M-2909F	Rhyolitic Volcanic Ash	Arizona	1	Ground Finer. Volcanic glass (index about 1.495) about 95 percent. Small proportions of feldspars, quartz and miscellaneous minerals

USBR Designation	Petrographic Classification	State	Activity Type	Petrographic Description
M-2625	Rhyolitic Volcanic Ash	Utah	1	Volcanic glass (index about 1.50) about 95 percent. Feldspars, quartz, calcium carbonate and miscellaneous rock and mineral fragments about 5 percent
M-2690	Rhyolitic Volcanic Ash	Arizona	1	Volcanic glass (index about 1.495) about 95 percent. Small proportions of feldspars, quartz and miscellaneous minerals
M-2748	Pumicite	Utah	1	Volcanic glass (index about 1.50) almost 100 percent
M-3036	Rhyolitic Pumicite	Utah	1	Volcanic glass (index about 1.50) about 90 percent. Feldspars, quartz and miscellaneous materials about 10 percent
M-3036F	Rhyolitic Pumicite	Utah	1	Ground Finer. Volcanic glass (index about 1.50) about 90 percent. Feldspars, quartz and miscellaneous materials about 10 percent
M-3069	Pumice	Arizona	1	Rhyolitic volcanic glass about 50-60 percent. Remainder comprised of amphiboles, quartz, feldspars and mica
M-3069F	Pumice	Arizona	1	Ground Finer. Rhyolitic volcanic glass about 50-60 percent. Remainder comprised of amphiboles, quartz, feldspars and mica
M-3074	Perlite	Colorado	1	Rhyolitic volcanic glass about 85 percent. Remainer comprised of feldspars, quartz and mica
M-3074F	Perlite	Colorado	1	Ground Finer. Rhyolitic volcanic glass about 85 percent. Remainer comprised of feldspars, quartz and mica
M-2961	Pumice	Utah	1	Volcanic glass (index about 1.50) about 95 percent. Feldspars, quartz and calcite about 5 percent
M-2961F	Pumice	Utah	1	Ground finer. Volcanic glass (index about 1.50) about 95 percent. Feldspars, quartz and calcite about 5 percent
M-3075	Perlite	New Mexico	1	Rhyolitic volcanic glass, about 90 percent. Mostly feldspar the remaining 10 percent
M-3075F	Perlite	New Mexico	1	Ground finer. Rhyolitic volcanic glass, about 90 percent. Mostly feldspar the remaining 10 percent
M-3070	Pumice	Utah	1	Altered rhyolitic volcanic glass, some montmorillonite clay about 60 to 70 percent. Quartz, feldspar, calcite, about 30 to 40 percent
M-3070F	Pumice	Utah	1	Ground finer. Altered rhyolitic volcanic glass, some montmorillonite clay about 60 to 70 percent. Quartz, feldspar, calcite, about 30 to 40 percent

USBR Designation	Petrographic Classification	State	Activity Type	Petrographic Description
M-3175	Volcanic Ash	Arizona	1	Primarily volcanic glass (index about 1.505), small amounts of pumice fragments, vesicular, dark gray, glass volcanic rock, feldspar, quartz, and amphibole
M-2719	Rhyolite Tuff	Utah	1	Somewhat altered volcanic glass (index about 1.50) about 80 percent. Small amount of montmorillonite type clay. About 20 percent feldspars, quartz, mica, and calcite
M-2896	Volcanic Ash	Utah	1	Consists essentially of slightly altered glass (index about 1.50). Small amounts of feldspars, quartz, and miscellaneous minerals.
M-2662	Rhyolitic Volcanic Ash	Arizona	1	Volcanic glass (index about 1.50) about 95 percent. Quartz and feldspars about 5 percent
M-2651	Rhyolite Tuff	Utah	1	Volcanic glass (index about 1.495) about 85 percent. Quartz, feldspars and small proportions of micas, hornblende, magnetite and miscellaneous minerals about 15 percent
M-2720	Rhyolite Tuff	Utah	1	Volcanic glass (index about 1.51) somewhat altered possible 55 percent. Montmorillonite type clay possibly 30 percent. Micas, feldspars, quartz, calcite and miscellaneous minerals about 15 percent
M-2894	Pumice	California	1	Consists essentially of volcanic glass (index about 1.50). Very small amounts of feldspars, quartz, and miscellaneous minerals
M-2663	Rhyolitic Volcanic Ash	Arizona	1	Volcanic glass (index about 1.50) about 93 percent. Traces of clay. Feldspar and quartz about 7 percent. Traces of amphiboles, micas and miscellaneous minerals
M-2717	Rhyolite Tuff		1	Volcanic glass (index about 1.50) over 95 percent. Quartz, feldspars, hornblende and miscellaneous minerals less and 5 percent
M-2661	Rhyolitic Volcanic Ash	Arizona	1	Volcanic glass (index about1.50) about 85 percent. Traces of clay. Feldspars and quartz about 15 percent. Very small amounts of Amphiboles, zircon, calcite and miscellaneous minerals
M-2655	Rhyolitic Volcanic Ash	Arizona	1	Composed essentially of volcanic glass (index about 1.50) partly altered to montmorillonite-type clay. Small proportions of miscellaneous minerals

USBR Designation	Petrographic Classification	State	Activity Type	Petrographic Description
M-2856	Volcanic Tuff	Utah	1	Predominantly volcanic glass (index about 1.51) intermixed with a zeolite mineral similar to heulandite. Moderate amount of quartz and plagioclase feldspars. Very small amounts of hornblende and micas
P-25	Rhyolite Pumicite	California	1	Very fine, white, loose, 77 percent glass (n=1.497) slight alteration. Trace opal
P-44	Rhyolite Pumicite	California	1	Fine, white, pumiceous. 80 percent glass(n=1.507). About 5 percent montmorillonite-type clay. Calcite, quartz, feldspars, etc 15 percent
P-46	Rhyolite Pumicite	Washington	1	Light gray, pulverulent, laminated. 65 percent glass (n=1.500). No alteration. Remainder comprises quartz, feldspars, etc.
9282-1	Opaline Rhyolite Pumicite	Montana	1, 2, 3b	Light-gray, firm, massive, fine grained. Composed of glass (N=1.500) (45 percent); opal (25 percent); montmorillonite- type clay (20 percent); quartz, feldspars, and biotite (10 percent)
P-49	Altered Basalt Tuff	Washington	1, 2, 3b	Coarse, buff, friable. Fragments of tachylite (n=1.580) constituting 75 percent of tuff, are imbedded in palagonite, opal, nontrite, and saponite
8838	Altered Rhyolite Tuff	Colorado	1, 3b	White, hard, massive, porous, very fine grained. Composed of glass (N=1.496) (40 to 50 percent), montmorillonite- type clay (50 percent), calcite (5 to 10 percent)
A-788	Altered Rhyolite Tuff	Texas	1, 3c	White to buff, friable, massive. Composed of glass (N=1.503) (20 percent); opal (10 percent); montmorillonite -type clay (10 percent); illite (40 percent); quartz, feldspars, carbonates, and miscellaneous minerals (20 percent)
8501	Opaline Shale	California	2	Gray, buff, and white; hard and porcelaneous to shaly. Composed of opal (70 percent); beidellite (10 percent); calcite (2 percent); and sand and silt-sized quartz (10 percent); and feldspars (5 percent); miscellaneous silt (3 percent)

USBR Designation	Petrographic Classification	State	Activity Type	Petrographic Description
P-2026	Opal	Washington	2	White to cream, hard, laminated, opal (N=1.430) inseparably admixed with beta- cristobalite (98 percent), quartz and chalcedony (2 percent)
M-2687	Diatomite	Utah	2	Opaline diatom fragments almost 90 percent. Quartz, feldspar and calcite about 10 percent
M-2687C1	Calcined Diatomite	Utah	2	Calcined with muffle furnace closed at 1400F for 4 hours
M-2676	Diatomaceous Earth	Nevada	2	Opaline diatom fragments about 70 percent. Quartz, feldspars and small amounts of miscellaneous minerals such as micas, hornblende and zircon about 30 percent
M-2679	Diatomaceous Earth	Utah	2	Opaline diatom fragments about 80 percent. Very small amount of montmorillonite-type clay. Quartz and feldspars almost 15 percent. Mica and illite about 5 percent
M-2680	Diatomaceous Earth	Utah	2	Opaline diatoms about 75 percent. Traces of clay. Quartz, feldspars and calcite almost 25 percent. Small amounts of micas, hornblende and miscellaneous minerals
M-3027C	Calcined Diatomaceous Earth	Arizona	2	Opaline diatom fragments about 50 percent. Calcite and quartz about 15 percent each, feldspars and micas about 10 percent each. Calcined with muffle furnace closed at 1600F for 3 hours
M-3176	Diatomite	Nevada	2	Almost entirely opaline silica
P-26	Diatomite	Washington	2	White, pulverulent, massive. Composed of broken opaline tests of diatoms 95 percent. Illite-type clay 5 percent. Trace of silt
P-51	Diatomite	Washington	2	Very fine, white, pulverulent, massive 95 percent opaline tests of diatoms. 5 percent clay
8383-2	Opaline Rhyolite Tuff	Montana	2, 3a	White, friable, granular, massive, Composed of opal (50 percent); anauxite (40 to 45 percent); montmorillonite (5 percent); quartz, feldspars, and biotite (1 to 2 percent)
7926	Raw Opaline Shale	California	2, 3b	Buff to white, soft and shaly to hard and porcelaneous, laminated. Composed of opal (25 percent); beidellite with alpha-cristobalite (35 percent); calcite and dolomite (22 percent); quartz (6 percent); feldspars (10 percent); miscellaneous silt (2 percent)

USBR Designation	**Petrographic Classification**	**State**	**Activity Type**	**Petrographic Description**
7926C	Calcined Opaline Shale	California	2, 3b	Calcined at plant, 1500-1700F. Buff to white, soft and shaly to hard and porcelaneous, laminated. Composed of opal (25 percent), beidellite with alpha-cristobalite (35 percent), calcite and dolomite (22 percent), quartz (6 percent), feldspars (10 percent), miscellaneous silt (2 percent)
P-74	Opaline Shale	California	2, 3b	Gray and buff, hard, finely porous and highly absorptive. Composed of opal (35 to 40 percent), beidellite (10 to 15 percent), calcite (5 percent), and sand and silt sized quartz (20 percent), feldspars (20 percent) and miscellaneous minerals (5 percent)
M-2537	Oil-Impregnated Shale	California	3	Calcined clay, about 80 percent and trace of opal. About 20 percent quartz and feldspar
M-2626	Calcined Shale	California	3	About 50 percent calcined clay, remainder quartz and feldspar
M-2529	Diatomaceous Clay	California	3	Clay, calcined by producer. Quartz and feldspar about 15 percent
None	Kaolin Clay	Florida	3a	Received in pulverized condition. Composed of kaolinite 96 percent and quartz 4 percent
9444	Kaolin Clay	South Carolina	3a	Received in pulverized condition. Composed of kaolinite (99 percent) and quartz (1 percent)
A-471	Siliceous Shale	Wyoming	3b	Gray, hard, laminated, fine grained. Composed of montmorillonite-type clay (55 percent); quartz (35 percent); feldspars (5 percent); carbonates and miscellaneous minerals (5 percent)
9126-3	Altered Rhyolite Pumicite	Oregon	3b	Reddish-brown, fine grained. Composed of montmorillonite- type clay (65 percent), opal (5 percent), and feldspars, quartz, and other essentially inert minerals (25 to 30 percent)
M-2653	Bentonite Clay	Arizona	3b	Composed predominantly of a sodium type of montmorillonite clay. Quartz about 10 percent. Small proportions of miscellaneous minerals
M-2653C1	Calcined Bentonite Clay	Arizona	3b	Calcined with muffle furnace closed at 1400F for 4 hours
M-2653C2	Calcined Bentonite Clay	Arizona	3b	Calcined with muffle furnace closed at 1600F for 4 hours

USBR Designation	Petrographic Classification	State	Activity Type	Petrographic Description
M-2654	Bentonite Clay	Utah	3b	Composed predominantly of a sodium type of montmorillonite clay and a very small proportion of kaolinite-type clay. Barite in moderate amount, quartz iron oxides and miscellaneous minerals about 10 percent
M-2654C1	Calcined Bentonite Clay	Utah	3b	Calcined with muffle furnace closed at 1400F for 4 hours
M-2654C2	Calcined Bentonite Clay	Utah	3b	Calcined with muffle furnace closed at 1600F for 4 hours
M-2834C	Calcined Bentonite Clay	Arizona	3b	Composed predominantly of a sodium type of montmorillonite and extremely small proportions of kaolinite. Small proportions of quartz and miscellaneous minerals. Calcined with muffle furnace closed at 1600F for 3 hours
M-2669C	Calcined Clay	Utah	3b	Predominantly a montmorillonite type of clay. Cristobalite possibly 20 percent. Quartz, feldspars and calcite about 15 percent. Miscellaneous silt about 5 percent. Calcined with muffle furnace closed at 1600F for 4 hours
P-54	Basalt	Washington	3b	Hard, fine grained, gray, vesicular. Composed of labradorite 40 percent, with interstitial palagonite and nontronite 55 percent. Dust-like megnetite 5 percent
9445	Clay	Utah	3b	White, pulverulent, laminated. Composed of calcium-beidellite with alpha-cristobalite 80 percent. Calcite 5percent, quartz 5 percent, feldspars 5 percent, miscellaneous silt 5 percent
M-2828	Calcareous Shale	Utah	3c	Clays of mixed types containing principally illite and smaller proportions of kaolinite and possibly montmorillonite constitutes over half of the sample

USBR Designation	Petrographic Classification	State	Activity Type	Petrographic Description
M-2828C1	Calcined Calcareous Shale	Utah	3c	Calcined with muffle furnace closed at 1600F for 3 hours. At 1600° F the X-ray patterns of the oxidized and unoxidized materials are almost identical. Melilite, a complex silicate of calcium and aluminum with smaller amounts of magnesium and iron appears, and also a small amount of anorthite feldspar . Illite, calcite, kaolinite, and lime are absent and the quartz remains unchanged
M-2828C2	Calcined Calcareous Shale	Utah	3c	Calcined with muffle furnace closed at 1800F for 3 hours. At 1800° F, the oxidized sample shows a weakening of the melilite pattern, a slight increase in strength of the anorthite feldspar and a new phase, a pyroxene similar to augite, but low in iron content appears. In the unoxidized sample, the melilite phase continues to strengthen and a small amount of anorthite feldspar is formed. Quartz remains unchanged in both the oxidized and unoxidized material
M-2828C3	Calcined Calcareous Shale	Utah	3c	Calcined with muffle furnace closed at 2000F for 3 hours. At 2000° F, the melilite phase has disappeared from the oxidized sample, and the pyroxene and anorthite constituents increase in quantity, quartz remaining unchanged. The melilite in the unoxidized sample has begun to disappear, and the pyroxene and anorthite show an increase in strength, the quartz remaining as before
M-2907C1	Calcined Calcareous Shale	Utah	3c	Clays of mixed type containing principally illite and smaller proportions of kaolinite and possibly montmorillonite constitutes over half of the sample. Calcium carbonate about 25 percent. Smaller proportions of quartz and iron sulfide. Calcined with muffle furnace open at 1600F for 4 hours

USBR Designation	Petrographic Classification	State	Activity Type	Petrographic Description
M-2907C2	Calcined Calcareous Shale	Utah	3c	Clays of mixed type containing principally illite and smaller proportions of kaolinite and possibly montmorillonite constitutes over half of the sample. Calcium carbonate about 25 percent. Smaller proportions of quartz and iron sulfide. Calcined with muffle furnace closed at 1800F for 3 hours
M-2904	Shale	Wyoming	3d	About half of the sample is montmorillonite-type clay. Also, small amounts of kaolinite and illite clay. Moderately large proportion of quartz and a moderately small proportion of feldspars
M-2908C	Calcined Shale	Wyoming	3d	About half of the sample is montmorillonite-type clay. Also, small amounts of kaolinite and illite clay. Moderately large proportion of quartz and a moderately small proportion of feldspars. Calcined with muffle furnace closed at 1600F for 4 hours
M-3004	Shale	Wyoming	3d	About half of the sample is montmorillonite-type clay. Also, small amounts of kaolinite and illite clay. Moderately large proportion of quartz and a moderately small proportion of feldspars
P-53	Clayey Silt	Washington	3d	Gray, soft, massive, absorptive, porous. Composed of beidellite-nontronite 10 percent. Vermiculite 25 percent, illite 5 percent, kaolinite 5 percent, muscovite 20 percent, quartz 10 percent, feldspars 2 percent, and calcite 23 percent
P-180	Altered Rhyolite Tuff	California	4	White to mottled, firm, compact, massive. Composed of clinoptilolite (10 percent), beidellite (1.5 percent), crystals and rock fragments (5 percent)

Appendix B

Chemical and Physical Properties of Potential Sources of Natural Pozzolans

USBR Designation	**Petrographic Classification**	**SiO_2 + Al_2O_3 + Fe_2O_3**	**MgO**	**Equivalent Alkalis (Na_2O + $0.658K_2O$)**	**LOI**	**SO_3**	**Blaine Fineness (cm^2/g)**	**Specific Gravity**	**Reduction in Expansion (% from control at 14 days)**	**Water Requirement (% of control)**	**SAI (% of control at 28 days)**
A-858	Rhyolite Pumice								70		
9126-1	Rhyolite Pumicite								86		
M-2540	Pumice	87.5	0.01	1.4	3.6	0.01	6845	2.36	78	101	99
M-2681	Volcanic Ash	87.3	0.18	0.6	4.2	0.03	4440	2.34	74	102	82
M-2858	Volcanic Ash	87.2	0.30	1.3	4.2	0.02	7059	2.37	82	101	94
M-2858F	Volcanic Ash	87.2	0.30	1.3	4.2	0.02	8018	2.43		99	97
M-2861	Pumicite	88.42	0.17	1.6	3.9	trace	4440	2.41	86	101	98
M-2861F	Pumicite	88.42	0.17	1.6	3.9	trace	9665	2.38	84	99	100
M-2718	Pumice	87.1	0.25		4.2	trace	6053	2.34	71	97	101
M-2883	Pumice	86.62	0.14	1.1	2.2	0.01	5088	2.41	59	101	85
M-2883F	Pumice	86.62	0.14	1.1	2.2	0.01	7383	2.44	72	97	98
M-2677	Rhyolitic Volcanic Ash	95.4	0.35		4.8	0.02	3542	2.34	75	102	78
M-2677F	Rhyolitic Volcanic Ash	95.4	0.35		4.8	0.02	4500	2.33	73	103	86
M-2677F1	Rhyolitic Volcanic Ash	95.4	0.35		4.8	0.02	5500	2.38	72	103	88
M-2835	Rhyolitic Volcanic Ash	82.4	0.61	1.1	6.1	0.01	4344	2.36	57	102	81
M-2835F	Rhyolitic Volcanic Ash	82.4	0.61	1.1	6.1	0.01	7704	2.39	69	101	102
M-2835C	Rhyolitic Volcanic Ash						4344	2.36	53	101	78
M-2835C1	Rhyolitic Volcanic Ash						4344	2.35	47	102	79
M-2835C2	Rhyolitic Volcanic Ash						4344	2.36	51	102	81
M-2835C3	Rhyolitic Volcanic Ash						4344	2.36	57	102	81
M-3078	Pumice	88.2	0.48	1.3	2.5	0.05	7018	2.34	69	102	87
M-2942	Pumice	86.24	0.21	1.26	5.05	0.04	7696	2.37	68	107	81

USBR Designation	Petrographic Classification	SiO_2 + Al_2O_3 + Fe_2O_3	MgO	Equivalent Alkalis (Na_2O + $0.658K_2O$)	LOI	SO_3	Blaine Fineness (cm^2/g)	Specific Gravity	Reduction in Expansion (% from control at 14 days)	Water Requirement (% of control)	SAI (% of control at 28 days)
M-2942F	Pumice	86.24	0.21	1.26	5.05	0.04	9403	2.38	76	107	89
M-2909	Rhyolitic Volcanic Ash	79.3	1.79	1.19	9.33	0.03	7651	2.31	61	105	71
M-2909F	Rhyolitic Volcanic Ash	79.3	1.79	1.19	9.33	0.03	8846	2.38	58	104	89
M-2625	Rhyolitic Volcanic Ash	80.7	0.60		7.63	0.30	4169	2.35	75	102	80
M-2690	Rhyolitic Volcanic Ash	85.6	0.65		5.68	trace	5907	2.34	69	101	83
M-2748	Pumicite	83.1	0.37		5.35	0.12	4317	2.34	64	103	80
M-3036	Rhyolitic Pumicite	86.8	0.33	1.04	4.9	0.09	5590	2.38	65	101	81
M-3036F	Rhyolitic Pumicite	86.8	0.33	1.04	4.9	0.09	7156	2.38	78	97	91
M-3069	Pumice	78.7	1.44	1.06	3.43	trace	5319	2.5	70	98	83
M-3069F	Pumice	78.7	1.44	1.06	3.43	trace	8055	2.5	69	98	96
M-3074	Perlite	87.3	0.25	1.16	2.61	trace	4113	2.37	68	98	74
M-3074F	Perlite	87.3	0.25	1.16	2.61	trace	7042	2.37	65	98	98
M-2961	Pumice	83.5	0.27	0.92	5.15	trace	3578	2.34	54	100	67
M-2961F	Pumice	83.5	0.27	0.92	5.15	trace	7324	2.35	81	95	94
M-3075	Perlite	78.3	0.30	1.18	2.49	0.10	4623	2.33	58	97	71
M-3075F	Perlite	78.3	0.30	1.18	2.49	0.10	8604	2.35	65	97	94
M-3070	Pumice	79.5	1.01	1.34	9.32	trace	5055	2.38	57	102	74
M-3070F	Pumice	79.5	1.01	1.34	9.32	trace	7992	2.47	54	99	92
M-3175	Volcanic Ash	80.7	1.02	1.57	3.59	0.16	7372	2.49	63	97	91
M-2719	Rhyolite Tuff	83.7	1.05		5.65	0.04	5907	2.46	53	107	86
M-2896	Volcanic Ash	85.9	0.59	1.67	5.62	0.11		2.33	71	103	80
M-2662	Rhyolitic Volcanic Ash	82.2	1.38	0.8	7.33	0.00	7634	2.31	48	106	84

USBR Designation	Petrographic Classification	SiO_2 + Al_2O_3 + Fe_2O_3	MgO	Equivalent Alkalis (Na_2O + $0.658K_2O$)	LOI	SO_3	Blaine Fineness (cm^2/g)	Specific Gravity	Reduction in Expansion (% from control at 14 days)	Water Requirement (% of control)	SAI (% of control at 28 days)
M-2651	Rhyolite Tuff	84.04	1.61		4.33	0.01	5824	2.43	41	102	76
M-2720	Rhyolite Tuff	82.1	1.68		6.74	0.02	6843	2.41	44	110	76
M-2894	Pumice	88.1	0.64		1.52	0.03		2.4	71	102	74
M-2663	Rhyolitic Volcanic Ash	84.2	0.77		5.89	0.00	4379	2.34	47	106	73
M-2717	Rhyolite Tuff	82.7	0.97		6.88	0.01	6306	2.31	53	108	71
M-2661	Rhyolitic Volcanic Ash	79.1	2.87		6.64	0.00	6745	2.42	47	106	71
M-2655	Rhyolitic Volcanic Ash	79.3	2.63		10	0.56	8988	2.29	54	114	70
M-2856	Volcanic Tuff	84.4	1.35		6.07	0.01		2.47	64	109	74
P-25	Rhyolite Pumicite	85.0	0.43								
P-44	Rhyolite Pumicite	84.2	1.33	6.2				2.44			80
P-46	Rhyolite Pumicite	82.7	0.96	5.0				2.36			75
8501	Opaline Shale	89.7	0.70	1.4					96		
P-2026	Opal								86		
M-2687	Diatomite	83.2	1.22		7.5	0.08	14643	2.2	96	122	67
M-2687C1	Calcined Diatomite	90.3	1.37		0	0.10	18481	2.16	97	118	79
M-2676	Diatomaceous Earth	90.8	0.88		90	0.80	15128	2.23	82	126	77
M-2679	Diatomaceous Earth	90.2	0.75		3.28	0.01	20378	2.13	95	118	79
M-2680	Diatomaceous Earth	88.1	0.95		4.51	0.25	22780	2.17	95	117	76
M-3027C	Calcined Diatomaceous Earth	89.7	1.73		4.84	0.18		2.38	87	114	73
M-3176	Diatomite	87.6	0.67	0.38	1.23	3.73					
P-26	Diatomite	82.1	2.29					2.01			97
P-51	Diatomite	82.4	1.81	2.0				2.06			93

USBR Designation	Petrographic Classification	SiO_2 + Al_2O_3 + Fe_2O_3	MgO	Equivalent Alkalis (Na_2O + $0.658K_2O$)	LOI	SO_3	Blaine Fineness (cm^2/g)	Specific Gravity	Reduction in Expansion (% from control at 14 days)	Water Requirement (% of control)	SAI (% of control at 28 days)
M-2537	Oil-Impregnated Shale	91.6	1.41	0.66	1.86	1.16		2.44	89	111	84
M-2626	Calcined Shale	77.6	2.98	0.14	4.8	0.54	10924	2.53	87	109	86
M-2529	Diatomaceous Clay			0.3	0.5	0.02		2.38	94	110	86
P-180	Altered Rhyolite Tuff	83.0	0.40	3.8				2.3	61		78
9282-1	Opaline Rhyolite Pumicite								90		
P-49	Altered Basalt Tuff	81.1	4.55	3.2				2.64			66
8838	Altered Rhyolite Tuff								72		
A-788	Altered Rhyolite Tuff								86		
8383-2	Opaline Rhyolite Tuff						10808	2.23	95		73
7926C	Calcined Opaline Shale	81.8	3.00				16823	2.5	80	115	75
7926	Raw Opaline Shale	83.9	2.00	1.0					80		
P-74	Opaline Shale	87.4	0.86	1.7				2.29			74
9444	Kaolin Clay	83.6	0.20	0.9	0.2			2.35	54		57
None	Kaolin Clay	84.5	0.20	0.2					43		
A-471	Siliceous Shale	94.1	1.70	1.0		0.70			37		
9126-3	Altered Rhyolite Pumicite								98		
M-2653	Bentonite Clay	81.3	1.98		11.3	0.25	4231	2.51	19	143	37
M-2653C1	Calcined Bentonite Clay	90.48	2.18		1.42	0.28	7512	2.52	49	103	84
M-2653C2	Calcined Bentonite Clay						7512	2.52	92	101	109
M-2654	Bentonite Clay	86.4	2.07		8.55	0.23	5264	2.68	22	152	33
M-2654C1	Calcined Bentonite Clay	92.2	2.18		1.86	0.11	9183	2.56	70	106	80

USBR Designation	Petrographic Classification	SiO_2 + Al_2O_3 + Fe_2O_3	MgO	Equivalent Alkalis (Na_2O + $0.658K_2O$)	LOI	SO_3	Blaine Fineness (cm^2/g)	Specific Gravity	Reduction in Expansion (% from control at 14 days)	Water Requirement (% of control)	SAI (% of control at 28 days)
M-2654C2	Calcined Bentonite Clay						9183	2.63	87	103	107
M-2834C	Calcined Bentonite Clay	92.48	2.14		0.34	0.06	7992	2.55	73	107	79
M-2669C	Calcined Clay	91.9	3.99		0.41	0.37		2.46	84	105	77
P-54	Basalt	90.1	0.61	0.3				2.63			72
9445	Clay	74.9	3.78	0.8				2.21	87		37
M-2828	Calcareous Shale	61	2.40		21.11	0.58		2.51	11	212	47
M-2828C1	Calcined Calcareous Shale	71.35	2.29		1.16	0.87		2.64	42	107	86
M-2828C2	Calcined Calcareous Shale	73.24	2.14		1.11	1.07		2.77	38	107	96
M-2828C3	Calcined Calcareous Shale	71.78	2.20		1.34	0.96		2.77	32	105	88
M-2907C1	Calcined Calcareous Shale	53.98	1.88		6.38	0.98		2.81	56	113	69
M-2907C2	Calcined Calcareous Shale	54.27	2.45		6.04	1.15		2.78	47	107	79
M-2904	Shale	93.38	2.35	0.76	0.17	0.03		2.5	78	103	90
M-2908C	Calcined Shale	92	2.36		0.46	0.38		2.55	78	106	86
M-3004	Shale	92.8	1.64	0.93	0.11	0.10		2.55	69	102	92
P-53	Clayey Silt	76.7	3.57	3.5				2.56			49