Draft Literature Review

USE OF ALTERNATIVE POZZOLANIC MATERIALS TOWARDS REDUCING CEMENT CONTENT IN CONCRETE PAVEMENTS

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NCE

Reno, NV
1885 S. Arlington Ave, Suite 111
Reno, NV 89509

Minnesota Department of Transportation

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Use of Alternative Pozzolanic Materials Towards Reducing Cement Content in Concrete Pavements

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Prepared for:

Minnesota Department of Transportation
Office of Research & Innovation
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

Prepared by:

NCE
Applied Pavement Technology, Inc (APTech)
Sutter Engineering, LLC

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1 Literature Review

1.1 BACKGROUND

The production of portland cement (ASTM C150) involves pyroprocessing raw materials in a rotary kiln in a process that is both energy intensive and emits substantial quantities of greenhouse gas (GHG) emissions into Earth's atmosphere. According to the EPA, the cement manufacturing sector reported emissions of more than 66 million metric tons of CO_{2eq} in 2020, which was an increase of 20% compared to 2011. Cement manufacturing is also responsible for emitting over 500,000 tons of sulfur dioxide, nitrogen oxide, and carbon monoxide each year, making it the third largest industrial source of pollution in the US (EPA 2022). It is therefore desirable to reduce the quantity of portland cement produced.

One strategy being investigated to accomplish this is to replace some of the portland cement in the cementitious materials with a supplementary cementitious material (SCM). This is currently standard practice, with MnDOT typically replacing up to 30% of portland cement with an ASTM C618 Class F fly ash. In some markets and applications, it is not uncommon to see replacement levels of 60% or more when using an SCM such as slag cement (ASTM C989). SCMs not only reduce the carbon footprint of cement through replacement, but some of the most common SCMs are industrial byproducts that would otherwise end up in landfills. Additionally, appropriate SCM(s) in correct dosages can be beneficial to fresh and hardened concrete properties through hydraulic activity, pozzolanic activity, or both (CP Tech Center 2022).

Unfortunately, one of the biggest limitations in expanding the use of SCMs is their continued availability. Fly ash is a byproduct of burning coal in electric power plant, being collected from the flue gases after the glass particles have condensed. Slag cement is a byproduct of refining iron ore in a blast furnace, where the molten blast furnace slag is run through a granulator to create glassy mineral phases that are finely ground into cement. Today, sources of fly ash and slag cement are decreasing in the US and alternative SCMs are being sought to meet the future need of increasing SCM usage.

This study focuses on non-traditional SCMs in the U.S. that contribute to the properties of concrete primarily through the pozzolanic reaction. Several types of pozzolanic materials and their effects on concrete mixtures are described, along with current test methods and considerations to be made during design and construction. Selected research studies are presented related to the specific pozzolan products being evaluated at the MnROAD Low-Carbon Concrete Test Site. At this time, there are not many documented case studies with the products being evaluated at MnROAD; however, this study aims to fill in many of those knowledge gaps.

1.2 ALTERNATIVE POZZOLAN MATERIALS

1.2.1 Introduction

The use of SCMs has become common practice in the past 50 years, both for their environmental benefits as well as the technical benefits they provide to concrete (Taylor et. al 2019). SCM type and dosage is carefully chosen to accomplish a balance between achieving benefits, such as mitigating alkali-silica reaction (ASR), improving workability, and reducing permeability, and limiting negative impacts such as slower setting time, increased risk of early-age cracking, and lower early-age strength (Wang et al. 2018). SCMs are used to substitute a portion of portland cement, contributing to concrete properties through hydraulic or pozzolanic activity or both. Hydraulic activity is where a material chemically reacts with water to form cementitious compounds, whereas pozzolanic activity is where a siliceous or aluminosiliceous material, when in finely divided form and combined with moisture, chemically reacts with calcium hydroxide, forming calcium silicate hydrate and other cementitious compounds (Kosmatka and Wilson 2016*).* This chemical reaction reduces calcium hydroxide and creates a finer pore structure, resulting in increased durability (ACI 2003). Pozzolans can be categorized into two main categories – natural and artificial. Examples of both natural and artificial pozzolans along with the applicable specifications are summarized in Table 1. The following sections provide a summary of each type of pozzolan material.

1.2.2 Natural Pozzolans

Natural pozzolans come from natural mineral deposits and are classified by ASTM C618 (AASHTO M 295) as Class N pozzolans. They were some of the first materials used as an SCM when discovered to mitigate ASR and have been found to control temperature rise in concrete and improve resistance to sulfate attack as well. While natural pozzolans are becoming an alternative to fly ash and slag cement for general purpose concrete, primary deposits are limited in the US to the western states (Taylor et al. 2019), although recent interest has resulted in new deposits being brought to market. Some examples of natural pozzolans include calcined shale, calcined clay, metakaolin, vegetable ash, and pumice.

Calcined Shale

Shale is a fine-grained sedimentary rock that results from the consolidation of clay, silt, or mud. To alter its physical properties for use as a pozzolan in concrete, it is heated in a rotary kiln to temperatures ranging from 1800°F to 2000°F. Its use in the US as a pozzolan was documented as early as 1932 in California by the Santa Cruz Portland Cement Company to make portland-pozzolan cement. This portland-pozzolan cement was notably used in construction of the Golden Gate Bridge and the Bay Bridge (Meissner 1950).

Table 1. Examples of alternative pozzolan materials and specifications

Pozzolan Materials Category	Examples of Alternative Pozzolan Materials	Standard Specification for Individual Material	Standard Specification for Blended Cements
Natural pozzolans	Calcined shale	ASTM C618/AASHTO M295	ASTM C595
	Calcined clay		
	Metakaolin		
	Pumice		
	Volcanic ash (and variants)		
	Diatomaceous earth		
Artificial pozzolans	Class C and Class F fly ash		
	Silica fume	ASTM C1240	
	Highly reactive pozzolans	AASHTO M 321	
	Ground glass	ASTM C1866	
	Others	ASTM C1709	

Calcined Clay

Calcined clay, such as kaolin, has been in use as an SCM for a long time and is an abundant material. It was notably used in San Francisco bridge construction in the 1930s. Calcined clays containing kaolinite react quickly in comparison to other more siliceous pozzolans, such as fly ash. However, the use of calcined clays comes with challenges as they have higher surface area, thus increasing water demand (Scrivener et al 2017).

Vegetable Ashes

The most studied vegetable ash is silica-rich rice husk ash (RHA), although several other ashes are produced from firing agricultural wastes, such as from sugar cane or other types of biomass. RHA is an agricultural by-product, resulting from the ash produced when rice husk is used as a biofuel. Like calcined clays, RHA has a high surface area, which increases water demand but also increases its chemical reactivity. Since RHA is a by-product of rice-milling, the main obstacle to widespread use is seasonal and geographical variability (Scrivener et al 2017).

Metakaolin

Metakaolin is a unique type of calcined clay and is a highly reactive pozzolan made from high-purity kaolin clay. It is produced using a low-temperature calcination process and is ground finer than traditional calcined clay, to about 0.04 to 0.08 mil (Hanson 2017 and Taylor et al. 2019). It is used when very low permeability or very high strength is required (Taylor et al. 2019). An example of commercially available metakaolin for use as an SCM is **Optipozz™**.

Pumice

Pumice, a natural pozzolan that has been used as an SCM in the U.S. for over a century, is a low-density porous volcanic rock formed by extruded lava. Ground pumice meets all the chemical requirements and most of the physical requirements listed in ASTM C618 for Class N pozzolans.

Many studies have shown that the use of finely ground pumice as an SCM can result in decreased compressive strengths, although one study showed that as pumice particle sized was decreased, the difference between the compressive strength of pumice and control concrete samples was lessened. The same study, which was an evaluation of **Hess Pumice**, also showed a decrease in the heat of hydration. Water demand can also increase with the use of pumice, as the interconnected vesicles in pumice can absorb and hold water, and more water may also be required to cover the jagged edges of ground pumice. Like other SCMs, using pumice has been shown to increase resistance to both ASR and sulfate attack (Seraj et al. 2014, Ramasamy and Tikalsky 2012).

Zeolite

Another natural mineral that has been used as a pozzolan is zeolite. Natural zeolites are hydrated alumino-silicates that occur predominately in altered volcanic tuffs that can be associated with substantial amounts of clays, feldspars or glass (Merens et al., 2009). One zeolitic product used at MnROAD is **Carbon Limit**, which is a non-calcined material blended with a catalyst. An added attractiveness of this product is that it will sequester additional carbon dioxide while in-service beyond what would be adsorb by conventional concrete. Because Carbon Limit does not fit easily under ASTM C618, its use can be evaluated using ASTM C1709, *Standard Guide for Evaluation of Alternative Supplementary Cementitious Materials (ASCM) for Use in Concrete*.

1.2.3 Artificial Pozzolans

Fly Ash

A material resulting from pulverized coal combustion, fly ash is the most widely used SCM in concrete and is included in approximately 50 percent of all ready-mixed concrete (ACI 2003, PCA 2000). Different fly ashes exhibit varying degrees of pozzolanic and hydraulic properties. For example, low calcium Class F fly ashes are pozzolans but can exhibit hydraulic properties, while high calcium Class C fly ashes are hydraulic materials that can have pozzolanic properties (Taylor et al. 2019). The main difference between a Class C fly ash and Class F fly ash is its chemical composition. According to ASTM C618-22, both Class F and Class C fly ash must have a minimum combined silicon dioxide, aluminum dioxide, and iron oxide of 50 percent. Class C fly ash will have a calcium oxide content greater than 18%, whereas a Class F fly ash will have a calcium oxide content equal to or less than 18%.

Due to the increased use of alternative energy sources in the US, the supply of fly ash has decreased, which has necessitated the use of less conventional sources of pozzolan. One example is reclaimed coal ash. In years past, fly ash supply often exceeded demand and excess fly ash was dry stockpiled or stored in surface impoundments along with other waste including bottom ash. Pulverized coal combustion not only produces traditional fly ash, but bottom ash is produced as well. Bottom ash is the coarse ash that settles to the bottom of the boiler, and it has the potential to be used in concrete if processed including grinding (Arce et al. 2021).

Silica Fume

Silica fume is a byproduct of the production of silicon and ferrosilicon alloys in an electric arc furnace, heated to a temperature of more than 3,600°F. Oxygen is removed from the silicon, separating the silica from the oxygenated silica fume. After the silica fume has cooled and condensed, it can then be collected and processed for use in concrete. Small quantities of silica fume can be used without significantly increasing water demand, but when used in larger quantities, significant increases in water demand are incurred and workability suffers. Silica fume has been shown to increase concrete durability, significantly reducing permeability, increasing corrosion resistance, decreasing ASR, and increasing sulfate resistance (Hanson 2017). It is often used in situations where a high degree of impermeability is required, as well as in high-strength concrete (Kosmatka and Wilson 2016).

Ground Glass

Waste glass accounted for 4.2% of all municipal solid waste in the US. in 2018, and until recently, it was a material that was avoided in concrete (EPA 2022) as it was thought that crushed glass would increase the potential for ASR. In the past 20 years, it has been discovered that waste glass powder can result in a pozzolanic reaction in concrete and it has been shown to reduce the risk of ASR (AzariJafari et al. 2022). The recent use of glass powder in concrete has led to the development of its standard specification, ASTM C1866, which was published in 2020. **Pozzotive®** is one example of commercially available ground glass pozzolan.

1.2.4 Products Used in this Study

The commercially available products used in the MnROAD study and their associated pozzolan types and corresponding standard specification as previously described are summarized in Table 2.

Table 2. Product classifications and specifications

Product Name	Pozzolan Type	Standard Specification
Hess Pumice	Natural Pozzolan - Pumice	ASTM C618/AASHTO M295
Optipozz™	Natural Pozzolan - Metakaolin	
3M™ Natural Pozzolan	Natural Pozzolan - Other	
Pozzotive®	Artificial Pozzolan - Ground Glass	ASTM C1866
Carbon Limit	Natural Pozzolan - Other	ASTM C1709
CP Tech Center Optimized	Artificial Pozzolan – fly ash + reducing cement content through optimized aggregate gradation	

Table 3 and Table 4 summarize the effects of pozzolan materials on fresh and hardened concrete properties, respectively. The effects of SCMs on concrete properties have been shown to be additive (Taylor 2014).

Table 3. Effects of Pozzolans on fresh properties of concrete (Thomas and Wilson 2022)

	Fly ash		Silica fume	Natural pozzolans		
	Class F	Class C		Calcined Shale	Calcined clay	Metakaolin
Water demand	↓	↓	↑	↔	↔	↑
Workability	↑	↑	↓	↑	↑	↓
Bleeding and segregation	↓	↓	↓	↔	↔	↓
Setting time	↑	↨	↔	↔	↔	↔
Air content	↓	↓	↓	↔	↔	↓
Heat of hydration	↓	↨	↔	↓	↓	↔

Key: ↓ Decreases, ↑ Increases, ↨ May increase or decrease, ↔ No impact

Table 4. Effects of Pozzolans on hardened properties of concrete (Thomas and Wilson 2022)

	Fly ash		Silica fume	Natural pozzolans		
	Class F	Class C		Calcined Shale	Calcined clay	Metakaolin
Early age strength gain	↓	↔	↑	↓	↓	↑
Long term strength gain	↑	↑	↑	↑	↑	↑
Abrasion resistance	↔	↔	↔	↔	↔	↔
Drying shrinkage and creep	↔	↔	↔	↔	↔	↔
Permeability and absorption	↓	↓	↓	↓	↓	↓
Corrosion resistance	↑	↑	↑	↑	↑	↑
Alkali-silica reactivity	↓	↓	↓	↓	↓	↓
Sulfate resistance	↑	↨	↑	↑	↑	↑
Freezing and thawing	↔	↔	↔	↔	↔	↔
Deicer scaling resistance	↔ ↓	↔ ↓	↔ ↓	↔ ↓	↔ ↓	↔ ↓

Key: ↓ Decreases, ↑ Increases, ↨ May increase or decrease, ↔ No impact, ↔ ↓ May lower or have no impact

1.3 GLOBAL WARMING POTENTIAL STUDIES OF ALTERNATIVE POZZOLAN MATERIALS

Several studies have been conducted comparing the carbon footprint of concrete made solely with portland cement versus concrete made with cements blended with pozzolan materials. The following is a summary of the findings from those studies:

- CO_2 emissions from concrete made solely with portland cement, concrete made with blended cement containing 25% by weight calcined clay (low-grade kaolin), and concrete made with blended cement containing 25% by weight calcined shale (illitic shale) was 313.2 $kgCO_2eq/m^3$, 234.9 $kgCO_2eq/m^3$, and 234.9 $kgCO_2eq/m^3$ concrete, respectively (Cordoba et. al, 2020).
- An LCA evaluation mortar with calcined clay and limestone filler in reinforced concrete showed an increase in compressive strength (28 days) in comparison to portland cement concrete and had a much lower global warming potential (GWP) (Bautista et. al, 2022).
- GWP for limestone calcined clay cement (LC3) was investigated at 0%, 35%, 50%, and 65% LC3 by weight, as shown in Figure 1.

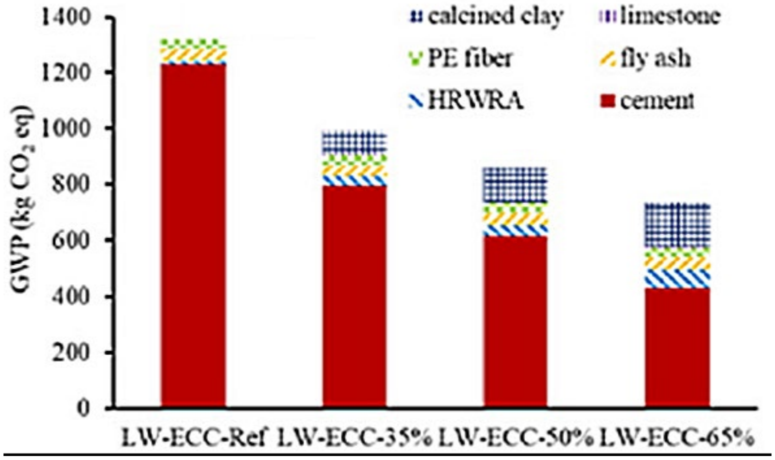

Figure 1. GWP of cement mixed with increasing percentage of LC3 (Zhou et al., 2022).

- The effects of substituting portland cement with metakaolin and industrial wastes, including silica fume (SF), granulated blast-furnace slag (GGBS), and fly ash (FA), were found in ultra-high-performance concrete (UHPC) (Figure 2).

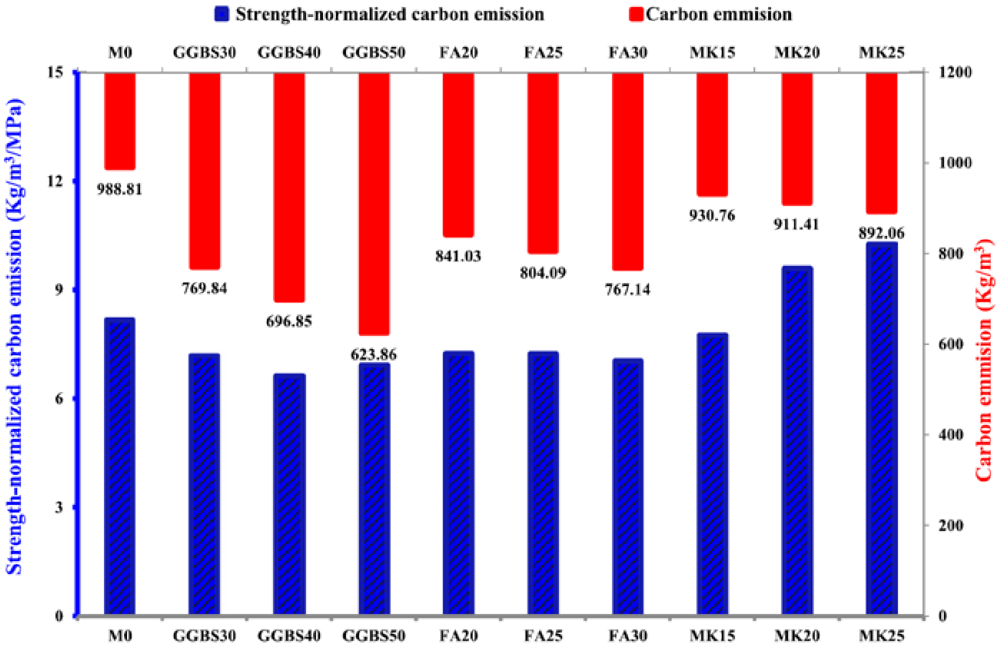

Figure 2. Carbon emissions from UHPC samples (Abdellatief et al., 2023).

- An LCA of self-compacting concrete containing natural pumice pozzolan at varying percentages (0%, 10%, 20%, and 30%) was conducted, and the results are shown in Figure 3.

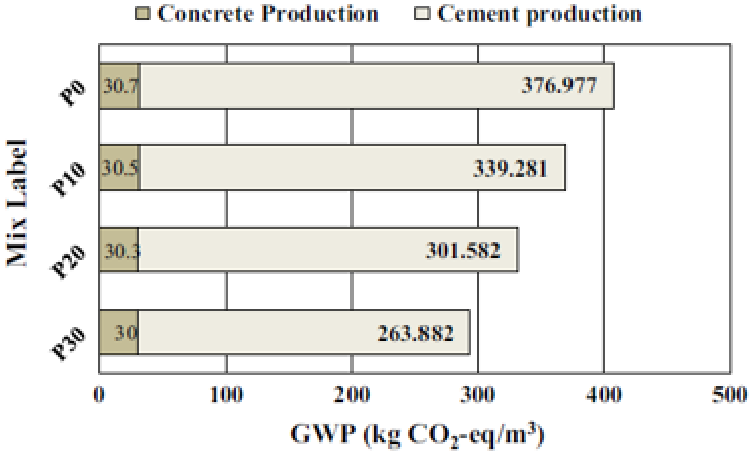

Figure 3. GWP production from cement and concrete production for concrete containing natural pumice pozzolan (Hedayatinia et a.l, 2019).

- Compressive strength and GWP for self-consolidating concrete (SCC) mixtures with cement replacement by Class F fly ash (F) and limestone powder (L) are shown in Figure 4.

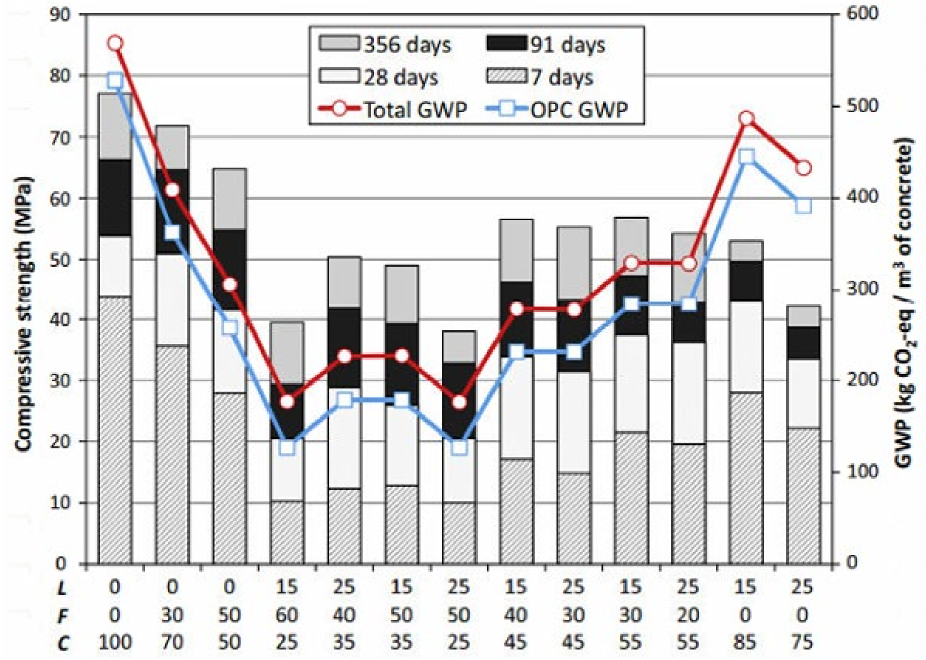

Figure 4. Compressive strength and GWP for SCC containing Class F fly ash and limestone powder (Celik et al., 2015).

1.4 TESTING CONSIDERATIONS FOR ALTERNATIVE POZZOLAN MATERIALS

1.4.1 Testing Alternative Pozzolan Materials

Pozzolans are characterized by several chemical and physical properties. Fly ash and natural pozzolans must meet the requirements specified in ASTM C618, which follows the testing methods described in ASTM C311 as listed in Table 5. There are times when a cement company will provide a blend of portland cement with one or more pozzolans or other SCMs. These binary or ternary systems must meet the requirements set forth in ASTM C595 for blended hydraulic cements. For the MnROAD project, the base cement was an ASTM C595 Type IL portland-limestone cement, so in essence all the ASCM concrete mixtures were either ternary or, in the case of the 3M natural pozzolan mixture, quaternary cementitious blends.

Table 5. Characterization test methods listed in ASTM C311

Property Type	Description	Specification(s) and Test Standard(s)
Chemical Properties	Silicon dioxide plus aluminum oxide plus iron oxide content	ASTM C114[a]
	Calcium oxide content	
	Sulfur trioxide content	
	Moisture content	
	Loss on ignition	
Physical properties	Fineness by sieving	ASTM C430[a,b]
	Strength activity index	ASTM C109[a,b]
	Water requirement	ASTM C1437[a]
	Autoclave expansion	ASTM C151[a,b]
	Sulfate resistance	ASTM C1012[a]
	Alkali-silica reactivity	ASTM C1567[a] ASTM C227[b]

[a] Natural pozzolan, Class C fly ash, Class F fly ash
[b] Pozzolan for use in blended cements

1.5 GUIDELINES FOR PRACTICAL USE

1.5.1 Concrete Mixture Design Considerations

Structural Design

Strength is a primary concern for concrete pavement structural design. Concrete mixtures with SCMs are routinely proportioned to achieve the desired strength, although strength gain is often slowed with pozzolanic SCMs. In addition to strength, concrete mixtures placed in harsh environments (freeze-thaw cycles, aggressive deicing chemicals, sulfate exposure, etc.) must be designed to resist deterioration while in service. Pavement slabs are also sensitive to drying shrinkage and temperature gradients that can result in curvature that negatively impacts ride quality and amplifies stresses that may cause cracking. Many of these performance attributes are addressed in AASHTO R 101-22, *Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures*.

Mixture Design

Considerations that should be made in the concrete mixture design process for ternary mixtures are summarized in Table 6.

Table 6. Concrete mixture design considerations for ternary blends (Taylor 2014)

Parameter	Considerations
Workability	• Primary factors: Water Content and admixture usage • SCM type and dosage
Setting time	• Primary factors: SCM type and dosage ○ Typically, increasing SCM dosage increases setting time
Cracking risk	• Curing and sawing • Combination of setting time, moisture and thermal gradients, stiffness, and strength
Strength	• Primary factors: *w/cm*, SCM type and dosage, use of admixtures, weather • Long-term strength governed by structural requirements • Rate of strength development controlled by construction practices
Stiffness and creep	• Rarely controlled – affect structural performance and cracking risk
Permeability	• Primary factors: *w/cm* • SCM type and dosage and degree of hydration
Durability	• Appropriate use of sufficient SCMs to prevent ASR and sulfate attack
Sustainability	• Increased with use of increasing amounts of SCMs • Must be balanced with need to control side effects of SCM use, such as delayed setting time and slower hydration

Interactions

The side effects and interactions of multiple SCMs in a concrete mixture are additive. For example, if one product has been shown to accelerate strength gain and another product has been shown to lower strength gain, then the result of combining those products will most likely be neutral. Another consideration that should be made is that the chemistry of multiple products and the rest of the concrete mixture may not be compatible, and material testing should be done to ensure the mixture will perform as planned (Taylor 2014).

1.5.2 Concrete Construction Considerations

Table 7 summarizes considerations that should be made when constructing concrete using ternary blends.

Table 7. Concrete construction considerations for ternary blends (based on Taylor 2014)

Parameter	Considerations
Form Removal/Opening to Traffic	• Setting times may be delayed, especially for mixtures with high SCM dosages and those with low alkali and calcium contents • Form removal/opening time may be delayed • Strength development should be monitored to ensure safety when forms are removed
Joint Sawing	• Delayed set time may require changes in sawing practice, especially in cold weather • Sawing window may be short due to mixture gaining strength slowly while still shrinking • Consider use of early entry saws • Very low alkali cement with high dosage of SCMS can result in increased cracking risk
Surface Finishing	• Should not be started until bleeding has stopped ○ In highly evaporative conditions surface begins to dry before bleeding stops • Bleeding is controlled by cementitious materials content of the mixture and rate of hydration ○ Rate of hydration affected by temperature ○ Changing SCM type and dosage will change bleeding • Conduct tests on trial batches to find when and how much bleeding occurs
Curing	• Becomes more critical in slowly hydrating systems • In drying conditions with high dosages of SCMs, increased risk for plastic shrinkage cracking ○ Use of evaporation retarders or provision of fog sprays can help • Cold weather - extra effort may be needed to keep slowly hydrating systems warm so hydration can continue until required performance is achieved
Extreme Weather	• Many cold weather issues addressed above

1.5.3 Selected Research Studies Featuring Alternative Pozzolan Materials

There are not many pavement case studies currently available demonstrating the use of the alternative pozzolanic materials being evaluated. Therefore, this section summarizes research studies that have been conducted on the pozzolan products that were used.

Hess Pumice

Research on Hess Pumice was conducted by the University of Utah (Ramasamy and Tikalsky 2012) and the University of Texas at Austin (Seraj et al. 2014). The Utah study focused on three different grades of Hess Pumice (DS200, DS325, and ultrafine pumice), whereas the Texas study was an evaluation of the performance of several types of alternative SCMs. The studies investigated:

- Health and safety
- Paste and mortar studies
    - Isothermal calorimetry
    - Rheological testing
    - TGA compression testing
    - Effect on drying shrinkage
    - Resistance to ASR
    - Resistance to sulfate attack
- Fresh concrete properties
    - Slump (ASTM C143)
    - Air content (ASTM C231)
    - Unit weight (ASTM C29)
    - Setting time (ASTM C403)
- Concrete strength and durability studies
    - Compressive strength (ASTM C39)
    - Drying shrinkage (ASTM C157)
    - ASR resistance (ASTM C1293)
    - Coefficient of thermal expansion (Tex-428-A)
    - Resistance to chloride penetration (ASTM C1202)

The findings from the University of Utah (Ramasamy and Tikalsky 2012) study on Hess Pumice are as follows:

- Hess Pumice was found to be pozzolanic.
- Different grades of pumice, even ones with the same chemical composition, were shown to behave differently in terms of hydration, which is attributed to varying particle size distribution.
- Ultrafine pumice showed improved performance over other grades in terms of hydration, strength, resistance to ASR and to sulfate attack.
- Water demand is high, but a mid-range water reducer could be used to reduce water demand.
    - In turn, this may help reduce setting time.
- Concerning health and safety, it was found that Hess Pumice natural pozzolans are free of Crystalline Silica and other hazardous materials.
- If application requires mainly high sulfate resistance and high ASR resistance, then DS200 and DS325 pumice should be used.
- If strength and durability are required, then ultrafine pumice can be used.
- The heat of hydration generated from the pumice concrete mixtures is less than mixtures with 100% cement.

The following were the findings of the University of Texas study on alternative SCM performance (Seraj et al. 2014):

- Pozzolanic reaction occurred in the pumice pozzolan pastes.
- The pumice pozzolan concrete mixture qualified for use in a Class 3 severe sulfate exposure environment at 15% and 25% replacement levels.
- Target slump of the pumice concrete mixture was achieved when a superplasticizer was added, leading to a final setting time of 3.4 hours. The control mixture had a setting time of 4.5 hours.
- In comparison to the control mixture, the pumice concrete mixture reached 95% of the control compressive strength at 90 days with 15% replacement and 99% of the control strength with 25% replacement.
- Pumice mixture had average ASR expansion of 0.022±0.007% at 15% replacement and 0.015±0.001% at 25% replacement, which is below the 0.04% limit in ASTM C1293.
- Pumice mixture met requirement for coefficient of thermal expansion (Tex-428-A) and had similar results to control mixture.
- Results showed that increasing SCM content increased resistance to chloride ion permeability.

- At 15% replacement, drying shrinkage was similar to control mixture, but at 25% replacement, drying shrinkage increased to more than 0.01% of the control.

Pozzotive® Ground Glass Pozzolan

Pozzotive® is a ground glass pozzolan from Urban Mining Industries, manufactured from waste bottle glass. It has been used in concrete projects throughout New York and Connecticut, including a cast-in-place concrete tower, in architectural and structural masonry units, pre-stressed concrete planks, pavers, and sidewalks. Research studies investigating the performance of Pozzotive® could not be found. A life cycle assessment (LCA) of Pozzotive® was conducted by Climate Earth in accordance with ISO 14040 and 14044, which will lead to the development of a Type III Environmental Product Declaration (Climate Earth 2020). The study captures the following life cycle stages:

- Raw material supply (A1)
    - Municipal recycling facility glass
    - grinding aids
- Transportation (A2)
    - Barge, truck, rail, and ship
    - Energy carriers (fuels)
- Manufacturing (A3)
    - Energy carriers (electricity and fuels)
    - Waste (end of life treatment of ancillary materials and any packaging)

Through LCA, it was determined that the majority of Pozzotive's® impacts come from the A3 life cycle stage, mainly due to electricity consumption from the grinding operation. The global warming potential (GWP) impact for a metric ton of Pozzotive® was 56 kg CO_{2eq}, whereas the industry average GWP in the U.S. for portland cement at the time of this study was 1,040 kg CO_{2eq}. The cradle to gate (A1-A3) GWP per cubic yard of concrete from U.S. Concrete/Eastern Concrete's Broadway Plant in New Jersey was calculated both with and without Pozzotive®, with the Pozzotive® mixture using 50% replacement. The concrete mixture without Pozzotive® had a GWP of 625 kg CO_{2eq}/cy while the mixture with 50% Pozzotive® cement replacement had a GWP of 361 kg CO_{2eq}/cy (Table 8).

Table 8. GWP comparison for concrete mixtures with and without Pozzotive®(Climate Earth 2020)

Mix Design/cubic yard			
Material	**Quantity**	**Without Pozzotive®**	**With Pozzotive®**
Type I/II Cement	lb	850	425
Pozzotive®	lb	0	425
Sand	lb	1,150	1,150
Stone 1	lb	1,000	1,000
Stone 2	lb	700	700
Water	gallon	34.7	34.7
Admixture 1	fluid oz	46.8	46.8
Admixture 2	fluid oz	17	17
Admixture 3	fluid oz	25.5	25.5
GWP (kg CO_{2eq}/cy)		**625**	**361**

3M^{TM} Natural Pozzolan

3M^{TM} Natural Pozzolan is a partial cement replacement mined from 3M's quarry in Wassau, WI. It is compliant with ASTM C618 Tables 1 and 2 and AASTHO M 295. A research study from the University of Minnesota was recently conducted investigating the feasibility of alternative SCMs in the production of precast, prestressed concrete. Material selection considerations for this study included cost, availability, particle size, and chemical composition, in addition to performance. The study included:

- 3 different types of portland cement during mortar mixture development
    - Type IL(10): an interground cement that includes 90% Type I portland cement + 10% ground limestone
    - Type III: ground finer than Type I – produces higher early strength due to increased reactivity of the cement
    - Type IIIL(10): 90% Type III portland cement + 10% ground limestone
- Fly ash
    - Class C fly ash
- Ground limestone
- Natural pozzolan
    - 3M^{TM} Natural Pozzolan from quarry in Wassau, WI
- 2 different types of ground glass pozzolan
    - Commercially available ground soda-lime container glass pozzolan

  - Recycled soda-lime plate glass

All mortar mixtures were made with a *w/cm* of 0.34 and included 0.25 ounces of superplasticizer. Two mortar mixtures were made with the 3M Natural Pozzolan:

- 70TypeIL(10)30NP: 30% of total cementitious material was 3M™ Natural Pozzolan + 70% Type 1L(10) portland cement
- 80TypeIL(10)20NP: 20% 3M™ Natural Pozzolan + 80% Type 1L(10) portland cement
- 70TypeIIIL(10)30NP: 30% 3M™ Natural Pozzolan + 70% Type IIIL(10) portland cement
- 70TypeIII30NP: 30% 3M™ Natural Pozzolan + 70% Type III portland cement

All mortar mixtures had a flow that was comparable to the control mixture (Type III portland cement + 30% fly ash). The flow requirement was 150%. Because this was a study on precast, prestressed concrete, the minimum compressive strength requirement was 3500 psi at 16 hours. The control mixture had a compressive strength of 3450 psi at 16 hours, which was less than the requirement. It is noted that this was most likely due to the mortar mixtures being prepare in a laboratory at lower temperatures than would be typical when placed in the field. The results for workability and compressive strength for the mixtures using 3M™ Natural Pozzolan are shown in Table 9. The only mixture that met the 3500 psi compressive strength requirement was the one using Type III portland cement combine with 30% natural pozzolan.

Table 9. Workability and compressive strength test results for 3M Natural Pozzolan mixtures (Moes et al. 2022)

Mixture	Temperature (°F)	Flow (%)	Compressive Strength (psi)		
			16 hr	7 day	28 day
70TypeIL(10)30NP	74.3	150	2920	6780	7880
80TypeIL(10)20NP	74.4	150	3320	7690	8770
70TypeIIIL(10)30NP	75.5	150	3180	6920	7980
70TypeIII30NP	74.3	150	3660	7170	9290

The mortar mixtures were also given weighted scores, based on cost, early strength, later strength, workability, and availability (Table 10). Each parameter was given a weight and each material was given a score of 1 to 5 for each parameter. The 3M™ Natural Pozzolan was given a score of 62, which was comparable to limestone and fly ash. Glass was given the lowest score, of 47, which was mainly attributed to its relatively high cost.

Table 10. Weighted decision chart (Moes et al. 2022)

Material	Cost	Early Strength	Later Strength	Workability	Availability	Score
Weight	5	5	2	3	3	
Limestone	5	4	3	1	4	66
Natural Pozzolan	4	3	3	4	3	62
Glass	1	2	4	4	4	47
Fly Ash	3	4	5	5	1	63

Recycled Glass Pozzolan

The study in 2019 focused on the evaluation of laboratory mixture designs using 20, 30, and 40% glass pozzolan (G20, G30, G40), as well as one mixture with 30% Class F fly ash (F30) and one mixture with 40% slag (S40) as SCMs (Krstic and Davolos, 2019). Additionally, a mixture with 100% cement (CM) was elaborated as a control group. Then, G20, G40, and F30 mixtures were used in a sidewalk project in Queens, NY, following New York City Department of Design and Construction specifications (NYC-DDC). The laboratory evaluation included tests for air content, slump, and temperature for test methods of fresh concrete; compressive strength, static modulus of elasticity, splitting tensile strength, flexural strength, and maturity for test methods of hardened concrete.

Due to their strong cementitious behavior, the S40 mixture reached the highest early compressive strength (7 days). Among the three mixtures with glass pozzolan, G20 reached higher early strength up to 28 days, but due to higher pozzolanic reactivity, both G30 and G40 showed higher strengths at 56 days. All three mixtures presented higher strength at all testing times than F30 and CM. Moduli of elasticity, splitting tensile strength, and flexural showed a similar trend. Flexural strength and compressive strengths for each mixture are shown in Figure 5.

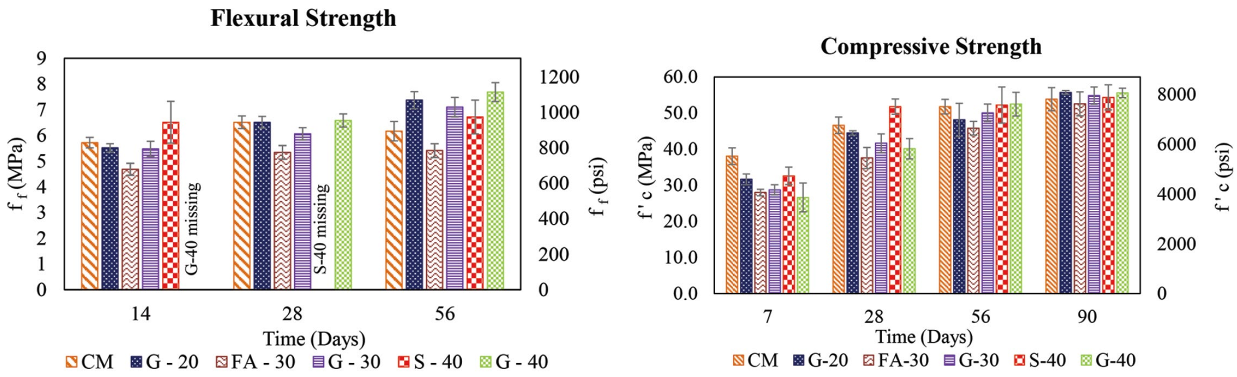

Figure 5. Flexural and compressive strengths for ground glass mixtures (Krstic and Davolos, 2019).

In the field, strength development followed the same trend as lab mixtures. In general, the strength for field samples was 13% lower. Still, at 28 days, the strength values were approximately 40% above the required design strength.

The two selected glass mixtures G20 and G40 by the NYC-DDC were successfully applied in a sidewalk project in Queens, NY. The mixtures were produced at a concrete plant, and then transported, placed, and finished using conventional practices. It must be noted that because the plant did not have a dedicated silo for glass pozzolan, the mixture was batched manually by adding the glass pozzolan from bags onto the conveyor belt already containing the dry constituents, and after mixing the ingredients the water and admixtures were subsequently added to the mixer.

1.6 SUMMARY

The alternative SCMs considered in this study are predominately pozzolans. They are from both natural and synthetic sources, and largely fit within existing specifications, most notably ASTM C618 and ASTM C1866. As the base cement in the study is an ASTM C595 Type IL, the blends within the concrete are either ternary or quaternary systems and therefore additional care in proportioning and placement will need to be exercised. As some of the ASCMs used are relatively new to the market, little information is available in the literature to review. As such, the information gathered in this study will be fundamental to advancing the use of these materials in the future.

2 References

1. Abdellatief, M., AL-Tam, S. M., Elemam, W. E., Alanazi, H., Elgendy, G. M., & Tahwia, A. M. 2023. Development of ultra-high-performance concrete with low environmental impact integrated with metakaolin and industrial wastes. *Case Studies in Construction Materials, 18.* 2023.

2. Alonso-Fariñas, B., Rodríguez-Galán, M., Arenas, C., Arroyo Torralvo, F., & Leiva, C. 2020. Sustainable management of spent fluid catalytic cracking catalyst from a circular economy approach. *Waste Management, V. 110, 10–19.* June 2020.

3. American Association of State Highway and Transportation Officials (AASHTO). 2021. *AASHTO M 295: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*. American Association of State Highway and Transportation Officials, Washington, DC.

4. American Association of State Highway and Transportation Officials (AASHTO). 2004. *AASHTO M 321: Standard Specification for High-Reactivity Pozzolans for Use in Hydraulic-Cement Concrete, Mortar, and Grout*. American Association of State Highway and Transportation Officials, Washington, DC.

5. American Society for Testing and Materials (ASTM). 2022. *ASTM C311/C311M: Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete*. American Society for Testing and Materials, West Conshohocken, PA.

6. American Society for Testing and Materials (ASTM). 2010. *ASTM C595/C595M: Standard Specification for Blended Hydraulic Cements*. American Society for Testing and Materials, West Conshohocken, PA.

7. American Society for Testing and Materials (ASTM). 2019. *ASTM C618: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*. American Society for Testing and Materials, West Conshohocken, PA.

8. American Society for Testing and Materials (ASTM). 2020. *ASTM C1240: Standard Specification for Silica Fume Used in Cementitious Mixtures*. American Society for Testing and Materials, West Conshohocken, PA.

9. American Society for Testing and Materials (ASTM). 2018. *ASTM C1437: Standard Test Method for Flow of Hydraulic Cement Mortar.* American Society for Testing and Materials, West Conshohocken, PA.

10. American Society for Testing and Materials (ASTM). 2018. *ASTM C1709: Standard Guide for Evaluation of Alternative Supplementary Cementitious Materials (ASCM) for Use in Concrete.* American Society for Testing and Materials, West Conshohocken, PA.

11. American Society for Testing and Materials (ASTM). 2020. *ASTM C1866: Standard Specification for Ground-Glass Pozzolan for Use in Concrete.* American Society for Testing and Materials, West Conshohocken, PA.

12. American Concrete Institute (ACI). 2003. *Use of Fly Ash in Concrete.* 232.2R. American Concrete Institute, Farmington Hills, MI.

13. American Concrete Institute (ACI). 2012. *Report on the Use of Raw or Processed Natural Pozzolans in Concrete.* 232.1R. American Concrete Institute, Farmington Hills, MI.

14. Arce, G. A., Radovic, M., Hossain, Z., Hassan, M. M., and Subedi, Sujata. 2021. *Evaluation of Alternative Sources of Supplementary Cementitious Materials (SCMs) for Concrete Materials in Transportation Infrastructure.* Transportation Consortium of South-Central States, Baton Rouge, LA.

15. AzariJafari, H. et al. 2022. *Open-loop Recycling of Glass in Concrete Provides Upcycling Opportunities.* Massachusetts Institute of Technology, Cambridge, MA.

16. Bautista, B. E., Ongpeng, J. M. C., & Razon, L. F. 2022. LCA of Mortar with Calcined Clay and Limestone Filler in RC Column Retrofit. *Sustainability (Switzerland), V. 14, I. 3.* January 2022.

17. Bianco, I., Ap Dafydd Tomos, B., & Vinai, R. 2021. Analysis of the environmental impacts of alkali-activated concrete produced with waste glass-derived silicate activator – A LCA study. *Journal of Cleaner Production, V. 316.* September 2021.

18. Blengini, G. A., Busto, M., Fantoni, M., & Fino, D. 2012. Eco-efficient waste glass recycling: Integrated waste management and green product development through LCA. *Waste Management, V. 32 I. 5, 1000–1008.* October 2011.

19. Celik, K., Meral, C., Petek Gursel, A., Mehta, P. K., Horvath, A., & Monteiro, P. J. M. 2015. Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended portland cements containing fly ash and limestone powder. *Cement and Concrete Composites, V. 56, 59–72.* November 2014.

20. *Cementitious Materials*. National Concrete Pavement Technology Center (CP Tech Center). (2022). Retrieved December 8, 2022, from https://cptechcenter.org/cementitious-materials/

21. Climate Earth. 2020. *Pozzotive® Screening LCA – Pre-Production.* Climate Earth, Pt Richmond, CA.

22. Cordoba, G. P., Zito, S. v, Sposito, R., Rahhal, V. F., Tironi, A., Thienel, C., & Irassar, E. F. 2020. *Concretes with Calcined Clay and Calcined Shale:*

Workability, Mechanical, and Transport Properties. American Society of Civil Engineers, Reston, VA.

23. Environmental Protection Agency (EPA). 2022. *Glass: Material-Specific Data*. EPA. Retrieved from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/glass-material-specific-data

24. Environmental Protection Agency. (2022). EPA. Retrieved December 8, 2022, from https://www.epa.gov/enforcement/cement-manufacturing-enforcement-initiative#:~:text=The%20cement%20sector%20is%20the,nitrogen%20oxide%2C%20and%20carbon%20monoxide.

25. Faridmehr, I., Nehdi, M. L., Nikoo, M., Huseien, G. F., & Ozbakkaloglu, T. 2021. Life-cycle assessment of alkali-activated materials incorporating industrial byproducts. *Materials, V. 14, I. 9.* May 2021.

26. Hanson, K. 2017. SCMs in Concrete: Natural Pozzolans. *Precast Inc. Magazine, 2017 – September-October.*

27. Hanson, K. 2017. SCMs in Concrete: Silica Fume. *Precast Inc. Magazine, 2017 – July-August.*

28. Hedayatinia, F., Delnavaz, M., & Emamzadeh, S. S. 2019. Rheological properties, compressive strength and life cycle assessment of self-compacting concrete containing natural pumice pozzolan. *Construction and Building Materials, V. 206, 122–129.* May 2019.

29. Hossain, Z. and Tamzidul, K. 2019. *Use of Rice Husk Ash (RHA) in Flowable Fill Concrete Mix Material.* Transportation Consortium of South-Central States. Baton Rouge, LA.

30. International Organization for Standardization (ISO). 2006. *ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework.* International Organization for Standardization, Geneva, Switzerland.

31. International Organization for Standardization (ISO). 2006. *ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines.* International Organization for Standardization, Geneva, Switzerland.

32. Koladharan, G., Vayghan, A. G. , and Rajabipour, F. 2019. *Review, Sampling, and Evaluation of Landfilled Fly Ash.* American Concrete Institute, Farmington Hills, MI.

33. Kosmatka, S. H. and M. L. Wilson. 2016. *Design and Control of Concrete Mixtures. 16th Edition.* EB0001.15. Portland Cement Association, Skokie, IL.

34. Krstic, M., Davalos, J.F. 2019. Field Application of Recycled Glass Pozzolan for Concrete. *ACI Materials Journal.* July 2019.

35. Liu, R., Durham, S. A., Rens, K. L., & Ramaswami, A. 2012. Optimization of Cementitious Material Content for Sustainable Concrete Mixtures. *Journal of Materials in Civil Engineering, V. 24, I. 6, 745–753.* December 2011.

36. Meissner, H.S. 1950. *Pozzolans used in Mass Concrete.* American Society for Testing and Materials, Philadelphia, PA.

37. Mertens, G., R. Snellings, K. Van Balen, B. Bicer-Simsir, P. Verlooy, and J. Elsen. 2009. "Pozzolanic Reactions of Common Natura Zeolites with Lime and Parameters Affecting Their Reactivity." *Cement and Concrete Research.* Vol. 39. Elsevier.

38. Moes, E.A., Christiansen, M.U., Dymond, B.Z. 2022. *Precast, Prestressed Concrete Made with Alternative Supplementary Cementitious Materials.* University of Minnesota, Minneapolis, MN.

39. Nie, Y., Shi, J., He, Z., Zhang, B., Peng, Y., & Lu, J. 2022. Evaluation of high-volume fly ash (HVFA) concrete modified by metakaolin: Technical, economic and environmental analysis. *Powder Technology, 397*. January 2022.

40. Panesar, D. K., Seto, K. E., & Churchill, C. J. 2017. Impact of the selection of functional unit on the life cycle assessment of green concrete. *International Journal of Life Cycle Assessment, V. 22, I. 12, 1969–1986.* February 2017.

41. Portland Cement Association (PCA). 2000. *Survey of Mineral Admixtures and Blended Cements in Ready Mixed Concrete*. Portland Cement Association, Skokie, IL.

42. Ramasamy, U. and Tikalsky, P. 2012. *Evaluation Report of Hess Pumice.* University of Utah. Salt Lake City, UT.

43. Scrivener, K. L., John, V. M., and Gartner, E. M. 2017. *Eco-efficient cements: Portential economically viable solutions for a low-CO2 cement-based materials industry.* UN Environment, Economy Division, Energy and Climate Branch, Paris, France.

44. Seraj, S., Cano, R., Liu, S., Whitney, D., Fowler, D., Ferron, R., Zhu, J., and Juenger, M. 2014. *Evaluating the Performance of Alternative Supplementary Cementitious Material in Concrete.* Center for Transportation Research, Austin, TX.

45. Taylor, P., Tikalsky, P., Wang, K., Fick, G., Wang, X. 2012. *Development of Performance Properties of Ternary Mixtures.* National Concrete Pavement Technology Center, Ames, IA.

46. Taylor, P. 2014. *The Use of Ternary Mixtures in Concrete.* National Concrete Pavement Technology Center, Ames, IA.
47. Taylor, P. C., T. J. Van Dam, L. L. Sutter, and G. J. Fick. 2019. *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual. Second Edition.* National Concrete Pavement Technology Center, Iowa State University, Ames, IA.
48. Thomas, M., and Wilson, M. L. 2002. *Supplementary Cementing Materials for Use in Concrete, CD038*. Portland Cement Association, Skokie, Illinois.
49. Van Dam, T. 2013. *Supplementary Cementitious Materials and Blended Cements to Improve Sustainability of Concrete Pavements.* National Concrete Pavement Technology Center, Ames, IA.
50. Wang, X., Taylor, P., Yurdakul, E., and Wang, X. 2018. An Innovative Approach to Concrete Mixture Proportioning. *ACI Materials Journal, V. 115, No. 5, September 2018.*
51. Zhou, Y., Gong, G., Xi, B., Guo, M., Xing, F., & Chen, C. 2022. Sustainable lightweight engineered cementitious composites using limestone calcined clay cement (LC3). *Composites Part B: Engineering, 243.* 2022.

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