USE OF AN INDUSTRIAL BYPRODUCT (J-ROX) AS A SUPPLEMENTARY CEMENTITIOUS MATERIAL FOR CONCRETE

by

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ABSTRACT

SAMANTHA DOUGHTY. Use of an Industrial Byproduct (J-Rox) as a Supplementary Cementitious Material for Concrete. (Under the direction of DR. BRETT TEMPEST)

Cement production is an inherently carbon-intensive process which represents two-thirds of all greenhouse gas (GHG) emissions associated with cement manufacturing. Although humanity has come to depend on cement for construction projects of all kinds, the resulting 1:1 ratio of carbon dioxide (CO_2) emissions to cement product is responsible for approximately 5-8% of total anthropogenic emissions. In the face of a worsening climate crisis, the construction industry is searching for effective solutions for reducing the environmental impact of concrete production without sacrificing access to one of the world's most in-demand materials.

Supplementary cementitious materials (SCMs) have been utilized by the concrete industry for decades as a financially advantageous solution for reducing the cement content of concrete mixtures without sacrificing, and in many cases improving, quality. In the appropriate proportions, use of an SCM can also improve the strength and durability of concrete materials. In response to increasing regulation of coal combustion throughout the United States (U.S.) the concrete industry is actively searching for alternative SCMs to replace fly ash, the most popular SCM and a byproduct of coal combustion. This project evaluates a coproduct of phosphoric acid fertilizer production (J-Rox) for use as an SCM in concrete applications and a viable candidate for beneficial reuse.

The efficacy of J-Rox as an SCM was determined based on tests of paste, mortar, and concrete samples produced using various types of J-Rox at cement replacement rates of 15%, 20% and 25%. These samples were compared to control samples containing 100% ordinary portland cement (OPC) and 20% fly ash to evaluate the mechanical performance of the J-Rox SCM. Five (5) different J-Rox materials were tested in paste and mortar applications and the best performing J-Rox were then selected for additional testing in concrete applications. The preliminary testing determined that the gypsum-based J-Rox materials (J-Rox 4 and J-Rox 5) would provide the most comparable performance to fly ash in concrete applications.

Results of concrete testing showed that the J-Rox SCM material could be used to create concrete mixtures that performed better than, or comparably to, the control mixtures in tests of strength (compressive strength, modulus of elasticity, Poisson's ratio) and durability (surface resistivity, unrestrained shrinkage) at cement replacement rates of 15% and 20%. Combining J-Rox in a ternary blend comprised of 15% J-Rox, 35% ground granulated blast-furnace slag (GGBFS), and 50% OPC was especially successful and could provide a very economical mixture in terms strength, durability, and reduced environmental impact.

Environmental impact was evaluated based on the potential of the J-Rox SCM to address all three pillars of sustainability (i.e., the creation of environmental, societal, and economic benefits). These pillars were explored by viewing J-Rox through the lens of industrial ecology (IE), in which the output from one industry is used as an input for another to achieve a circular exchange of resources within the supply chain. The findings of this study suggest that the use of J-Rox as an SCM in concrete could improve the sustainability of the concrete by reducing demand of raw materials and extending the service life of structures through the beneficial reuse of an industrial byproduct.

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DEDICATION

I humbly dedicate this work to the beautiful planet we call home and to all who have lost their lives fighting to protect it. With all the love in my heart and the passion in my soul, I promise you will not be forgotten.

"I like to envision the whole world as a jigsaw puzzle…
if you look at the whole picture, it is overwhelming and terrifying,
but if you work on your little part of the jigsaw
and know that people all over the world are working on their little bits,
that's what will give you hope."
- Jane Goodall

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LIST OF ABBREVIATIONS

CO_2	carbon dioxide
°C	degrees Celsius
°F	degrees Fahrenheit
AASHTO	American Association of State Highway and Transportation Officials
ACAA	American Coal Ash Association
ACI	American Concrete Institute
Al_2O_3	aluminum oxide
As	arsenic
ASTM	American Society for Testing and Materials
C	carbon
C&D	construction and demolition
CaO	calcium oxide
Cd	cadmium
cf	cubic foot
CH	calcium hydroxide
Cr	chromium
DOT	Department of Transportation
EIA	Energy Information Administration
EIP	eco-industrial park
EPA	Environmental Protection Agency
EPD	environmental product declaration
ES	ecosystem services
F	fluorine
FA	fly ash
FDOT	Florida Department of Transportation

Fe_2O_3	ferric oxide
FHWA	Federal Highway Administration
FL	Florida
ft	foot
g	gram
GGBFS	ground granulated blast furnace slag
GHG	greenhouse gas
IE	industrial ecology
in	inch
IPCC	International Panel on Climate Change
IS	industrial symbiosis
JR-1	J-Rox 1 (Gyp/Sand/Clay)
JR-2	J-Rox 2 (Low Silica)
JR-3	J-Rox 3 (High Silica)
JR-4	J-Rox 4 (GypRox)
JR-5	J-Rox 5 (GypRox)
K_2O	potassium oxide
kΩ•cm	Kilohm-centimeter
lb	pound
LCA	life cycle assessment
LCI	life cycle inventory
LFG	landfill gas
MgO	magnesium oxide
min	minutes
mL	milliliter
mm	millimeter

MOE	modulus of elasticity
MRF	Materials Recovery Facility
MSW	municipal solid waste
Na_2O	sodium oxide
NC	North Carolina
Ni	nickel
OD	oven dry
OPC	ordinary portland cement
P2O5	phosphorus pentoxide
Pb	lead
pcf	pounds per cubic food
PCR	product category rule
pcy	pounds per cubic yard
psi	pounds per square inch
S	sulfur
SCM	Supplementary Cementitious Material
SDG	Sustainable Development Goal
SES	socio-ecological system
SG	specific gravity
SiO_2	silicon dioxide
SNA	social network analysis
SOS	self-organizing symbiosis
SSD	saturated-surface dry
U	uranium
UK	United Kingdom
UNC	University of North Carolina

U.S.	United States of America
με	microstrain
UN	United Nations
USDA	United States Department of Agriculture
w/c	water to cementitious material ratio
Zn	zinc

CHAPTER 1: INTRODUCTION

1.1 Overview and Problem Statement

As one of the most commonly used building materials globally, concrete has become a staple of the construction industry for projects of all shapes and sizes. The simple recipe consisting of coarse aggregate, fine aggregate, and water, bound together with cement has effectively changed the world. Yet despite its diverse functionality and affordability, the sustainability of concrete production, like most materials production, can be improved.

Greenhouse gas emissions, biodiversity loss through habitat degradation, and contamination of freshwater sources are just a few of the environmental impacts associated with the mining and processing of limestone to produce cement (Mohamad et al., 2002). Such impacts have consequences for nature's ability to provide us with the ecosystem services (ES) upon which we all depend. Not only will the continuation of unsustainable practices bring us closer to the imminent climate catastrophe that scientists warn is on the horizon, but the unimproved production of concrete is not something future generations can rely on to support their urban growth as the environmental and economic costs will become too great.

Furthermore, attempting to satisfy the growing global demand for concrete through the continued consumption of finite raw materials has led to a reduced availability of limestone in many regions. This has severe societal and economic implications for the future (Wang et al., 2017). Reducing industry dependence on raw materials will allow the human race to continue reaping the benefits of concrete at a lower financial and environmental cost. As such, it is necessary to identify adequate alternatives to ensure the many benefits of concrete remain accessible to future generations.

The use of supplementary cementitious materials (SCMs) in concrete mixture designs has proven effective in enhancing the mechanical properties and longevity of concrete while reducing the amount of cement used in its production and reducing the industrial refuse waste stream. The most popular SCMs are often sourced from industrial byproducts (e.g., fly ash, slag, etc.), however as environmental regulations become more stringent and supplies of traditional SCMs are diminished there is a growing urgency to find new alternative sources throughout the waste stream (Cavalline and Sutter 2024).

Identifying such ways to reduce the environmental impact of the concrete industry is expected to become increasingly more essential as the global population, and infrastructure required to sustain this population, continues to grow. The purpose of this thesis is to evaluate the feasibility of using an industrial byproduct of the phosphoric acid production industry (J-Rox) as a supplementary cementitious material (SCM), and to develop a prospective analysis of the environmental impact of a potential industrial symbiosis network centered on these materials. This work is the second phase of a study, with other findings published in Summers (2021).

1.2 Objectives and Scope of Study

The specific objectives of the study are as follows:

- To evaluate if J-Rox can serve as an effective substitute for cement as an SCM;
- To determine how the use of J-Rox in concrete structures can improve performance and durability;
- To evaluate the improved sustainability of concrete made with J-Rox; and,
- To evaluate the market potential of J-Rox in reducing environmental impacts from the construction/concrete industry through the creation of an industrial symbiosis (IS) network.

1.3 Organization of Thesis

This thesis is organized into six chapters which consist of this brief introduction followed by a literature review providing background information on: the sustainability impacts of cement/concrete, the mechanical implications of using SCMs and their role in an industrial ecology network, and a market analysis of key materials. The remaining portions of this thesis present the methodology used to evaluate the study, the subsequent test results and their analysis, and lastly summarize the conclusions and recommendations for future research on this topic.

CHAPTER 2: LITERATURE REVIEW

2.1 Sustainability Impacts Due to Cement and Concrete Use

As defined by the United Nations (UN) Brundtland Commission in 1987, sustainability is "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, n.d.). Although this definition is arguably the most popular, most definitions of the term are based on a common (but not necessarily universal) foundation relating three interconnected pillars: environmental, social, and economic. It is generally understood that sustainable development requires balancing the goals, constraints, and impacts of each pillar. Initiatives that fail to address or consider the interactions between all three pillars are unlikely to maintain and/or meet their sustainability goals (Purvis et al., 2019).

The widespread implementation of concrete in urban landscapes around the globe has provided an unparalleled advantage for increasing social equity and creating economic opportunities. Over the last century, accessible concrete has allowed countries to quickly and with relative structural ease, provide social necessities (e.g., housing, medical treatment, and health services) and broaden access to education and culture. However, an imbalanced focus on social and economic benefits compared to the environmental costs prevents concrete production from being considered a truly sustainable process.

2.1.1 Environmental Impacts

The construction industry has contributed significantly to the two most critical environmental stressors facing the modern world: air pollution and water management. The energy used in the mining and processing of limestone for cement (i.e., embodied energy) is responsible for significant greenhouse gas (GHG) emissions as well as negative environmental impacts related to land use changes, biodiversity loss, noise pollution, dust emissions, and changes in aquifer regimes. Replacing portions of cement with compatible SCMs, which are often wastes or byproducts, can effectively minimize the embodied energy of concrete by reducing inputs (i.e. energy demand) and outputs (i.e. emissions) associated with the mining and processing of raw materials. Incorporating SCMs into concrete mixture designs can also extend the service life of structures through improved mechanical performance and long-term durability. Overall, utilizing SCMs provides a multifaceted solution to limiting waste throughout each stage of a structure's life cycle (Duchesne, 2021; Kupwade-Patil, et al., 2018).

2.1.1.1 Greenhouse Gas Emissions

In 2018 alone, global production of portland cement exceeded 4.1 gigatons (Gt), resulting in approximately 24 Gt of concrete material produced; production is expected to surpass 6 Gt by 2050. This poses concern since each ton of cement produced emits approximately one ton of carbon dioxide (CO_2). In fact, studies have shown that the production of portland cement is responsible for 5-8% of total anthropogenic emissions (Duchesne, 2021).

The majority of emissions associated with concrete production are attributed to the kilning process where the decomposition of limestone takes place (i.e., calcination). The calcination process represents two-thirds of all GHG emissions resulting from cement manufacturing whereas the fuel associated with the process is only one-third of emissions. This distribution makes the decarbonization of cement production especially difficult, leading the industry to identify alternative source materials (SCMs) with lower contents of calcium oxide (CaO) in attempts to avoid the impacts of calcination (Habert et al., 2020; Juenger et al., 2019; Duchesne, 2021).

Because concrete is the second most globally consumed substance (following water), the continued evolution of the industry standard to maximize the presence of SCMs in mixture designs can play a key role in mitigating the climate crisis. It is largely understood that the widespread adoption and further innovation of this practice would have a significant impact on keeping global warming below the 1.5°C limit recommended by the International Panel on Climate Change (IPCC) for avoiding the most disastrous climate predictions. Not only do SCMs reduce energy demand and prevent emissions related to the mining and production of raw materials, they also represent the beneficial reuse of waste to improve the durability and service life of structures (Duchesne, 2021).

2.1.1.2 Biodiversity Loss and Land Use Change

Natural systems are interconnected and cascading negative impacts from cement production are far-reaching, affecting nearly all 17 ecosystem services (ES) classified by Costanza et al. (1997). These impacts add up, spreading across spatial and temporal boundaries both locally and globally as demand increases. Some of the resulting slow variables and feedbacks are already observable from these practices while others have yet to come to light.

Society's overarching relationship with natural systems and processes is often referred to as a socio-ecological system (SES) and is defined by the changing variables and interactions occurring throughout the SES across various spatial and temporal scales. Slow variables represent the under-arching structure and conditions of the SES to which fast variables respond. Slow variables often best describe regulating ES such as air quality and water purification. Biggs et al., (2015) use the example of the Dust Bowl years in the U.S. during which "desertification-related regime shifts" occurred in response to poor agricultural practices (fast variables) that failed to incorporate erosion control or nutrient cycling (slow variables). Gradual changes to these slow variables over an extended period of time weakened the dominant feedback loops to the point that a random "shock" event (in this case, a drought) caused the SES to exceed the natural threshold and spiral into a new regime shift (Biggs et al., 2015).

In regard to the mining industry, soil formation is one of these slow variables. Opencast mining, the primary method for mining limestone, involves the total stripping of topsoil which takes thousands of years to develop into the fertile layer of soil ecosystems depend on. Soil formation is classified as a supporting ES and while this service may contribute indirectly to human wellbeing, it is quite literally the foundation for maintaining the processes and functions provided by other ES (i.e., provisioning, regulating, and cultural) (Costanza et al., 2017). Additionally, opencast mining requires the removal of native trees and vegetation which provide support for key ecosystem services and serve as habitats for many species.

The extent of mining's impact becomes even more detrimental as waste substances are excavated and dumped on open land, further disrupting the natural landscape. The resulting noise pollution and disruption of the landscape caused by mining activities fractures ecosystems and contributes to biodiversity loss. Since mining efforts take place relatively far from large human settlements, when left undisturbed these unpopulated areas often serve as comparatively biodiverse refuges where wildlife perform their roles within the ecosystem with limited interference (Habert et al., 2020). It is through a biodiverse ecosystem that humans have been able to develop medicines, grow food, utilize fibers, and provide countless other essentials. En masse these natural areas can have a significant benefit across spatial scales. Without such biodiversity, future generations will struggle to sustain the modern benefits we have grown to depend on (Diaz et al., 2006).

Furthermore, the resource and energy intensive mining process requires exorbitant amounts of fossil fuels and electricity. The combination of deforestation and the presence of heavy, carbon-emitting vehicles only serves to exacerbate the environmental impact within the ecosystem (Ganapathi and Phukan, 2020). Unlike the impact of opencast mining on the face of the earth, this brief summary has barely scratched the surface.

2.1.1.3 Water Use/Management

Only 20% of the water-use associated with concrete is attributed to the mixture itself. The majority of concrete-related water-use is allocated to the mining and processing of raw materials (quarrying, crushing, washing) which has a significant impact on surface and groundwater resources (Habert et al., 2020).

Surface water flow can be influenced by mining activities such as quarrying and may also be interrupted by excessive pumping of groundwater from quarries. This practice can effectively drain "contained" bodies of water such as ponds and wetlands by converting gaining streams (i.e., where groundwater emanates into streams) to losing streams (i.e., where water flows into groundwater systems). Furthermore, groundwater storage can be depleted through mining's resultant land-use changes which reroute aquifer recharge and increase runoff (Chen et al., 2013; Ganapathi and Phukan, 2020).

In addition to reducing availability, limestone mining usually causes a decline in water quality resulting from dust/particulate pollution and other effluents from quarries, such as silt, oil, fuel, waste, and other materials (Ganapathi and Phukan, 2020). This is consequential for both surface water and groundwater as the mining process strips sediment, minerals, rocks, and other organic layers which typically serve as a filter for the water prior to entering the water table. A study conducted in India investigated the impact limestone mining had on local water sources, identifying increases in pH, electrical conductivity, total dissolved solids, hardness, alkalinity, and calcium and sulfate concentrations (Ganapathi and Phukan, 2020). The resulting impact has negative implications for the health of the natural environment and serves to increase the effort and resources required by water treatment plants. Consequently, these chemical changes in water quality expedite the degradation of concrete which in turn increase the need for repairs and replacements of concrete infrastructure -- further exacerbating the cycle of mining and reduced ES resilience (Habert et al., 2020).

2.1.2 Societal Impacts

Modern society has become extremely dependent on concrete for its durability and diverse range of uses. The United Nations (2018) predicts that by 2050 the global population is expected to grow by 2.5 billion people; by that time 68% of the population is expected to live in urban areas (currently 55% as of 2018). Constructing and maintaining the infrastructure necessary to support this urban transition is guaranteed to increase demand for building materials.

In 2015 the United Nations (UN) identified 17 Sustainable Development Goals (SDGs) which built on decades of studies to identify a "blueprint to achieve a better and more sustainable future for all". These SDGs include actions that are expected to provide a sustainable path to addressing the many social, environmental, and economic challenges facing humanity on a global level. Included in these goals are actions that are directly applicable to the cement/concrete industry such as Goal 9: Industry, Innovation and Infrastructure which aims to "build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation"; Goal 11: Sustainable Cities and Communities which aims to "make cities and human settlements inclusive, safe, resilient and sustainable"; and Goal 12: Responsible Consumption and Production to "ensure sustainable consumption and production patterns" (United Nations, n.d.).

Figure 2-1. List of the United Nations' 17 Sustainable Development Goals (SDGs) (United Nations, n.d.)

Other goals have become more feasible as a result of concrete such as Goal 1: No Poverty, Goal 3: Good Health and Wellbeing, Goal 4: Quality Education, Goal 6: Clean Water and Sanitation, Goal 7: Affordable and Clean Energy, and Goal 8: Decent Work and Economic Growth. Concrete is affordable and provides nearly anyone with the ability to construct a diverse range of reliable, long-lasting infrastructure. Essential services such as hospitals, schools, water treatment facilities, and power plants become more attainable through the use of concrete.

The social equity resulting from concrete's accessibility and capacity to improve living conditions is unparalleled, especially for developing countries. However, these countries are now faced with the unfair expectation of providing their citizens with infrastructure and social development opportunities while producing a mere fraction of the emissions given precedent by already-developed nations, the same nations responsible for producing the majority of anthropogenic emissions to date (Akan et al. 2017). Carbon data available from 1750 through 2021 clearly show that the United States and the combined 28 countries making up the European Union are respectively responsible for 29% and 20% of the cumulative CO_2 emissions from fossil fuels and industry (not including land use change). This is in contrast to developing areas such as China, India, or the entirety of Africa which are only responsible for 17%, 4%, and 3% of cumulative CO_2 emissions to date, respectively (Global Carbon Budget, 2022).

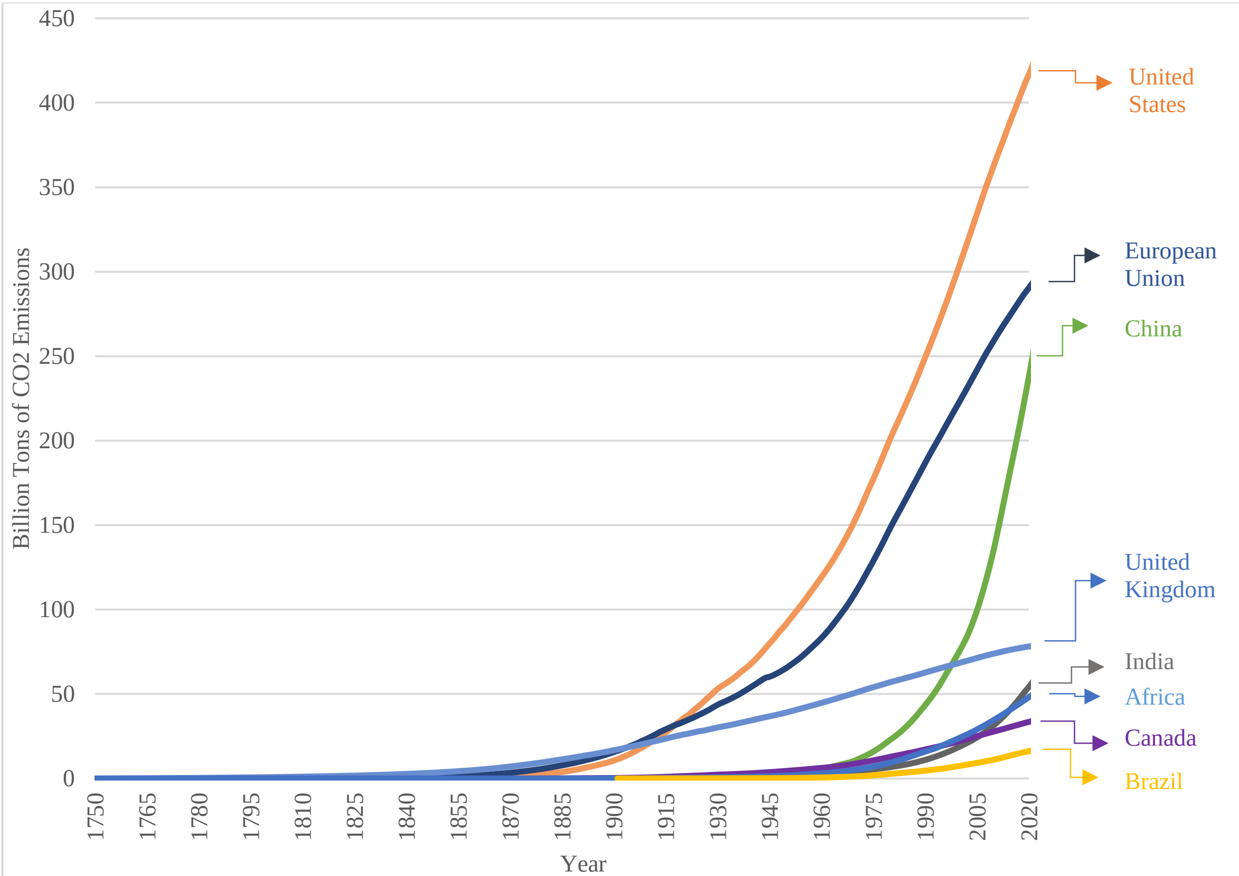

Figure 2-2. Cumulative CO_2 emissions produced from fossil fuels and industry (not including land use change) since 1750 (Global Carbon Budget, 2022)

2.1.3 Economic Impacts

Concrete is a relatively low-cost material to produce (cost per unit volume), especially when it is produced and mined local to where it is used. However, as discussed in Section 2.1.1, the environmental and social consequences of acquiring materials near developing urban areas are often unfeasible as most people understandably do not want to live close to active mines. This logistical constraint results in higher costs associated with the long-distance transportation of heavy aggregates and raw materials to supply the demand for construction materials within populated areas (Habert et al. 2020; UN Environment et al., 2018). Because of this and other factors, there is a growing need to source concrete materials locally in ways that introduce limited damage/interference to the environment and local communities.

While concrete is relatively inexpensive now, simple supply and demand indicates that as the finite natural resources required to produce concrete are diminished, the cost of acquiring these materials will increase. This factor is especially relevant to developing countries attempting to advance the prosperity of their nation (UN Environment et al., 2018). Additionally, the environmental impacts of climate change, which are already causing the frequency and intensity of natural disasters to rise, will pose new demand for construction and rebuilding efforts. In combination with a dwindling supply, this is likely to accelerate demand further, potentially reducing the ability of local/global supply chains to easily acquire affordable materials during times of instability.

2.1.4 Measuring Sustainable Impacts

2.1.4.1 Life Cycle Assessments (LCAs)

In recent years, concrete manufacturers have been especially interested in lowering the environmental impact of their products and processes to meet a growing demand for "greener" concrete. Many manufacturers believe that remaining competitive in the industry will require the increased adoption of a lower carbon footprint and overall more sustainable practices (Gursel et al., 2014). Life Cycle Assessments (LCAs) are a common practice for evaluating the environmental impact of a product with regard to the "inputs, outputs, and potential environmental impacts of a product system throughout its life cycle" (Rahla et al., 2019; International Organization for Standardization (ISO), 2006). The LCA approach is often used by decision makers involved in business, politics, and manufacturing levels to make environmentally conscious business decisions (Nicoara et al., 2020; Hossain et al., 2018).

Evaluating the LCA of concrete involves considerations for the design, production, service life, and end-of-life disposal for a specific mixture. The LCA includes a life cycle inventory (LCI) analysis, an impact assessment, and a final interpretation based on the previously defined goal, scope and system boundaries of the product (Nicoara et al., 2020; Rahla et al., 2019). Because there is no uniform approach to conducting an LCA, significant variability can be introduced depending on the system boundaries of the study, incomplete and/or unavailable data, and the comprehensiveness and accuracy of the LCI used. This variability can make comparisons between LCAs especially difficult (Gursel et al., 2014). Results of an LCA may also be skewed from bias of the assessor depending on the tone, approach, or objective of the study. In addition to an LCA, decision-makers are recommended to consider other decision criteria such as cost and performance (U.S. EPA, 2018).

2.1.4.2 Environmental Product Declarations (EPDs)

The global surge in urbanization and worsening climate crisis has created a growing demand for sustainable building materials and environmental transparency in the construction industry. As a result, environmental impact assessments are growing in popularity. Attempts to standardize environmental reporting have been introduced in the construction industry via the International Environmental Product Declaration (EPD) system. An EPD is an independently verified and registered summary report evaluating the life cycle environmental impacts of a material's production across the supply chain. Also referred to as Type III Environmental Declarations, EPDs were developed by the industry in accordance with the International Organization for Standardization (ISO) Standard 14025 (ISO, 2006) to provide a database of clear and consistent information regarding the environmental performance of similar types of materials and products (Portland Cement Association, n.d.; Rangelov et al., 2021).

EPDs of similar products are developed using a standardized set of rules, requirements, and guidelines, referred to as a Product Category Rule (PCR), and used to conduct a Life Cycle Assessment (LCA). Conducting the LCA in accordance with the relevant PCR helps ensure the EPDs for similar products are developed from comparable data and analysis methods which minimizes variability and allows for a more equal and comprehensive comparison of environmental impacts. The end-product of an EPD resembles the nutritional label found on food products and communicates key information regarding the life cycle environmental impact of products (EPD International, n.d.).

Summary of
Environmental Product Declaration

Central Concrete

Mix 340PG9Q1

San Jose Service Area

EF V2 Gen Use P4000 3" Line 50% SCM

Performance Metrics

28-day compressive strength	4,000 psi
Slump	4.0 in

Environmental Impacts

Impact name	Unit	Impact per m3	Impact per cyd
Total primary energy consumption	MJ	2,491	1,906
Concrete water use (batch)	m3	6.66E-2	5.10E-2
Concrete water use (wash)	m3	8.56E-3	6.55E-3
Global warming potential	kg C02-eq	271	207
Ozone depletion	kg CFC-11-eq	5.40E-6	4.14E-6
Acidification	kg S02-eq	2.26	1.73
Eutrophication	kg N-eq	1.31E-1	1.00E-1
Photochemical ozone creation	kg 03-eq	46.6	35.7

Figure 2-3. Example of an EPD for a concrete mixture design by Central Concrete Supply Co. (U.S. DOT Federal Highway Administration (FHWA), 2019)

2.2 Supplementary Cementitious Materials (SCMs)

Over the past few decades, SCMs have become an integral part of the concrete industry with over 95% of ready-mix concrete plants in the U.S. utilizing SCMs (or using cements pre-blended with SCMs during production, such as slag cements), resulting in the presence of SCMs in over 60% of the country’s modern concrete mixtures (National Ready Mixed Concrete Association, 2019; Juenger and Siddique, 2015). Because SCMs can replace significant portions of cement in mixtures (upwards of 30%, currently) they can significantly reduce the CO_2 emissions associated with concrete production and the mining of raw materials while simultaneously reducing costs. In the appropriate proportions, SCMs are also used to increase the longevity, mechanical performance, and durability of concrete mixtures (Juenger et al., 2019).

2.2.1 Types of SCMs

SCMs are chosen for their likeness in characteristics to portland cement or ability to support or enhance hydration reactions, but they are unable to serve as the stand-alone binder in a concrete mixture. Natural SCMs (e.g., pumice, perlite, and vitric ash) can be sourced from glasses and volcanic rocks, although the most popular SCMs consist of industrial wastes such as fly ash, silica fume, and slag (Juenger et al., 2019). In many cases, these industrial SCMs have reduced the need for the mining and processing of virgin materials with the added benefit of reducing the environmental and financial burden of landfilling industrial waste/byproducts. The close proximity of industry to urban areas (in comparison to mining activities) also reduces impacts related to the transportation of building materials, thus furthering economic and environmental benefits (Carpenter and Gardner, 2008). It is noted, however, that SCMs still require transport over substantial distances to serve some markets.

Fly ash, a coal-combustion residue of thermal power stations, is one of the most popular SCMs and can successfully replace 15%-30% of cement by weight (Pandey, 2020). Two categories of fly ash are recognized by ASTM International: Class C fly ash consisting of greater than 50% of key oxides (combined silica, alumina, and iron oxide); and Class F fly ash which consists of greater than 70% of key oxides. Due to its increased availability and resistance to alkali-silica reaction and sulfate attack, Class F fly ash is the most utilized in the United States. When included in concrete mixtures, the oxides present within fly ash enhance both fresh-state and hardened-state properties of concrete through improved workability, pumpability, and strength gain at later ages. Further benefits include a refined pore structure within mixed concrete which reduces permeability as well as the heat of hydration reaction (Al-Shmaisani et al., 2019).

2.2.2 Chemical Compositions of SCMs

Although the chemical composition of SCMs can vary significantly, their overall efficacy is largely attributed to the additional pozzolanic effect produced when the SCMs react with calcium hydroxide (CH) during hydration of the cement (Glosser et al., 2019). Pozzolans typically feature high quantities of silica or silica and aluminum that, when finely divided and exposed to moisture, chemically react with CH at standard temperatures to form compounds with cementitious properties (American Concrete Institute (ACI), n.d.).

Pozzolans are sought after for concrete applications due to their ability to improve the strength and chemical resistance. Pozzolans also reduce the rate of heat evolution throughout hydration reactions. Although this slows the strength development of hardened concrete, a greater overall strength is achieved once cured (Tritsch et al., 2021; Summers, 2021). The particle shape, surface texture, and fineness of the specific pozzolans used may result in an increased or decreased water demand. Fly ash, for example, typically decreases water demand while many other pozzolans increase the water demand (American Concrete Institute, n.d.; Jia, et al., 2024).

2.2.3 Issues with Currently Available SCMs

Fly ash, the most popular and effective SCM to date and a byproduct of burning coal, is growing short in supply in many areas due increased governmental regulation of coal-fired power plants and overall pushes to transition into cleaner energy sources. In the U.S. over 40% of coal-fired power plants have closed since 2014, and according to the U.S. Energy Information Administration (EIA), plans are in place to retire 28% of the remaining plants by 2035. In similar fashion, the UK plans on retiring all of its coal-fired power plants by 2025; the Netherlands intends to do the same by 2030 (Juenger et al., 2019; U.S. Energy Information Administration (EIA), 2021). While this may seem like a blow to the concrete industry, all is not lost. The dwindling supply of fly ash has opened the door for other industrial byproducts to be introduced as SCMs, further emphasizing a founding principle of fostering socio-ecological/systematic resilience: maintaining diversity and redundancy (Biggs et al., 2015).

Assessing potential risks of incorporating these waste products as common construction materials is just as important as identifying their mechanical and economic benefits as SCMs. Like fly ash, some SCMs may consist of chemical elements that are harmful to human and/or environmental health. By containing these materials inside of concrete, it is possible to prevent their exposure to the environment. However, changes in the pH level of the concrete during the initial reaction and exposure to the elements may mobilize them. Other possibilities for exposure such as inhalation hazards may also pose risks, especially to construction workers (Chen et al., 2024).

2.3 Use of Industrial Byproducts in Concrete

There is no shortage of industrial byproducts being disposed of through local and global supply chains. Many of these “waste”, “byproduct”, or “coproduct” materials are being evaluated for their efficacy as SCMs that improve the sustainability and durability of concrete while simultaneously keeping toxic refuse out of the waste stream (Cavalline et al., 2024). Recently, the discovery of a new process for manufacturing phosphoric acid in the production of fertilizer has introduced a new potential SCM in concrete applications, a coproduct referred to as J-Rox. J-Rox has a similar mineralogical content to common SCMs like fly ash. However, unlike the coal market, the market for phosphoric acid grew 4.5% from 2008 to 2018. At a global scale it is expected to continue growing by nearly 4% per year (IHS Markit, 2018).

2.3.1 Enhancing Industry Resilience through Industrial Ecology

Although aggregate extraction and mining practices result in many environmental consequences, they are not inherently unsustainable. However, when paired with generations of poor resource management, the consequences snowball into the large conglomerate of negative externalities seen today. This is what makes the beneficial reuse of industrial byproducts as SCMs such an attractive option for reducing the environmental impact of concrete production (Habert et al., 2020; Juenger et al., 2019). The beneficial reuse of “waste” materials mirrors principles of natural systems in which waste in one system becomes food for another. Due the interconnectedness within and between social, industrial, and environmental systems these principles can be applied to similar solutions across industries of all kinds. The concept of applying these principles to industrial processes is commonly known as industrial ecology (IE), which may be the key for enhancing the resilience of the construction industry and reducing the strain on ES (Chopra and Khanna, 2014).

IE is an elegant, nature-based solution that simultaneously confronts modern societal, environmental, and economic challenges by taking inspiration from natural ecology and food web interactions to improve the efficiency of the supply chain (Ramsheva and Remmen, 2018; Geyer and Jackson, 2004; Lowe and Evans, 1995; Nodehi and Taghvaee, 2022). Attempts to bring this multifaceted approach to the concrete industry are exemplified through the use of SCMs which significantly reduce the need for raw material, can effectively improve the durability and longevity of concrete, and make use of toxic waste products that would otherwise require complex or questionable disposal methods (Habert et al., 2020; Suhendro, 2014). The far-reaching impacts of this solution reduce the strain on ES across every stage of the production process.

Simply put, utilizing a variety of source materials to meet structural needs benefits both the construction industry and the natural environment. From an environmental standpoint, a decreased demand for raw material correlates to a decreased demand for mineral extraction, meaning that more natural areas remain intact. From an industry standpoint, reducing dependence on specific finite resources improves the resilience of the supply chain through the introduction of diversity and redundancy to the market.

Because infrastructure is quite literally the "foundation" of the industrialized world (and the barrier between the man-made and natural worlds), implementing sustainable systems at this level represents both a top-down and bottom-up approach to enhancing the resilience of ES and the construction industry. Addressing the efficiency of the "foundation" without also addressing the efficiency of its base components and resultant products is like trying to solve climate change solely through direct air carbon capture while continuing the same consumption and emission practices that made it necessary in the first place.

2.3.2 Applying Industrial Ecology to the Construction Industry

Industrial ecology (IE) is the larger field in which designs for industrial systems are inspired by the principles of biological ecosystems for the purpose of developing a circular management of resources within supply chains. When IE is implemented on a regional or local scale it is often referred to as industrial symbiosis (IS). In the field of biological ecology, symbiosis is a term used to describe “a closed and often long-term interaction between two or more biological species” which can be beneficial to both participants (Li, 2017; Morales and Diemer, 2019; Morales et al., 2022). Similarly, IS is often defined as the implementation of IE principles through the establishment of symbiotic relationships occurring at the inter-firm level. As further defined by Domenech et al., IS consists of “organizations operating in different sectors of activity that engage in mutually beneficial transactions to reduce waste and byproducts, finding innovative ways to source inputs and optimizing the value of the residues of their processes” (2019).

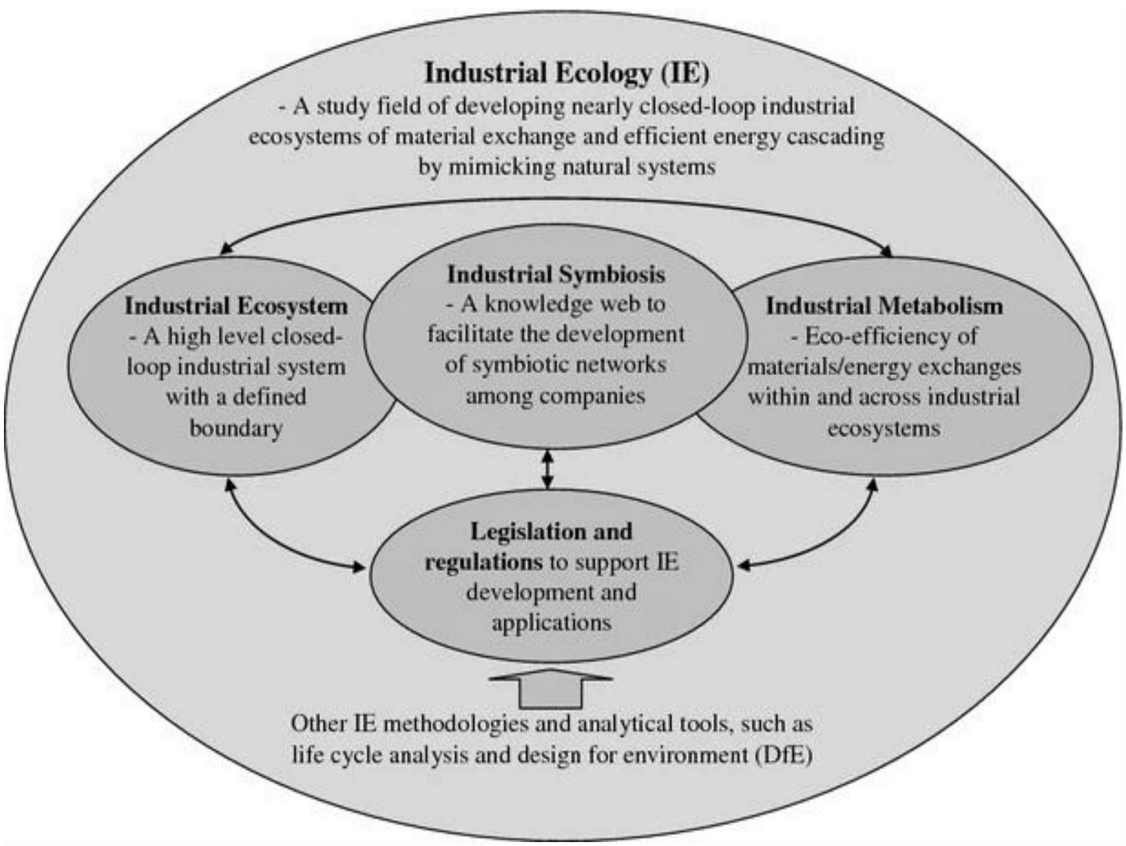

Figure 2-4. The interrelated components of industrial ecology (Li, 2017)

The early 1990s and 2000s saw a surge in global research investigating the implementation of IE and IS networks. Small-scale IS networks within the U.S. are often referred to as Eco-Industrial Parks (EIP), essentially representing “a community of businesses located together in a common property”, which share and/or exchange materials, energy, or infrastructures and use the waste outputs of one firm as an input for another (Valenzuela-Venegas, et al., 2018). Regardless of the scale, the ultimate goal of an EIP, IS, or IE network is the conservation of natural and economic resources. An effective IE-based system is designed to reduce costs associated with production, materials, energy use, insurance, and liabilities by improving operating efficiency. All of this is achieved without sacrificing public image, overall quality, or worker health, and provides a valuable stream of income from the use and sale of wasted materials (Perrucci et al., 2022).

2.3.3 Non-Technical Aspects of an Industrial Ecology Network

2.3.3.1 Stakeholder Involvement and Participation

The most crucial element of a successful IE or IS network is the social aspect of inter-firm relations, unfortunately, it is also the least researched and least understood. IE is dependent on a multidisciplinary network of actors and stakeholders within the system cooperating to achieve mutual success. A successful IE network is built around sets of industries that are simultaneously different but fit each other with an inherent dependence on the recruitment of "scavenger" or "decomposer" businesses that utilize, produce, or trade second-hand materials (Song et al., 2018; Bellantuono et al., 2017). As defined by Noronha (1999), the main function of a decomposer in the IE context is to break down material into simpler components for reuse, while scavengers are businesses that perform "waste recovery, reuse, repair and remanufacture activities" as their primary function. As in natural ecosystems, these types of businesses are necessary for maintaining balance in an IE network.

Stakeholders may include tenant firms, industrial park managers, suppliers and consumers, neighboring societies, and/or local governments (Perrucci et al., 2022; Song et al., 2018). Failure to develop a sense of trust between these stakeholders is a common dilemma impacting the success of an IS network. A lack of trust often stems from the desire to remain independently competitive and is expressed by a reluctance to disclose details of production processes, making it more difficult to maximize the reuse of byproducts and identify compatible sources to supply each firm's respective input materials. In these cases, trust is often supplemented with expensive, restrictive contracts between firms. Successful attempts to more easily establish trust have involved the focus on non-competitive waste streams for materials that are particularly expensive or unsustainable to dispose of. In these scenarios, firms achieve mutual prosperity and benefits while avoiding rivalry (Alexandrescu et al., 2016; Perrucci et al., 2022).

Social embeddedness is a term used to describe the non-material ties throughout a system that show how stakeholders are involved and describe the informal information channels used throughout the system (Song et al., 2018; Alexandrescu et al., 2016; Hewes and Lyons, 2008). Systems with high social embeddedness are often the most successful. In fact, EIPs designed around existing, long-term relationships between specific firms (in some cases firms were related by a former parent company) had the most success in IS and utility sharing (Vermeulen, 2006).

2.3.3.2 Management System and Agency Support

Managing the diverse reactions and relationships between stakeholders is another essential task in developing a successful IS network. As a network grows, having a site-wide waste exchange management system that 1) manages the flow of supplies, 2) manages interfirm relationships, and 3) manages the design of procurement standards and specs gains increasing importance (Song et al., 2018).

A successful IS system requires a clear understanding of information regarding the types and quantities of materials used, wastes generated, and the energy requirements of each firm. This information is essential to achieving productivity and efficiency. A site-wide management system aids in maintaining the appropriate mix of compatible companies as industries come and go from the system. Just like in natural systems, an IE network is a living thing that should be expected to evolve and change over time alongside the market. A thorough understanding of the particular inputs and outputs throughout the entire system is vital for recruiting new businesses, thus maintaining an optimal mixture of compatible companies within the IE network (Perrucci et al., 2022).

An effective management system can act as a coordinating body that maintains the cooperative relationships between firms by guaranteeing the commitment of those involved, understanding each firm's perspective, and enhancing communication (Perrucci et al., 2022; Song et al., 2018). Social network analysis (SNA) is often used to analyze IS relationships by identifying key actors and helping to understand the success, resilience, and efficiency of the system as a whole to measure the social embeddedness of a system (Song et al., 2018; Alexandrescu et al., 2016). SNA provides an analysis of both horizontal and vertical channels through which the actors may organize themselves, independent of the individual subjectivity of those actors (Alexandrescu et al., 2016).

Other components of the site-wide management system include a design of procurement standards and specs as well as assuming the responsibility (and liability) involved with managing any surplus wastes that are not utilized within the system. In some cases, this is managed through participation in a regional waste exchange program which buffers interdependence and introduces a level of consistency during market-driven fluctuations (Perrucci et al., 2022; Song et al., 2018).

2.3.3.3 Collaboration with Authorities and the Community

As the regulatory authority for environmental policies and industry standards, studies of IE networks emphasize an importance on working in close collaboration with government entities throughout the development of an IS network (Arbolino et al., 2018). However, historically speaking, planned IE/IS/EIP networks conceptualized in a pre-development stage and supported using strong government subsidies have proven unsuccessful compared to networks which develop through a more organic approach. Although the U.S. is one of the global leaders in publishing research related to EIPs, the failure rate for EIP implementation in the U.S. is drastically higher than any other nation. This has been at least partially attributed to a heavy-handed government presence in EIP programs within the U.S. as compared to nations with high EIP success rates such as the Netherlands. Identifying the ideal level of governance is often nuanced. Government overreach is known to lead to ineffective outcomes as conflicting policies and agendas interfere with the efficiency of the park's overall mission (Perrucci et al., 2022).

Instances where governments take the lead to implement a "build and recruit" model often place too much emphasis on matching multiple flows to achieve the technical aspect of symbiosis. Although seemingly logical, this approach often neglects stakeholder input and does nothing to build the trust and cooperation required to achieve sustainable results. Such government overreach was shown to complicate the design process due to variance in policies and agendas between government agencies and overall poor communication between all involved. This often resulted in an atmosphere of competition instead of cooperation, which allowed firms to cherry pick the policies that best satisfied their own priorities. Overall, regulations had a greater impact when they were flexible (Perrucci et al., 2022; Chertow and Ehrenfeld, 2012).

It is worth mentioning that the most successful and well-known example of IE in practice, the IS at Kalundborg, Denmark, was not the product of a carefully planned IS design. It started as two individual companies with a motivation to reduce wastes through the pursuit of profitable exchange and developed over several decades into a network of 16 firms exchanging waste materials through IS. Kalundborg consists of "oil refineries, a pharmaceutical company, an electric power plant, a gypsum plate factory, a cement factory, a fish nursery, and city heating works from the nearby community" (Chae et al., 2010). This type of self-organizing symbiosis (SOS) model is built around individual firms voluntarily acting on their own accord.

Perhaps the most beneficial impact governments can have on fostering IE are environmental regulations to encourage waste exchange and reuse that indirectly benefit IE networks such as increased taxes on industrial/commercial waste disposal at landfills or subsidies for businesses engaged in beneficial reuse of waste products (Bellantuono et al., 2017; Chertow and Ehrenfeld, 2012). Governments can also be helpful in providing platforms for like-minded businesses to connect and share resources, as exemplified by the United States EPA Recycling Toolkit. Through this online database, users can access resources such as databases for material exchange, tools for program management, funding opportunities, and more based on the specific needs/parameters of a program.

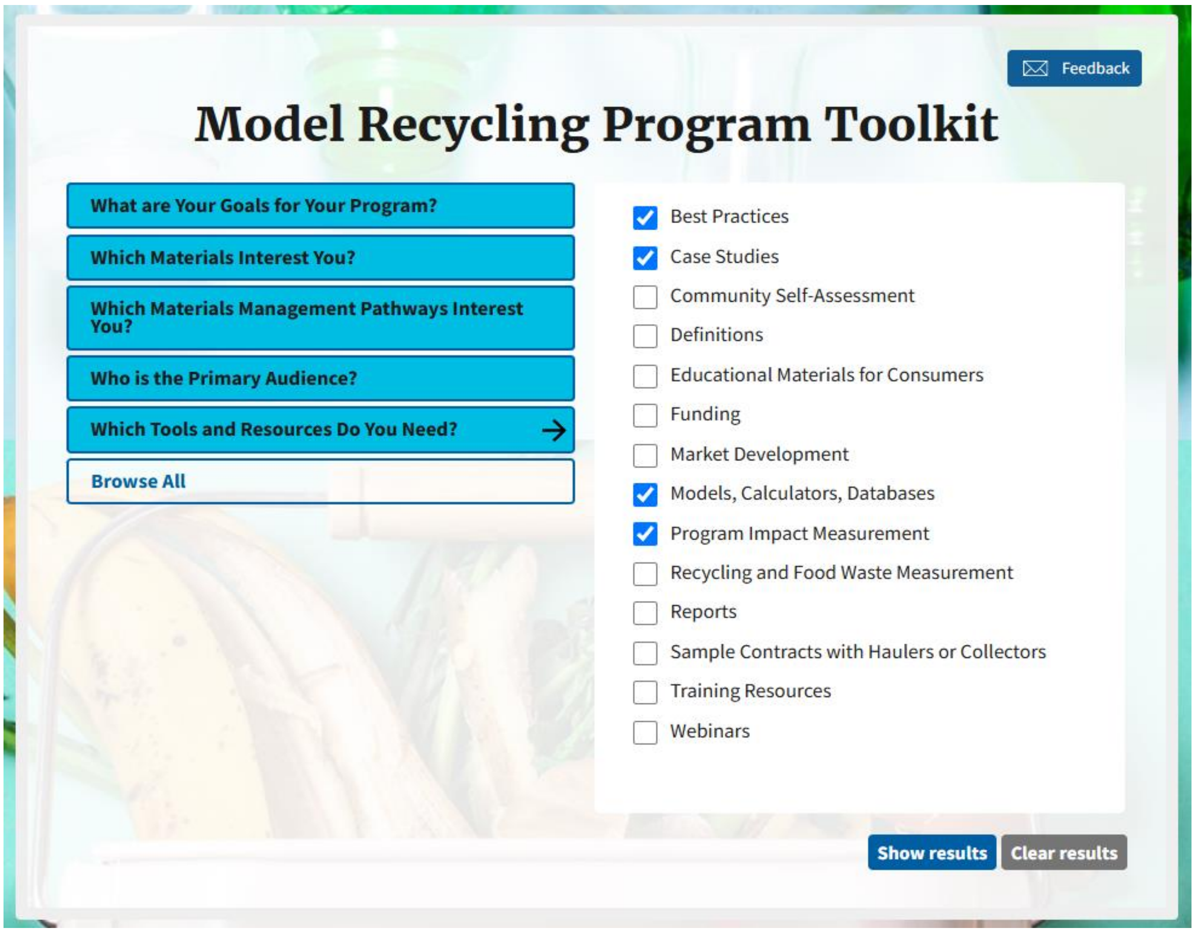

Figure 2-5. Representation of Available Resources Provided by the EPA Recycling Toolkit (U.S. EPA, 2024)

Similar to government involvement, community support can either make or break the real-world application of an EIP or IS network. There is an understandable, yet unfortunate stigma attached to industrial waste management, thus utilizing waste products in an EIP can be met with resistance from the community. Like the degree of social embeddedness impacts the inter-firm relations within an IE network, the level of community embeddedness is also a crucial component. A well-functioning EIP can serve as a sense of pride for the surrounding community due to the vast potential for economic and environmental benefits, but without adequate education and involvement from community stakeholders throughout the planning stage an EIP may not have the chance to thrive and grow (Perrucci et al., 2022).

The importance of community involvement is exemplified through the ReVenture site proposed in Charlotte, NC. This site was designed to convert a former industrial site to a 700-acre eco hub including solar fields, composting, biofuel production, conversion to “green” fuels, open space, wildlife enhancements, and office space catering to “green business”. Furthermore, the original design included a county-run wastewater treatment plant and facilities that would, in contrast to traditional incineration, generate power through the conversion of municipal solid waste (MSW) into synthetic gas (Marks, 2011).

Despite the environmental benefits and the promise of bringing more than 1,000 jobs to the community, a lack of community support resulted in the dilution of the ReVenture project from a 50-megawatt garbage-to-energy plant to two biomass units producing a combined 3.3 megawatts of electricity (Downey, 2014). Community concerns included “the potential for air pollutants from waste conversion, existing poor air quality at local schools, a lack of experience from ReVenture developers in waste-to-energy conversion, and the proximity of the project to the Catawba River” (Marks, 2011). Local groups opposed the project and “considered it a ‘dirty’ technology” (Downey, 2014).

Contrary to the public's perception, waste-to-energy projects such as this can actually improve local air quality since the methane gas that would typically be emitted into the atmosphere is instead captured and converted into a renewable energy source (U.S. EPA, 2024). As of 2024 these projects have soared in popularity and have proven to be effective and resourceful ways to reduce GHG emissions associated with waste disposal while simultaneously providing an in-demand revenue stream and diversifying domestic energy production (U.S. EPA, 2024). Had the specifics of waste-to-energy projects been properly communicated to the public, this component of the ReVenture project could have represented a truly sustainable solution that satisfied all three pillars of sustainability. Although ReVenture initially received financial incentives provided by the local government, the project would have benefited from developer and governmental collaboration on education programs to ease public concern.

The developer was notably "blindsided" by the opposition. Once on a fast-track to fruition with negotiations underway for anchor firms including a $200 million wastewater treatment plant and a $156 million gasified-waste plant, progress on ReVenture abruptly stalled. The public opposition created a ripple effect which spawned hesitation in policy makers/public officials and led to the brisk retraction of government incentives. Without firm governmental support, negotiations between prospective firms dried up. By the time the revised ReVenture was up and running three years later, it was operating a completely different design on a footprint barely one-sixth of the original plan. Among the new firms established at the site was an electronics recycling company, a bio-engineered textile manufacturer, and an electric vehicle assembly plant (Downey, 2014). Although still somewhat successful, this is a prime example of what may happen when trust between stakeholders (e.g., the local community) is not achieved.

2.3.3.4 Geographic Proximity

When discussing IS or IE networks, the first aspect often considered involves the proximity of participating businesses to each other. Maintaining a relatively short physical distance improves efficiency and profitability within the network by eliminating excess costs and logistics associated with transportation (Lowe and Evans, 1995). However, proximity can be relative and is not necessarily a requirement for the initial implementation of a successful IE network. Each network is unique. Depending on the businesses involved, the specifics of their geographical locations, and/or other variables, it may be more effective to develop areas between firms instead of building new facilities around the existing ones from the start. Factors pertaining to the local culture and specific environmental conditions of the landscape should be considered in this aspect of IE design to ensure the system's (Perrucci et al., 2022).

In the Kalundborg Symbiosis example, the IS network was not restricted to firms of adjacent plots of land; instead, the IS naturally developed based on the unique factors applied to each relationship (e.g., distance, geographic features, community cohesiveness, etc.). One of the factors contributing to Kalundborg's success is a commitment to the coevolution of the IS network and the community. The city of Kalundborg's total population is approximately 16,000 people, of which approximately 4,500 are employed throughout the network of 16 local businesses (Kalundborg Symbiosis, n.d.). Over several decades the network has become a component of the community's identity, and because of this the network is strong and resilient.

Figure 2-6. Geographic representation of the Kalundborg industrial symbiosis network (Kalundborg Symbiosis, n.d.)

2.3.4 Material Flows

Flows within an IE network are either incoming, outgoing, or internal and transport a variety of components (e.g., materials, energy, information, etc.) (Song et al., 2018; Bellantuono et al., 2017). The most essential type of flow is arguably the energy source. Energy flows within an IE or IS network are similar to those of natural ecosystems, the main difference being that IEs require energy inputs throughout each stage of the system whereas the embodied energy produced by lower organisms in natural systems is transferred (Shmelev, 2011). At Kalundborg Symbiosis, material flows consisting of various energy sources, water resources, and materials are exchanged through the network, as exhibited in Figure 2-7.

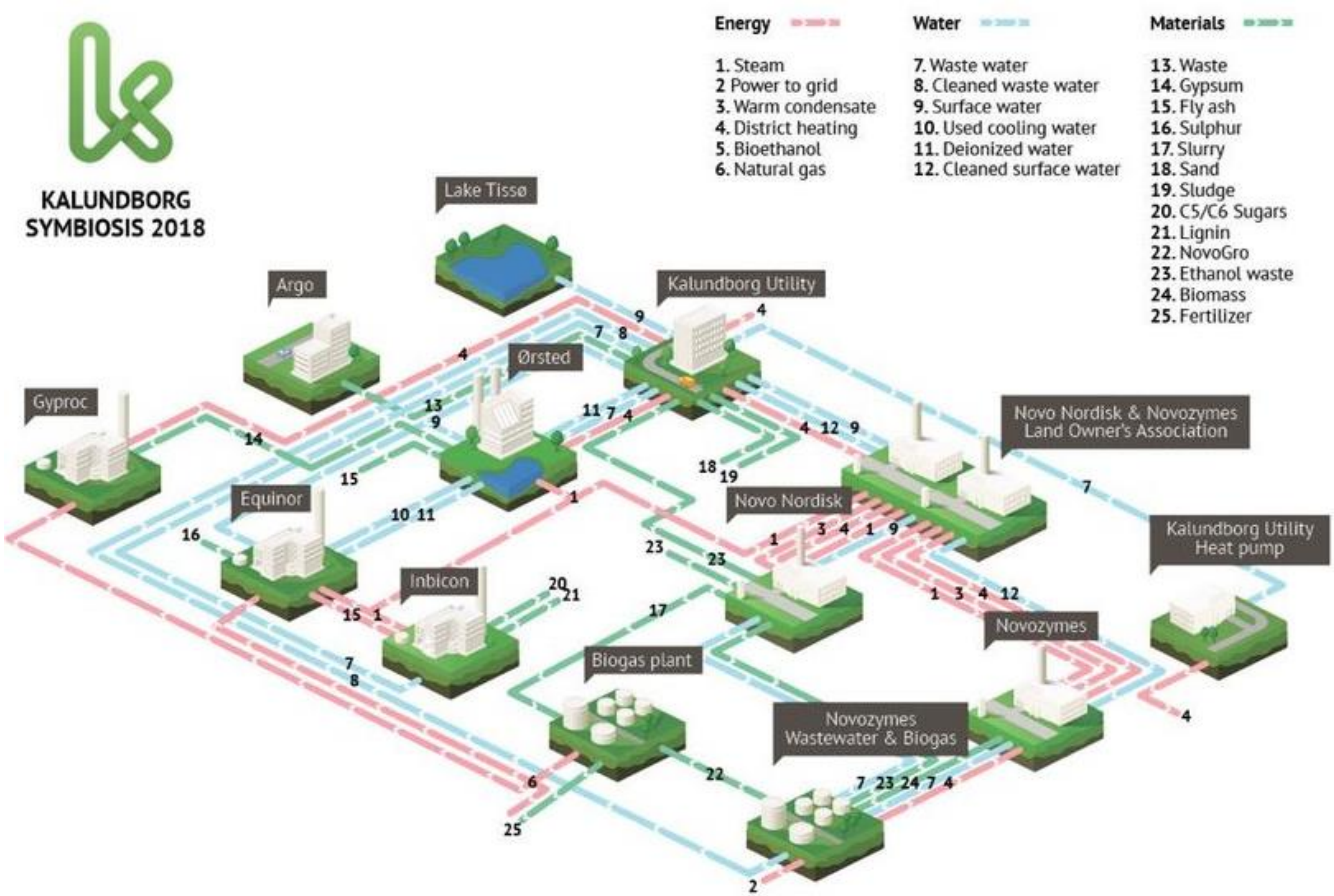

Figure 2-7. Representation of material flows through the Kalundborg industrial symbiosis network (Kalundborg Symbiosis, n.d.)

All industries, regardless of potential involvement in an IE network, are dependent on specific energy sources; this makes energy one of the simpler/more straightforward flows to recycle/exchange between industries. The energy sources are often powerplants or power stations, but energy could also come in the form of heat, water, or gas. Most often agreements are made with local power plants to reroute waste energy for industrial use; however, IE energy suppliers could also include other industrial facilities such as leather manufacturers which produce large volumes of wastewater, solid waste processors such as municipal landfills which often practice landfill gas harvesting, or other industries (U.S. EPA, 2022).

Once identified, an informal audit of this energy should be surveyed to understand 1) what the main energy supplies, 2) where the excess energy goes, 3) the kind of excess energy produced, and 4) the potential levels at which this excess energy can be utilized (Lowe and Evans, 1995). Of course, having an energy producer within an IE network is not exclusively required, but it can be a simple place to start as energy producers are compatible with a variety of industries and the use of recaptured energy can reduce costs significantly. However, optimization of energy production and use within an IE network can also be developed over time as the energy needs of the network are better understood (Chae et al., 2010).

2.3.4.1 Potential of Construction Materials in IE/IS Networks

Because they often have non-competitive waste streams, there is significant potential in EIP or IE networks centered around construction waste. In these networks, high costs associated with both the disposal of construction waste and the acquiring of raw materials helps to maximize the benefits between parties while minimizing the perceived risk (Perrucci et al., 2022). Examples of material flows for concrete materials are shown below in Figure 2-8.

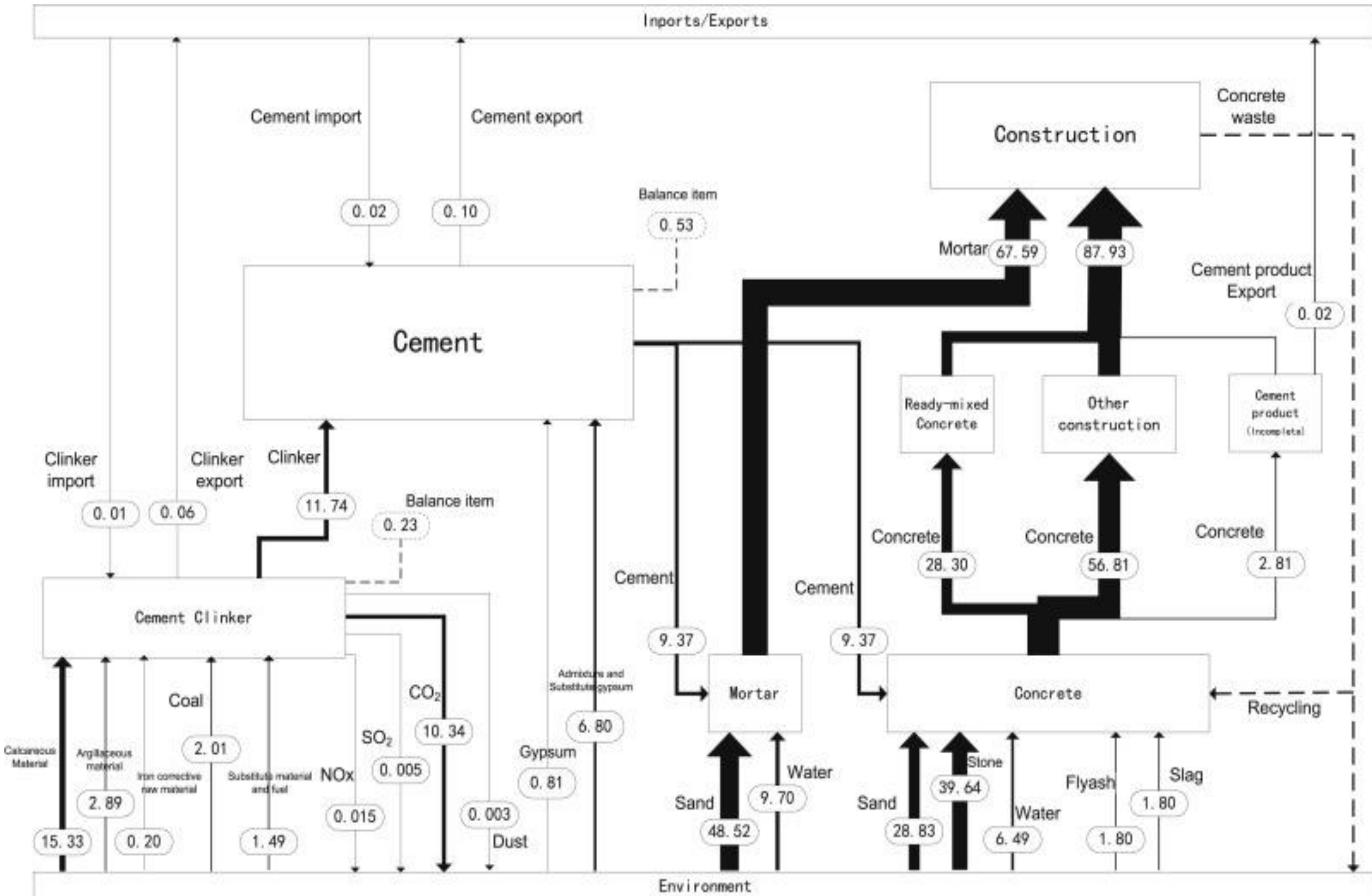

Figure 2-8. Representation of material flows throughout the cement industry in China for 2010 (Wang et al., 2016)

2.3.4.2 Use of Industrial Byproducts in SCMs

In recent decades industrial wastes such as fly ash, a byproduct of burning coal, have successfully served as SCMs to improve the sustainability of concrete. SCMs can also improve durability through mechanisms such as reduced water demand, improved workability, durability against cracking due to thermal and drying shrinkage, reinforcement corrosion, sulfate attack, and alkali-silica expansion (Van Dam, 2013; Struble and Godfrey, 2004). Such benefits of one of the world's most popular SCMs have revolutionized the concrete industry; however, as fossil fuels are being phased out around the world, there is a growing need to identify safe new alternatives that can provide the same benefits.

2.3.4.3 Use of Industrial Byproducts as Aggregates

The demand for aggregates is quickly increasing to keep up with the construction boom resulting from trends in increased urbanization. To fill this demand industrial byproducts have also been used as alternatives to natural aggregates (e.g., limestone, gravel, gabbro, sand, etc.). Similar to SCMs, the goal of using industrial byproduct aggregates is to reduce ecological strain while reducing costs and improving mechanical properties of concrete (Palankar et al., 2015).

Aggregates can be selected based on their characteristics to provide different properties to a mixture depending on its intended application. Variation between materials provides the opportunity to create specialized mixtures that address specific structural issues. A variety of waste materials/industrial byproducts are being explored for use as aggregate substitutes. Examples of these materials include coal ash, blast furnace slag, fiberglass waste materials, waste plastics, rubber waste, and sintered sludge pellets (de Brito and Saikia, 2012). Results from these studies identify a continued need for the identification of suitable materials and processes and have yet to identify uniform results. Recommendations for future research suggest waste materials with high concentrations of SiO_2, Al_2O_3 and CaO are the most promising. This is due to the formation of C-S-H gel or Na-Al H gel during the reaction which impacts properties such as bulk density and particle density. Other findings emphasize pelletization to produce aggregates with round smooth surfaces which enhance the viscosity and flowability of concrete since fine cement particles are more easily able to fill spaces between round aggregates opposed to their angular counterparts (Kwek and Awang, 2021).

2.4 Market Analysis of Key Industries

Like concrete, modern society has grown heavily dependent on phosphoric acid, largely for fertilizer applications. The ability to process phosphoric rock into essential nutrients has given humanity the ability to support and feed more people than ever before. Predictions by the UN Department of Economics and Social Affairs estimate that the global population will reach 9.7 billion by 2050, 68% of which are expected to live in urban areas (United Nations, n.d.). Growing populations correlate with a steadily rising demand for food production, a demand currently met through the use of fertilizers. As shown in the market, developing regions and countries have the highest demand for fertilizer (Markets and Markets, 2022).

In many ways this demand is a double-edged sword. A quickly growing population has led to rapidly increasing rates of industrialization and urbanization, which in turn put increased stress on the environment's ability to produce necessary ecosystem services (ES). Maximum output is required at a time when land and other resources are at an all-time scarcity. The expansion of agriculture is now in fierce competition with urbanization and industrialization for land resources. Farmers have adapted by maximizing crop yields through a dependence on fertilizers and other nutrients (Research and Markets, 2022).

2.4.1 Global Supply Chain

Phosphoric Acid

The industry approximates the value of the global phosphoric acid market at USD 35.2 billion in 2023 with projections expected to reach USD 54.0 billion by 2032 (Fortune Business Insights, 2024; Markets and Markets, 2023). Although phosphoric acid is used in many applications such as fertilizers, feed and food additives, industrial products, detergents, water treatment products, metal treatment products, etc., fertilizers account for the largest global market share year after year (Markets and Markets 2022).

Nitrogen, phosphorus, and potassium are all essential components of fertilizer. However, because phosphorus and potassium are mined minerals, some countries are at a geological disadvantage when it comes to availability. A 2022 report by the USDA Foreign Agricultural Service found that one-third of the world's phosphorus is manufactured by China, the largest global producer, followed by the United States, India, Morocco, and Russia, respectively. In total these five countries produce over three-quarters of the global phosphorus supply. In 2021, Asia Pacific was the largest market for phosphoric acid (namely China, India, and Indonesia) (Jones and Nti, 2022).

SCMs

The industry approximates the global value of the SCM market at USD $12 billion in 2021 with projections expected to reach $17 billion in 2028. “SCM” is a broad category that covers a variety of materials but fly ash (types C and F) makes up more than 50% of the market share, 75% of which is associated with the construction industry. Although recent regulations have spread throughout the U.S. and Europe, production of fly ash is growing in Asia with 60% of the total growth expected to come from China and India. Due to rapid urbanization, it is predicted that Asia-Pacific will account for more than 50% of the total market share for fly ash by 2025. Unless dependable sources of alternative SCMs are identified domestically, the U.S. will become reliant on expensive, and emission-heavy imports from overseas to meet future demand (SkyQuest Technology Consulting, 2022).

Since many SCMs are industrial byproducts, the SCM market is expected to thrive under the new era of increased environmental regulation. In a time when rising populations bring a high and non-negotiable demand for carbon-conservative infrastructure, the building and construction industry has responded to this call to action with SCMs. These factors will continue to open new market opportunities.

2.4.1.1 United States Market

Phosphoric Acid

According to the Mineral Commodity Summary by the U.S. Geological Survey, approximately 21 million tons of marketable phosphate product (valued at $1.9 billion) was mined and processed in the U.S. in 2022. EPA estimates show that 90% of this production occurs in the southeastern U.S. (Florida, North Carolina, Tennessee) with the remainder being produced in Idaho and Utah. The report identifies Florida and North Carolina as accounting for more than 75% of the total domestic output of phosphate; however, the majority is produced in Florida. In fact, Florida is the world's largest phosphate producing area in the U.S. as of 2023 (U.S. EPA, 2023; Jasinski, 2020).

Approximately 10% of global fertilizer usage occurs in the U.S., the majority of which is used to produce grains and oilseed, as indicated by the USDA Foreign Agricultural Service (Jones and Nti, 2022). Although the U.S. manufactures the majority of its nitrogen and phosphate fertilizers, an estimated 20% is still imported. The imports are typically potassium based; however, a portion of imports are also made up of nitrogen and phosphorus-based fertilizers. Some of these imported fertilizers are processed further in manufacturing and blending facilities to make compound fertilizers which are then reexported to international markets.

SCMs

As revealed by the 2021 Production and Use Survey and Results News Release published by the American Coal Ash Association (ACAA), "the use of all coal combustion products in cement production increased 14% to 5.6 million tons" in 2021. Additionally, the use of fly ash in concrete has continued to increase to 11.9 million tons. As of July 2022, the only U.S. state that was not home to at least one coal-fired power plant was New Jersey. The majority of active plants are concentrated in the Midwest with nearly 27% located in Indiana, Kentucky, Texas, and Illinois; however, many other eastern and Midwest states are scattered with fly ash disposal pits that could potentially be harvested for use in concrete applications.

2.4.2 Recent Market Impacts

2.4.2.1 COVID-19

Phosphoric Acid

The global coronavirus pandemic resulted in significant disruptions to the global supply chain for industries of all kinds; the phosphoric acid industry was no exception. During this period both main supplies and manufacturing lines were disrupted which resulted in shortages throughout each stage of the supply chain (Research and Markets, 2022). Since fertilizer is the main application of phosphoric acid, the resulting impact of decreased production and availability of phosphoric acid caused a significant decrease in crop production and led to global food shortages and inflation during the pandemic. Although problematic, this global crisis further emphasizes the importance of reducing dependence on phosphoric acid imports within the United States.

SCMs

Data provided by the Energy Information Administration (EIA) showed the coronavirus pandemic resulted in the lowest level of coal production in the U.S. since 1965 due to decreased industrial production and commercial activity. Naturally, impacts from this decrease in production sent ripple effects through the fly ash market. Further disruptions to other construction materials throughout the global supply chain and prolonged shutdowns halted construction projects during the height of the pandemic. Although disruptions to the supply chain and a halt in construction activities decreased the global demand for SCMs, the overall demand is expected to increase quickly over the next decade as the backlog of construction projects are completed and urbanization continues (Business Market Insights, 2022; Exactitude Consultancy, 2023).

2.4.2.2 Russia-Ukraine War

Before the world had a chance to recover from the coronavirus pandemic, the Russian invasion of Ukraine threw an additional hurdle into the global supply chain, especially in terms of fertilizer. Historically speaking, Russia has been a major exporter of the phosphate fertilizers upon which much of the world depends. War-time restrictions on nitrogen, phosphate, and potash fertilizer exports were put in place through June 2022 which removed 15% of the global fertilizer supply. Although detrimental to global food security, these financial impacts were limited due to contracts between Russia and countries importing material which were contracted in 2021 for 2022 plantings, prior to the restrictions taking effect (Jones and Nti, 2022).

The continued financial strain on the fertilizer industry is expected to worsen domestically and internationally for agriculture going forward. Further uncertainty is likely to worsen until the end of the Russia-Ukraine war since increasing production is not something that can happen instantaneously. Assuming the necessary mineral reserves are available, ramping up production is expected to take an average of three to five years using current methods - a solution made more difficult by the limited geographic availability of phosphate and potash reserves (Jones and Nti, 2022).

In addition to disruptions in Russian fertilizer exports, the political conflict has also halted Ukrainian fertilizer production. The International Fertilizer Association reported 1.58 million metric tons of fertilizer produced in Ukraine during 2019 which supplied over 75% of its domestic nitrogen needs. In 2021 it was reported that 65% of Ukrainian imported fertilizers were sourced from Russia and Belarus through contracts and reserves purchased prior to the eruption of the current conflict. The resulting impact is expected to have heavy implications for the global supply chain due to Ukraine's position as a major grain and oilseed exporter (Jones and Nti, 2022).

<u>SCMs</u>

The ongoing Russia-Ukraine war has resulted in high energy costs and has further hindered the already weakened global commodities markets. Furthermore, continued military efforts are expected to result in further uncertainty throughout the steel, oil, and energy markets (Global Data, 2022).

2.4.2.3 Restrictions and Sanctions

Globalization has noted financial benefits; however, the system is far from resilient. This is proven through the impacts that seem to snowball throughout the supply chain given the slightest upset. In addition to the blockage of traditional Russian shipping routes through the Black Sea, curtailments of Russian natural gas resulted in a surge in European natural gas prices in 2021 leading to reduced production of ammonia (a crucial component of nitrogen fertilizer production). In response to rising coal prices, China began rationing electricity usage which impacted the production of certain fertilizer plants. This prompted the Chinese government to implement a quota on fertilizer exports to secure their domestic supply and ensure food security - an additional blow to the global supply (Jones and Nti, 2022).

The Russia-Ukraine war has led many countries to implement restrictions on Russian and Belarusian imports which further limit the global supply since these countries are major suppliers to the global fertilizer market. In response to these sanctions, Russia implemented restrictions on nitrogen and complex nitrogen fertilizer exports through June 2022. Although the guarantee of Russia's fertilizer exports was later codified to maintain fertilizer exports through the end of 2022, the uncertainty within the market is only expected to worsen.

2.4.2.4 Diminishing Global Supply

Phosphoric Acid

Phosphate fertilizer production is limited by two crucial constraints: geographic availability and quality. Phosphate rock is a non-renewable finite resource which takes millions of years to develop. The majority of phosphate rock reserves are located in Morocco, the United States, and China, leaving the rest of the world heavily dependent on international trade (Ryszko et al., 2023; Cooper et al., 2011). The viability of available phosphate rock in these countries is further hindered by quality and grade. Large high-grade deposits are often geographically limited to (former) continental shelves (Cooper et al., 2011). Lower grade phosphate rock can be obtained from igneous rock sources and then upgraded to higher concentrations through mining processes (Edixhoven et al., 2014). However, the quality of phosphate deposits are anything but uniform and can vary significantly within a local mine (Ryszko et al., 2023). It is noted that other non-mineral sources of phosphate, such as guano and ground fish meal are used in some areas of the world in lieu of phosphate-containing rock (Ijaz Muhammad, et al., 2021).

To turn phosphate rock into phosphoric acid, these source materials are processed using either thermal or wet processes. Because of the lower energy demand, wet processes are more common throughout the industry. During the wet processes, phosphate rock is reacted with sulfuric acid at temperatures of 70-80°C which results in a concentration of approximately 26-30% P_2O_5. The material is then processed two additional times to obtain P_2O_5 concentrations of 40% and 50% respectively and then clarified to obtain quantities acceptable for use in fertilizer applications. Despite this intricate technique, the wet process produces phosphoric acid that still contains impurities (Ryszko et al., 2023). This production effort is financially and environmentally burdensome, producing large quantities of waste products (e.g., mine tailings waste, phosphogypsum). The last several decades have seen the depletion of the most accessible high-quality phosphate rock deposits in the U.S., leading to limited and tightly controlled resources for wet-acid producers across the nation (Novaphos, 2022). Although there seem to be conflicting interpretations of models of global phosphate rock reserves, it is clear that the current phosphate industry must become more financially and environmentally efficient to become resilient against changing market flows (Heckenmuller et al,. 2014).

<u>SCMs</u>

Fly ash has played a significant role in efforts to decarbonize the cement industry, and as regulations and demand increase while supplies dwindle, landfill harvesting has become an increasingly attractive option for suppliers. Only an approximated 27% of fly ash produced over the past two decades has been diverted for beneficial reuse. Despite the high likelihood of meeting performance attributes for concrete applications, most of the remaining 73% was disposed of in landfills and impoundments due to low market demand at the time of its production. The U.S. has produced fly ash since the early 1900s, leaving stockpiles scattered across the country. While some of this material is likely unsuitable for concrete applications or available for harvesting, there are options for accessing these reserves given the appropriate financial and technical conditions (Tritsch et al., 2020).

Harvested fly ash requires specific preparation to achieve adequate standards for use in concrete. Landfill harvesting involves site characterization, drying to meet moisture content limits, screening and size separation (i.e., separating fly ash from bottom ash commingled during disposal), and additional beneficiation to remove excess carbon. This can be an elaborate, expensive, and energy intensive process. Because of this, fly ash is often only harvested from waste sites when sufficient market demand not being met by fresh fly ash sources, when there is sufficient quantity of fly ash within a reserve site to support extraction long enough to pay off the capital investment, and/or amidst regulations or legislative pressure to utilize a disposal site for beneficial reuse (Tritsch et al., 2020). Depending on other materials commingled with fly ash in specific waste sites, additional processes to treat and separate ash may be required, resulting in further expenses and carbon generation since the reaction requires fossil fuels. Landfill harvesting of fly ash is not necessarily straightforward and, therefore, the concrete industry is still looking toward other materials to fill the need for fly ash (Cavalline and Sutter, 2024).

2.4.3 Industry Innovations

The discovery of a new method for processing phosphoric acid for fertilizer production has the potential to revolutionize the phosphate industry. In contrast to traditional methods of phosphoric acid manufacturing, new technology can produce high-quality phosphoric acid from low-quality rock with high impurities. Instead of producing large quantities of waste products (e.g., mine tailings waste, phosphogypsum), this new process developed by Florida-based company Novaphos, Inc. creates a coproduct, referred to as J-Rox, which is a solid calcium silicate product that remains after the phosphate or sulfur content of the feed is extracted (Novaphos, 2022).

The Novaphos technology can utilize phosphate deposits that were previously deemed too low-grade by traditional industrial processes; the process can even utilize mine waste tailings. Furthermore, this new process does not require sulfur or ammonia, thus simplifying the production process and reducing waste. This simultaneously addresses the need to reduce import dependency and identify reliable sources of raw materials that enable an “end-to-end production of phosphates within the U.S. for many years to come" (Novaphos, 2022).

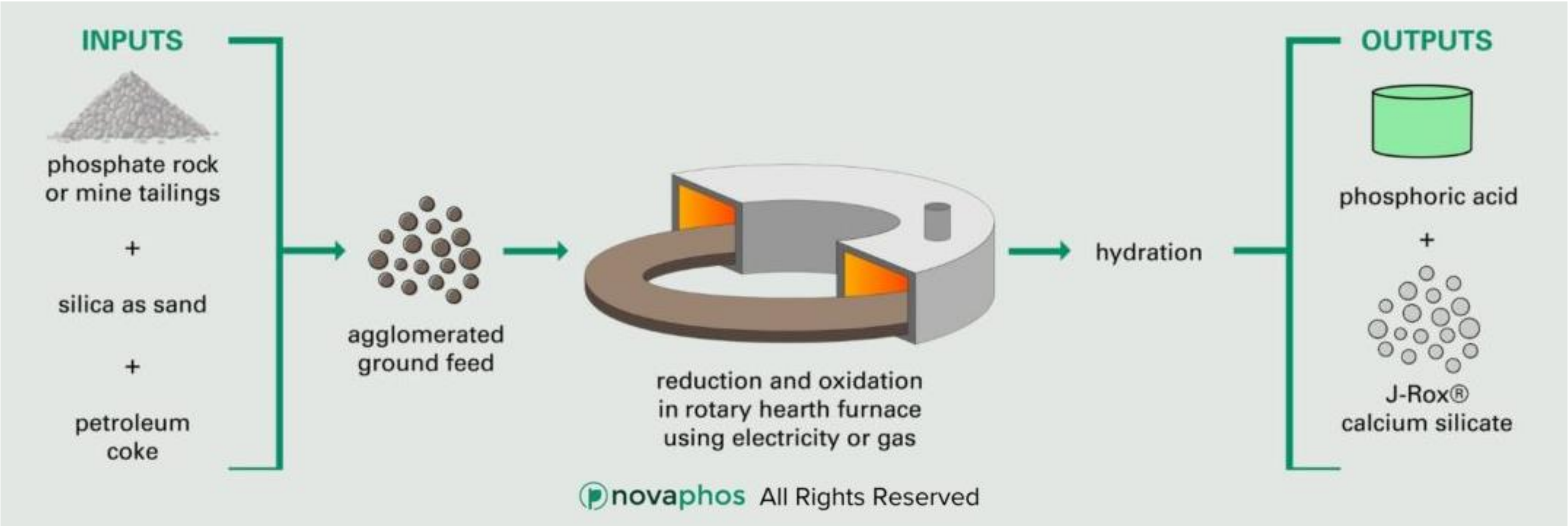

Figure 2-9. Novaphos Phosphoric Acid Production Process (Novaphos, n.d.)

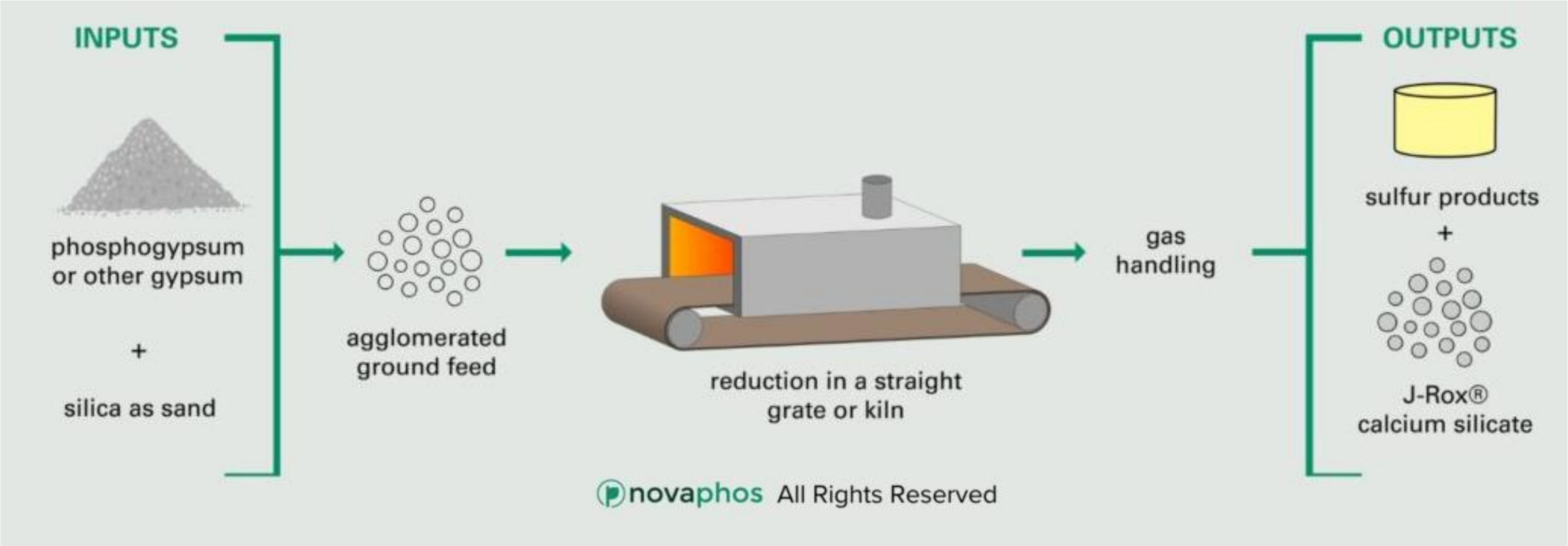

Figure 2-10. Novaphos Phosphogypsum Recycling Process (Novaphos, n.d.)

The lower quality source material is used to manufacture a phosphoric acid process for high quality material that can be used throughout the phosphate chain. The phosphogypsum waste produced through traditional methods is avoided and replaced with a useful coproduct (J-Rox) which has its own beneficial reuses throughout the construction industry as an SCM, a fine aggregate, and even as a silicon fertilizer. This process confines the rock metallic impurities (e.g. radium, cadmium, and arsenic) within the J-Rox and results in a purer phosphoric acid product.

The financial benefits from this process are enticing to producers. In comparison to traditional wet acid process, the Novaphos process reduces the mining cost of P_2O_5 in phosphate rock and is able to gain additional value through the use of mine tailings. Additionally, there are no disposal costs associated with gypsum, and expenses related to the downstream processing to upgrade the acid are avoided. Over time and with increased economies of scale, Novaphos expects the capital cost per unit of P_2O_5 to decrease further. These manufacturing plants can be deployed efficiently at much smaller scale, allowing production to occur closer to U.S. consumers and further reducing logistical costs and environmental impacts. Because the J-Rox coproduct can be used to replace portions of cement in concrete applications, the overall greenhouse gas emissions associated with the phosphoric acid process may be reduced with the offset from avoided cement production (Novaphos, 2022).

2.5 Research Needs

As discussed throughout this chapter, the construction industry has developed a dependence on select industrial byproduct SCMs and aggregates for use in concrete applications due to their exceptional ability to reduce costs, improve the strength and durability of concrete, and keep significant quantities of material out of the waste stream. With typical combustion-based SCMs growing in short supply due to increased environmental regulation, there is a growing immediacy within the industry to identify comparable substitutions that will not be affected by the global transition away from fossil fuels.

In addition to evaluating the use of J-Rox as an SCM in concrete applications, the goal of this project is to further identify the potential of J-Rox in reducing environmental impacts from the construction/concrete industry through the creation of an industrial symbiosis network. This evaluation was conducted by performing a variety of tests on paste, mortar, and concrete specimens containing certain percentages of cement replacement with J-Rox (SCM). Tests were performed on fresh (i.e., paste, mortar, and concrete) and hardened specimens, with both mechanical property and durability performance tests compared to control specimens (i.e., 100% cement and 20% fly ash).

The sustainability and market potential of an industrial symbiosis network centered on J-Rox in a scavenger/decomposer role was determined by evaluating the nature of the current market (i.e., material flows and general manufacturing process of existing SCMs and J-Rox), understanding that the industry demand is not being met through current SCMs (i.e., environmental, economic, social), and acknowledging what is required for the evolution of an effective and efficient J-Rox focused industrial symbiosis network. The results from this project will provide a use for the material(s) that benefit the construction industry and provide additional information for the market implications of a J-Rox focused industrial symbiosis network.

CHAPTER 3: METHODOLOGY

3.1 Introduction

To evaluate the efficacy of J-Rox as a SCM, paste and mortar samples were produced at 15%, 20%, and 25% cement replacement rates. In response to the results of mortar testing, concrete samples were produced using the highest performing J-Rox samples at 15% and 20% replacement rates, as well as a ternary blend of 15% J-Rox and 35% ground granulated blast furnace slag (GGBFS) totaling a 50% cement replacement rate.

Hardened mortar samples were tested for compressive strength, while concrete samples were tested for their fresh properties (i.e., slump, air content, unit weight, mixture temperature) as well as mechanical properties (i.e., compressive strength, sulfate resistance, modulus of elasticity, shrinkage, electrical resistivity). Test results for both concrete and mortar samples were compared to control samples of 100% ordinary portland cement (OPC) and 20% fly ash. The applicability of utilizing J-Rox samples as a SCM was evaluated based on comparability to the performance of the two (2) control mixtures.

3.2 Materials Description and Characteristics

The following section provides details about the materials used throughout the testing program. This includes information regarding the source location and key chemical and/or physical properties of the materials which were identified through in-house testing, or test results obtained from the supplier.

3.2.1 Cementitious and Supplementary Cementitious Materials

Five (5) samples of J-Rox with varying chemical compositions were provided by Novaphos. The chemical composition and physical properties are shown below in Table 3-1. It should be noted that the elemental weights of JR-1 were given as Na and K, instead of Na_2O and K_2O, respectively.

Table 3-1: Identifying Data and Chemical Analysis of J-Rox Samples

Parameter	Units	Cement Type I	Fly Ash (Type F)	Gyp / Sand / Clay (JR-1)* 7/20/2021	Low Silica (JR-2) 4/9/2022	High Silica (JR-3) 4/8/2022	GypRox (JR-4) 4/9/2022	GypRox (JR-5) 11/3/2022
SiO_2	%	20.1	52.7	65.1	32.8	52.2	57.1	69.5
CaO	%	63.6	2.1	18.8	35.3	23.6	25.2	19.9
P_2O_5	%	0	0.21	5.9	14.3	11.2	4.2	5.7
SO_4	%	0	0	2.5	2.3	1.2	7.2	1.6
S	%	0	0	0.92	0.8	0.5	1.3	0.6
Fe_2O_3	%	3.5	11.12	1.52	2.5	1.8	0.53	0.5
Al_2O_3	%	4.8	26.7	1.44	1.8	1	0.4	0.2
MgO	%	1.4	1.1	0.2	3.3	2	0.28	0.2
F	%	0	0	0.64	1.6	1.2	0.2	0.3
Na_2O	%	0	0.34	0.15	0.4	0.3	0.03	0.1
K_2O	%	0	2.24	0.2	0.1	0.1	0.06	0
C	%	0	0	0.1	2.4	3.5	0.03	0
As	ppm	Not Available	Not Available	4.5	1.4	1.2	1.2	5.3
Cd	ppm	Not Available	Not Available	1.5	0.3	0.2	0.7	1.2
Cr	ppm	Not Available	Not Available	60	72	55	29	28.8
Ni	ppm	Not Available	Not Available	12	153	122	11	22.6
Pb	ppm	Not Available	Not Available	6.3	0.6	1.4	3.9	1.8
Zn	ppm	Not Available	Not Available	25	13	14	43	17.2
U	ppm	Not Available	Not Available	50	63	42	0	4.7
*Note: Chemical properties were defined with slightly different elements for JR-1. The chemical analysis of Na_2O was reported as Na, and K_2O was reported as K.								

Although oxide analysis is standard practice within the industry for depicting the composition of concrete materials (i.e., fly ash, cement, slag, etc.), it may present a one-dimensional view of the relationship between composition and the performance of resulting materials. Factors such as the mineralogic form of the element (e.g., calcium can be present as lime, sulfate, etc.), or the reactivity of the mineral or element (e.g., glassy, amorphous, etc. which dictates reactivity) have varying impacts on concrete/mortar performance which cannot be evaluated from an oxide analysis alone.

While oxide analysis may not provide a conclusive correlation between composition and performance, it can provide some direction for further exploration/comparison of additional material attributes (i.e., composition, size, and surface characteristics). A graphical analysis of each material's chemical composition is included in Figure 3-1; additional information regarding the particle size analysis for the five (5) J-Rox materials is also included in Figures A.1 through A.5 of the attached Appendix.

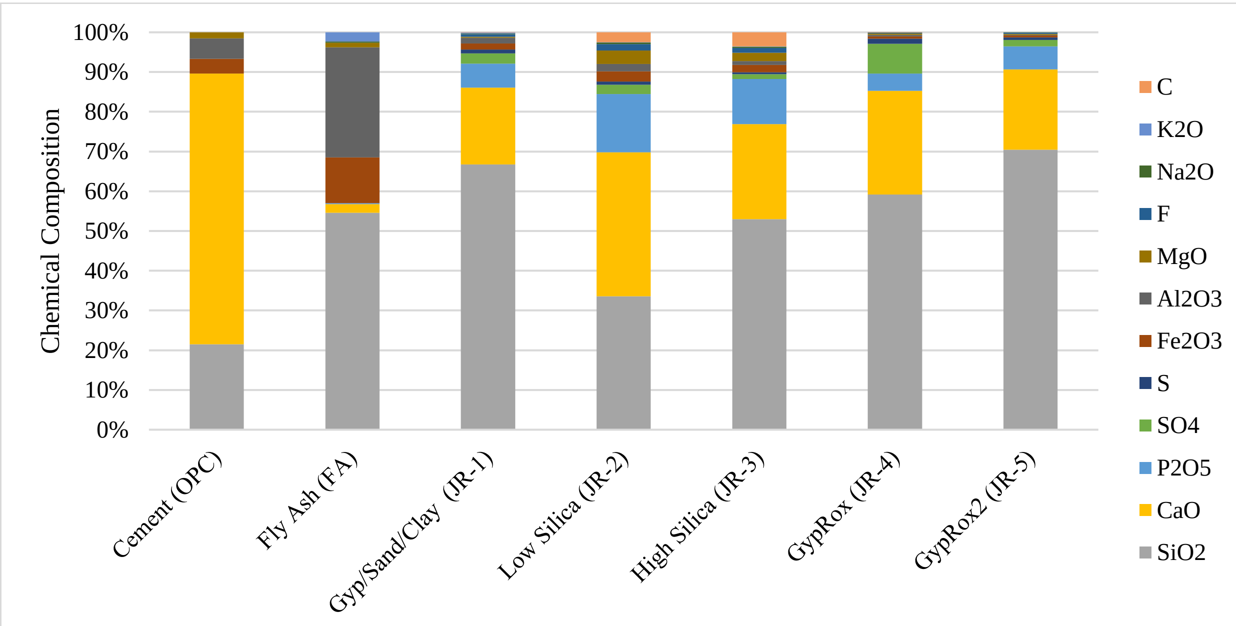

Figure 3-1. Chemical composition of J-Rox materials compared to OPC and fly ash

3.2.2 Aggregates

Characterization tests were conducted for the Florida limestone coarse aggregate supplied by Vulcan Materials. Following the procedures described in ASTM C136/136M-19 "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates" (ASTM 2019), a sieve analysis of the aggregate was performed. Per the standard, a sample of the material was oven dried to a constant mass at 230 °F prior to sieving via a Gilson Company mechanical sieve shaker. Based on the observed nominal maximum size of 25 mm (1 in.), a test sample size of 22 lbs was selected in accordance with ASTM C136/136M-19. Results of the sieve analysis are shown in Table 3-2.

Table 3-2. Sieve Analysis of Florida Coarse Aggregate (ASTM C136/136M-19)

Sieve Size (in)	Mass Retained (lb)	% Retained	Cumulative % Retained	% Passing
1” (25 mm)	0.231	1	1	99
3/4" (19 mm)	7.369	25	25	75
1/2" (12.5 mm)	13.768	44	69	31
3/8" (9.5 mm)	5.104	16	86	14
No. 4 (4.75 mm)	3.671	12	98	2
Pan	0.750	2	100	0
Total	30.893		309	
		Fineness Modulus	**3.09**	

Additional characterization of the aggregate was conducted for determining the relative density (specific gravity) and absorption of the provided aggregate, per standards described in ASTM C127-15 “Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate” (ASTM 2019). The aggregate sample was immersed in water for 24 ± 4 hours prior to testing to ensure all pores were fully saturated. The mass of the sample was recorded throughout each stage of the test: mass of oven-dry (OD) test sample in air, mass of saturated-surface dry (SSD) test sample in air, and the apparent mass of the saturated test sample in water at 23 ± 2.0 °C. These values were used to calculate the relative density of the sample in different conditions in accordance with the standard. Results from the characterization tests can be found in Table 3-3.

Table 3-3. Relative Density (Specific Gravity) & Absorption of Florida Coarse Aggregate

Coarse Aggregate Characterization [ASTM C127-15]			
Bulk Specific Gravity (OD)	**Specific Gravity (SSD)**	**Apparent Relative Density (SG)**	**Absorption (%)**
3.39	3.54	4.00	4.50

Fine aggregate of natural silica sand meeting the ASTM C33/C33M-18 “Standard Specification for Concrete Aggregates” (ASTM 2018) was sourced from a natural sand pit quarry in Lemon Springs, North

Carolina. Previous studies determined that the material had a specific gravity of 2.62 and absorption of approximately 1.48% (Theilgard, 2022).

3.3 Testing Program

The following testing program was developed to evaluate J-Rox as an SCM. For this phase of the project, Novaphos supplied two forms each of J-Rox (JR-2 and JR-3) and GypRox (JR-1 and JR-4) for use in mixture designs as replacement of cement in the percentages shown in Table 3-5, 3-6, and 3-7.

Each J-Rox material's performance as an SCM was initially evaluated based on the mechanical properties of the resulting paste (i.e., set time testing) and mortar (i.e., compressive strength and sulfate attack testing) mixtures. After assessing the overall performance of each potential SCM in paste and mortar applications, one J-Rox material was selected for further development within a mixture to test the fresh and hardened properties of concrete produced using the selected material as an SCM. A summary of the testing program for Task 1 is shown in Table 3-4. All tests were performed in accordance with ASTM and/or AASHTO standards, as listed below.

Table 3-4. Summary of Testing Program

Mixture	Name of Test	Test Standard	Testing Age (days)	No. of Replicates
Paste	Set Time	ASTM C191-21, "Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle" (ASTM 2021)	0	1
Mortar	Compressive Strength	ASTM C109/109M-21, "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars" (ASTM 2021)	3, 7, 28, 56, 91	3
	Sulfate Attack	C1012/C1012M − 18B, "Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution" (ASTM 2018)	7, 14, 21, 28, 56, 91, 105	3
Fresh Concrete	Temperature	AASHTO T 309, "Standard Method of Test for Temperature of Freshly Mixed Portland Cement Concrete" (AASHTO 2020)	Fresh	1
	Slump	C143/C143M − 20, "Standard Test Method for Slump of Hydraulic-Cement Concrete" (ASTM 2020)	Fresh	1
	Air Content	ASTM C231/C231M − 17A, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method" (ASTM 2017)	Fresh	1
	Fresh Density (Unit Weight)	ASTM C138/C138M − 17A, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method" (ASTM 2017)	Fresh	1

Table 3-4. Summary of Testing Program (cont.)

Mixture	Name of Test	Test Standard	Testing Age (days)	No. of Replicates
Hardened Concrete	Electrical Resistivity	AASHTO T 358-15, "Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration." (AASHTO 2017)	3, 7, 28, 56, 91	3
	Compressive Strength	ASTM C39/C39M-21, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." (ASTM 2021)	3, 7, 28, 56, 91	3
	Modulus of Elasticity & Poisson's Ratio	ASTM C469/C469M − 14, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression." (ASTM 2014)	28	2
	Shrinkage	ASTM C157/C157M − 17, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete." (ASTM 2017)	Per Standard	3

3.4 Paste Samples

3.4.1 Set Time

Paste mixtures were batched for the purpose of conducting set time tests for mixtures containing each type of J-Rox/Gyp-Rox at cement replacement rates of 15%, 20%, and 25%. These paste mixtures were produced following the procedure outlined in ASTM C305-20, "Practice for Mechanical Mixing of Hydraulic-Cement Pastes and Mortars of Plastic Consistency" (ASTM 2020). The water content for each paste mixture was determined in accordance with ASTM C187-16 "Standard Test Method for Amount of Water Required for Normal Consistency of Hydraulic Cement Paste" (ASTM 2016). Per the standard, a normal consistency of cement paste is achieved when the plunger of the Vicat apparatus settles to a point 10 ± 1 mm below the original surface within 30 seconds of being released.

Upon identification of the appropriate water content, the paste sample was used to determine setting time, following the procedure outlined in ASTM C191-21 "Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle" (ASTM 2021). A summary of these paste mixture materials and proportions is shown below in Table 3-5, with exception of the 25% JR-1 mixture (Gyp/Sand/Clay G-Rox) which could not be performed due to an insufficient amount of JR-1 material remaining.

Table 3-5: Paste Mixture Materials and Proportions

Sample	Paste Components [Setting Time Testing ASTM C191-21]		
	OPC (g)	Water (g)	J-Rox (g)
100% Cement Control	650	195	0
20% Fly Ash Control	520	190	0
15% J-Rox Replacement of Cement			
15% Gyp/Sand/Clay G-Rox (15 JR-1)	550	190	100
15% Low Silica (15 JR-2)	550	190	100
15% High Silica (15 JR-3)	550	195	100
15% GypRox (15 JR-4)	550	200	100
15% GypRox (15JR-5)	550	195	100
20% J-Rox Replacement of Cement			
15% Gyp/Sand/Clay G-Rox (15 JR-1)	520	195	130
15% Low Silica (15 JR-2)	520	197	130
15% High Silica (15 JR-3)	520	195	130
15% GypRox (15 JR-4)	520	207	130
15% GypRox (15 JR-5)	520	175	130
25% J-Rox Replacement of Cement			
25% Gyp/Sand/Clay G-Rox (25 JR-1)	490	200	160
25% Low Silica (25 JR-2)	490	205	160
25% High Silica (25 JR-3)	490	190	160
25% GypRox (25 JR-4)	490	195	160
25% GypRox (25 JR-5)	490	185	160

3.5 Mortar Mixtures

3.5.1 Compressive Strength

Mortar mixtures were prepared and tested in accordance with ASTM C109/C109M-21, "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in or [50 mm] Cube Specimens)" (ASTM 2021). Each mortar mixture was mechanically mixed with a Hobart paddle mixer following standards described in ASTM C305-20 "Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency" (ASTM 2020). Per the standard, mortar mixtures were designed in a ratio of 1-part cement and 2.75-parts of sand proportioned by mass. The water content of each mixture was selected to achieve a flow of 110 ± 5 % in 25 drops of the flow table, in accordance with Practice C1437-20 “Standard Test Method for Flow of Hydraulic Cement Mortar” (ASTM 2020). Designs for the mortar mixtures are shown in Table 3-6.

Table 3-6: Mortar Mixture Materials and Proportions

Sample	**Mortar Components [Compressive Strength Testing ASTM C109/C109M − 21]**					
	OPC (g)	**Water* (g)**	**J-Rox (g)**	**Fly Ash (g)**	**Fine Agg** (g)**	**Flow (%)**
100% Cement Control (100-OPC)	1000	580	0	0	2750	111
20% Fly Ash Control (20FA)	800	535	0	200	2750	111
15% J-Rox Replacement of Cement						
15% Gyp/Sand/Clay G-Rox (15JR-1)	850	545	150	0	2750	107
15% Low Silica (15JR-2)	850	610	150	0	2750	110
15% High Silica (15JR-3)	850	615	150	0	2750	112
15% GypRox (15JR-4)	850	560	150	0	2750	106
15% GypRox (15JR-5)	850	600	150	0	2750	108
20% J-Rox Replacement of Cement						
20% Gyp/Sand/Clay G-Rox (20JR-1)	800	595	200	0	2750	111
20% Low Silica (20JR-2)	800	595	200	0	2750	107
20% High Silica (20JR-3)	800	600	200	0	2750	112
20% GypRox (20JR-4)	800	590	200	0	2750	106
20% GypRox (20JR-5)	800	600	200	0	2750	114
25% J-Rox Replacement of Cement						
25% Gyp/Sand/Clay G-Rox (25JR-1)	750	595	250	0	2750	105
25% Low Silica (25JR-2)	750	595	250	0	2750	110
25% High Silica (25JR-3)	750	600	250	0	2750	107
25% GypRox (25JR-4)	750	590	250	0	2750	107
25% GypRox (25JR-5)	750	610	250	0	2750	111

* Water content has been adjusted to account for fine aggregate absorption; 1.48% [45 g]
** Fine Agg. refers to ASTM C33 Natural Silica Sand

The flow and workability of all batches mixed was largely consistent, but at a slightly variable water content. This variation in water content was required to meet the flow requirements, per ASTM C1437-20 “Standard Test Method for Flow of Hydraulic Cement Mortar” (ASTM 2020), in which the flow is defined as the resulting increase in average base diameter of the mortar mass after experiencing

25 drops of the flow table within 15 seconds. The standard requires this flow to be 110% ± 5% of the original base diameter of the mold. Original attempts to maintain uniformity between water contents resulted in flows that did not meet the standard and produced cubes of uneven consistency.

The procedure described in ASTM C305-20 requires that water be adjusted to allow each mixture being compared to meet a target flow. This approach, often used in masonry applications, is different from the common approach used by concrete technologists to maintain constant water to cementitious materials ratio (i.e., w/cm ratio). Although the amount of water required to achieve a target flow (i.e., workability) for these mixtures differ slightly, the variation between all measured flows was less than approximately 10%. The 20% fly ash control mixture required 45 g less water to achieve the same flow as the 100% OPC control mixture. This could be expected due to the spherical nature of the fly ash particles, which provide improved workability without the addition of water.

3.5.2 Sulfate Attack

Mortar mixtures were designed to test the length of change of mortar bars immersed in a sulfate solution in accordance with ASTM C1012/C1012M-18B "Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to Sulfate Solution" (ASTM 2018). Sample batches made of six (6) mortar bars of 1- by 1- by 11 ¼ -in [25 by 25 by 250-mm], and nine (9) 2-in mortar cubes [50 mm] were batched and tested for each of the four (4) J-Rox materials, in addition to a 100% OPC and 20% fly ash control.

Figure 3-2. Photograph of sulfate attack testing on 1- by 1- by 11-in mortar bar

These mortar mixture designs had their water content adjusted for the absorption rate of the fine aggregate (i.e., 1.48%, approximately 65 g of absorption water) in addition to the water required to satisfy the water-cement (w/c) ratio of 0.485 required by ASTM C1012/C1012M-18B. While an absorption rate of 1.48% (Theilgard, 2022) could seem too low to affect the mixture, samples produced without adjusting for absorption exhibited low workability and displayed an inconsistent dispersion of materials upon demolding.

It should be noted that instead of adjusting the water content of mixtures to adhere to a specific flow, as in ASTM C109/C109M-21, sulfate attack testing per ASTM C1012/C1012M − 18B required a consistent w/c ratio between samples. Designs for the mortar mixtures used in this test are shown below in Table 3-7.

Table 3-7: Mortar Mixture Designs for Sulfate Attack Testing

Sample	**Mortar Components [Sulfate Attack Testing ASTM C1012/C1012M − 18B]**				
	OPC (g)	**Water* (g)**	**J-Rox (g)**	**Fly Ash (g)**	**Fine Agg** (g)**
100% Cement Control (100-OPC)	1500	790	0	0	4125
20% Fly Ash Control (20FA)	1200	790	0	300	4125
15% J-Rox Replacement of Cement					
15% Gyp/Sand/Clay G-Rox (15JR-1)	1275	790	225	0	4125
15% Low Silica (15JR-2)	1275	790	225	0	4125
15% High Silica (15JR-3)	1275	790	225	0	4125
15% GypRox (15JR-4)	1275	790	225	0	4125
15% GypRox (15JR-5)	1275	790	225	0	4125
20% J-Rox Replacement of Cement					
20% Gyp/Sand/Clay G-Rox (20JR-1)	1200	790	300	0	4125
20% Low Silica (20JR-2)	1200	790	300	0	4125
20% High Silica (20JR-3)	1200	790	300	0	4125
20% GypRox (20JR-4)	1200	790	300	0	4125
20% GypRox (20JR-5)	1200	790	300	0	4125
25% J-Rox Replacement of Cement					
25% Gyp/Sand/Clay G-Rox (25JR-1)	1125	790	375	0	4125
25% Low Silica (25JR-2)	1125	790	375	0	4125
25% High Silica (25JR-3)	1125	790	375	0	4125
25% GypRox (25JR-4)	1125	790	375	0	4125
25% GypRox (25JR-5)	1125	790	375	0	4125
* Water content has been adjusted to account for fine aggregate absorption; 1.48% [65 g] ** Fine Agg. refers to ASTM C33 Natural Silica Sand					

3.6 Concrete Mixtures

Concrete samples were mixed using SCMs (i.e., fly ash, J-Rox, slag) at varying replacement rates, in accordance with ASTM C192/C192M-19, “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory” (ASTM 2019). In order to accommodate the available supply of coarse aggregate, the batch size was reduced from 3.1 cf to 1.74 cf for batches following the controls. Batch designs for the various concrete mixtures are displayed in Table 3-8.

Table 3-8: Concrete Mixture Designs

Mixture	Concrete Mixture Components (lb/yd^3) [ASTM C192/C192M-19]						
	OPC	**Fly Ash**	**GGBF Slag**	**J-Rox**	**Water**	**Coarse Agg***	**Fine Agg****
100% Cement Control (100-OPC)	640	0	0	0	237	1814	1410
20% Fly Ash Control (20FA)	512	128	0	0	237	1814	1370
15% J-Rox Replacement of Cement							
15% J-Rox 4 (15JR-4)	544	0	0	96	237	1814	1375
15% J-Rox 5 (15JR-5)	544	0	0	96	237	1814	1375
20% J-Rox Replacement of Cement							
20% J-Rox 4 (20JR-4)	512	0	0	128	237	1814	1364
20% J-Rox 5 (20JR-5)	512	0	0	128	237	1814	1364
15% J-Rox and 35% Slag Replacement of Cement							
15% J-Rox 4 / 35% Slag Mixture (15JR-4 / 35S)	320	0	224	96	237	1814	1359
15% J-Rox 5 / 35% Slag Mixture (15JR-5 / 35S)	320	0	224	96	237	1814	1359

* Coarse Agg. refers to coarse aggregate used in concrete mixture
** Fine Agg. refers to ASTM C33 Natural Silica Sand

3.6.1 Fresh Concrete Tests

3.6.1.1 Slump

Testing for the slump of each freshly mixed concrete batch was performed in accordance with ASTM C143/C143M-20, "Standard Test Method for Slump of Hydraulic-Cement Concrete" (ASTM 2020). Workability of the mixture was reinforced through the incorporation of a mid-range water reducing admixture which preserved the low w/c ratio of 0.37 while still achieving a target slump of 3- to 5-inches to facilitate the casting of specimens.

3.6.1.2 Air Content

Immediately after mixing, the air content of each batch of fresh concrete was measured in accordance with ASTM C231/C231M − 17A, “Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method” (ASTM, 2017). Although the mixes were not required to achieve a specific air content per the scope of this project, this parameter helped provide a comparison of material distribution between mixtures and may provide useful information for future comparisons with alternative concrete mixtures.

3.6.1.3 Unit Weight

The unit weight was determined by following the procedure outlined in ASTM C138/138M-17A, “Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete” (ASTM 2017). This test provided useful data for confirming the accuracy of the air content reported via the pressure method (ASTM C231/C231M − 17A, 2017) and the proportion of materials within the mixture.

3.6.2 Hardened Concrete Tests

3.6.2.1 Compressive Strength

Compressive strength testing was conducted on concrete samples molded into 4- by 8-in cylinders. Testing was performed in accordance with ASTM C39/C39M-21, “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens” (ASTM, 2021) at ages of 3, 7, 28, 56, and 91 days.

3.6.2.2 Surface Resistivity

The durability of the 4- by 8-in concrete cylinders was tested following procedure outlined in AASHTO T 358-22, “Standard Test Method of Test for Surface Resistivity Indication of Concrete’s Ability to Resist Chloride Ion Penetration (AASHTO, 2022). As a non-destructive test, surface resistivity was tested prior to compressive strength testing at ages of 3, 7, 28, 56, and 91 days. Per the standard, this test was performed on the cylinders immediately after removal from the moist curing room, with the sample wetted to saturated surface-dry (SSD), to limit variability between results.

Figure 3-3. Photograph of surface resistivity testing performed on 4- by 8-in concrete cylinder

3.6.2.3 Modulus of Elasticity (MOE) and Poisson’s Ratio

Modulus of elasticity (MOE) and Poisson’s ratio of 4- by 8-in concrete cylinders was determined in accordance with ASTM C469/C469M − 14, “Standard Test Method for Static MOE and Poisson’s Ratio of Concrete Compression” (ASTM, 2014). Per the standard, this test was performed only after obtaining a 28-day compressive strength reading to ensure the test did not exceed 40% of the ultimate strength during the load and displacement measurements.

3.6.2.4 Shrinkage

Unrestrained shrinkage testing was conducted on samples molded into rectangular beams measuring 4- by 4- by 11-in. Each beam was tested in accordance with ASTM C157/C157M − 17, “Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete” (ASTM, 2017). The beams were stored in a lime water bath within an environmental chamber maintaining a temperature of 73 ± 3 °F [23 ± 2 °C] and a relative humidity of 50 ± 4% immediately after demolding. The initial shrinkage reading was taken after samples had soaked for thirty minutes, after which they were returned to the limewater bath for 28 days. Following the 28-day reading, samples were removed from the limewater and left to cure inside the environmental chamber for the remainder of the testing program.

Figure 3-4. Photograph of shrinkage testing performed on a 4- by 4- by 10-in concrete prism

CHAPTER 4: TEST RESULTS

4.1 Introduction

The following chapter includes a summary of resulting data obtained throughout the testing program outlined in Chapter 3 of this thesis. Tests were conducted on paste and mortar samples containing five (5) J-Rox types of varying composition (i.e., Gyp/Sand/Clay, High Silica, Low Silica, and Gyp-Rox) at cement replacement rates of 15%, 20%, and 25%. Based on the resulting paste and mortar data, tests were conducted on fresh and hardened concrete samples containing two different types of J-Rox at replacement rates of 15%, 20%, and an additional mixture containing 15% J-Rox and 35% GGBFS (i.e., a total cement replacement rate of 50%).

4.2 Paste Mixtures

4.2.1 Set Time

Set time tests were conducted on paste samples containing J-Rox at various replacement rates. The samples were prepared and tested following the procedure outlined in ASTM C191-21. The results of the set time tests are displayed in Table 4-1 and Figure 4-1 with the exception of the 25% JR-1 (Gyp/Sand/Clay G-Rox) mixture which could not be performed due to an insufficient quantity of available JR-1 material remaining at the time of testing.

Table 4-1: Initial and Final Setting Times for Paste Samples

Sample	Setting Time Testing [ASTM C191-21]		
	Mix and Mold Time	Initial Set Time	Final Set Time
	(min)	(min)	(min)
100% Cement Control (100-OPC)	6.67	185	277
20% Fly Ash Control (20-FA)	4.28	364	274
15% J-Rox Replacement of Cement			
15% Gyp/Sand/Clay G-Rox (15JR-1)	6.17	200	306
15% Low Silica (15JR-2)	6.60	206	322
15% High Silica (15JR-3)	4.58	201	335
15% GypRox (15JR-4)	4.92	203	395
15% GypRox (15JR-5)	4.57	240	395
20% J-Rox Replacement of Cement			
15% Gyp/Sand/Clay G-Rox (20JR-1)	7.25	182	337
15% Low Silica (20JR-2)	4.00	222	334
15% High Silica (20JR-3)	4.27	231	349
15% GypRox (20JR-4)	4.62	162	290
15% GypRox (20JR-5)	4.20	243	289
25% J-Rox Replacement of Cement			
25% Gyp/Sand/Clay G-Rox (25JR-1)	-	-	-
25% Low Silica (25JR-2)	4.58	266	410
25% High Silica (25JR-3)	4.40	233	394
25% GypRox (25JR-4)	4.85	197	350
25% GypRox (25JR-5)	4.63	300	350

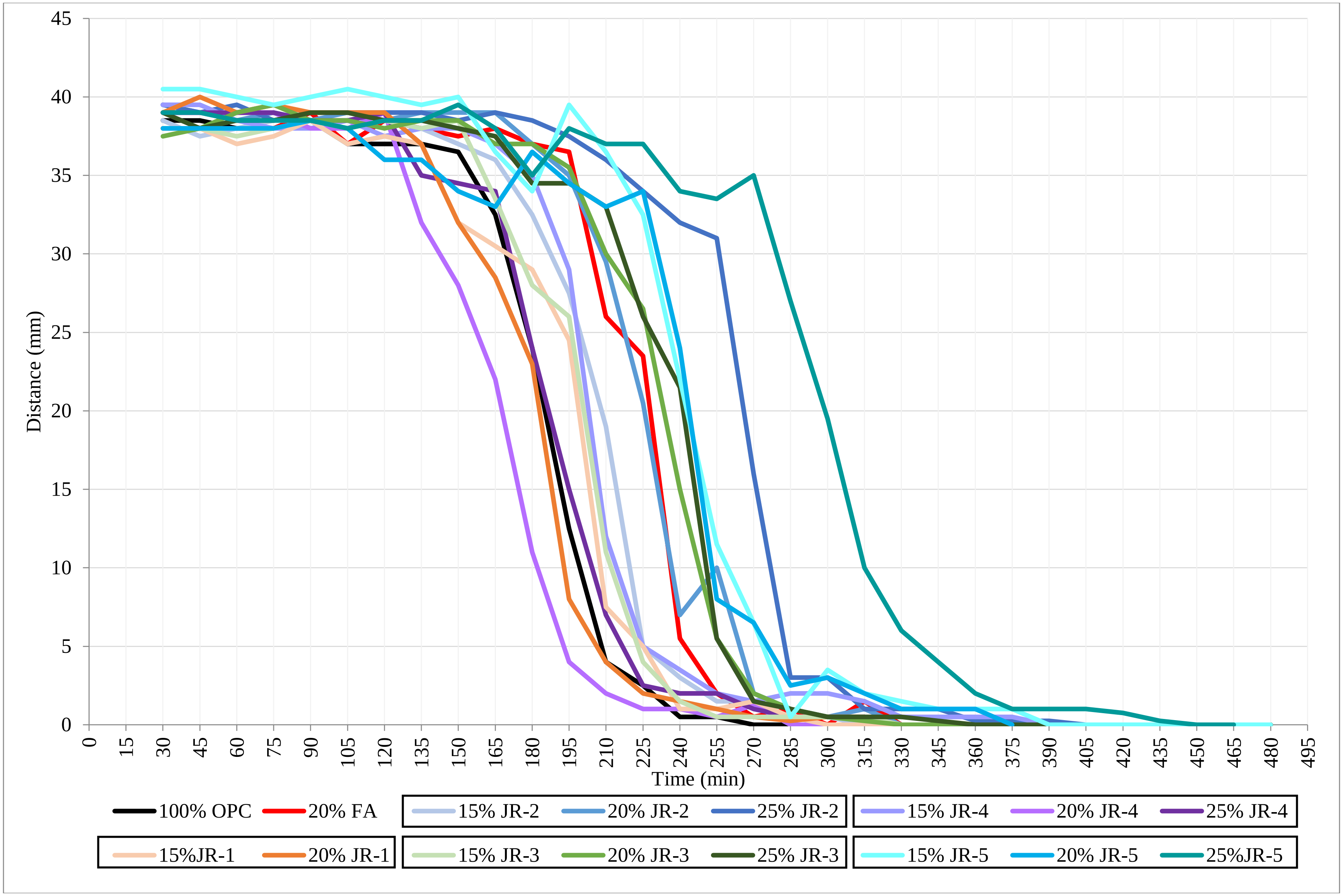

Figure 4-1. Setting time results for J-Rox paste mixtures

4.3 Mortar Mixtures

4.3.1 Compressive Strength

Compressive strength tests were conducted on mortar samples containing J-Rox at various replacement rates. The samples were prepared and tested following the procedure outlined in ASTM C109/C109M − 21 at 3, 7, 28, 56, and 91 days. Typically, three (3) specimens were tested and averaged for the 3-day, 7-day, and 28-day results reported in Table 4-2. Due to the volume of material available for the project and subsequently the number of specimens that could be prepared, two (2) specimens were typically tested and the results averaged for the 56-day tests and one (1) specimen was typically tested for the 91-day test, with the exception of JR-5 samples in which three (3) specimens were tested at each age throughout the testing program. Table 4-2 shows the average compressive strength value of each mixture and the percent change in compressive strength between testing ages.

Table 4-2: Results of Compressive Strength Tests of Mortar Mixtures

Mixture ID	**Average Compressive Strength of Mortar Mixtures (psi)**								
	3-day	**7-day**	**Δ**	**28-day**	**Δ**	**56-day**	**Δ**	**91-day**	**Δ**
100% Cement Control (100-OPC)	3,913	4,362	11%	5,153	18%	5,740	11%	5,723	0%
20% Fly Ash Control (20-FA)	3,147	3,756	19%	4,960	32%	5,809	17%	6,139	6%
15% J-Rox Replacement of Cement									
15% Gyp/Sand/Clay G-Rox (15JR-1)	3,271	3,712	13%	4,453	20%	5,283	19%	5,338	1%
15% Low Silica (15JR-2)	3,123	3,289	5%	4,350	32%	4,781	10%	4,980	4%
15% High Silica (15JR-3)	2,825	3,324	18%	4,270	28%	4,681	10%	4,730	1%
15% GypRox (15JR-4)	3,183	3,687	16%	4,492	22%	5,091	13%	4,763	-6%
15% GypRox (15JR-5)	2,652	2,953	11%	3,964	34%	4,462	13%	4,926	10%
20% J-Rox Replacement of Cement									
20% Gyp/Sand/Clay G-Rox (20JR-1)	2,682	3,243	21%	4,359	34%	4,795	10%	5,475	14%
20% Low Silica (20JR-2)	2,248	2,565	14%	3,542	38%	3,684	4%	4,265	16%
20% High Silica (20JR-3)	2,408	2,759	15%	3,742	36%	3,998	7%	4,148	4%
20% GypRox (20JR-4)	2,302	2,868	25%	3,664	28%	4,233	16%	4,448	5%
20% GypRox (20 JR-5)	2,603	2,781	7%	3,482	25%	4,006	15%	4,358	9%
25% J-Rox Replacement of Cement									
25% Gyp/Sand/Clay G-Rox (25JR-1)	2,308	3,027	31%	4,013	33%	4,730	18%	5,223	10%
25% Low Silica (25JR-2)	2,417	2,783	15%	4,140	49%	4,671	13%	4,873	4%
25% High Silica (25JR-3)	2,314	2,788	20%	3,864	39%	4,484	16%	4,733	6%
25% GypRox (25JR-4)	2,373	2,887	22%	3,826	33%	4,531	18%	4,615	2%
25% GypRox (25JR-5)	2,337	2,510	7%	3,125	25%	3,763	20%	3,746	0%

As shown in Figures 4-2 and 4-3, the data indicated some versions of J-Rox were more effective at certain cement replacement rates than others. Overall, the JR-1 (Gyp/Sand/Clay G-Rox) mixtures consistently exhibited the highest average compressive strength values throughout the testing program, followed by JR-4 (GypRox).

At a 15% cement replacement rate, JR-1 (Gyp/Sand/Clay G-Rox) and JR-4 (GypRox) showed the highest average compressive strength consistently, apart from the 91-day test in which JR-2 produced the second compressive strength. However, because the remaining cubes were split to accommodate the addition of a 56-day test into the testing program (i.e., two cubes tested at 56 days and one cube tested at 91 days), the decrease in JR-4's compressive strength for the 91-day test may be an artifact of expected variability and the limited number of specimens tested.

At the 20% cement replacement rate, JR-1 (Gyp/Sand/Clay G-Rox) consistently produced the highest average compressive strength out of all five (5) J-Rox mixtures. JR-4 (GypRox) exhibited the second highest compressive strength values for all testing ages, with the exception of the 3-day and 28-day results, in which the mixture was outperformed by JR-5 (GypRox) and JR-3 (High Silica), respectively.

At the 25% cement replacement rate, the JR-3 (High Silica) and JR-4 (Gyp-Rox) mixtures exhibited nearly identical average compressive strength values through the 28-day test. However, the overall trend indicates that JR-1 (Gyp/Sand/Clay) and JR-2 (Low Silica) mixtures were the strongest for this higher replacement rate.

The strongest average compressive strength value of a J-Rox mixture throughout the testing program was observed at 91 days from 20JR-1 (Gyp/Sand/Clay G-Rox at a 20% cement replacement rate) and produced a comparable result to the 100% OPC control. Still, the highest performing mortar mixture was observed as the 20% fly ash control. The results of compressive strength testing of mortar mixtures are grouped by percent cement replacement and by J-Rox material in Figures 4-2 and 4-3, respectively.

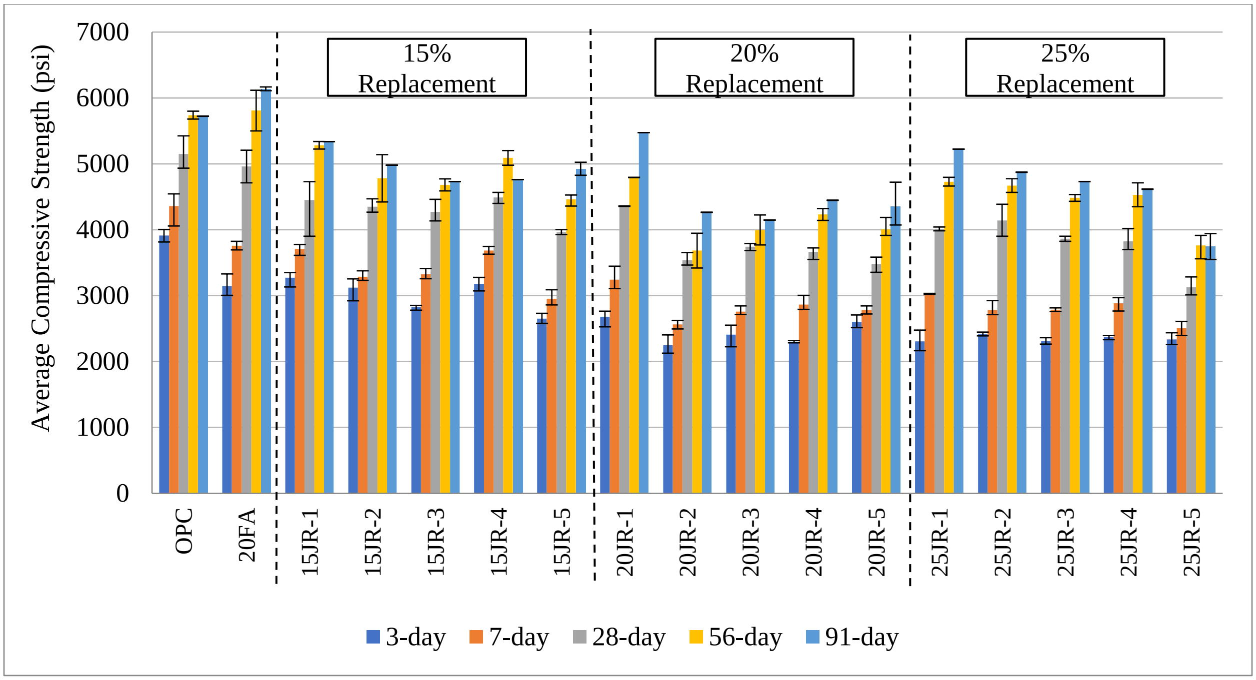

Figure 4-2. Compressive strength results of J-Rox replacement of cement mortar mixtures (grouped by % replacement)

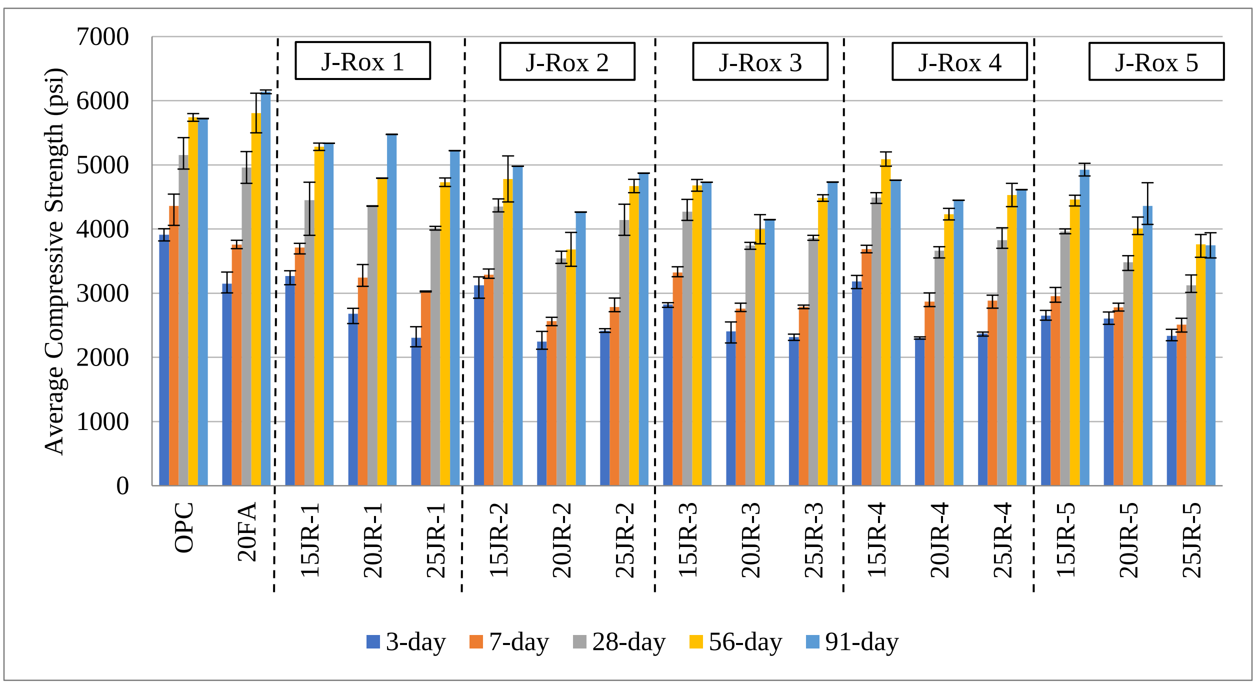

Figure 4-3. Compressive strength results of J-Rox replacement of cement mortar mixtures (grouped by material)

4.3.2 Sulfate Attack

Sulfate attack testing (Figure 4-4 and Table 4-3) was conducted on mortar samples containing J-Rox at various cement replacement rates. The samples were prepared and tested following the procedure outlined in ASTM C1012/C1012M − 18B. Six (6) bars were tested for each mixture, and the results shown are the average.

Sulfate attack test results show relative performance to the control mixtures. The performance targets for concrete mixtures exposed to sulfates vary greatly depending on local exposure conditions and the risk associated with the structure's performance. JR-4 and JR-1, respectively, were observed to have the least percent change across each individual testing period at cement replacement rates of 15% and 20% when compared with other J-Rox samples. At a replacement rate of 25%, the least percent change over each individual testing period was observed from JR-1 and JR-2, respectively.

At the final testing age of 26 weeks, JR-1 outperformed both the 100% OPC and 20% fly ash control at all three cement replacement levels. At the same age, JR-4 exhibited less shrinkage than both controls at the 15% and 20% replacement rates. At the 25% cement replacement rate JR-4 was outperformed by the OPC control, however JR-4 still exhibited less shrinkage than the fly ash control.

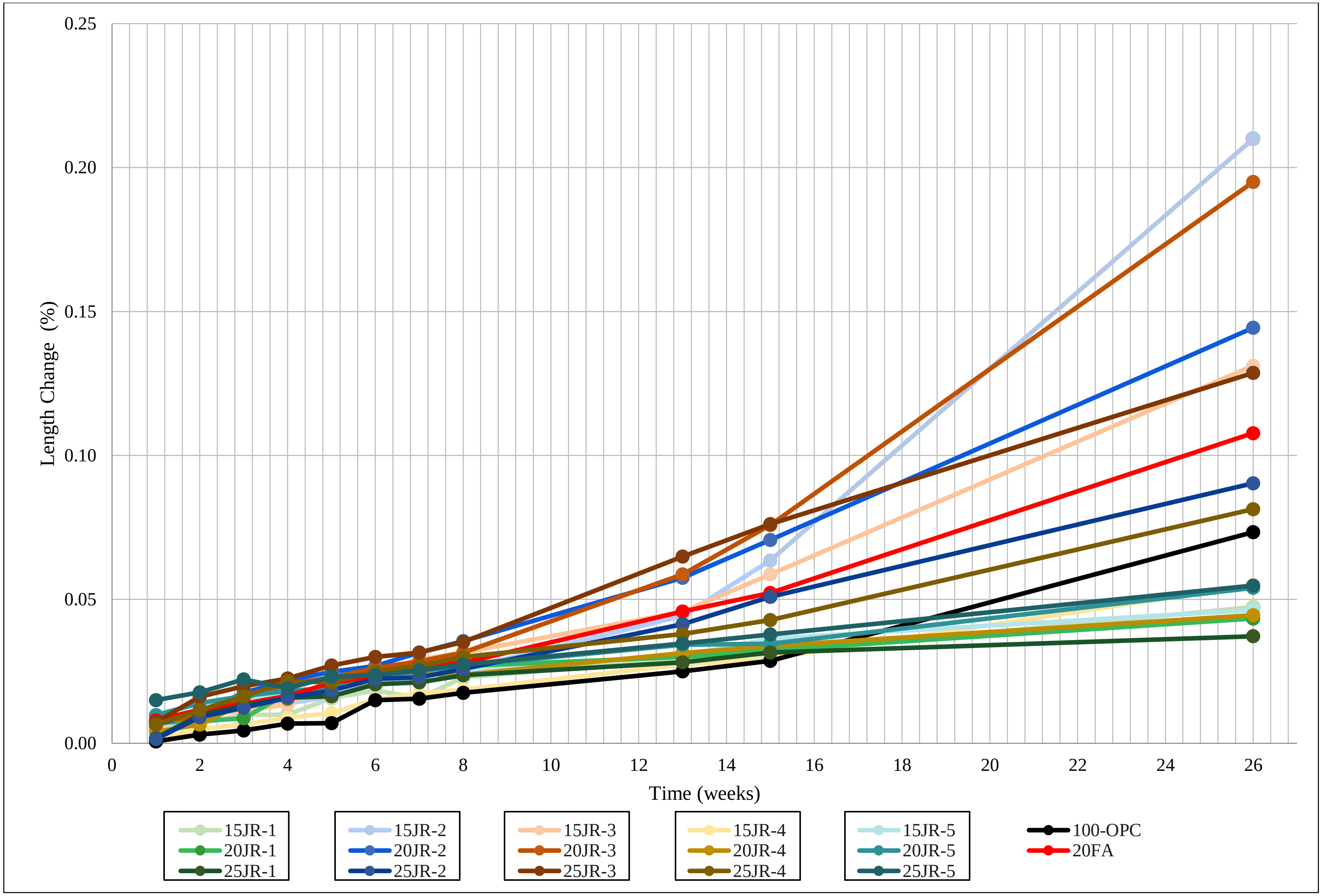

Figure 4-4. Sulfate attack testing results of J-Rox replacement of cement mortar mixtures

Table 4-3: Results of sulfate attack tests of mortar mixtures, showing overall length change at each measurement level and length change between each interval

Mixture	**Length Change per Week (× 10^{-4} %)**																					
	1	**2**	**Δ**	**3**	**Δ**	**4**	**Δ**	**5**	**Δ**	**6**	**Δ**	**7**	**Δ**	**8**	**Δ**	**13**	**Δ**	**15**	**Δ**	**26**	**Δ**	**Total Δ**
100OPC	7	30	23	45	15	68	23	70	2	150	80	155	5	175	20	250	75	287	37	733	447	727
20FA	80	117	37	137	20	165	28	210	45	233	23	270	38	280	10	458	178	523	65	1078	555	998
15JR-1	53	70	17	98	28	100	2	157	57	183	27	157	-27	228	72	293	65	312	18	473	162	420
15JR-2	60	83	23	125	42	138	13	163	25	223	60	260	38	258	-2	443	185	635	193	2100	1465	2040
15JR-3	57	100	43	112	12	135	23	217	82	245	28	292	47	315	23	457	142	587	130	1312	725	530
15JR-4	12	50	38	65	15	88	23	105	17	153	48	173	20	187	13	273	87	295	22	550	255	538
15JR-5	88	140	52	152	12	167	15	197	30	217	20	233	17	253	20	303	50	363	60	463	100	375
20JR-1	72	77	5	87	10	173	87	193	20	225	32	250	25	268	18	300	32	323	23	433	110	362
20JR-2	63	107	43	175	68	218	43	248	30	268	20	315	47	355	40	575	220	707	132	1443	737	1380
20JR-3	75	93	18	157	63	205	48	228	23	262	33	285	23	315	30	587	272	758	172	1950	1192	1875
20JR-4	40	65	25	140	75	153	13	185	32	222	37	242	20	238	-3	313	75	338	25	445	107	405
20JR-5	98	140	42	164	24	182	18	192	10	230	38	250	20	270	20	342	72	346	4	540	194	442
25JR-1	18	98	80	130	32	158	28	163	5	205	42	212	7	237	25	282	45	315	33	372	57	353
25JR-2	15	90	75	123	33	158	35	183	25	223	40	228	5	258	30	413	155	508	95	903	395	888
25JR-3	73	162	88	198	37	225	27	270	45	300	30	315	15	352	37	648	297	762	113	1287	525	1213
25JR-4	65	115	50	163	48	215	52	212	-3	250	38	268	18	300	32	380	80	428	48	813	385	748
25JR-5	150	177	27	222	45	192	-30	232	40	237	5	253	17	273	20	347	73	378	32	548	170	398

*Table compares samples by week. The delta (**Δ**) symbolizes the percent change in length compared to the previous week. Total **Δ** represents the total length change of each sample based on the initial length comparator readings.

4.4 Concrete Mixtures

4.4.1 Fresh Concrete

Table 4-4 presents the test results for fresh properties of concrete mixtures. Although the unit weight and air content of freshly mixed concrete was generally uniform for all batches, in accordance with ASTM C138/C138M − 17A, "Standard Test Method for Density (Unit Weight), Yield, and Air Content of Concrete" (ASTM 2022), differences in unit weights of control mixtures and those following are a result of changes in cement quantities (SG = 3.15) and replacement with lighter SCM materials (J-Rox and fly ash SG = approximately 2.2). Batch sizes ranged from 1.5 to 3.1 cf, with smaller batches used once flexural strength beams were removed from the testing program to conserve coarse aggregate.

Table 4-4: Fresh Properties of Tested Concrete Mixtures

Mixture	Slump (in)	Air Content	Unit Weight (pcf)	Temp (°F)	Water Reducer (mL)
100% Cement Control (100-OPC)	3.25	1.80%	146.6	87	70
20% Fly Ash Control (20FA)	4.50	2.30%	143.0	88	60
15% J-Rox Replacement of Cement					
15% J-Rox 4 (15JR-4)	3.50	2.30%	144.6	64	65
15% J-Rox 5 (15JR-5)	3.00	1.60%	142.1	64	50
20% J-Rox Replacement of Cement					
20% J-Rox 4 (20JR-4)	3.75	2.70%	144.6	61	50
20% J-Rox 5 (20JR-5)	3.75	2.40%	142.6	64	55
15% J-Rox / 35% Slag Replacement of Cement					
15% J-Rox 4 / 35% Slag Mix (15JR-4 / 35S)	5.00	2.50%	143.4	64	60
15% J-Rox 5 / 35% Slag Mix (15JR-5 / 35S)	4.50	2.50%	141.9	62	50

Changes observed in the unit weight of the mixtures are likely attributed to variation in the specific gravity (SG) of SCM materials (i.e., different J-Rox types, the incorporation of slag, etc.). These changes could also be explained by the natural variability associated with the sample selected from the batch for unit weight measurement. As shown in Table 4-4, the unit weights of each mixture decreased with increases in cement replacement. It should be noted that the 100% OPC control was shown to have the highest unit weight as a result of the material's higher significant gravity (SG_{OPC} = 3.15), whereas the J-Rox/Slag mixtures which combined replace 50% of the cement in the mixture show the lowest unit weight ($SG_{JR\text{-}4}$ = 2.2; SG_{GGBFS} = 2.89). Although the unit weight of the J-Rox 5/Slag mixture was slightly lower than the other batches, the discrepancy could be due to natural variability in the sample selected from the batch to be measured, a slightly lower specific gravity of J-Rox 4, or other causes.

4.4.2 Hardened Concrete

4.4.2.1 Compressive Strength

Compressive strength testing was conducted on 4- by 8-in concrete cylinders containing SCMs (i.e., fly ash, J-Rox, slag) at various replacement rates in accordance with ASTM C39/C39M-21, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" (ASTM 2021) at 3, 7, 28, 56, and 91 days. Typically, three (3), but in all cases at least two (2), cylinders were tested at each age and the averages are reported in Table 4-5.

Table 4-5. Average Compressive Strength of 4- by 8-in Concrete Cylinders

Mixture ID	**Average Compressive Strength of Concrete Mixtures (psi)**								
	3-day	**7-day**	**Δ**	**28-day**	**Δ**	**56-day**	**Δ**	**91-day**	**Δ**
100% Cement Control (100-OPC)	5,106	5,613	10%	6,511	16%	6,786	4%	6,694	-1%
20% Fly Ash Control (20FA)	3,916	4,646	19%	5,840	26%	6,146	5%	6,207	1%
15% J-Rox Replacement of Cement									
15% J-Rox 4 (15JR-4)	4,460	5,246	18%	5,763	10%	6,394	11%	6,905	8%
15% J-Rox 5 (15JR-5)	3,845	4,816	25%	5,767	20%	5,903	2%	7,593	29%
20% J-Rox Replacement of Cement									
20% J-Rox 4 (20JR-4)	3,934	4,706	20%	5,870	25%	5,540	-6%	6,529	18%
20% J-Rox 5 (20JR-5)	3,719	4,737	27%	5,680	20%	6,294	11%	7,082	13%
15% J-Rox / 35% Slag Replacement of Cement									
15% J-Rox 4 / 35% Slag Mixture (15JR-4 / 35S)	3,036	4,731	56%	5,961	26%	6,453	8%	6,928	7%
15% J-Rox 5 / 35% Slag Mixture (15JR-5 / 35S)	2,358	3,122	32%	5,598	79%	6,213	11%	7,372	19%

The mixtures containing J-Rox 4 at both 15% and 20% replacement rates outperformed the 20% fly ash control mixture's compressive strength at nearly all ages except at 28 days, for which the resulting average compressive strength of the three mixtures were nearly identical (i.e., 15JR-4, 20JR-5, and 20FA all within approximately 75 psi of each other) and 56 days. At 56 days, the 20% J-Rox 4 sample exhibited an unexplained decrease in strength from the 28-day test. At 91 days this mixture reported the lowest overall compressive strength of the J-Rox samples, yet this final compressive strength value exceeded that of the fly ash control by over 300 psi.

Even the J-Rox 4/Slag mixture, which demonstrated an overall slower strength gain across the testing program, exceeded the compressive strength of the fly ash control at a testing age of 7 days after a 56% increase in strength from the 3-day result. The following 28-day and 56-day results of the J-Rox 4/Slag mixture exhibited the highest average compressive strength of all tested samples containing SCMs at their respective testing ages, second only to the 100% OPC control. By the 91-day test, the J-Rox 4/Slag mixture outperformed both control mixtures in terms of average compressive strength.

Similarly, the J-Rox 5/Slag mixture also demonstrated a slower strength gain until exhibiting a 79% increase between the 7-day and 28-day results. Upon the completion of the 91-day test, the J-Rox 5 mixes exhibited the highest compressive strength at each replacement rate without exception, exceeding that of both control mixtures. Out of the three (3) J-Rox 5 mixtures, the highest compressive strength value throughout the compressive strength testing program was observed from the 15% J-Rox 5 mixture followed closely by the J-Rox 5/Slag mixture at 7,593 psi and 7,372 psi, respectively. The results of compressive strength testing of concrete mixtures are grouped by percent cement replacement and by J-Rox material in Figures 4-5 and 4-6, respectively.

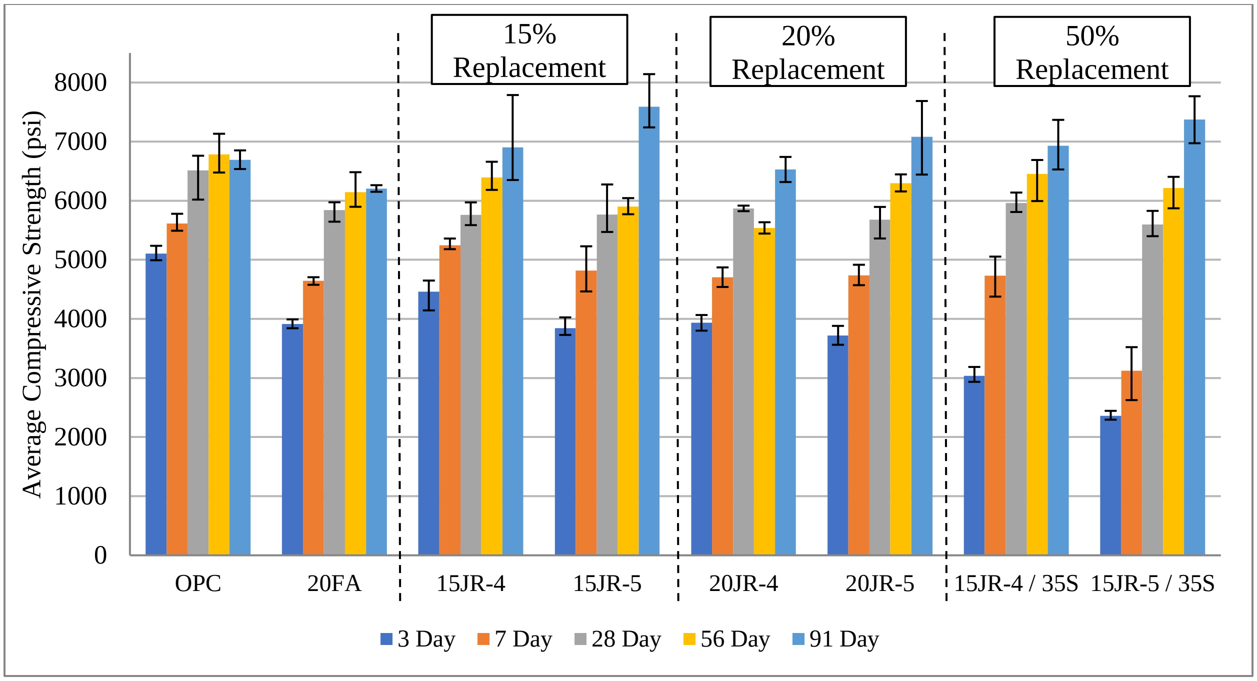

Figure 4-5. Compressive strength testing results of J-Rox replacement of cement (grouped by % replacement)

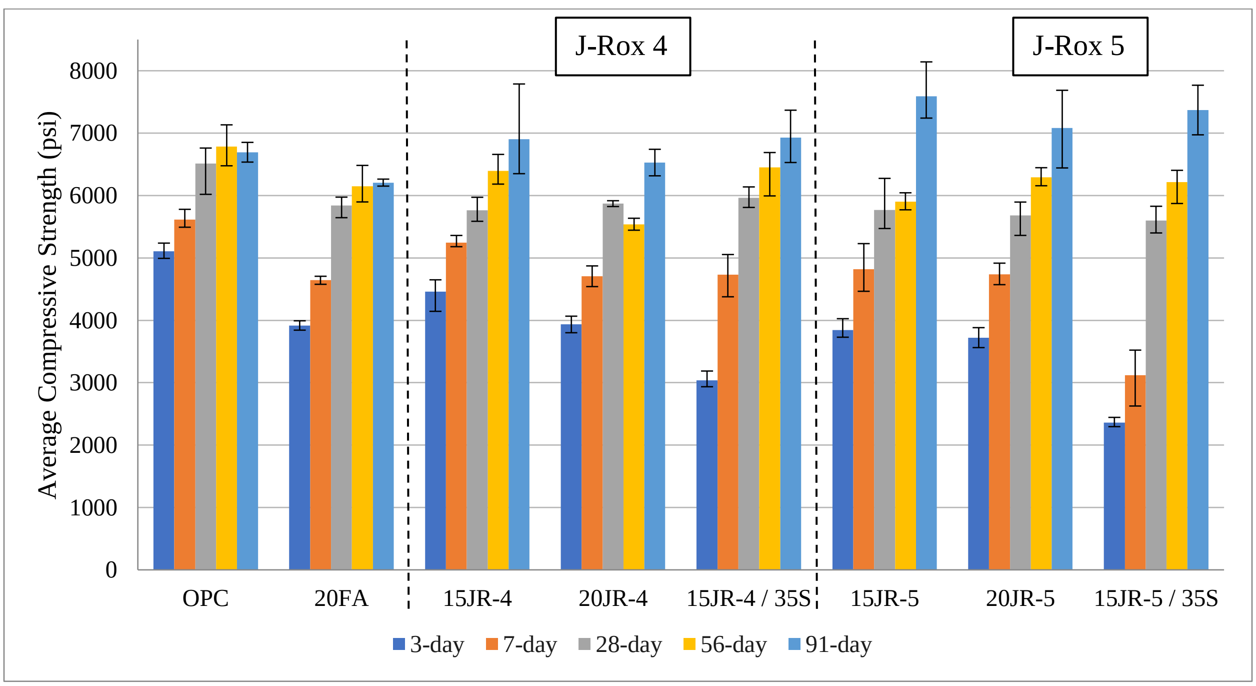

Figure 4-6. Compressive strength testing results of J-Rox replacement of cement (grouped by material)

It should be noted that the 91-day tests of the control samples (100% OPC and 20% FA) were conducted on 6- by 12-in cylinders which were created for the purpose of MOE testing prior to the adjustment of the testing program. The compression testing equipment available for conducting this test on larger cylinders required careful observation of dual gauges and the manual operation of machinery at critical points during loading by two (2) operators for each test, whereas the available equipment was otherwise capable of monitoring and addressing these factors autonomously on the 4- by 8-in cylinders.

For this reason, it was determined that more accurate MOE data would result from testing the 4- by 8-in cylinders as opposed to the 6- by 12-in. Furthermore, since the control batches were mixed prior to the decision to conduct compression testing at 56 days, utilizing the 6- by 12-in cylinders for the final compression test eliminated the need to rebatch the control mixtures to obtain the necessary number of specimens. Because compressive strength values tend to stabilize by 91 days it was assumed that conducting this test on the larger cylinders would have a minimal impact on the results, however this may have contributed to the smaller difference in compressive strength compared to their 56-day results. Still, the influence could have also been negligible.

Research comparing the compressive strengths of 4- by 8-in and 6 by 12-in cylinders indicated that the correlation factor k_s relating the compressive strength test results for these two (2) cylinder sizes can be assumed to be within the strength range of 2,900 psi to 8,700 psi (Day 1994), although k_s increases with increasing compressive strength. Pistilli and Williems (1993) found that for cylinders of compressive strengths ranging from 4,000 to 9,000 psi tested with neoprene pads, no differences existed between 4- by 8-in and 6 by 12-in cylinders. Research by Vandegrift and Schindler (2005) found that k_s decreases with increasing compressive strengths, and recommended a procedure for correlating results from the two (2) cylinder sizes if used for quality assurance. Regardless, 28-day compressive strength results for all J-Rox mixtures are well over 5,000 psi, indicating satisfactory strength for many applications.

4.4.2.2 Surface Resistivity

The concrete cylinders tested for compressive strength (Section 4.3.2.1) were also tested for electrical resistivity following the procedure outlined in AASHTO T 358-22 "Standard Test Method for Surface Resistivity Indication of Concrete's ability to Resist Chloride Ion Penetration" (AASHTO 2017) at 3, 7, 28, 56, and 91 days. Results of the surface resistivity tests of 4- by 8-in concrete cylinders are presented in Table 4-6.

Table 4-6: Surface Resistivity of 4- by 8-in Concrete Cylinders

Mixture ID	Average Resistivity (kΩ•cm) [AASHTO T 358-22]				
	3-day	**7-day**	**28-day**	**56-day**	**91-day**
100% Cement Control (100-OPC)	4.4	4.7	6.3	7.2	8.3*
20% Fly Ash Control (20FA)	3.7	4.3	7.4	10.9	15.1*
15% J-Rox Replacement of Cement					
15% J-Rox 4 (15JR-4)	3.9	4.6	5.8	6.9	7.8
15% J-Rox 5 (15JR-5)	3.9	4.5	5.5	6.1	7.0
20% J-Rox Replacement of Cement					
20% J-Rox 4 (20JR-4)	4.0	4.7	5.8	6.2	7.8*
20% J-Rox 5 (20JR-5)	4.1	4.5	5.7	6.6	6.7
15% J-Rox / 35% Slag Replacement of Cement					
15% J-Rox 4 / 35% Slag Mixture (15JR-4 / 35S)	4.9	9.3	15.9	18.1	20.5
15% J-Rox 5 / 35% Slag Mixture (15JR-5 / 35S)	4.4	7.2	12.7	15.6	18.2

* Note that 6- by 12-inch cylinder was used for these tests due to specimens remaining at time of testing. This value has been adjusted using the correction factors developed by Morris et al. (1996) and provided in AASHTO T 358-22.

The results of testing show the 15% J-Rox 4/35% Slag samples had the highest resistivity; their performance exceeded that of both control batches. The average resistivity for the 3-day test was equivalent to the 100% OPC control. At 15% and 20% cement replacement rates, the J-Rox 4 samples tested higher than the 20% fly ash control through the 7-day test, but the resistivity seemed to stagnate for the following 28-day and 56-day tests in contrast to the 20% fly ash control which proceeded to increase.

Testing of the J-Rox 5 mixtures produced results similar to the test results from the J-Rox 4 mixtures, albeit slightly lower. The most significant decrease between J-Rox 4 and J-Rox 5 resistivity results was observed between the J-Rox/Slag mixtures, however these results for both ternary mixtures were still significantly higher than both controls across all testing periods.

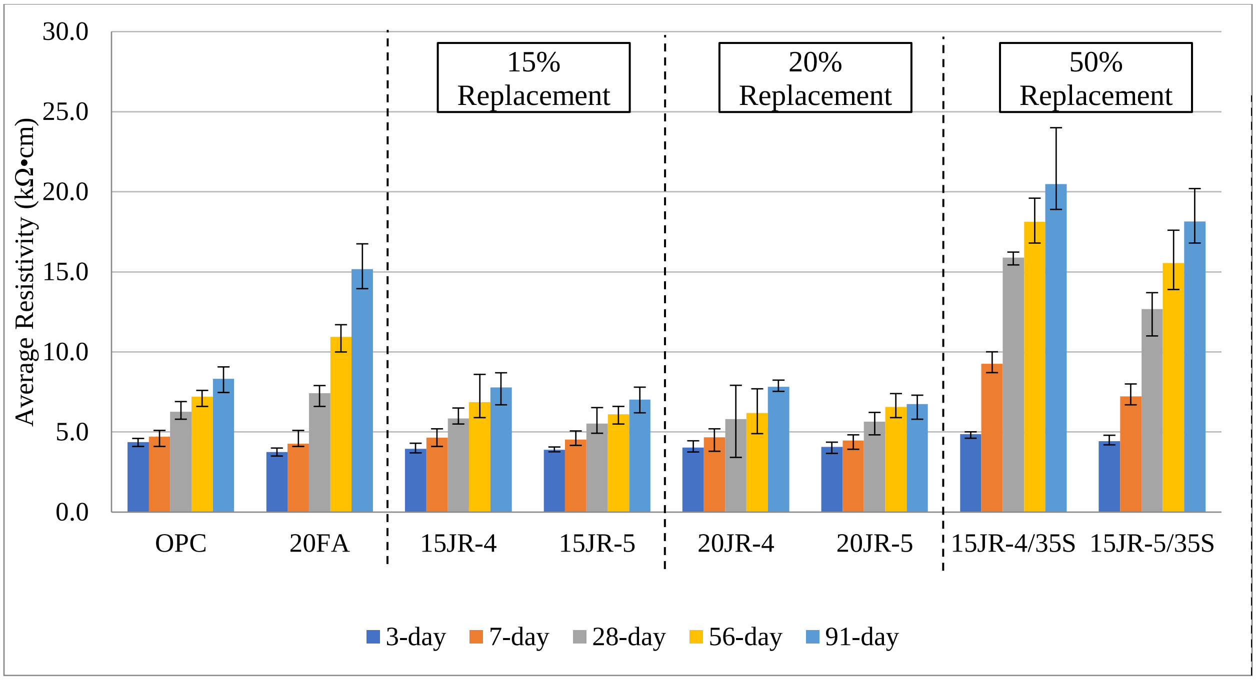

Figure 4-7. Surface resistivity testing results of J-Rox replacement of cement (grouped by % replacement).

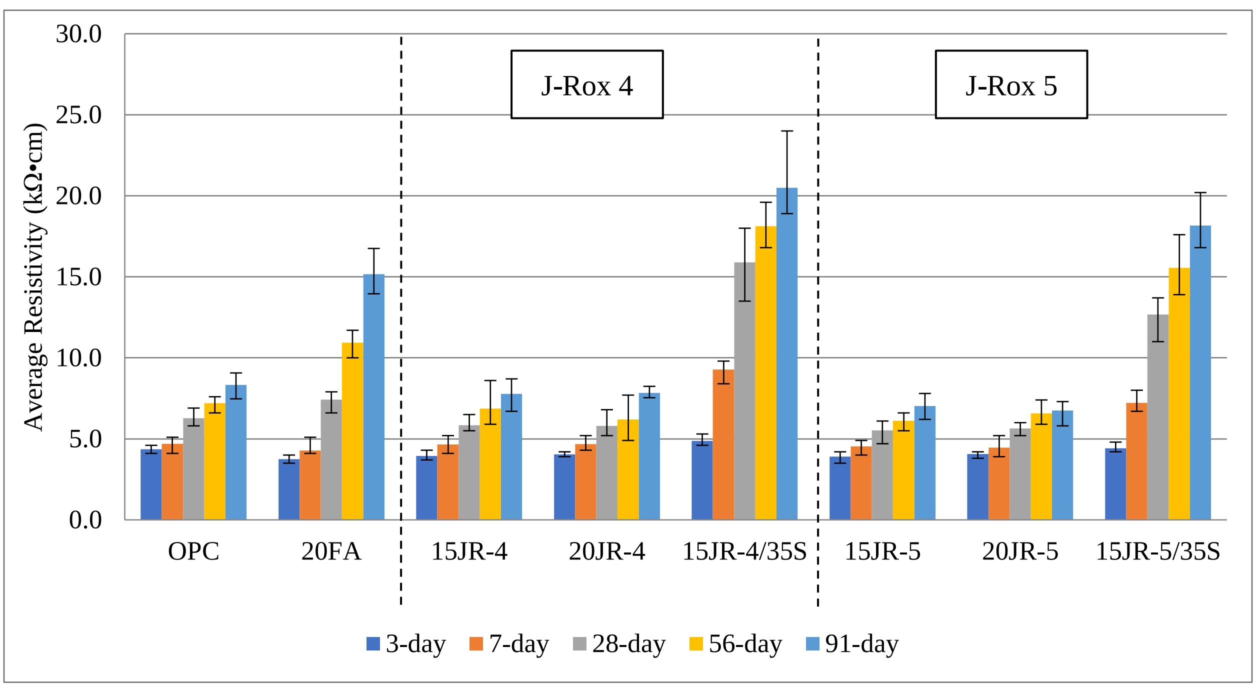

Figure 4-8. Surface resistivity testing results of J-Rox replacement of cement (grouped by material)

4.4.2.3 Modulus of Elasticity and Poisson’s Ratio

The Modulus of Elasticity (MOE) and Poisson’s Ratio of the 4- by 8-in concrete cylinders was determined in accordance with ASTM C469/C469M − 14, “Standard Test Method for Static MOE and Poisson’s Ratio of Concrete Compression” (ASTM, 2014). Table 4-7 lists the results of MOE and Poisson’s Ratio testing at 28 days. Typically, two (2) specimens were tested for MOE and Poisson’s Ratio, and the average(s) reported.

Table 4-7: Modulus of Elasticity and Poisson’s Ratio of 4- by 8-in Concrete Cylinders at 28 days

Mixture ID	MOE (psi)	Poisson's Ratio
100% Cement Control (100-OPC)	3.50E+06	0.197
20% Fly Ash Control (20FA)	2.94E+06	0.185
15% J-Rox Replacement of Cement		
15% J-Rox 4 (15JR-4)	3.08E+06	0.156
15% J-Rox 5 (15JR-5)	3.00E+06	0.143
20% J-Rox Replacement of Cement		
20% J-Rox 4 (20JR-4)	3.08E+06	0.143
20% J-Rox 5 (20JR-5)	3.25E+06	0.16
15% J-Rox / 35% Slag Replacement of Cement		
15% J-Rox 4 / 35% Slag Mixture (15JR-4 / 35S)	3.20E+06	0.156
15% J-Rox 5 / 35% Slag Mixture (15JR-5 / 35S)	3.38E+06	0.178

Results of Modulus of Elasticity (MOE) and Poisson’s Ratio testing were shown to be the highest for the J-Rox 5 mixtures across all percent replacement rates with the exception of the 15% cement replacement samples where the J-Rox 4 samples exhibited slightly higher results. Still, MOE test results of both J-Rox 4 and J-Rox 5 were higher than the 20% fly ash samples at all cement replacement rates, as shown in Figures 4-9 and 4-10.

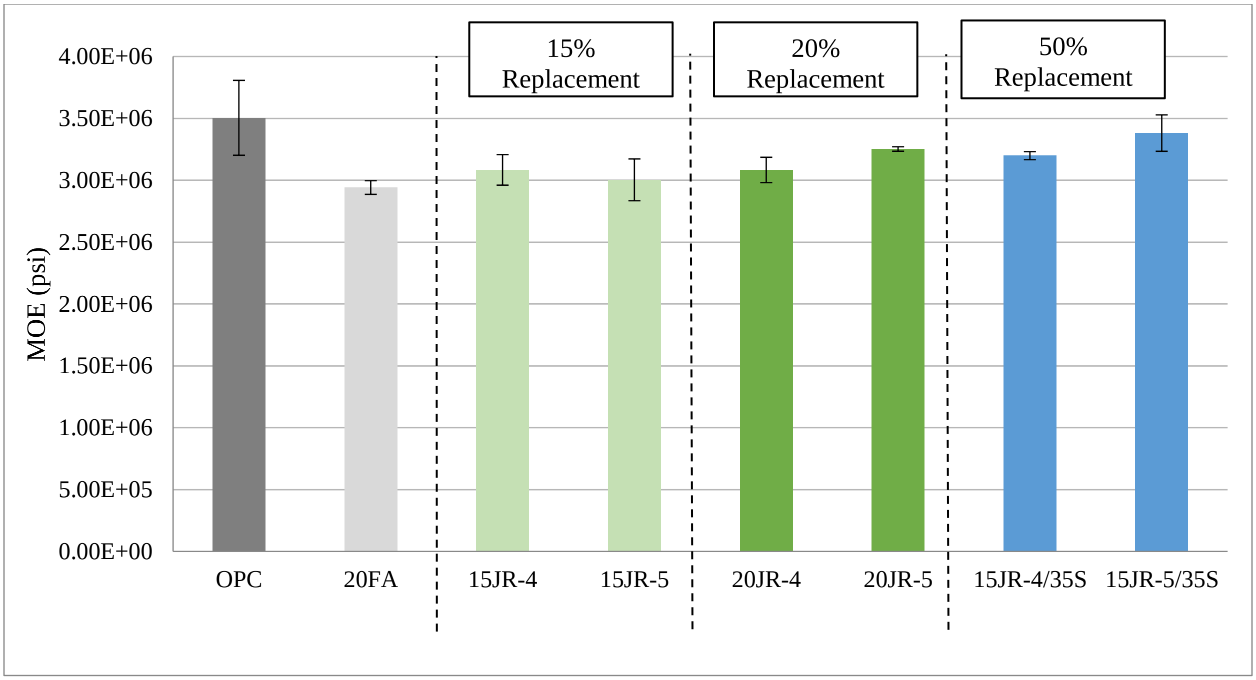

Figure 4-9. MOE testing results of J-Rox replacement of cement at 28 days (grouped by % replacement)

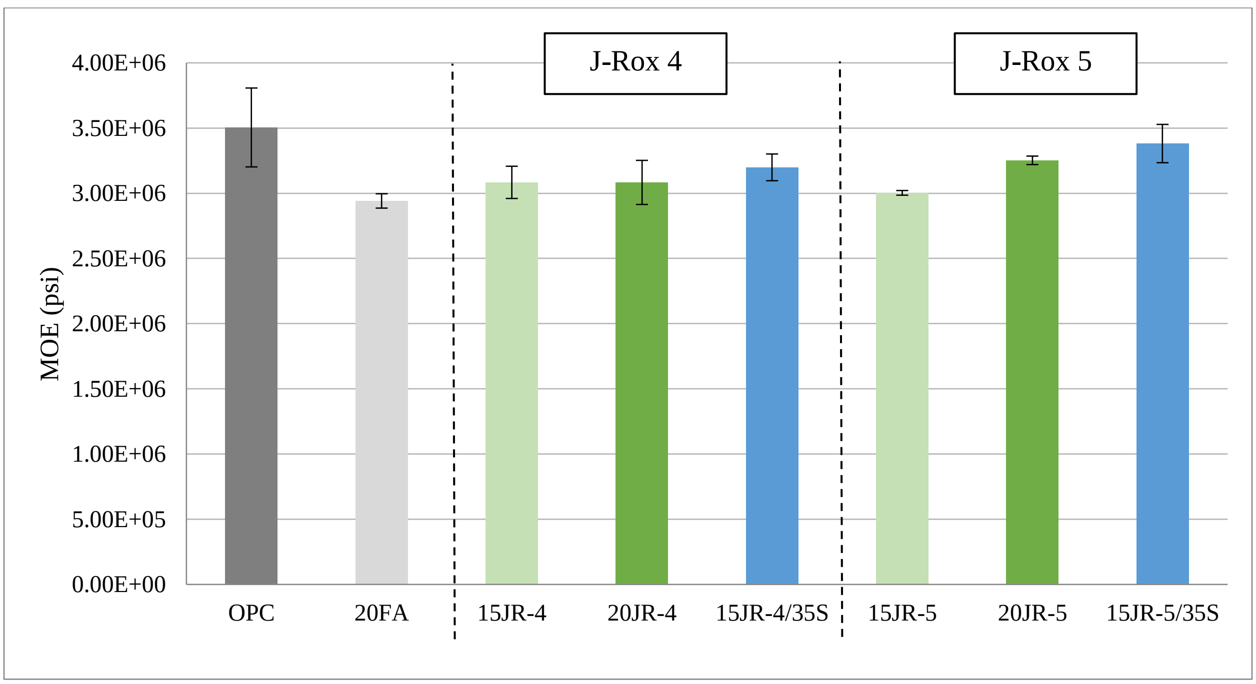

Figure 4-10. MOE testing results of J-Rox replacement of cement at 28 days (grouped by material)

Similar to the MOE test results, the corresponding results for Poisson's Ratio were higher for the J-Rox 5 samples in comparison to the J-Rox 4 samples, with the exception of the 15% cement replacement rate. However, in contrast to MOE testing, both control mixtures tested as having a higher Poisson's Ratio than any of the samples containing J-Rox.

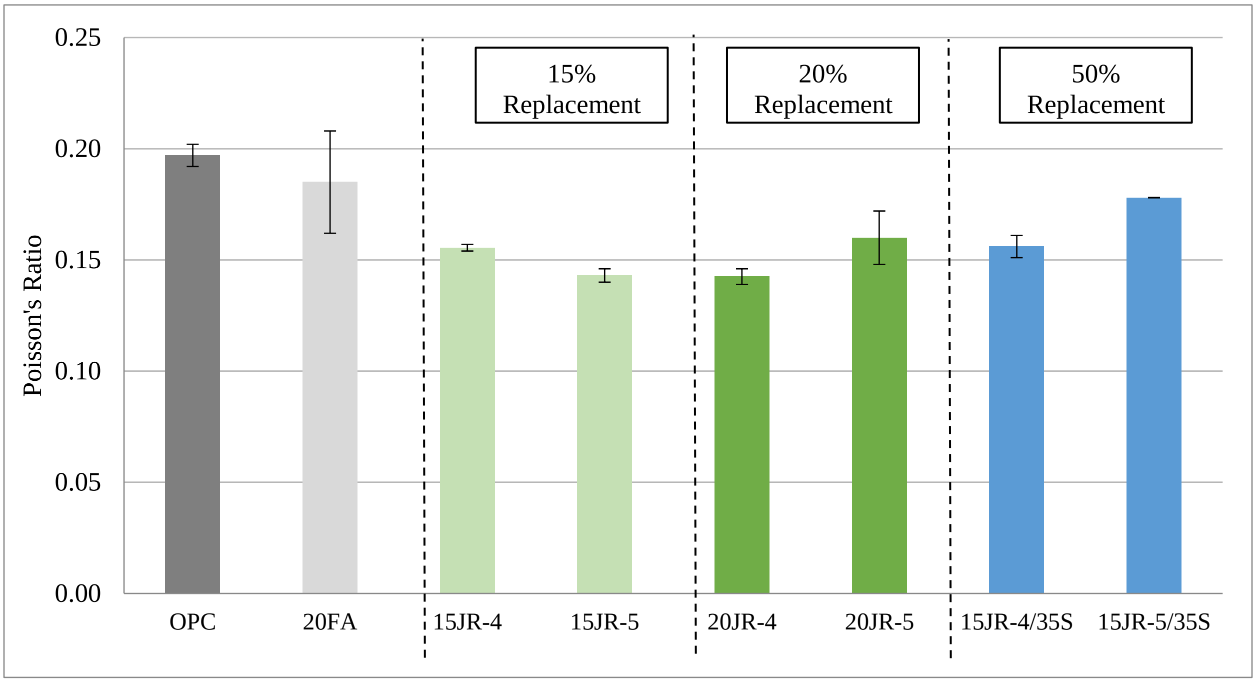

Figure 4-11. Poisson's Ratio testing results of J-Rox replacement of cement at 28 days (grouped by % replacement)

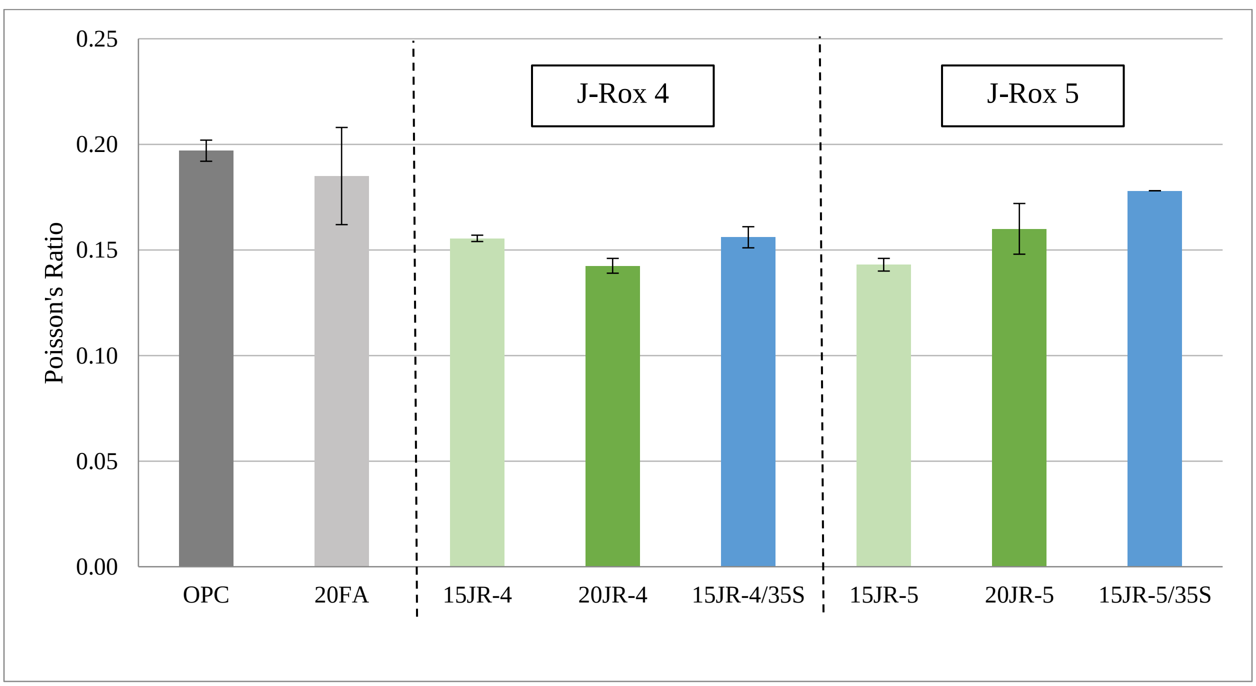

Figure 4-12. Poisson's Ratio testing results of J-Rox replacement of cement at 28 days (grouped by material)

4.4.2.4 Shrinkage

The results of unrestrained shrinkage testing per ASTM C157/C157M − 17 show that at 56 days after mixing, the J-Rox 4/Slag samples exhibited the least shrinkage out of all samples tested, including both controls. At the same age, the samples also exhibiting minimal shrinkage are 20% J-Rox 4 mixture, the 20% fly ash control, and the J-Rox 5/Slag mixture, respectively. Overall, the 100% OPC control mixture exhibited more shrinkage over the testing program than any of the samples containing SCMs. Three (3) beams were cast for each mixture, and the average measurements are reported below in Table 4-8 and Figure 4-13.

Table 4-8: Percent Length Change of Hardened Concrete Beams (in microstrain) from initial demolding, with increasingly negative values indicating shrinkage

Days after placement in environmental chamber	Unrestrained Shrinkage of 4- by 8-in Concrete Beams (με) [ASTM C157/C157M – 17]							
	Control Mixtures		15% Cement Replacement		20% Cement Replacement		50% Cement Replacement (15% J-Rox/ 35% Slag)	
	100% OPC	20% Fly Ash	J-Rox 4	J-Rox 5	J-Rox 4	J-Rox 5	J-Rox 4	J-Rox 5
0	-183	203	10	3	170	-13	75	20
4	-350	77	-33	27	100	20	45	7
7	-300	60	-63	40	0	30	35	40
14	-407	--	-140	-67	33	-73	30	13
21	-473	-67	-210	-190	-37	-200	8	-47
28	-547	-130	-357	-267	-123	-270	-35	-160
56	-663	-223	-350	-363	-190	-350	-110	-280

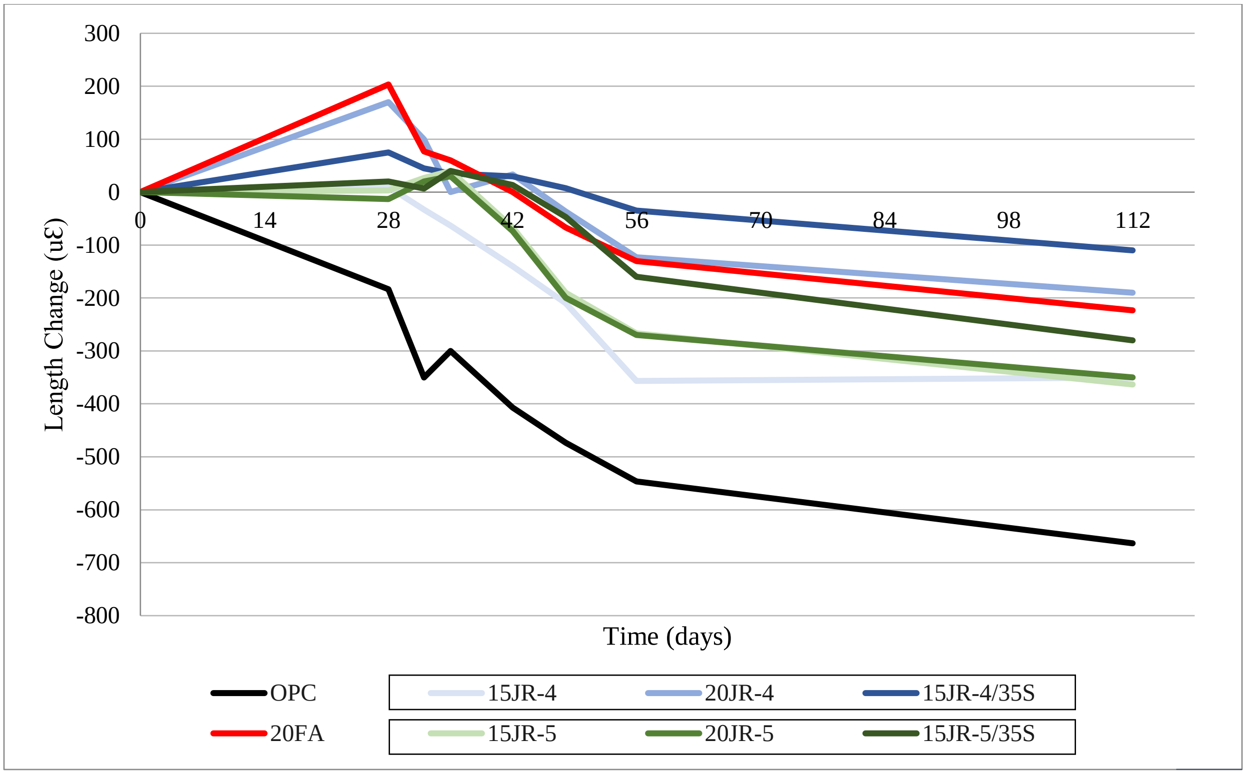

Figure 4-13. Unrestrained shrinkage of 4- by 8-in concrete beams

CHAPTER 5: ANALYSIS OF RESULTS

5.1 Introduction

This chapter serves to summarize the test results of paste, mortar, and concrete samples containing varying quantities and types of J-Rox. Each J-Rox mixture was analyzed against the two control mixtures i.e., 100% ordinary portland cement (OPC) and 20% fly ash (FA), and overall industry standards in the context of performance, durability, and sustainability.

This chapter will also provide an overview of a theoretical industrial symbiosis (IS) network consisting of relationships between J-Rox/Novaphos and the concrete industry. This overview includes an evaluation of the sustainability and market potential of this theoretical network, the industry relationships required to make this effective, and a graphical representation of the IS network.

5.2 Analysis of Results

Five (5) J-Rox samples of varying composition were evaluated for their use as an SCM in concrete applications. Based on the initial testing of mortar and concrete, the most promising results were observed from the samples containing GypRox (JR-1 and JR-4). The results of these tests led to the additional testing of JR-5, another GypRox sample produced using an alternative manufacturing process. These three (3) J-Rox types have the most similar chemical composition in terms of oxide analysis.

Although an oxide analysis is often provided by manufacturers of cement and SCMs to define materials, this form of analysis may not necessarily present a full picture of the composition and reactivity of each element. This is due in part to the multiple mineralogic forms that may fall under the same oxide classification and the analysis seldom includes mineralogical phases of the oxides (i.e. crystalline or amorphous). As discussed in Section 3.2.1, these varying mineralogic forms of elements can have very different impacts on reactivity and/or the overall performance of concrete and mortar mixtures. Still, oxide analysis is a useful and necessary tool which can provide direction for further exploration of material attributes.

5.2.1 Paste Results

5.2.1.1 Set Time Testing

The variation in set times between J-Rox mixtures could be attributed to the different chemical compositions and replacement rates, and/or varying particle size distribution of the J-Rox. From a chemical composition standpoint, set times between samples may be affected by the silicon dioxide (SiO_2) content of each J-Rox material. Table 5-1 displays the varying chemical composition of each J-Rox material. The darker green cells demonstrate which types of J-Rox contain the highest percentage of each parameter, whereas the white cells have the lowest percentage of each parameter. The distribution of the remaining values on this scale are represented as the respective color gradient between green and white.

Table 5-1. Comparison of J-Rox Chemical Composition with Set Time Results for Paste Samples

Parameter	Units	Gyp/Sand/Clay (JR-1)	Low Silica (JR-2)	High Silica (JR-3)	GypRox (JR-4)	GypRox (JR-5)
SiO_2	%	65.1	32.8	52.2	57.1	69.5
CaO	%	18.8	35.3	23.6	25.2	19.9
P_2O_5	%	5.9	14.3	11.2	4.2	5.7
SO_4	%	2.5	2.3	1.2	7.2	1.6
S	%	0.92	0.8	0.5	1.3	0.6
Fe_2O_3	%	1.52	2.5	1.8	0.53	0.5
Al_2O_3	%	1.44	1.8	1	0.4	0.2
MgO	%	0.2	3.3	2	0.28	0.2
F	%	0.64	1.6	1.2	0.2	0.3
Na_2O	%	0.15	0.4	0.3	0.03	0.1
K_2O	%	0.2	0.1	0.1	0.06	0
C	%	0.1	2.4	3.5	0.03	0

The strongest trends were observed when comparing the results of the materials with the lowest and highest concentrations of SiO_2 (JR-2 and JR-5, respectively). When compared to other samples of the same cement replacement rate, the final setting time of JR-5 generally seemed to decrease as the cement replacement (SiO_2 content) increased, whereas the setting time of JR-2 generally seemed to increase with an increased cement replacement (and a lower SiO_2 content, in comparison to other mixtures). This was expected due to the relationship between SiO_2 and CaO, in which higher SiO_2 content is often correlated with lower quantities of lime (CaO) which contributes to quicker setting time. Still, oxide analysis cannot determine the elemental form of CaO in these mixtures (e.g., lime or calcium sulfate). This impact of SiO_2 content on setting time of cement paste has, however, been observed in previous studies (Zhuang and Chen, 2019) where mixtures containing higher percentages of SiO_2 also showed reduced setting time. In this study, J-Rox 5 had a relatively high SiO_2 content (and low CaO content) and a relatively slow initial set time, which may be explored further in future study.

Particle size also impacts set time, and as can be seen in Appendix A, each version of J-Rox was ground to a slightly different particle size distribution. For each J-Rox material, most particles were between 10 and 100 microns, but a significant portion of particles ranged between 1 and 10 microns. J-Rox 2, 3, and 4 had a portion of particles less than 1 micron, which would support more reaction and potentially impact set times. It is noted that the fineness of J-Rox can be adjusted by the producer to assist in achieving the desired performance of the material.

5.2.2 Mortar Results

5.2.2.1 Water Demand

Per C1437-20 “Standard Test Method for Flow of Hydraulic Cement Mortar” (ASTM 2020), the water demand of each mixture was evaluated in the context of achieving a target workability (i.e., a flow of 110 ± 5 % in 25 drops of the flow table). For mortars produced with different J-Rox types, differences in the water demand required to achieve the target flow are suspected to be a function of 1) the fineness of the J-Rox, 2) the chemical composition of the J-Rox, and 3) the porosity of the J-Rox particles. Additional studies could be performed to further explore the impact of J-Rox composition on the subsequent water demand required to achieve the ASTM C305-20 flow.

Out of the five J-Rox mixtures, JR-4 was observed to have an overall lower water demand than the other J-Rox variations. Other notable trends include the increased percent replacement of cement in samples of JR-1, JR-4, and JR-5 positively correlating with increased water demand; in contrast samples of JR-2 and JR-3 showed a negative correlation between these two variables in which an increased cement replacement rate resulted in a decreased water demand. The color pattern shown below in Table 5-2 illustrates the distribution, ranging from the highest water demand (light green/white) to the lowest water demand (dark green) for each cement replacement category.

Table 5-2: Comparison of Water Demand of Mortar Mixtures

Sample Type	**Grams of Water Required to Achieve Target Workability Per ASTM C1437-20**		
	15% Cement Replacement	**20% Cement Replacement**	**25% Cement Replacement**
Gyp/Sand/Clay G-Rox (JR-1)	545	595	595
Low Silica (JR-2)	610	595	595
High Silica (JR-3)	615	600	600
GypRox (JR-4)	560	590	590
GypRox (JR-5)	600	600	610
100% Cement Control (100-OPC)	580		
20% Fly Ash Control (20FA)	535		

Samples exhibiting a positive correlation between cement replacement rate and water demand (i.e., JR-1, JR-4, and JR-5) were all comprised of a gypsum-based feedstock. The JR-1 and JR-4 samples were also shown to have the highest compressive strength at the final testing age of 91 days. Figures 5-1 and 5-2 show the relationship between 91-day compressive strength and water demand. This relationship indicates that J-Rox 1 and J-Rox 4 samples, containing the gypsum-based feedstock, required less water to achieve higher or comparable compressive strength values at 91 days compared to J-Rox comprised of the silica-based feedstock.

The results for J-Rox 1 were comparable to the OPC control at all three (3) cement replacement rates in terms of average 91-day compressive strength and water demand. However, out of all samples tested, the 20% fly ash control exhibited the highest compressive strength and lowest water demand.

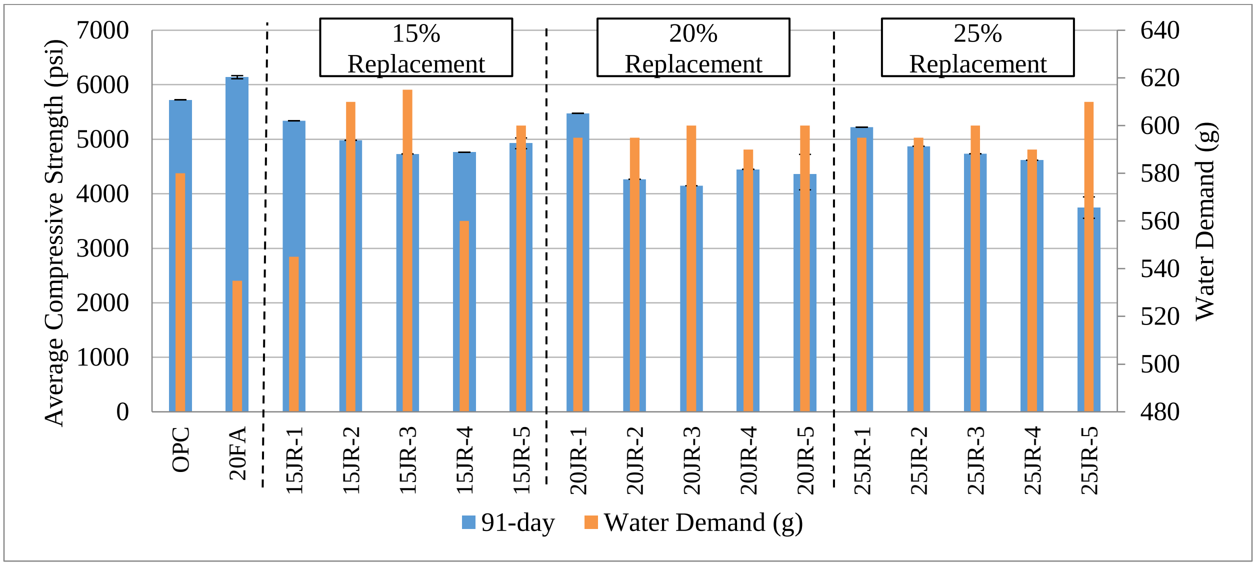

Figure 5-1. Water demand vs 91-day compressive strength of mortar cubes (grouped by % replacement)

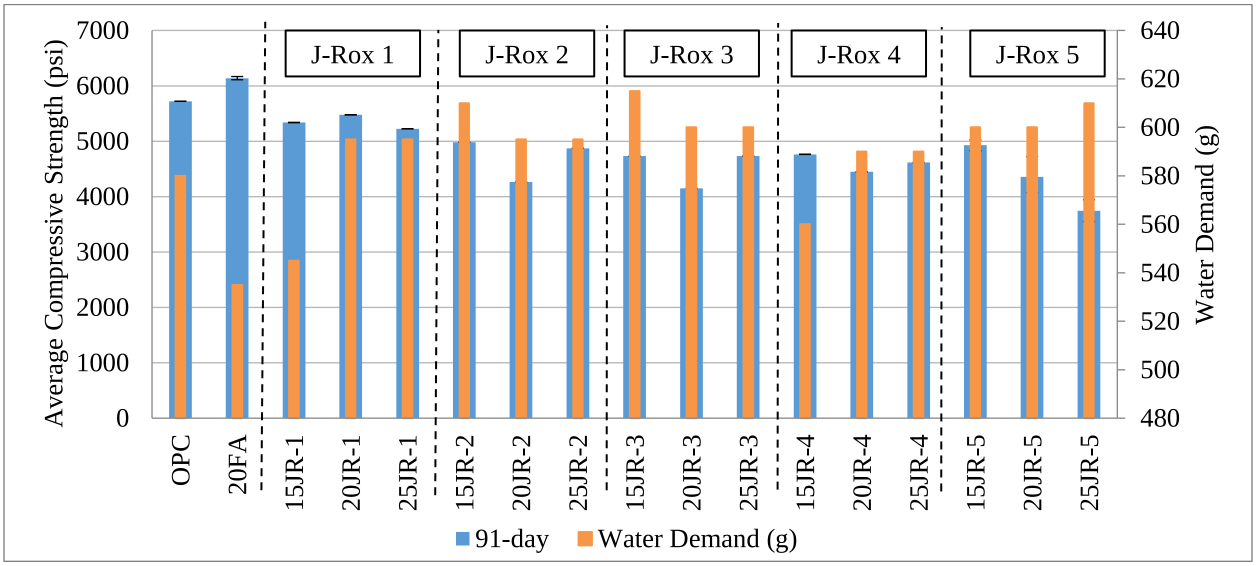

Figure 5-2. Water demand vs 91-day compressive strength of mortar cubes (grouped by material)

2.2.2 Compressive Strength

When comparing only the results of J-Rox samples, the mortar cubes containing JR-1 consistently exhibited the highest average compressive strength at all cement replacement rates (15%, 20%, and 25%) throughout the testing program. For cement replacement rates of 15% and 20% the second highest average compressive strength values were observed from samples containing JR-4, however at a replacement rate of 25% the second highest average compressive strength was observed from the JR-2 samples.

<u>Comparisons to Industry Standards</u>

Section 353 "Concrete Pavement Slab Replacement", specified by the Florida Department of Transportation (FDOT), requires a minimum 28-day compressive strength of 3,000 psi for pavement slabs, and a minimum compressive strength of 1,600 psi prior to opening the slab to traffic. As shown below in Figures 5-3 and 5-4, based on the average compressive strength values of tested specimens, all J-Rox mortar mixtures exhibit adequate strength requirements for slab replacement.

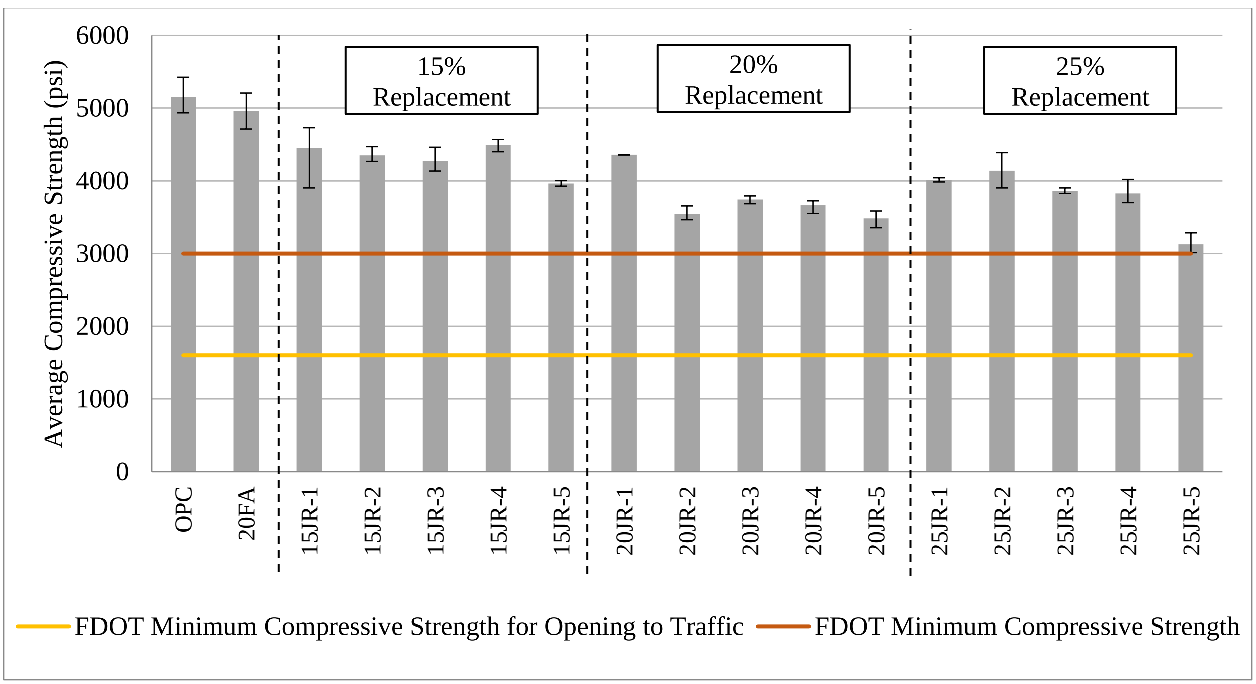

Figure 5-3. 28-day Compressive strength results of J-Rox replacement of cement mortar mixtures (grouped by % replacement)

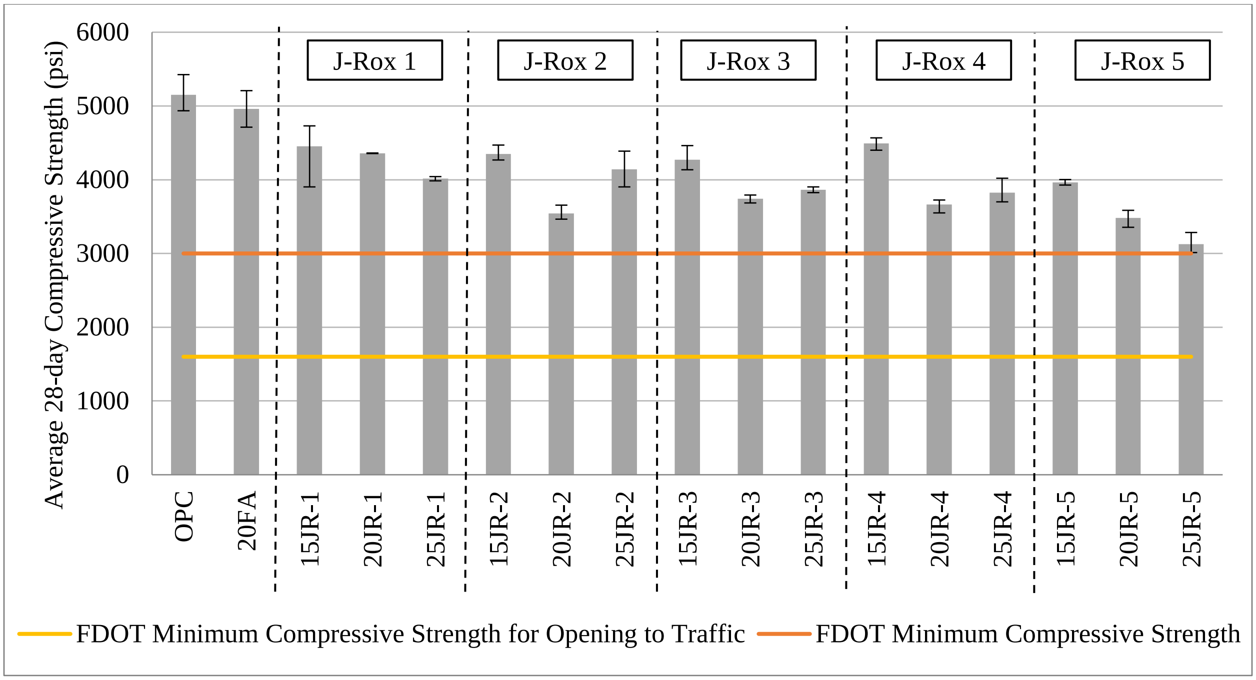

Figure 5-4. 28-day Compressive strength results of J-Rox replacement of cement mortar mixtures (grouped by material)

5.2.2.3 Sulfate Attack Testing

When only comparing the results of samples containing J-Rox, the mortar bars containing JR-4 consistently exhibited the least percent change across all cement replacement rates (15%, 20%, and 25%) throughout the testing program. For cement replacement rates of 15% and 20% the second lowest length change was observed from samples containing JR-1, however at a replacement rate of 25% the second lowest length change was observed from the JR-2 samples. Because length change is an indicator of sulfate-related expansion, results of sulfate attack testing is used as an indicator for durability.

The variation in length change between J-Rox samples is visualized below in Table 5-3, wherein the color variation is based on comparisons between all samples for each specific testing age (week). Samples demonstrating the least percent length change for that week are represented by green; samples demonstrating the most percent length change for that week are represented in red. The distribution of the remaining values on this scale are represented as the respective color gradient between green and red.

Table 5-3. Representation of length change of mortar beams during sulfate attack testing (grouped by J-Rox Material)

Week	Length Change per Week (× 10-4 %), grouped by J-Rox material																
	100-OPC	20FA	JR-1			JR-2			JR-3			JR-4			JR-5		
			15%	20%	25%	15%	20%	25%	15%	20%	25%	15%	20%	25%	15%	20%	25%
1	7	80	53	72	18	60	63	15	57	75	73	12	40	65	88	98	150
2	30	117	70	77	98	83	107	90	100	93	162	50	65	115	140	140	177
3	45	137	98	87	130	125	175	123	112	157	198	65	140	163	152	164	222
4	68	165	100	173	158	138	218	158	135	205	225	88	153	215	167	182	192
5	70	210	157	193	163	163	248	183	217	228	270	105	185	212	197	192	232
6	150	233	183	225	205	223	268	223	245	262	300	153	222	250	217	230	237
7	155	270	157	250	212	260	315	228	292	285	315	173	242	268	233	250	253
8	175	280	228	268	237	258	355	258	315	315	352	187	238	300	253	270	273
13	250	458	293	300	282	443	575	413	457	587	648	273	313	380	303	342	347
15	287	523	312	323	315	635	707	508	587	758	762	295	338	428	363	346	378
26	733	1078	473	433	372	2100	1443	903	1312	1950	1287	550	445	813	463	540	548

* The color gradient demonstrates how each sample compares to others at the same testing age (week), ranging from the smallest percent change (green) to the largest percent change (red).

Results indicate that the JR-1, JR-4, and JR-5 mixtures performed comparably to the 100% OPC control and even begun to outperform the control at 26 weeks (6 months). Both JR-1 and JR-4 outperformed the fly ash control; by 26 weeks, the 25% JR-2 mixture outperformed the fly ash control as well.

Comparisons to Industry Standards

Results can be compared to ACI 318 limits to support sulfate resistance in different exposure categories, or to other sulfate attack testing limits for transportation structures and/or pavements. Typically, cements are considered sulfate resistant if the expansion does not exceed 0.1% after a selected range of time (often 6 to 18 months) (Ferraris et al., 2018). It could be assumed that the 18-month target would be selected for exposure to extremely aggressive sulfate solutions, while the 6-month target would be selected for less aggressive sulfate exposure environments. The only type of J-Rox which did not meet the criteria, or exhibit less shrinkage than the fly ash control, at any replacement rate was JR-3.

Based on the ACI 318 limits, the JR-1 mixtures at all three (3) cement replacement rates could meet the classification for sulfate resistance in less aggressive sulfate exposure environments. The results also indicate that the 15% and 20% JR-4 mixtures, and the 25% JR-2 mixture would also meet the ACI 318 limit for sulfate resistance in less aggressive sulfate exposure environments. At this testing age, the 25% mixtures for JR-4 and JR-2 produced results comparable to the OPC control, and outperformed the fly ash control which did not meet the ACI 318 limit at 26 weeks. The results of sulfate attack testing compared to the ACI 318 limit are shown in Figure 5-5.

Although the 25% JR-2 mixture was the only of the JR-2 mixtures to stay within the ACI limit at 6 months, the results indicate that the sulfate resistance of JR-2 mixtures increases with an increased cement replacement rate. This trend was also observed in JR-1, whereby sulfate resistance increased with each increase in the cement replacement rate. Overall, the results demonstrated that even at the highest cement replacement rate (25%) multiple types of J-Rox could successfully meet the 26-week limit, suggesting that the increased use of J-Rox as an SCM proposes sustainability benefits by both reducing the amount of cement used in a concrete mixture and increasing the service life of structures in sulfate rich environments. These trends could be analyzed in future studies to determine how larger cement replacement rates of J-Rox could further improve the durability of concrete structures.

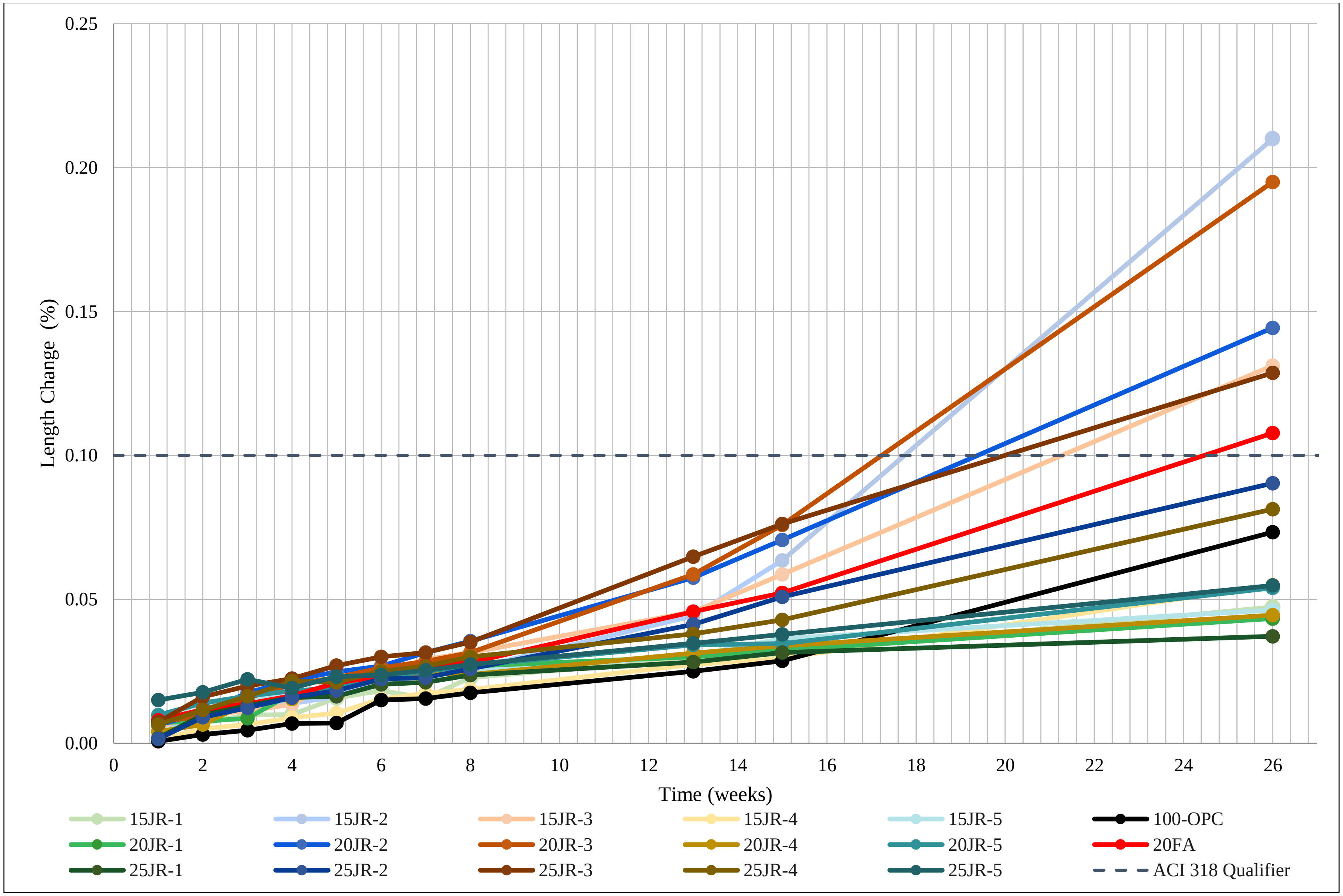

Figure 5-5. Results of Sulfate Attack testing on 1- by 1- by 11 ¼ -in Mortar Beams Compared to ACI 318 qualifier for sulfate resistance

5.2.3 Hardened Concrete

The results identified samples containing JR-5 as having the highest strength factors (i.e., compressive strength and MOE), while the JR-4 mixtures tested better for durability (i.e., surface resistivity and shrinkage). These differences could be attributed to the varying chemical compositions of key oxides within each type of J-Rox. Although both JR-4 and JR-5 were both sourced from a gypsum-based feedstock, JR-5 had comparatively higher concentrations of SiO_2 and P_2O_5, while JR-4 had higher concentrations of CaO, Fe_2O_3, and Al_2O_3, as shown in Table 5-4.

Table 5-4: Composition of Key Oxides in JR-4 and JR-5

Parameter	Units	JR-4	JR-5
SiO_2	%	57.1	69.5
CaO	%	25.2	19.9
P_2O_5	%	4.2	5.7
Fe_2O_3	%	0.53	0.5
Al_2O_3	%	0.4	0.2
Note: Highlighted cells represent highest percent composition between JR-4 and JR-5 SCM material			

The weighted values of each oxide within the concrete samples were calculated to identify the percent weight included in each concrete sample. The percent weights of key oxides for each concrete mixture are shown in Table 5-5.

Table 5-5. Chemical Comparison of Oxide Concentrations Between Concrete Mixtures

Oxide	Percent Weight (%)							
	Control Mixtures		15% Cement Replacement		20% Cement Replacement		50% Cement Replacement (15% J-Rox/ 35% Slag)	
	100% OPC	20% Fly Ash	J-Rox 4	J-Rox 5	J-Rox 4	J-Rox 5	J-Rox 4	J-Rox 5
SiO_2	3.1%	8.3%	9.0%	10.9%	9.0%	11.0%	8.5%	10.2%
CaO	9.9%	0.3%	4.0%	3.1%	4.0%	3.1%	4.3%	3.6%
P_2O_5	0.0%	0.0%	0.7%	0.9%	0.7%	0.9%	0.6%	0.8%
Fe_2O_3	0.0%	0.0%	1.1%	0.3%	1.1%	0.3%	1.0%	0.2%
Al_2O_3	0.5%	1.8%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

5.2.3.1 Compressive Strength

Comparisons to Industry Standards

Out of all samples tested, including the OPC and fly ash controls, the highest 91-day compressive strength achieved was by the 15% J-Rox 5 mixture at 7,593 psi. The lowest compressive strength was observed from the 20% fly ash control at 6,207 psi.

As stated in the ACI 318-19, "Building Code Requirements for Structural Concrete", (ACI 2019), most structural concrete applications require a minimum compressive strength of 2,500 psi to 5,000 psi. Based on the results of compression testing, concrete containing J-Rox SCM at replacement rates of up to 20% and the ternary SCM mixture at replacement rates of up to 50% (i.e., 15% J-Rox/35% Slag blended mixtures) can achieve the compressive strength required for many structural applications.

The ACI code requirements are also in line with state DOT requirements. Although the use of J-Rox SCMs in pavement design would represent a low-risk first application for a new material, testing indicated that even J-Rox mortar samples could satisfy FDOT's minimum strength requirements for pavements (e.g., 28-day compressive strength of 3,000 psi for pavement slabs and a minimum compressive strength of 1,600 psi prior to opening the slab to traffic). The compressive strength values of J-Rox concrete samples were expectedly higher than their mortar counterparts, and testing indicated that they may satisfy the more stringent requirements reserved for structural applications.

As shown in Figure 5-6, the FDOT standards are based on the 28-day compressive strength of concrete, the maximum w/c ratio, and the mixture's target slump value; the combination of these three (3) properties are used to define the class of concrete (FDOT, 2022). All tested mixtures meet the 28-day compressive strength requirements and maximum w/c ratio for Class I through IV concrete (3,000-5,500 psi). The only mixture throughout the testing program to demonstrate a slump of three (3) inches was the 15% J-Rox 5 concrete; neither one of control samples met this requirement. Still, all mixtures tested achieved a target slump of three (3) to five (5) inches. Future studies should be conducted to further evaluate the ability of concrete mixtures utilizing J-Rox as an SCM to meet this slump requirement through varied mixture designs. The compressive strength values of the tested mixtures compared to the aforementioned FDOT requirements are shown below in Figure 5-7.

Table 346-3
Master Proportion Table

Class of Concrete	28-day Specified Minimum Compressive Strength (f'c) (psi)	Maximum Water to Cementitious Materials Ratio (pounds per pounds)	Target Slump Value (inches)
I (Pavement) (1)	3,000	0.50	1.5 or 3
II (3)	3,400	0.53	3 (2)
II (Bridge Deck)	4,500	0.44	3 (2)
III	5,000	0.44	3 (2)
III (Seal)	3,000	0.53	8
IV	5,500	0.41(4)	3 (2)
IV (Drilled Shaft)	4,000	0.41	8.5
V (Special)	6,000	0.37(4)	3 (2)
	6,500	0.37(4)	3 (2)
VI	8,500	0.37(4)	3 (2)
VII	10,000	0.37(4)	3 (2)

Notes:
(1) Meet the requirements of Section 350.
(2) Increased slump and slip form concrete as defined in 346-3.1.
(3) For precast three-sided culverts, box culverts, endwalls, inlets, manholes and junction boxes, the target slump value and air content will not apply. The maximum allowable slump is 6 inches, except as noted in (2). The Contractor is permitted to use concrete meeting the requirements of ASTM C478 (4,000 psi) in lieu of the specified Class II concrete for precast endwalls, inlets, manholes and junction boxes.
(4) When silica fume or metakaolin is required, the maximum water to cementitious material ratio will be 0.35. When ultrafine fly ash is used, the maximum water to cementitious material ratio will be 0.30.

Figure 5-6. FDOT Section 346 Structural Portland Cement Concrete, 2022

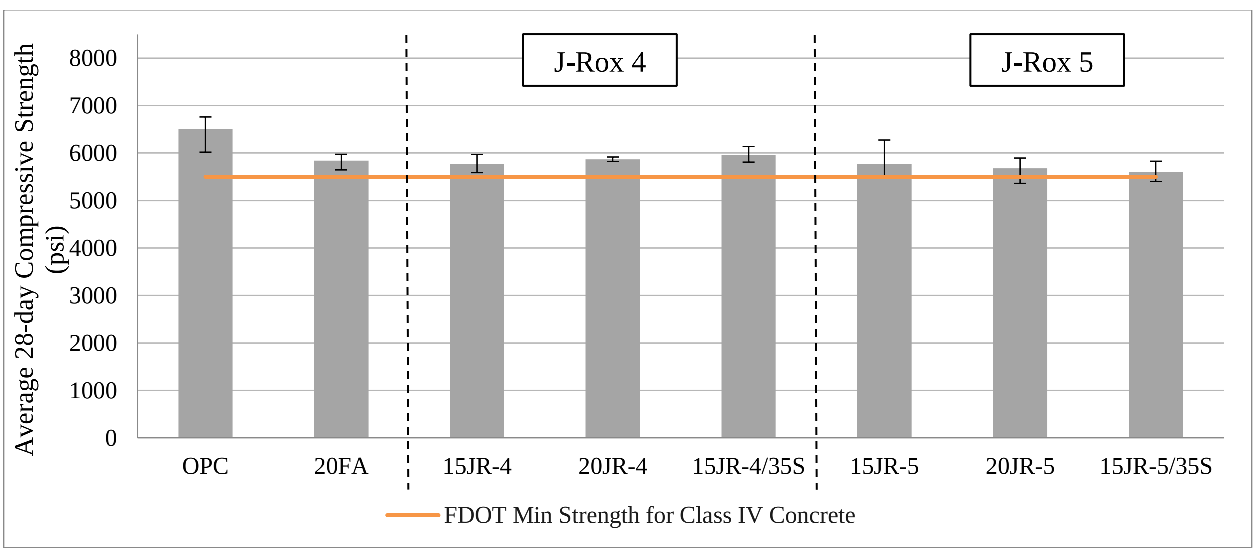

Figure 5-7. 28-day compressive strength values compared to FDOT minimum concrete strength requirements

As shown in Figure 5-8, the NCDOT requires concrete structures to reach a minimum compressive strength of 2,400-3,000 psi prior to removal from of forms, depending on the portion of the structure (NCDOT, 2018). All mixtures demonstrated this minimum compressive strength at the first testing age of 3 days, with the exception of the 15% J-Rox 5/35% Slag blended mixture which exhibited an average compressive strength of 2,358 psi at 3 days. Future studies should evaluate the compressive strength of J-Rox concrete at 24 hours to determine if a mixture design of up to 20% J-Rox replacement of cement could satisfy the NCDOT requirement event more quickly. The compressive strength values of the tested mixtures compared to the NCDOT requirements are shown below in Figure 5-9.

TABLE 420-1 MINIMUM CONCRETE STRENGTH FOR REMOVAL OF FORMS AND FALSEWORK	
Portion of Structure	**Minimum Compressive Strength, psi**
Bridge Deck Slabs and overhangs for beam and girder bridges	3,000
Arch culverts, top slabs of box culverts, walls of box culverts when cast monolithically with the top slab or when the wall is 10 ft or more in height, caps and struts of substructures, diaphragms and other members subject to dead load bending	2,400

Figure 5-8. NCDOT Standard Specifications for Roads and Structures, January 2018

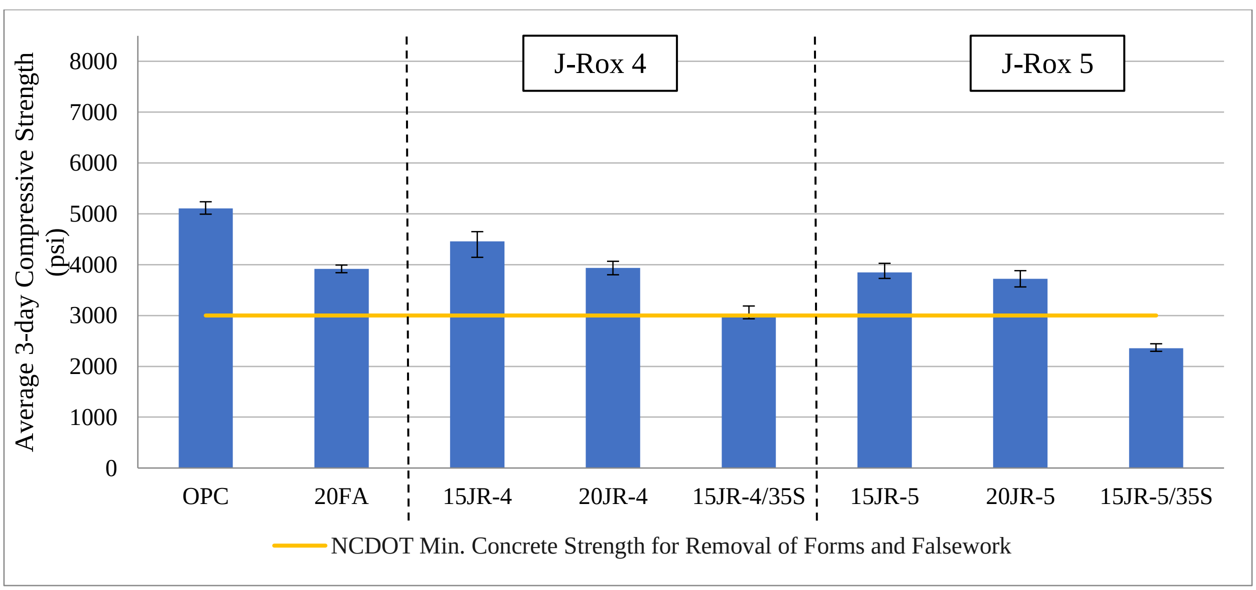

Figure 5-9. 3-day compressive strength values compared to NCDOT minimum concrete strength requirements

Influence of Oxides

Certain relationships were observed between the presence of key element oxides (P_2O_5, SiO_2, and CaO), and results for compressive strength of hardened concrete samples. Despite this observation, it should be noted that oxide analysis does not identify the form of elements present in each parameter and the subsequent influence these varying forms have on their reactivity. This is exemplified in the case of CaO in which some of the calcium may be present as lime, while other forms of calcium may be present as calcium sulfate. The presence and quantity of either form of calcium will have varying impacts the performance of concrete. Although oxide analysis may not allow for all relationships to be fully explored, it provides a solid basis for future comparisons.

When comparing the 91-day hardened concrete results obtained from samples containing JR-4 and JR-5, the JR-5 material had higher concentrations of P_2O_5 compared to its JR-4 counterparts. Upon isolating data for 91-day compressive strength and the percent weight of the oxides, minimal correlations were observed between the higher oxide concentrations and results for compressive strength. Although a minimal trend was observed between 91-day compressive strength and concentrations of P_2O_5, it should be noted that the overall variation in P_2O_5 concentrations was minimal (i.e., less than 1%). Based on the small range of P_2O_5, it cannot be determined that the P_2O_5 concentration of J-Rox SCMs have a significant influence on 91-day compressive strength of concrete cylinders. This relationship could be explored in a future study with more significant variations in the P_2O_5 of J-Rox SCMs.

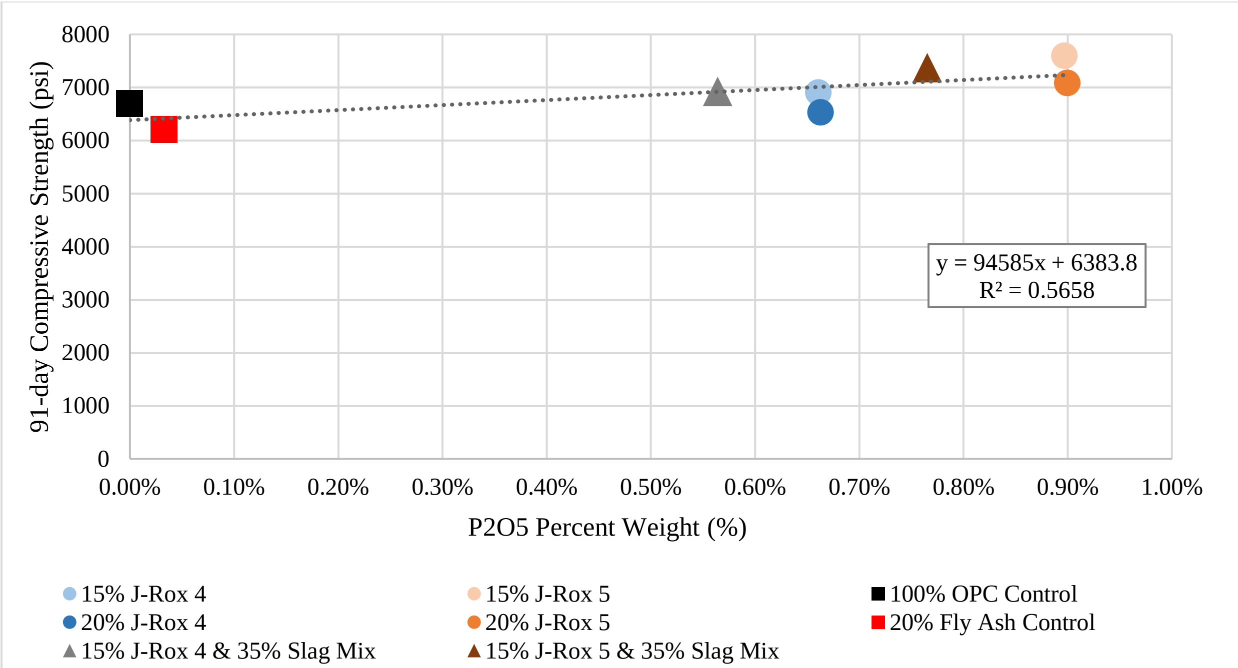

Figure 5-10. Comparison of 91-day compressive strength (psi) by percent weight of P_2O_5

Similarly, relationships were observed between concentrations of other key oxides (SiO_2 and CaO) and the compressive strength of concrete mixtures. As expected, increased concentrations of SiO_2 and CaO were found to correlate with higher compressive strength values. Previous studies have identified a relationship between compressive strength and the ratio of CaO to SiO_2 (Arimanwa et al., 2016), whereby higher sums of (CaO + SiO_2) correspond to higher compressive strength values. Both SiO_2 and CaO contribute to the compressive strength properties of concrete. These trends were observed throughout the data as the compressive strength of the JR-5 mixtures surpassed all other mixtures, including the controls. The relationship between the compressive strength and (CaO + SiO_2) contents of each mixture are shown below in Figure 5-12.

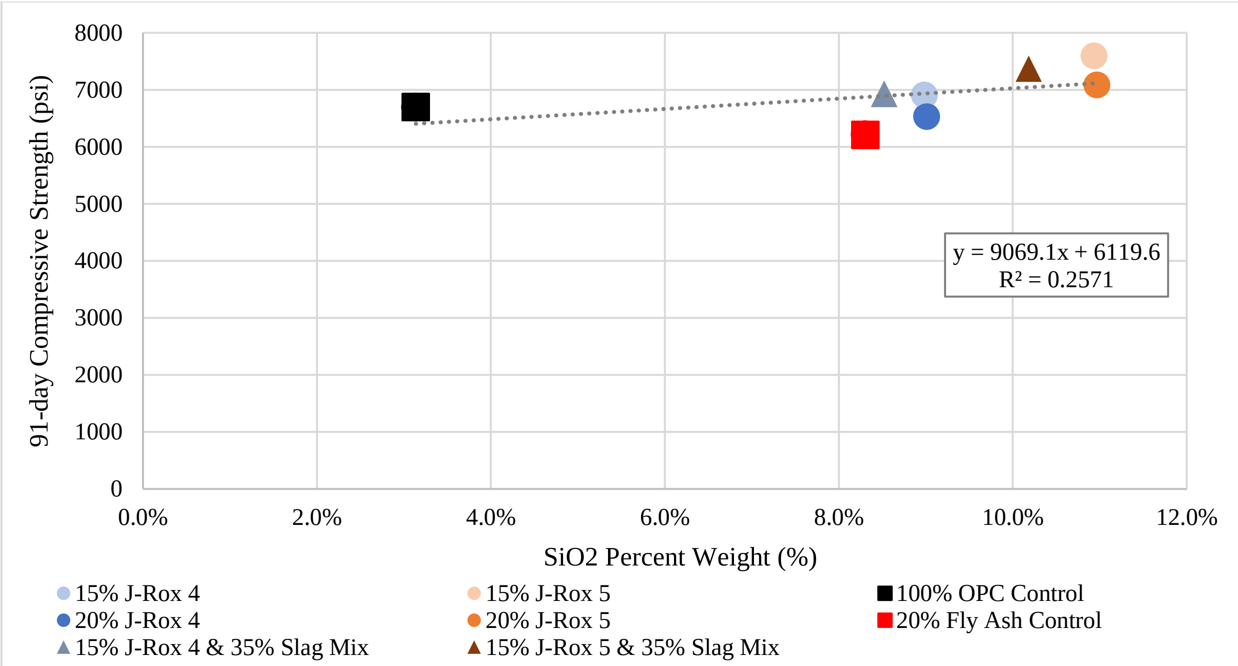

Figure 5-11. Comparison of 91-day compressive strength (psi) by percent weight of SiO_2.

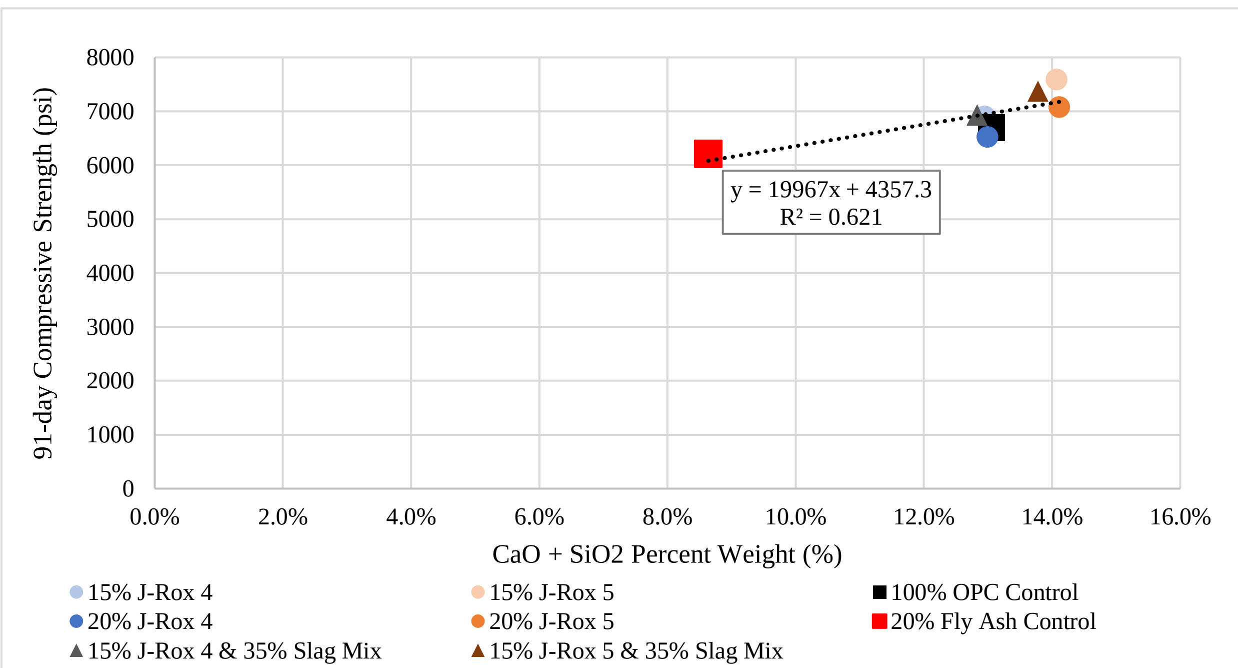

Figure 5-12. Comparison of 91-day compressive strength (psi) by percent weight of (CaO + SiO_2)

5.2.4.1 Modulus of Elasticity

Comparisons to Industry Standards

The American Concrete Institute (ACI), "Building Code Requirements for Structural Concrete" (ACI-318) describes two formulas for estimating MOE based on the 28-day compressive strength value and/or the unit weight of concrete. The results of MOE testing in this study are compared to these formulas, represented by trendlines, and shown below in Figure 5-13. All tested samples, including both controls, had tested MOE values below the ACI-318 predicted values which suggests that the presence of J-Rox alone did not contribute to the lower MOE. The MOE of concrete is largely influenced by the modulus of the aggregate in the mixture, which may explain the deviation from the ACI-318 predicted values. This could be confirmed in a future study which evaluates J-Rox SCM in mixtures with varying types of aggregate.

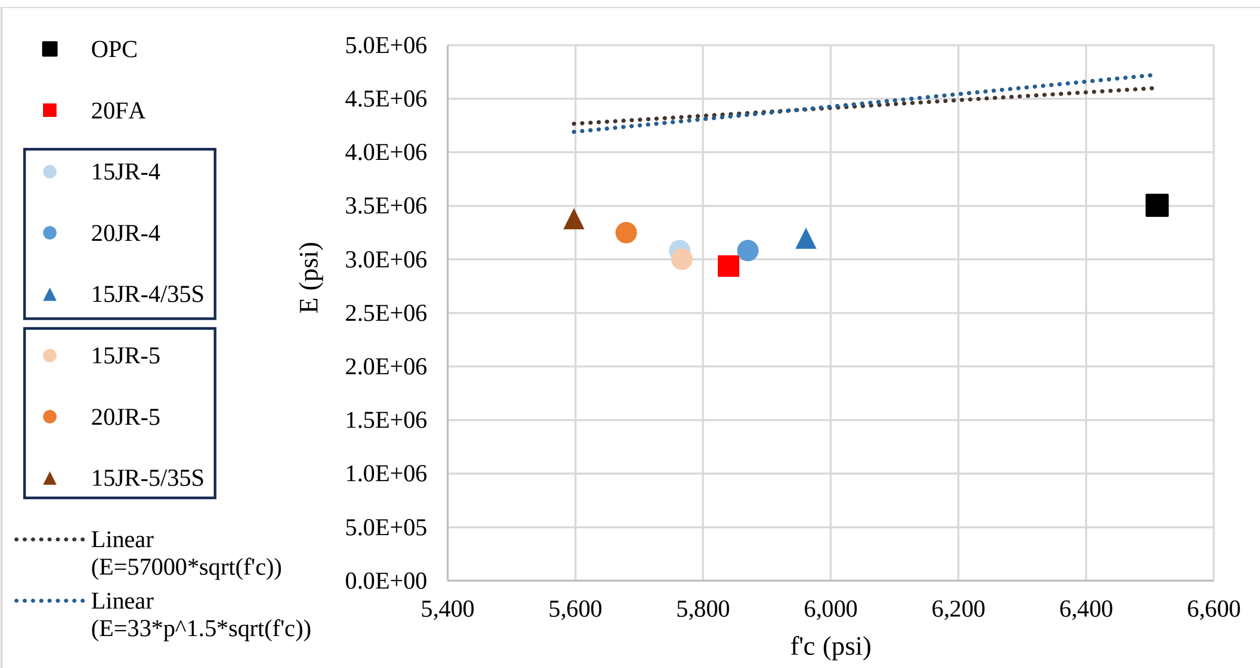

Figure 5-13. 28-day Compressive strength and MOE values compared to ACI-318 predicted values

Influence of Oxides

In contrast to the compressive strength results, the highest and lowest values obtained from MOE testing were the OPC and fly ash controls, respectively. Because the chemical composition of these mixtures had negligible P_2O_5 values, and two of the lowest SiO_2 values, it may indicate that these oxides were a non-factor for impacting MOE. As demonstrated in Figure 5-14 and 5-15, no significant trends were observed from the relationship between the concentration of these oxides and MOE of the J-Rox mixtures. As expected, higher concentrations of CaO resulted in higher MOE; this relationship is demonstrated in Figure 5-16.

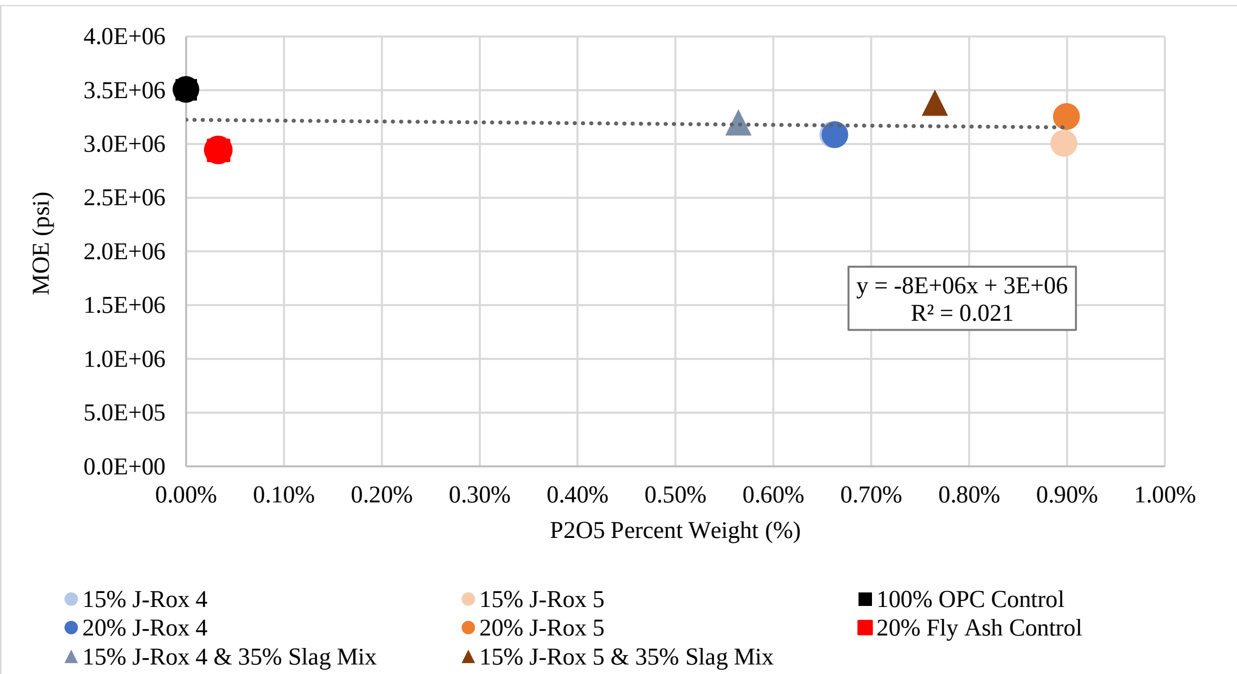

Figure 5-14. Comparison 28-day modulus of elasticity (psi) by percent weight of P_2O_5 concrete samples

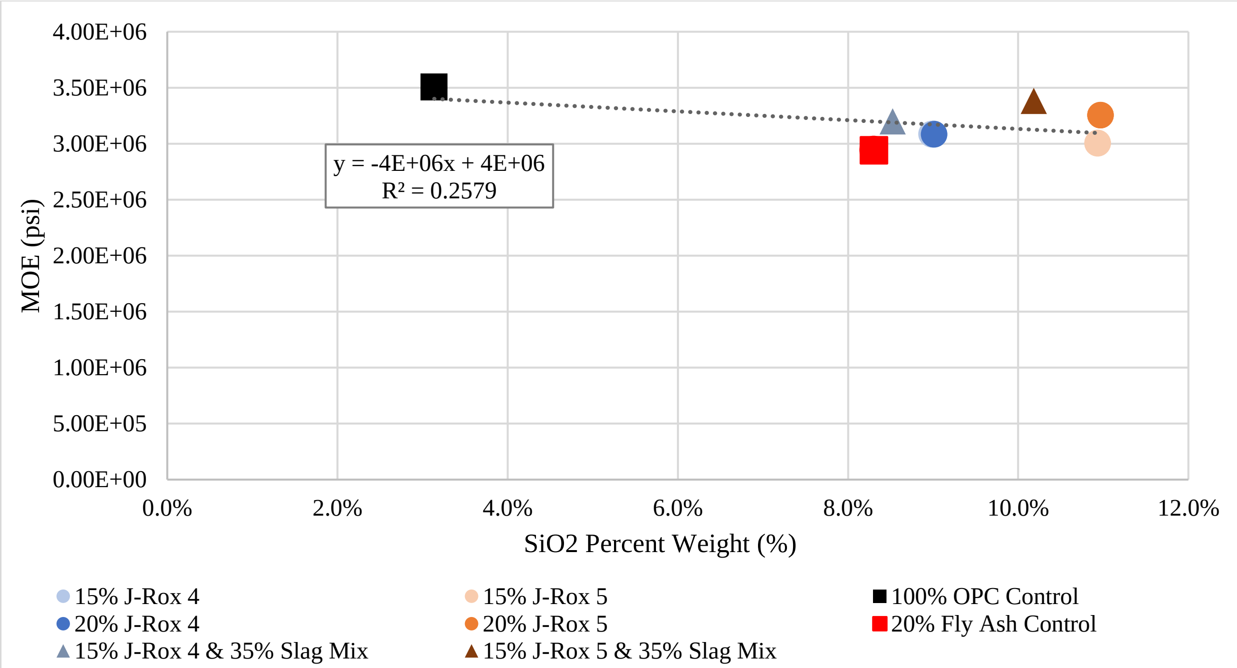

Figure 5-15. Comparison 28-day modulus of elasticity (psi) by percent weight of SiO_2 in concrete samples

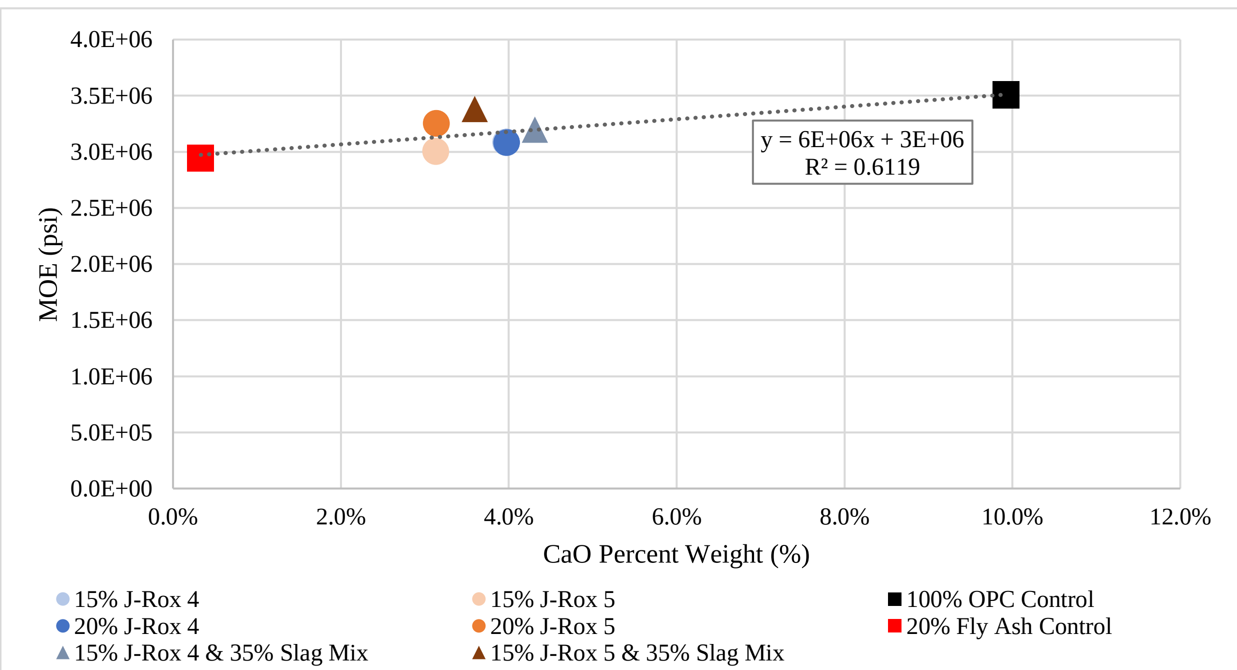

Figure 5-16. Comparison 28-day modulus of elasticity (psi) by percent weight of CaO in concrete samples

5.2.4.2 Surface Resistivity

Comparisons to Industry Standards

As defined by AASHTO T 358-22, “Surface Resistivity Indication for Concrete’s Ability to Resist Chloride Ion Penetration”, surface resistivity values between 12 kΩ•cm and 21 kΩ•cm represent a moderate chloride ion penetration. The ternary blend of J-Rox 4/Slag was nearly high enough to qualify as having “low” chloride ion penetration (20.5 kΩ•cm), well beyond that of the controls. Although the ternary mixtures and the fly ash control all qualified as having moderate chloride ion penetration per AASHTO 358-22, both ternary mixtures met this qualifier by 28 days whereas the fly ash control did not qualify until 91 days. The influence of J-Rox in ternary mixtures should be explored in future studies to further evaluate this connection and determine if J-Rox could be used in such a mixture to produce concrete that can achieve low chloride ion penetration. The surface resistivity results of 4- by 8-inch concrete cylinders are compared to the AASHTO 358-14 qualifiers for chloride ion penetration in Figure 5-17 below.

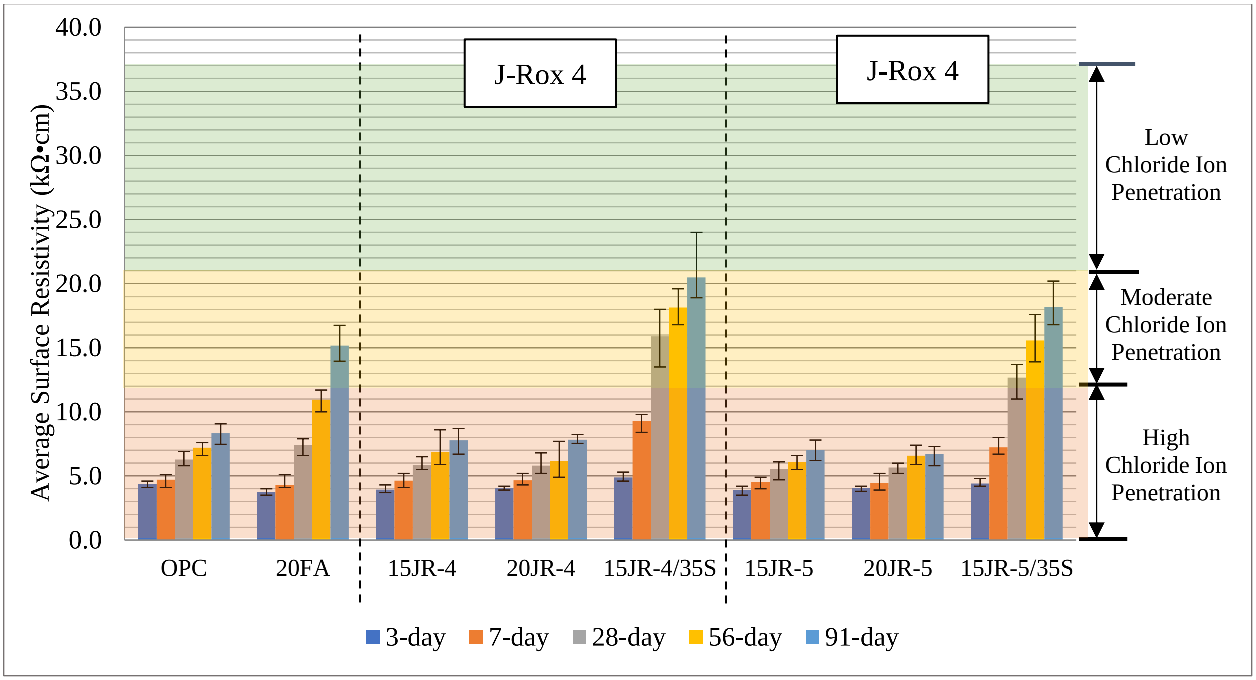

Figure 5-17. Comparison surface resistivity (kΩ•cm) by percent weight to AASHTO 358-14 qualifiers for chloride ion penetration

Influence of Oxides

As demonstrated in Figures 5-18 and 5-19, no significant relationships were observed between the percent weights of SiO_2 and P_2O_5 within mixtures and the surface resistivity. The highest resistivity values were obtained from the ternary 15% J-Rox/35% Slag blended mixtures using JR-4 and JR-5, respectively. The strongest relationship observed was in regard to the ratio of CaO to SiO_2, whereby the highest resistivity values were obtained from samples with the lowest CaO to SiO_2 ratios. This relationship is demonstrated in Figure 5-20.

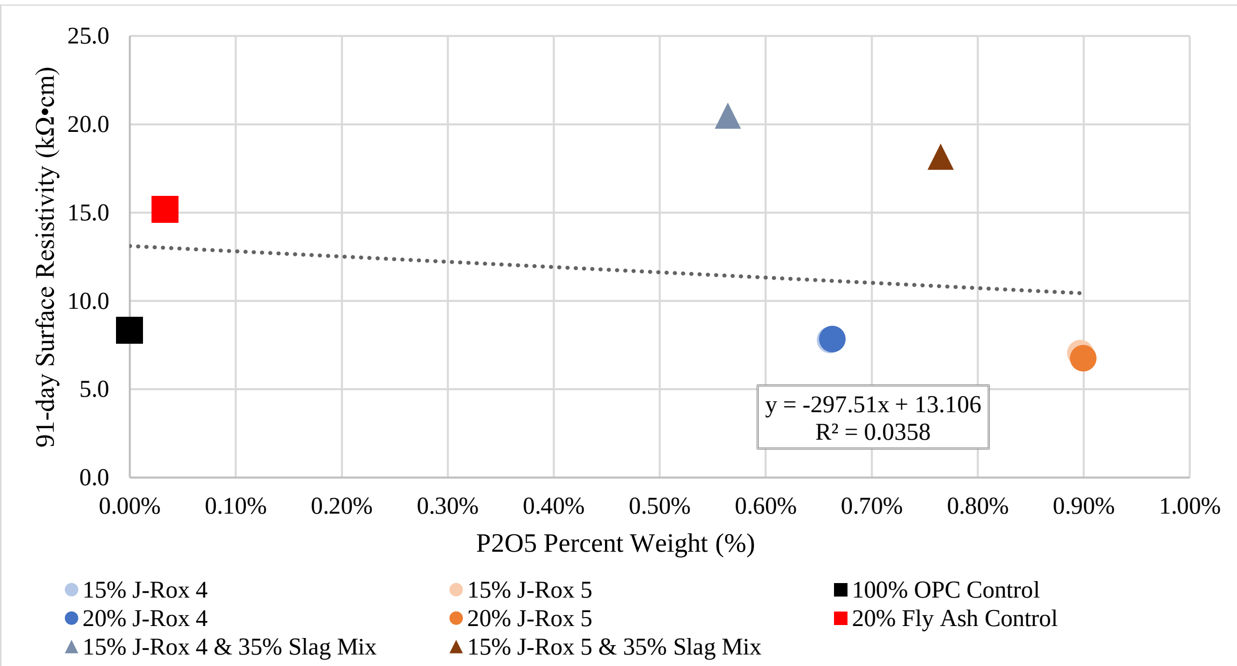

Figure 5-18. Comparison of 91-day surface resistivity results to the percent weight of P_2O_5 in concrete samples

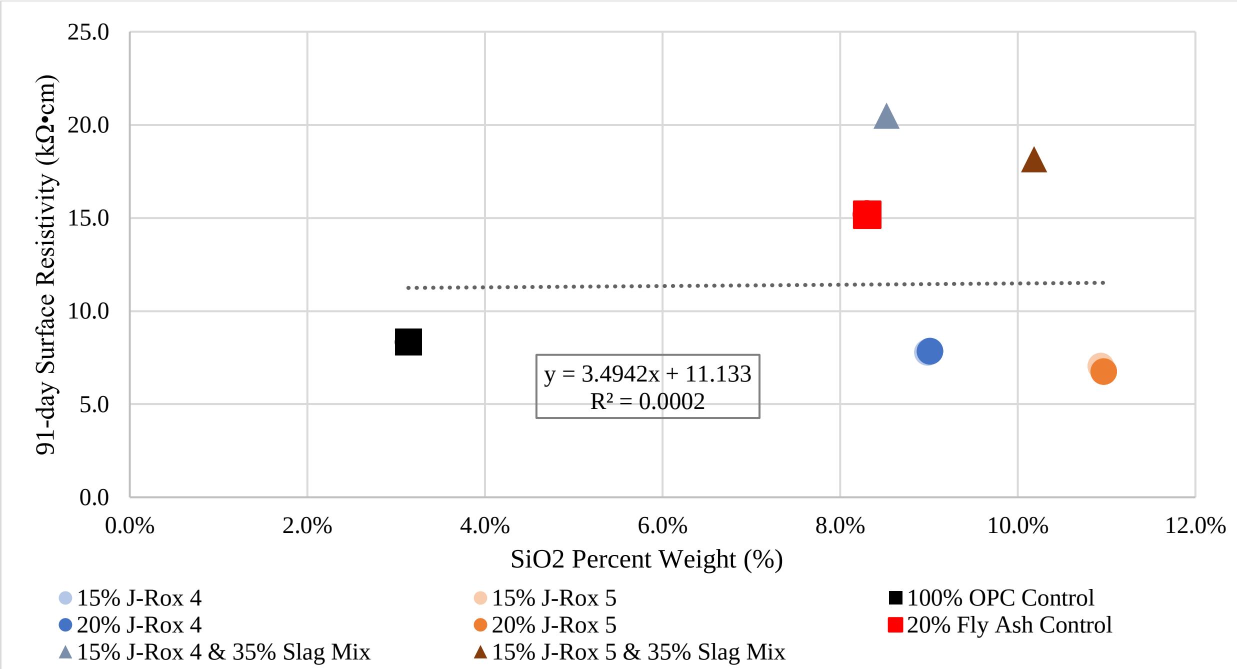

Figure 5-19. Comparison of 91-day surface resistivity results to the percent weight of SiO_2 in concrete samples

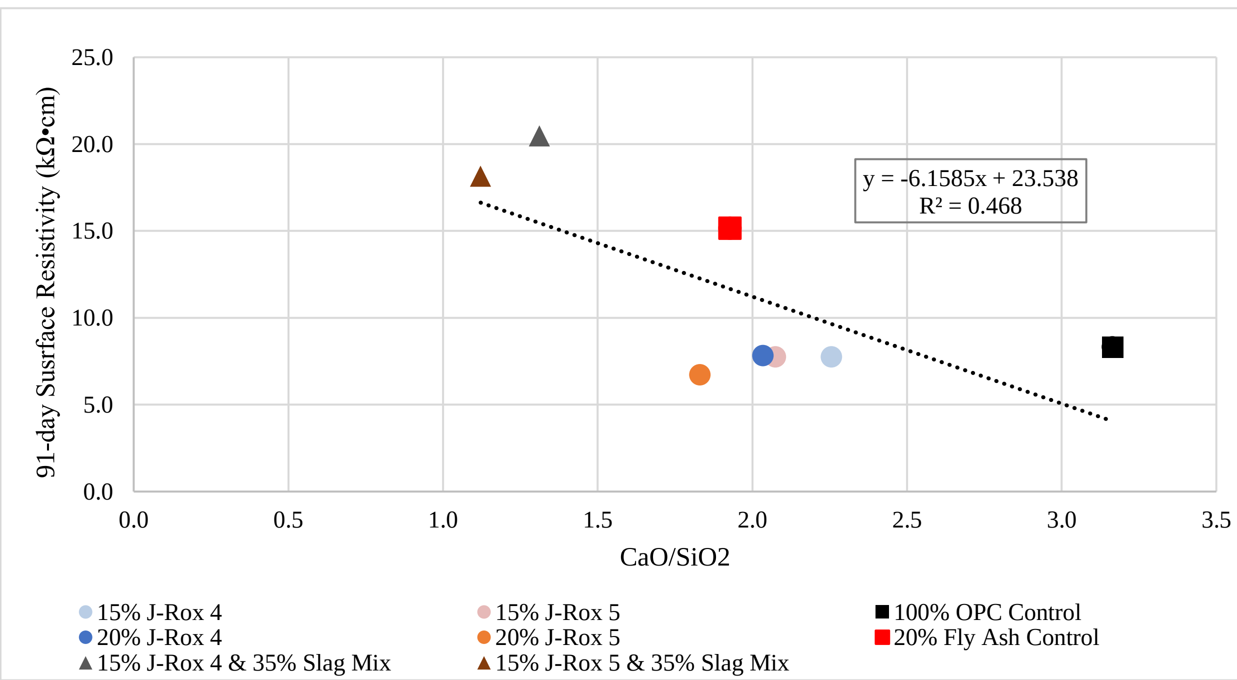

Figure 5-20. Comparison of 91-day surface resistivity results to compared to the CaO/SiO_2 ratio of concrete samples

5.2.4.3 Shrinkage

Comparisons to Industry Standards

The AASHTO R 101-22 standard for performance engineered concrete mixtures for pavements suggests a performance target of 420 microstrain at 28 days of drying (56 days of age). Published guidance regarding volumetric shrinkage targets include that the change in length due to drying shrinkage should be less than 0.04% at 28 days and 0.05% at 90 days to reduce the potential for cracking (Mokarem et al. 2003).

High Performance Concrete (HPC) for structural concrete has also been rated for performance, and shrinkage is included in the criteria. Based on the grading system, the lowest grade is given for concrete exhibiting unrestrained length change of 600-800 με, the middle grade for length change of 400-600 με, and the highest grade for length change less than 400 με (Russell et al. 2006). It is noted that at 28 days of drying (56 days of age), all J-rox mixtures exhibit drying shrinkage lower than the AASHTO R 101-22 recommendation of 420 microstrain. **The ternary blend of J-Rox 4 and slag exhibited extremely low shrinkage (35 microstrain) and exhibited the highest resistivity, indicating long term durability.**

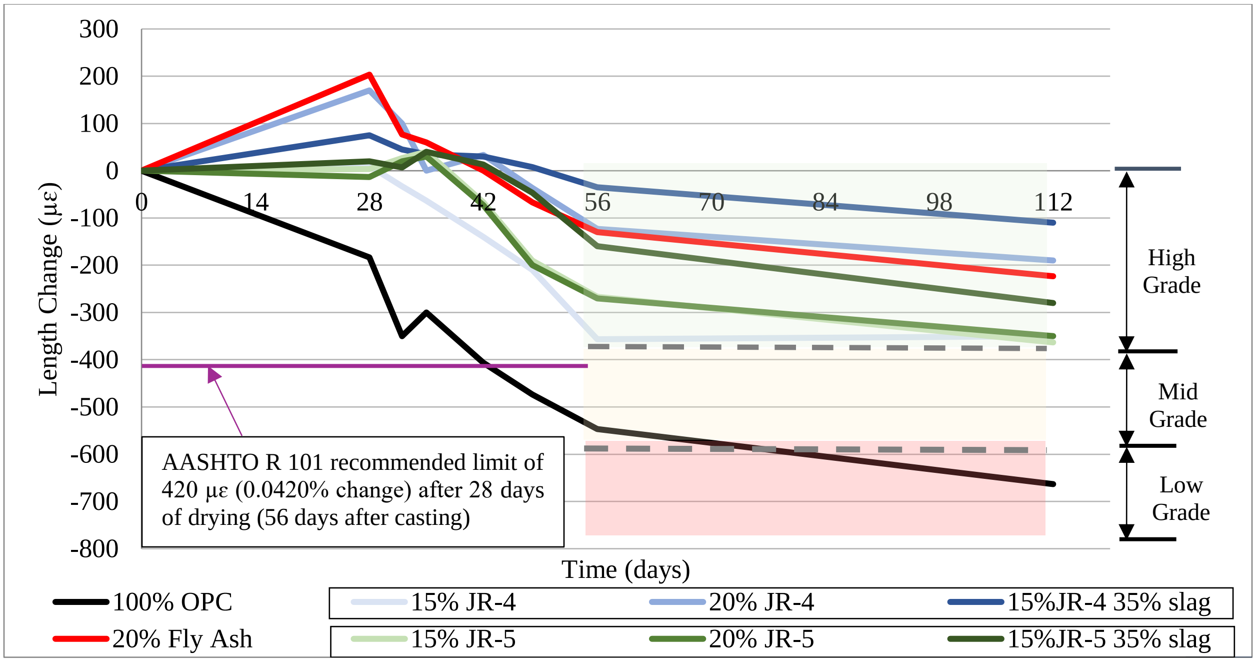

Figure 5-21. Shrinkage results compared to Russel et. al. 2006 qualifiers for high performance concrete

Influence of Oxides

The lowest degree of shrinkage was observed from the 15% JR-4 / 35% slag blend, followed by 20% JR – 4. These results were analyzed against the chemical composition of each J-Rox material and the degree of unrestrained shrinkage. As demonstrated in Figures 5-22 and 5-23, no significant trends were observed from the relationship between the percent weight of P_2O_5 and SiO_2 and unrestrained shrinkage of the J-Rox mixtures. As demonstrated in Figures 5-24 and 5-25, a potential weak correlation was observed between unrestrained shrinkage and the CaO/ SiO_2 ratio which could be verified in future studies.

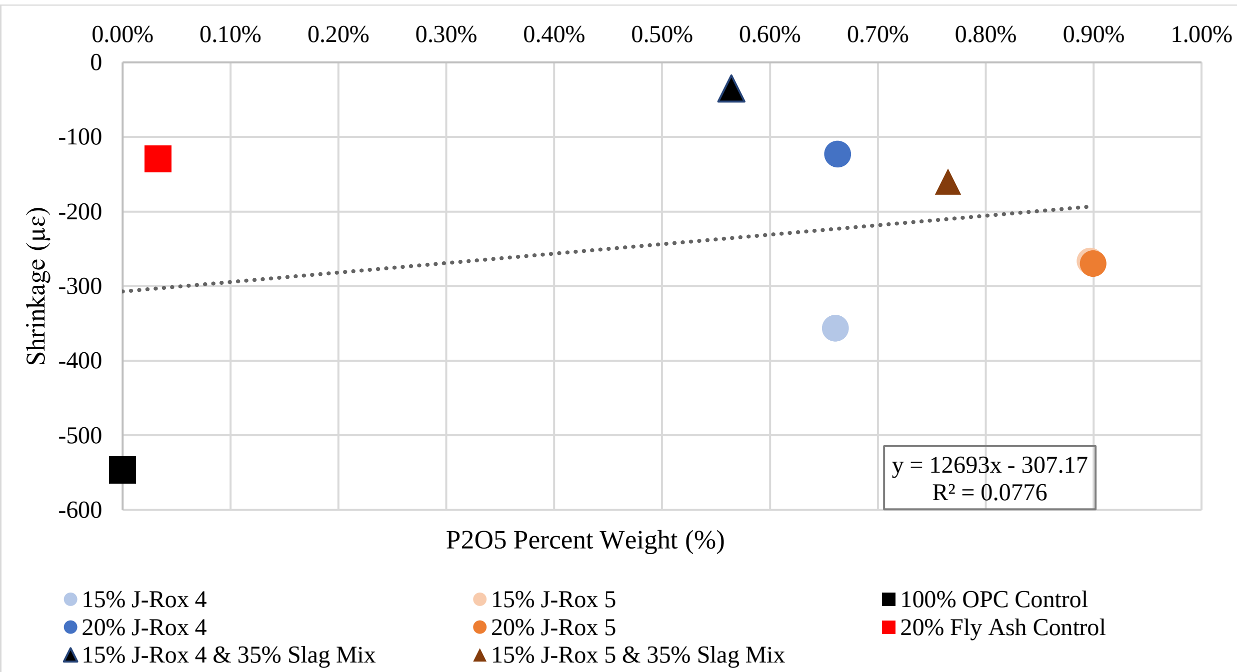

Figure 5-22. Unrestrained shrinkage results to compared to percent weight of P_2O_5

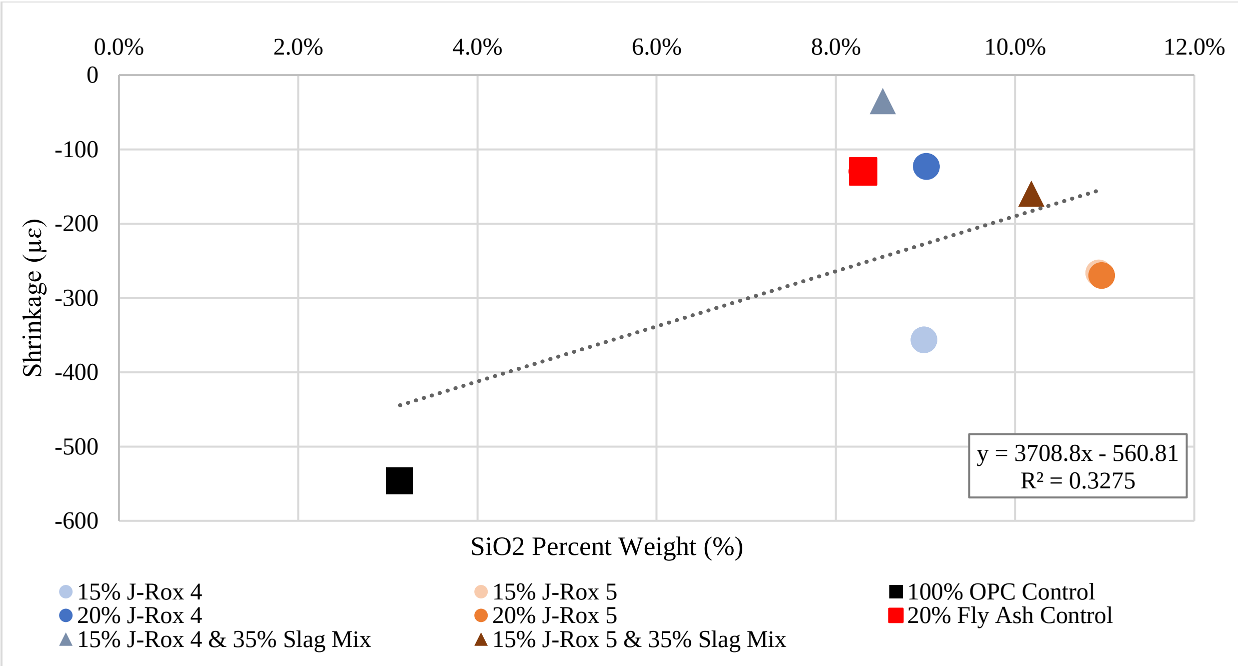

Figure 5-23. Unrestrained shrinkage results to compared to percent weight of SiO_2

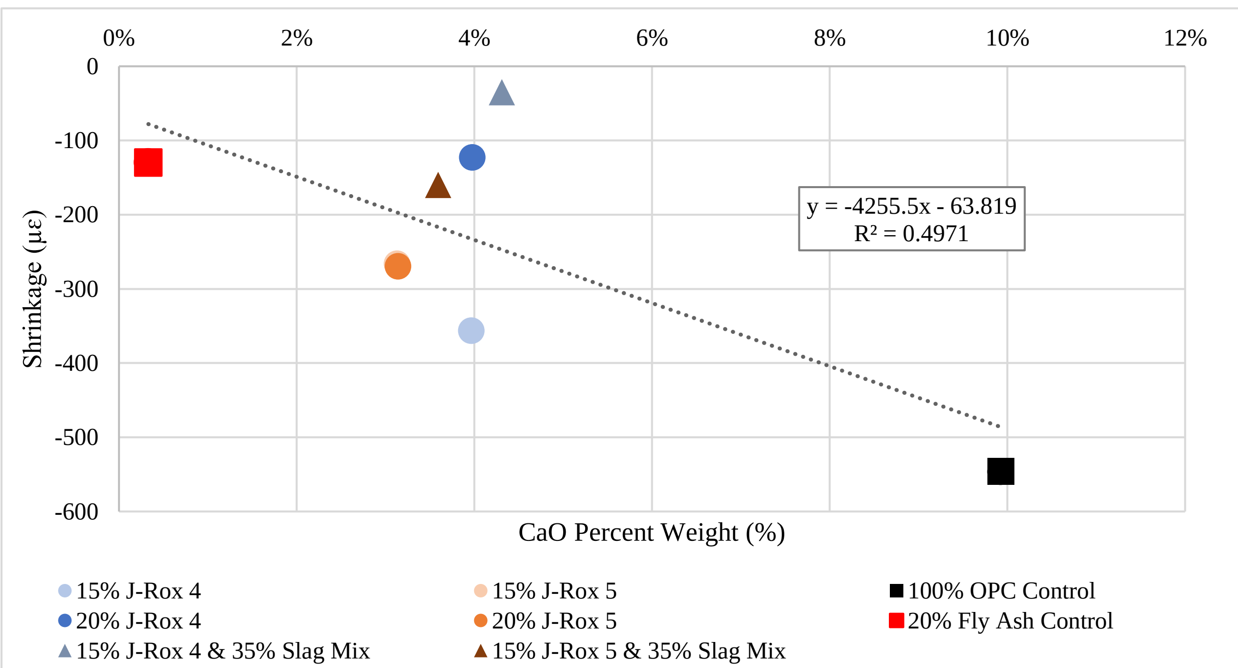

Figure 5-24. Unrestrained shrinkage results to compared to percent weight of CaO

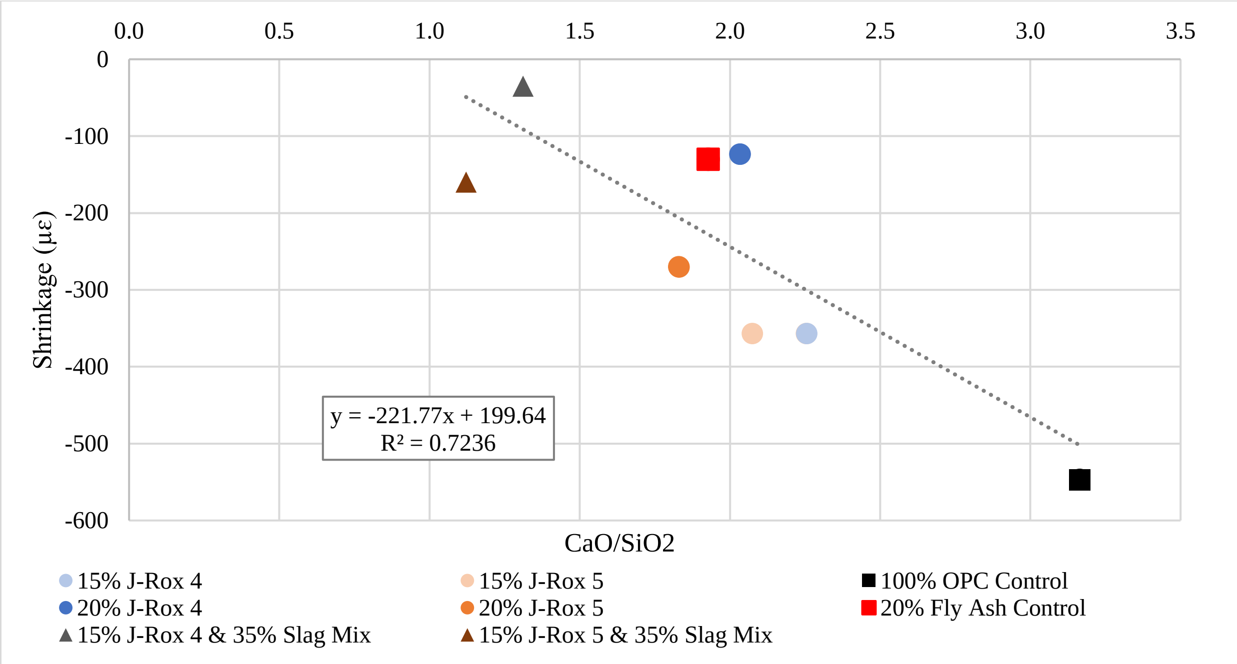

Figure 5-25. Unrestrained shrinkage results to compared to percent weight of CaO/SiO_2

5.2.4 Summary of Results

Testing of the paste, mortar, and concrete samples containing different J-Rox samples at cement replacement rates ranging from 15% to 25%, along with a review of the feed materials used in the creation of each type of J-Rox, was conducted to determine the efficacy of J-Rox as an SCM. This was determined based on comparisons between the samples containing the various types of J-Rox, and control samples consisting of 100% ordinary portland cement (OPC) and 20% fly ash.

The best-performing J-Rox mixtures were those with the GypRox base, (JR-1, JR-4, and JR-5). Overall, these samples were consistently observed to outperform the fly ash control (i.e., 91-day compressive strength, 28-day MOE, surface resistivity, and unrestrained shrinkage). Testing indicated that the samples containing JR-4 had better strength performance, while JR-5 samples had the better durability performance. The results of concrete testing are summarized in Table 5-6 below based on overall trends observed between the percent weights of key oxides and performance factors for strength and durability. The table also identifies the highest and lowest performing samples for each test.

Table 5-6. Summary of Concrete Testing Results

Parameter	Strength		Durability	
	Concrete Strength	**Highest MOE**	**Highest Resistivity**	**Lowest Shrinkage**
Highest J-Rox Performance	15% JR-5	15% J-Rox 5 / 35% Slag	15% J-Rox 4 / 35% Slag	15% J-Rox 4 / 35% Slag
Second Highest J-Rox Performance	15% J-Rox 5 / 35% Slag	20% J-Rox 5	15% J-Rox 5 / 35% Slag	20% J-Rox 4
Lowest J-Rox Performance	20% J-Rox 4	15% J-Rox 5	20% J-Rox 5	15% J-Rox 4
Notes	The three strongest samples were all JR-5 mixtures;	Out of all mixtures, the OPC control had the highest MOE, the FA control had the lowest	Both ternary mixtures had significantly higher surface resistivity at 91 days	The ternary blend of JR-4 and slag showed extremely low shrinkage (35 µE)
	For both JR-4 and JR-5, the 15% mixtures were stronger than the 20% mixtures	The 15% and 20% J-Rox 4 mixtures had identical MOE values (3.08E6)	The 91-day tests for both controls were conducted on 6- by 12-inch cylinders; these results were adjusted using the AASHTO T 358-22 correction factors	Nearly identical results from: - 20% JR-4 (-123 µE) & 20% FA (130 µE) - 15% JR-5 (-267 µE) & 20% JR-5 (-270 µE)
	The FA control had the lowest 91-day compressive strength out of all samples	None of the tested mixtures (including controls) met the projection ACI-318 predicted values		OPC control had most shrinkage overall

5.3 Potential Industrial Ecosystem/Symbiotic Network

5.3.1 Sustainability Impacts on the Concrete Industry

An IS relationship between J-Rox and cement products has the potential to address all three pillars of sustainability by creating environmental, societal, and economic benefits. Tests conducted on samples of concrete containing J-Rox as an SCM exceeded typical minimum compressive strength requirements for structural concrete by more than 2,000 psi. The samples also exhibited a higher compressive strength at 91 days than both the OPC and fly ash controls. Furthermore, concrete samples containing J-Rox exhibited higher durability performance than both sets of control samples in tests of surface resistivity and unrestrained shrinkage. These results confirm the value of J-Rox as a SCM in concrete applications.

The findings of this study suggest that the increased use of J-Rox SCMs could improve the sustainability of the concrete industry by reducing demand of raw materials and extending the service life of structures through the beneficial reuse of an industrial byproduct.

5.3.1.1 Environmental

Replacing portions of OPC with a J-Rox SCM in concrete mixtures provides an opportunity to enhance the resilience of ecosystem services by reducing industry dependence on the mining of finite raw materials. The potential impact of incorporating this type of symbiosis between the concrete and phosphoric acid industries extends beyond simply limiting impacts from land use change. This proposed relationship could significantly reduce impacts from CO_2 emissions and other GHGs associated with the mining of raw materials and the calcination process in cement production. Furthermore, the Novaphos process helps reduce waste beyond that of typical SCMs. Not only does the process avoid the production of large volume waste streams, but the source materials used in the Novaphos phosphoric acid process are made up of materials such as mine tailings and phosphogypsum that are classified as waste by other major companies. Overall, the beneficial reuse of J-Rox as an SCM has the potential to reduce the environmental impact of the construction industry throughout many levels of the supply chain.

The results of testing performed throughout this study support the conclusion that J-Rox SCMs could be used to develop concrete mixtures that meet typical performance requirements of the industry at a lower environmental cost than traditional methods. Future research should be conducted on this product to confirm and expand upon the findings of this study. To fully explore the degree to which J-Rox SCMs could improve the sustainability of concrete, a cradle-to-gate life cycle analysis (LCA) of the J-Rox production process should be performed based on the PCR for supplementary cementitious materials. The

PCR guidelines represent a consistent standard/basis upon which J-Rox can be accurately compared to other SCMs for the purpose of creating a verified EPD for the J-Rox SCM. The resulting EPD could then be used to conduct an LCA that evaluates J-Rox concrete blends, and more complex LCAs that evaluate the concrete beyond the manufacturing process (e.g., cradle-to-grave).

5.3.1.2 Societal

Symbiotic relationships with phosphoric acid manufacturers, such as Novaphos, could increase the resilience of the concrete industry, mitigating the challenges of ever-increasing environmental regulations and reducing dependence on imported material. As the facilitating organization, developing IS relationships with compatible companies locally, Novaphos could introduce opportunities for job creation within the community and allow all businesses involved in the IS network to benefit from a larger customer base. The Novaphos process could potentially provide further societal benefits by creating an incentive for the cleanup of waste sites by transforming toxic waste streams into beneficial products, resulting in healthier communities.

5.3.1.3 Economic

One of the strongest arguments for the utilization of J-Rox in an IS network may be the financial benefits. The costs for acquiring resources (reduced need for mining/processing virgin limestone and phosphate rock), as well as costs associated with waste disposal, could be significantly reduced when utilizing a J-Rox SCM in concrete applications. In addition, the results of this study suggest that using a J-Rox SCM can improve the durability of concrete structures and pavements, which could further reduce costs associated with the maintenance and repairs of concrete elements over their service life.

Utilizing a process with a naturally lower waste potential than its competitors would put this theoretical IS network at an advantage. The symbiotic nature of this business model could help firms avoid regulatory penalties other firms may become subject to without expensive upgrades to their existing systems/infrastructure while further reducing hefty costs associated with waste disposal. Additional economic benefits could be achieved by IS partners situated close enough to each other that they could share costs associated with infrastructure, research and development, and the design and maintenance of systems. As previously established in Chapter 2, firms separated by a reasonable distance are still capable of achieving a successful IS network; however, consolidating that distance when practical may yield additional financial benefits.

The market for sustainably acquired materials is growing rapidly in both the fertilizer and construction industries. A business model that limits waste and GHG emissions helps guarantee the resilience of the industry as it changes to meet future demands. This type of innovative and multidisciplinary methodology is also beneficial for attracting diverse talent. Furthermore, the beneficial reuse of J-Rox in concrete applications represents a revenue stream, and this increased efficiency paves the way for more competitive and innovative products.

5.3.2 Network Development

A "Guide for Industrial Symbiosis Facilitators" was developed by project partners of Kalundborg Symbiosis. This guide involves four general stages: 1) pre-emergence, 2) the facilitating organization, 3) symbiotic exchanges, and 4) ensuring the drive.

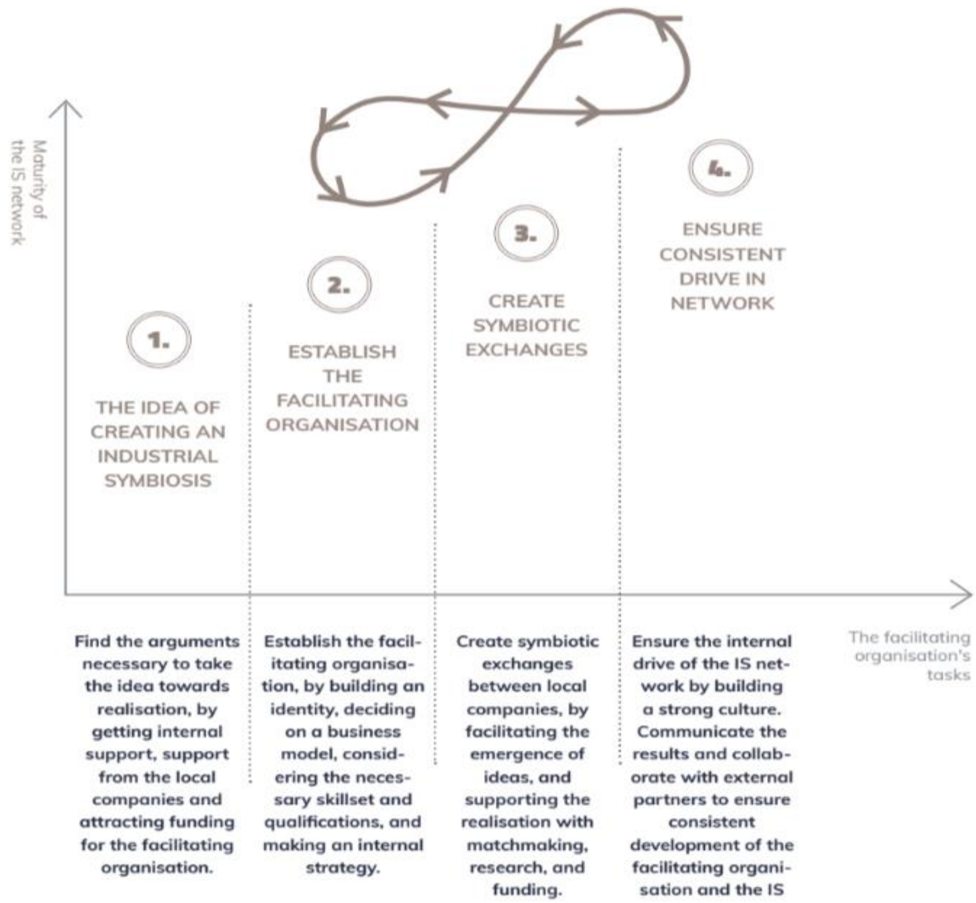

Figure 5-26. Representation of stages outlined in the Kalundborg Guide for Industrial Symbiosis Facilitators (Kalundborg Symbiosis, 2021)

In terms of the Kalundborg Guide, Novaphos may already meet the criteria to achieve the status of a "facilitating organization" in an IS network. The Novaphos business model is already rooted in the concept of symbiotic material exchange networks and has built an identity around reducing waste through the exchange and reuse of industry outputs. Furthermore, the research conducted for this thesis serves as an active example of stage three (i.e., Create Symbiotic Exchanges), "facilitating the emergence of ideas, and supporting the realization with matchmaking, research, and funding".

A main goal of the research conducted throughout this study was to evaluate the potential of J-Rox to serve as an SCM in concrete applications. This type of research is necessary for confirming the validity of the solution. The intent is that this, and future research, will help Novaphos solidify symbiotic connections with compatible companies. At this time, Novaphos is still experimenting with various aspects of their production processes and feed materials to identify the most effective options for reuse. As Novaphos solidifies the technical aspects of its processes, it will be essential to create a brand/culture of collaboration. The company and subsequent IS network should grow through an internalized motivation shared by those involved to promote consistent development of sustainable practices to ensure the longevity and resilience of the network.

5.3.3 Necessary Industry Relationships

By nature, an IS network is localized/regional; however, that does not mean relationships are required to develop while occupying the same physical space. IS networks are most effective when partnerships form between companies of compatible ideologies. Compatible waste streams, proximity, and innovative technical solutions alone are insufficient in developing IS between firms and may quickly be rendered irrelevant if partner firms do not share the same core values (Perrucci et al., 2022; Kalundborg Symbiosis, 2021). Overall, the success of any IS network depends on the social embeddedness and cooperation of all involved stakeholders. In addition to relationships between the facilitating organizations/tenant firms, important stakeholders also include policy makers, government officials, and the local community (Perrucci et al., 2022; Chertow and Ehrenfeld, 2012; Vermeulen, 2006).

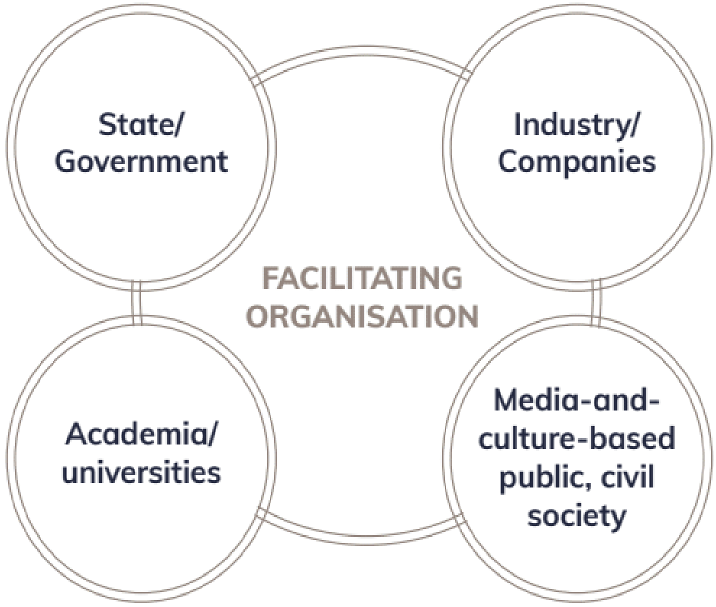

Figure 5-27. Representation of IS stakeholders (Kalundborg Symbiosis, 2021)

5.3.2.1 Identifying Compatible Firms and Industries

As established throughout Chapter 2, a successful IS network contains a diverse set of companies/industries in a local area. These relationships are shown to be most effective when they develop organically between firms that are already well established within the area and share a similar commitment to sustainability within their business model. The Kalundborg Guide recommends utilizing local business associations and networks as a resource for identifying prospective IS partners; connections made with companies working with significant quantities of inputs and outputs are more likely to embrace the concept of circular material flows (Kalundborg Symbiosis, 2021). An example of potential IS partners within the concrete industry and their associated services and products is shown in Figure 5-28.

A demolition company responsible for clearing structures for new construction may provide services such as material separation and/or recovered material storage; if this company engages in symbiotic exchange with a concrete recycling plant, the recovered material could be processed into recycled concrete for use as aggregate or fill material. The recycled material could then be sold to a concrete plant which manufactures pre-cast concrete components or ready-mix concrete blends; or it could be sold directly to a construction company for use in new concrete construction. Once these concrete elements reach the end of their service life the network could come full circle, back to the demolition company. An SCM manufacturer such as Novaphos could easily fit into this symbiotic exchange network in a similar role as the concrete recycling plant, where the byproduct/coproduct could be sold to a concrete plant or construction company to produce new concrete materials. Although encapsulating industrial byproducts in concrete may initially prevent their exposure to the environment, safety testing should be conducted prior to concrete recycling operations to identify potential unknown hazards these materials may present once deconstructed (e.g., mobilized dust, increased surface area of rubble, etc.).

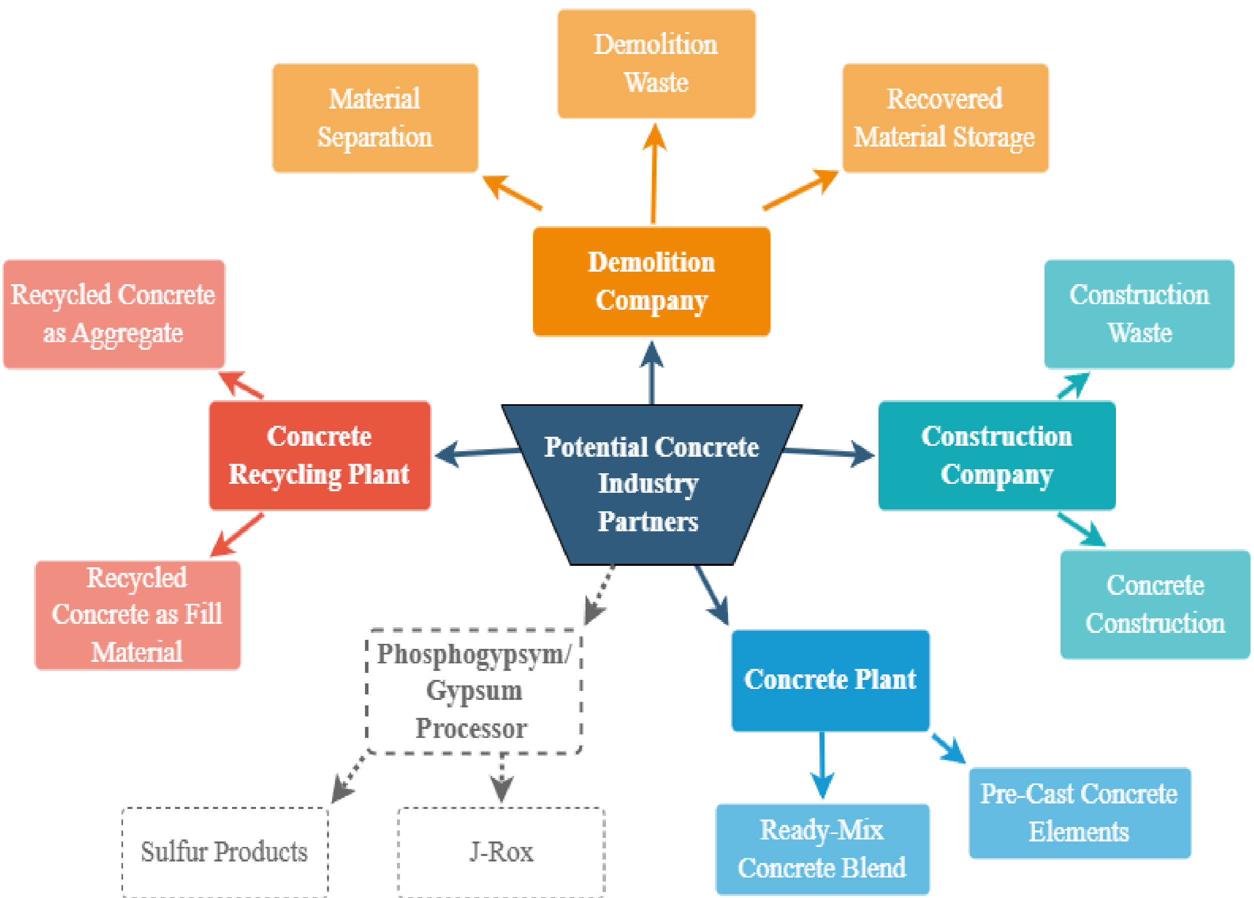

Figure 5-28. Representation of potential industrial symbiosis partners in concrete industry, inspired by Perrucci et al., 2022

Cohen-Rosenthal and McGalliard identified other potential areas of eco-industrial networking between like-minded firms that could prove beneficial to an IS network (1996):

Quality of Life/Community Connections	Cooperative Education Opportunities	Volunteer & Community Programs	Involvement in Regional Planning	Integrating Work & Recreation			
Materials	Common Buying	Customer/Supplier Relations	Byproduct Connections	Creating New Material Markets			
Transportation	Shared Commuting	Shared Shipping	Common Vehicle Maintenance	Alternative Packaging	Intra-network Transportation	Integrated Logistics	
Environment, Health, and Safety	Accident Prevention	Emergency Response	Waste Minimization	Multi-media Planning	Design for Environment	Shared Environmental Information Systems	Joint Regulatory Permitting
Energy	Green Buildings	Energy Auditing	Cogeneration	Spin-off Energy Firms	Alternative Fuels		
Information/Communication Systems	Internal Communications	External Information Exchange	Monitoring Systems	Computer Compatibility	Joint Management Information System for Park Management		
Marketing	Green Labeling	Accessing Green Markets	Joint Promotions (e.g. advertising, trade shows)	Joint Ventures	Recruiting New Value-Added Companies		
Production Processes	Pollution Prevention	Scrap Reduction & Reuse	Production Design	Common Subcontractors	Common Equipment	Technology Sharing & Integration	
Human Resources	Human Resources Recruiting	Joint Benefits Packages	Wellness Programs	Common Needs (payroll, maintenance, security)	Training	Flexible Employee Assignments	

Figure 5-29. Representation of “Potential Areas of Eco-Industrial Networking" from Cohen-Rosenthal and McGalliard (1996)

5.3.2.2 Government Relationships and Community Involvement

A successful IS network requires some degree of governmental support to thrive within a community. Working closely with a regulatory authority can help ease bureaucratic confusion, which is especially helpful for IE-centered projects since local governments are likely less familiar with the overarching principles and specific needs of such a network. Government support can also be beneficial when attempting to gain trust of the community by providing incentives and education on the specifics of the project or to obtain additional funding.

Government entities can play an important role in IS development by helping to promote and incentivize community benefits resulting from the project. Although government support is an asset, it should remain limited to ensure the integrity of the network's social embeddedness. As discussed in Chapter 2, government overreach can compromise the efficacy of an IS network through a heavy-handed focus on the technical aspects of the system without proper consideration of the system's social intricacies in decision making.

5.3.2.3 Research Partners

Continuing to work with research partners throughout the constant evolution of the IS network is a key aspect of remaining resilient against the changing needs of the future. Discovering new methods to process and recycle waste as companies with different material flows come and go is an essential service in an IS network. Working closely with research partners also provides firms with validity when presenting concepts to government entities and/or the public. New materials and processes will always face stronger critique than traditional counterparts upon their introduction to the marketplace. Furthermore, results of research can also be used to secure funding.

5.3.4 Theoretical IS Network

The figures below provide a representation of the general material flows taking place along the industrial food chain for both the construction and fertilizer industries; red lines represent materials for disposal, blue lines represent beneficial reuse applications of materials. Figure 5-30 represents a typical linear network, while Figure 5-31 shows potential waste exchange relationships that could be used to begin a circular network with Novaphos serving in an important decomposer role for wastes disposed of from both mining and fertilizer industries. Because construction materials often represent non-competing waste streams, developing symbiosis with the construction industry introduces a wide variety of opportunities in terms of material exchange. One such option incorporates the diversion of construction and demolition (C&D) waste from a solid waste management facility (e.g., landfill, waste processing facility, materials recovery facility (MRF), etc.).

Partnering with a solid waste facility would truly bring this theoretical IS network full circle as concrete waste could be removed from the waste stream prior to disposal in a landfill, then processed and separated at an MRF in preparation for beneficial reuse (e.g., as aggregate, structural fill, drainage applications, etc.). Some landfills may also have the ability to serve as an energy producer through the harvesting of landfill gas (LFG), however municipal solid waste (MSW) has a much higher LFG generation potential than C&D waste due to the presence of organic material (Agency for Toxic Substances and Disease Registry, 2001). Still, many facilities dispose of C&D waste and MSW together in the same landfill, or separately in adjacent landfills within the same facility. The Florida Department of Environmental Protection (2024) estimates that C&D waste “accounts for almost 25% of Florida’s total MSW stream.

A relationship with a large waste disposal facility could provide the added bonus of serving as a natural multidisciplinary hub by which new material streams can be identified and diverted from the landfill. Because landfills are already required to keep detailed records of the quantities and types of materials accepted at the facility, this existing record could be utilized to connect businesses with compatible inputs/outputs. Landfills may also be able to fill the role of assuming the responsibility involved with managing any surplus wastes that are not utilized within the system, if waste flows and landfill operation requirements are compatible. Potential economic benefits throughout the supply chain could include:

(1) Municipalities extending the service lives of their current facilities and reducing the need for expansions, which represent a significant expense. Although costs are heavily dependent on the location, conditions, and compliance requirements of an individual facility, an EPA Economic Impact Analysis from 2014 estimates that the total cost of expanding MSW landfills (i.e., site development, construction, equipment purchases, closure, and post-closure) is approximately $1.2 million per acre on the low end plus approximately $600,000 per year in annual operating costs (U.S. EPA, 2014). However, it should also be mentioned that the referenced impact analysis utilized data based on cost values from 2005-2012 which have not been adjusted for 2024 inflation. Because new federal and state regulatory requirements for landfill operation and maintenance have also grown more stringent in the past 12 years, additional operational and maintenance costs should be assumed for facilities to satisfy updated operational compliance requirements.

(2) Each landfill charges a ‘tipping fee’ to customers based on the weight and type of waste being disposed of. By diverting waste from away from the landfill and into the IS network, landfill customers could pay less in tipping fees. Other financial incentives could include compensating landfill customers disposing of compatible, in-demand material, or charging a discounted tipping fee.

(3) Producers utilizing the diverted product in new manufacturing would reduce costs associated with mining/developing and transportation of new raw materials. This would be especially lucrative for businesses reliant on imported material or resource-intensive production.

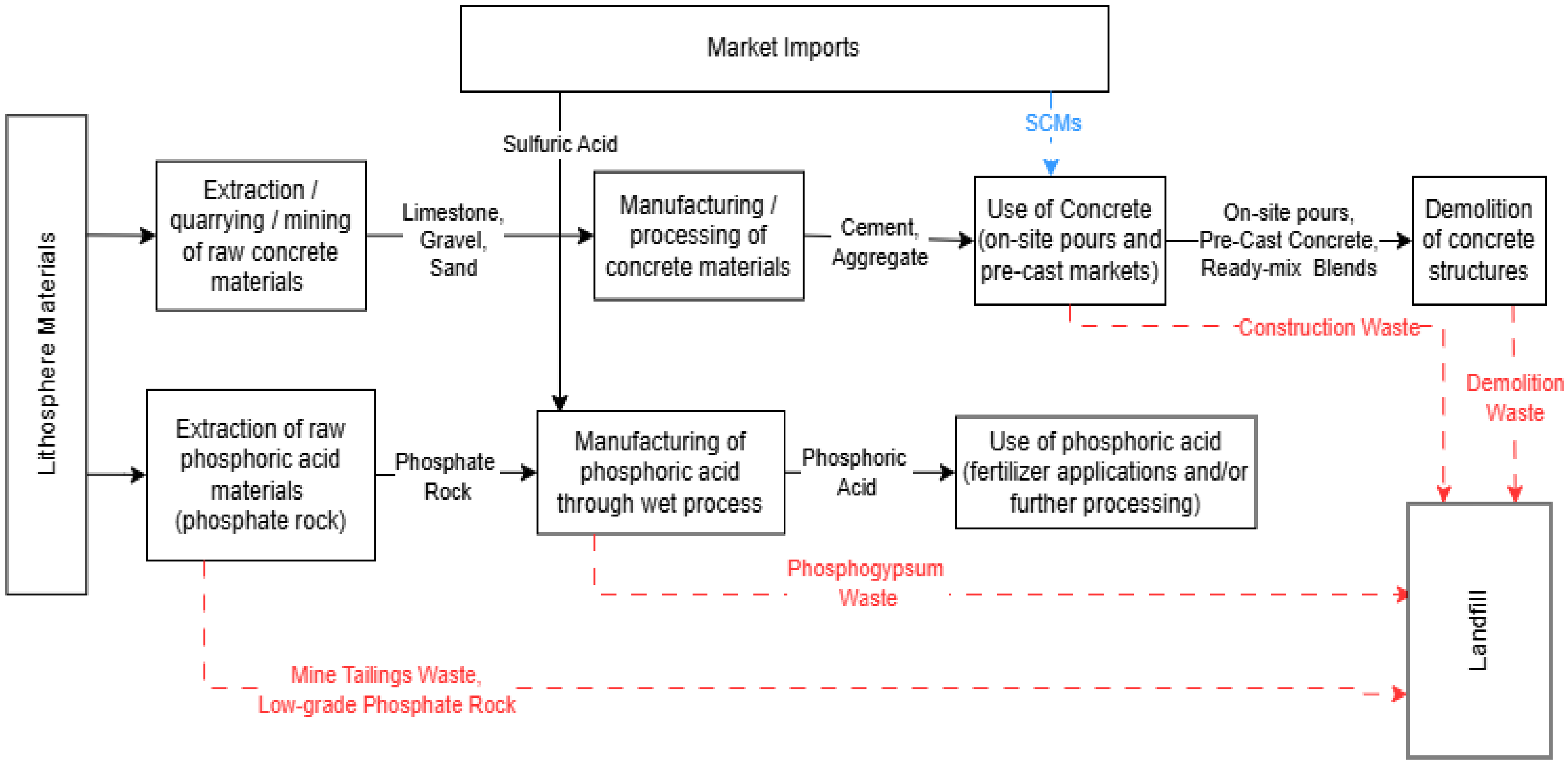

Figure 5-30. Representation of linear material flows between concrete and fertilizer industries

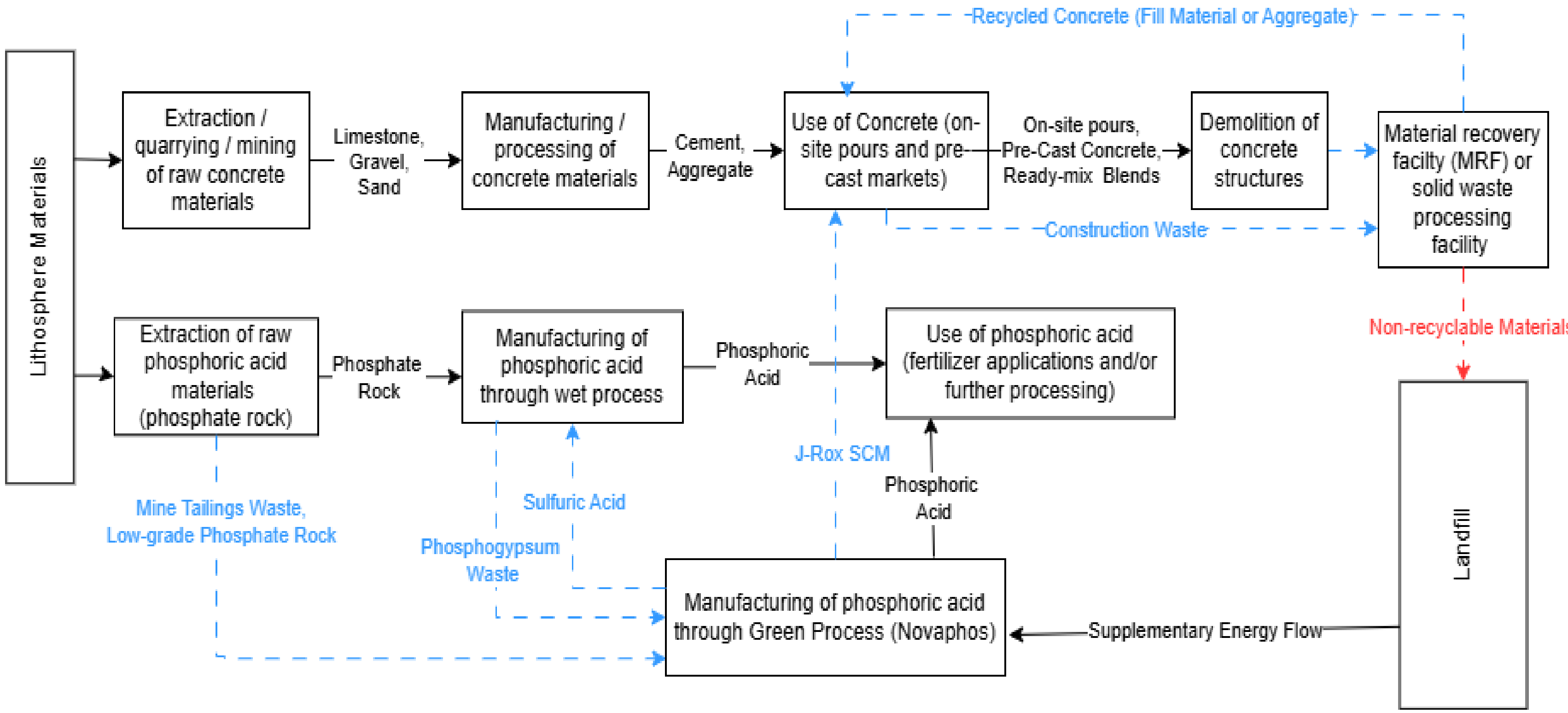

Figure 5-31. Potential material flows between the construction and fertilizer industries in an Industrial Symbiosis network, anchored by Novaphos/J-Rox

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This thesis presents the laboratory test results evaluating an industrial byproduct of the phosphoric acid fertilizer industry (J-Rox) as a supplementary cementitious material (SCM). J-Rox is a byproduct produced from a new method of manufacturing phosphoric acid for fertilizer applications, developed by Novaphos, in which low-quality forms of phosphorus rock are successfully processed into high-grade phosphoric acid for use in fertilizer applications. Unlike traditional methods for manufacturing phosphoric acid, the Novaphos process does not produce large volume radioactive waste streams, such as phosphogypsum.

The scope of this study was particularly focused on evaluating the ability of the best performing J-Rox mixture(s) to serve as an effective substitute for fly ash in concrete applications without sacrificing strength or durability. An analysis of the resulting data indicated that the subsequent J-Rox SCM materials were effective at cement replacement rates of up to 20%. In conjunction with a thorough literature review, this data was used to also develop a prospective analysis of a theoretical industrial symbiosis (IS) network supported by material exchanges between J-Rox and concrete products, and the potential influence these symbiotic relationships could have on fostering financial and environmental resilience within the concrete industry.

6.1 Conclusions

Testing of the paste, mortar, and concrete samples containing different J-Rox samples at cement replacement rates ranging from 15% to 25%, along with a review of the feed materials used in the creation of each type of J-Rox, was conducted to determine the efficacy of J-Rox as an SCM. This was determined based on comparisons between the samples containing the various types of J-Rox, and control samples consisting of 100% OPC and 20% fly ash. Throughout the course of the testing program, concrete samples containing J-Rox exhibited improved mechanical performance over control samples in every test except MOE.

The J-Rox mixtures with the best mechanical performance were those with the GypRox base, (JR-1, JR-4, and JR-5) which performed comparably to the fly ash controls. In the case of the concrete tests, the samples containing J-Rox consistently performed higher in tests of strength and durability compared to the fly ash control (91-day compressive strength, 28-day MOE, and surface resistivity). In nearly all tests, the ternary mixtures comprised of 15% J-Rox and 35% slag (combined 50% total cement replacement) provided superior results to the J-Rox-only mixtures. In many cases, mixtures containing only J-Rox provided results superior to the OPC and fly ash control mixtures. The following summarizes additional key findings:

<u>Fresh Properties</u>

- A relationship was observed between the percent concentration of SiO_2 and final setting time in which mixtures containing higher degrees of SiO_2 had a reduced set time. Setting times may have also been influenced by the particle size distribution of the various J-Rox materials. The particle size distribution of J-Rox can be controlled during production to help obtain the desired setting characteristics. Samples containing lower concentrations of SiO_2 had comparatively larger particle sizes; the longer set times observed in these cases might also have been a factor of a larger reaction from the increased surface area.
- A positive correlation between increased cement replacement rates (higher concentrations of J-Rox) and increased water demand was observed by samples containing the GypRox-based J-Rox SCM (JR-1, JR-4, and JR-5), whereas a negative correlation was observed between these variables for JR-2 and JR-3. A definitive explanation for this behavior was not identified, however it should be noted that mortar samples showing the positive correlation also produced the highest compressive strength results at 91 days.

<u>Mechanical Properties</u>

- <u>Compressive Strength of Concrete:</u> At the final testing age of 91 days all J-Rox samples, regardless of their cement replacement rate, exhibited higher compressive strength values than both control mixtures; the 20% fly ash control had the lowest compressive strength value at this age.
  - The JR-5 mixtures were observed to have a slower strength gain compared to the JR-4 mixtures. However, at 91 days, the three strongest concrete samples all contained JR-5 (15JR-5, 15JR-5 / 35S, and 20JR-5, respectively).
  - At 28 days, all J-Rox mixtures exceeded the FDOT minimum strength requirement for Class IV Concrete (5,500 psi).

- Compressive Strength of Mortar: Overall, the GypRox-based J-Rox mixtures (JR-1, JR-4, and JR-5) had higher compressive strength values compared to the silica-based J-Rox mixtures (JR-2 and JR-3), however, JR-2 showed the second highest 91-day compressive strength value at the 25% cement replacement rate. The mortar samples containing JR-1 consistently exhibited the highest compressive strength values compared to other J-Rox samples at all cement replacement rates followed by JR-4 samples.
    - All J-Rox samples, regardless of the cement replacement rate, satisfied the FDOT minimum compressive strength requirement of 3,000 psi.
- Modulus of Elasticity (MOE) and Poisson's Ratio: All concrete samples containing J-Rox exhibited a higher 28-day MOE than the 20% fly ash control; the highest MOE was observed from the 100% OPC control. The highest J-Rox values were observed from the J-Rox/Slag mixtures.
    - Increases in MOE and Poisson's ratio were observed to correlate with increased cement replacement rates in JR-5 mixtures. This was especially true of the J-Rox 5/Slag mixture (combined 50% cement replacement), which exhibited the highest MOE of all J-Rox samples tested. JR-4 was shown to have the same 28-day MOE at both the 15% and 20% replacement rates, but a higher Poisson's ratio at the 15% cement replacement rate.

Durability Performance

- Concrete mixtures containing both types of J-Rox performed significantly better in durability performance tests than either of the two control mixtures (100% ordinary portland cement, and 20% fly ash). JR-4 appeared to have the greatest effect on durability performance when compared to the other J-Rox materials, however the durability performance of JR-5 was still comparable. The ternary combination of 15% J-Rox/35% Slag consistently showed the best performance.
- Surface Resistivity: Both ternary blends of J-Rox/Slag exhibited the highest surface resistivity values across all testing ages, with the JR-4 blend producing slightly higher surface resistivity than JR-5. Both ternary blends consistently outperformed both control mixtures. In the J-Rox only mixtures, samples showed satisfactory performance comparable to the 100% OPC control. High resistivity is indicative of low porosity and suggests better resistance to cracking.
    - Both ternary blends met the AASHTO T 358-22 qualifier for "moderate chloride ion penetration" as early as 28 days; the 20% fly ash control only reached this threshold at the 91-day test.
- Unrestrained Shrinkage: All samples containing J-Rox exhibited less shrinkage than the 100% OPC control across every testing age and performed better (JR-4) or comparably (JR-5) to the 20% fly ash control; the ternary blend of J-Rox 4/Slag exhibited extremely low shrinkage (35 $\mu\varepsilon$). Both J-Rox materials showed that increased percent replacement of cement with the J-Rox SCM material resulted in lower shrinkage. The ternary blends of 15% J-Rox/35%Slag (a total cement replacement of 50%) represented the lowest shrinkage values for each respective type of J-Rox SCM. Minimal length change in shrinkage tests suggests better resistance to cracking.

- All J-Rox concrete samples met the AASHTO R 101-22 performance target of 420 με at 28 days of drying (56 days of age) and qualify for a "high grade" performance rating (less than 400 με) based on published guidance (Russell et al. 2006).

- Sulfate Attack: At the final testing age of 26 weeks, JR-1 and JR-5 both exhibited less shrinkage than the control mixtures at every cement replacement rate. JR-4 also exhibited less shrinkage than the controls at cement replacement rates of up to 20%, however at the 25% replacement rate showed slightly more shrinkage than the 100% OPC control, but less shrinkage than the 20% fly ash control.
    - All concrete mixtures containing JR-4 and JR-5 met the performance target according to Ferraris et al. (2018), with less than 0.1% expansion exhibited at 6 months (26 weeks), a common performance target for some less aggressive sulfate environments.

Industrial Symbiosis

- Market demand for both phosphoric acid and sustainable SCMs are increasing steadily in conjunction with rising population and urbanization rates.
- Opportunities for IS within the construction industry are extensive and extremely applicable due to the presence of non-competing waste streams and high costs associated with waste disposal.
- Development of a successful IS network is dependent on strong relationships between well-established firms that develop organically over time; expanding the IS network one company at a time is more feasible than attempting to design an entire industrial ecosystem from the start.
- Attempts to develop industry connections within an IS network are often more successful when they are based on a shared commitment to sustainability and waste reduction. This is a result of IS networks requiring trust, cooperation, and open communication to function at peak efficiency.

Sustainability

- Utilizing the J-Rox SCMs in concrete applications would likely provide benefits pertaining to all three pillars of sustainability (i.e., environmental, economic, and societal).
- Environmental benefits of utilizing J-Rox SCMs would include reduced impacts from mining practices (land use change, biodiversity loss, water quality); the beneficial reuse of an industrial byproducts and low-grade/waste materials (mine tailings, low-grade phosphorous rock, phosphogypsum) into high-grade products. Improved durability performance of concrete samples containing J-Rox represents the beneficial reuse of an industrial byproduct by extending the service life of concrete structures while simultaneously reducing the demand for new construction and the mining of new materials.
- Societal benefits of further developing symbiosis between J-Rox and concrete applications include enhanced regional resilience of the fertilizer and construction industries through reduced dependence on foreign imports, opportunities for local job creation and overall community cohesion.

- Economic benefits of the theoretical IS network include:
  - Reduced costs associated with mineral extraction and disposal. In comparison to fly ash, J-Rox represents a relatively consistent SCM source that would satisfy industry demand while avoiding high costs associated with landfill harvesting.
  - Additional revenue streams created from the beneficial reuse of “waste” materials, while simultaneously responding to the growing marked demand for sustainable construction materials.
  - Shared infrastructure reduces costs associated with operations (infrastructure, research and development, maintenance, etc.).

6.2 Recommendations for Future Work

Further research regarding the study of J-Rox in concrete applications should continue upon Novaphos’ final determination of feed materials in the production process. Since the data from this study indicated the GypRox-based materials (JR-1, JR-4, and JR-5) as providing the greatest mechanical advantage in concrete applications, further studies should be conducted to better explain the relationships between particle size, set time, chemical composition, and water demand. Grinding processes used in production could be studied and adjusted to assist with the water demand and set times of concrete and mortar produced using J-Rox.

Reducing the raw cement content of concrete mixtures will become increasingly important in the coming decades. The ternary blend (J-Rox, slag, and portland cement) mixtures likely provide a very economical and sustainable mixture in terms of both strength and durability. Additional studies exploring the combined potential of concrete mixtures containing both J-Rox and slag, as well as the potential of J-Rox in other ternary mixtures would further enhance the environmental benefits of this practice.

Future work in developing an IS network between J-Rox and the concrete industry should include the development of an EPD based on the existing PCR for SCMs so an LCA of J-Rox and J-Rox concrete can be compared against other SCMs. However, additional studies should be conducted prior to the integration of J-Rox concrete in concrete recycling operations to confirm its stability after demolition and identify potential risks to human health or the environment.

Government resources such as the EPAs Recycling Toolkit can be used to identify funding opportunities, compatible waste streams, and other logistical resources. Novaphos should continue to pursue research on their product and identify other businesses with a focus on the circular management of resources/symbiotic material exchanges, waste reduction, and sustainability as core values using tools such as the Kalundborg Guide for Industrial Symbiosis Facilitators.

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APPENDIX: PARTICLE SIZE ANALYSIS OF J-ROX MATERIALS

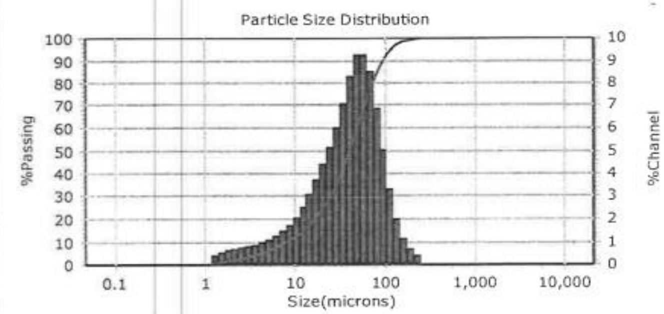
Microtrac
Total Solutions in Particle Characterization

- Particle Size Analysis -

C:\Microtrac\FLEX 11.1.0.4\Databases\novaphos2020.MDB

-Tabular Data -

Size(um)	%Chan	%Pass	Size(um)	%Chan	%Pass
1408	0.00	100.00	3.27	0.81	3.74
1184	0.00	100.00	2.750	0.76	2.93
995.6	0.00	100.00	2.312	0.69	2.17
837.2	0.00	100.00	1.945	0.60	1.48
704.0	0.00	100.00	1.635	0.49	0.88
592.0	0.00	100.00	1.375	0.39	0.39
497.8	0.00	100.00	1.156	0.00	0.00
418.6	0.00	100.00	0.972	0.00	0.00
352.0	0.00	100.00	0.818	0.00	0.00
296.0	0.00	100.00	0.688	0.00	0.00
248.9	0.42	100.00	0.578	0.00	0.00
209.3	0.66	99.58	0.486	0.00	0.00
176.0	1.14	98.92	0.409	0.00	0.00
148.0	1.99	97.78	0.344	0.00	0.00
124.5	3.31	95.79	0.2890	0.00	0.00
104.7	5.01	92.48			
88.00	6.88	87.47			
-200 74.00	8.52	80.59			
62.23	9.28	72.07			
52.33	9.27	62.79			
-325 44.00	8.31	53.52			
37.00	7.08	45.21			
31.11	6.00	38.13			
26.16	5.14	32.13			
22.00	4.41	26.99			
18.50	3.72	22.58			
15.56	3.07	18.86			
13.08	2.50	15.79			
11.00	2.07	13.29			
9.25	1.74	11.22			
7.78	1.49	9.48			
6.54	1.28	7.99			
5.50	1.11	6.71			
4.62	0.98	5.60			
3.89	0.88	4.62			



- Measurement Info -

Title
35/55/10 gyp/sand/clay GRox
Identifiers
35/55/10
7-29

Database Record	938
Run Number	Avg Of 3
Date	7/30/2021
Time	8:47 AM
Acquired Date	7/30/2021
Acquired Time	8:47 AM
Serial Number	S6309
Sample Cell ID	3151
Calculated Data	
Above Residual	0
Below Residual	0
Loading Factor	0.0441
Transmission	0.960
RMS Residual	0.828%
User Defined Calculations	
Name	Value
Recalculation Status	
Live-Meas : : Original :	

-SOP Info-

BALL MILL FEED(*)
Timing

Setzero Time	30 (sec)
Run Time	30 (sec)
Number of Runs	3
Multi-Run Delay	0 (min)
Delay First Meas.	Disabled
Analysis	
JDC Ball Mill Feed	
Refractive Index	1.60
Transparency	Transp
Shape	Irregular
WATER	
Refractive Index	1.33
Options:	
Filter	Enabled
Analysis Gain	0
Analysis Mode	S3000/3500
Perspective	
Progression	Standard
Distribution	Volume
Upper Edge(um)	1408
Lower Edge(um)	0.243
Residuals	Enabled

Summary

Data	Value
MV(um):	48.09
MN(um):	2.114
MA(um):	17.33
CS:	3.46E-01
SD:	33.48
Mz:	44.82
σι:	34.06
Ski:	0.2633
Kg:	1.030

Percentiles

%Tile	Size(um)
10.00	8.21
20.00	16.46
30.00	24.43
40.00	32.66
50.00	41.01
60.00	49.72
70.00	59.83
80.00	73.08
90.00	95.33
95.00	118.5

Peaks Summary

Dia(um)	Vol%	Width
41.01	100	66.95

7/30/2021 8:48 AM

FLEX
11.1.0.4

- Notes -

GRox final PSD

JR - SPCL "Concrete" Studies
7-19-21 / 7-29-21

Sample System(Wet)
Number of Rinses 3
Flow Rate (%) 55%
Deaeration Cycles 4

Figure A.1: Particle size analysis of JR-1 (Gyp/Sand/Clay)

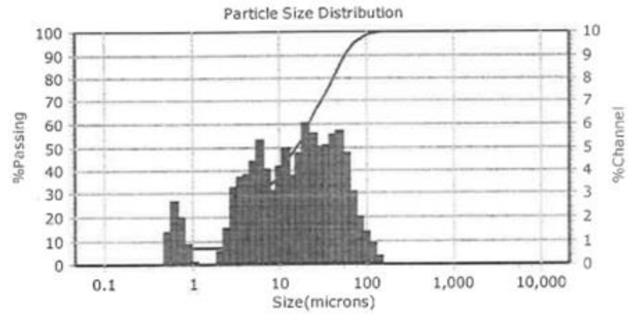
Microtrac

- Particle Size Analysis -

C:\Microtrac\FLEX 11.1.0.4\Databases\MTDatabase.MDB

-Tabular Data -

Size(um)	%Chan	%Pass	Size(um)	%Chan	%Pass
1408	0.00	100.00	3.27	3.26	12.35
1184	0.00	100.00	2.750	1.52	9.09
995.6	0.00	100.00	2.312	0.59	7.57
837.2	0.00	100.00	1.945	0.00	6.98
704.0	0.00	100.00	1.635	0.00	6.98
592.0	0.00	100.00	1.375	0.00	6.98
497.8	0.00	100.00	1.156	0.11	6.98
418.6	0.00	100.00	0.972	0.84	6.87
352.0	0.00	100.00	0.818	1.98	6.03
296.0	0.00	100.00	0.688	2.70	4.05
248.9	0.00	100.00	0.578	1.35	1.35
209.3	0.00	100.00	0.486	0.00	0.00
176.0	0.00	100.00	0.409	0.00	0.00
148.0	0.35	100.00	0.344	0.00	0.00
124.5	0.92	99.65	0.2890	0.00	0.00
104.7	1.38	98.73			
88.00	2.01	97.35			
74.00	3.08	95.34			
62.23	4.76	92.26			
52.33	5.70	87.50			
44.00	5.56	81.80			
37.00	5.11	76.24			
31.11	5.05	71.13			
26.16	5.59	66.08			
22.00	6.06	60.49			
18.50	4.77	54.43			
15.56	3.77	49.66			
13.08	4.95	45.89			
11.00	4.18	40.94			
9.25	3.12	36.76			
7.78	4.04	33.64			
6.54	5.31	29.60			
5.50	4.40	24.29			
4.62	3.81	19.89			
3.89	3.73	16.08			



- Measurement Info -

Title
UNC low SR JR 4-22
Identifiers
4-9-22
4-12-22 taken
Database Record 132
Run Number Avg Of 3
Date4/12/2022
Time 9:23 AM
Acquired Date4/12/2022
Acquired Time 9:23 AM
Serial Number S6309
Sample Cell ID 3151
Calculated Data
Above Residual 0
Below Residual 0
Loading Factor 0.0249
Transmission 0.957
RMS Residual 0.179%
User Defined Calculations
Name Value
Recalculation Status
Live-Meas : : Original :

-SOP Info-

SOP Name: None
Timing
Setzero Time 30 (sec)
Run Time 30 (sec)
Number of Runs 3
Multi-Run Delay 0 (min)
Delay First Meas. Disabled
Analysis
GLASS
Refractive Index 1.51
Transparency Transp
Shape Spherical
WATER
Refractive Index 1.33
Options:
Filter Enabled
Analysis Gain Default(2)
Analysis ModeS3000/3500
Perspective
Progression Standard
Distribution Volume
Upper Edge(um) 1408
Lower Edge(um) 0.243
Residuals Disabled

Summary Data	Value
MV(um):	23.92
MN(um):	0.689
MA(um):	5.06
CS:	1.187
SD:	21.56
Mz:	22.22
σι:	21.63
Ski:	0.514
Kg:	0.982

Percentiles %Tile	Size(um)
10.00	2.908
20.00	4.64
30.00	6.64
40.00	10.62
50.00	15.78
60.00	21.70
70.00	29.91
80.00	41.66
90.00	56.94
95.00	72.34

Peaks Summary

Dia(um)	Vol%	Width
45.67	33.9	38.82
19.38	20.2	8.43
10.52	12.2	3.51
4.71	26.7	3.39
0.663	7	0.237

4/12/2022 9:25 AM

FLEX
11.1.0.4

- Notes -

mlt
final ground product
149 lbs blue drum

Sample System(Wet)
Number of Rinses 3
Flow Rate (%)55%
Deaeration Cycles 4

Figure A.2: Particle size analysis of JR-2 (Low Silica)

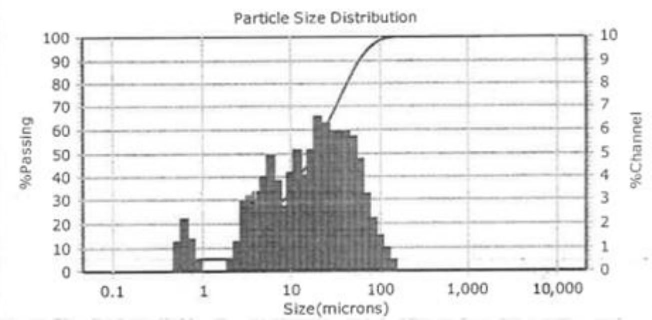
Microtrac

- Particle Size Analysis -

C:\Microtrac\FLEX 11.1.0.4\Databases\MTDatabase.MDB

-Tabular Data -

Size(um)	%Chan	%Pass	Size(um)	%Chan	%Pass
1408	0.00	100.00	3.27	2.96	9.95
1184	0.00	100.00	2.750	1.23	6.99
995.6	0.00	100.00	2.312	0.44	5.76
837.2	0.00	100.00	1.945	0.00	5.32
704.0	0.00	100.00	1.635	0.00	5.32
592.0	0.00	100.00	1.375	0.00	5.32
497.8	0.00	100.00	1.156	0.00	5.32
418.6	0.00	100.00	0.972	0.49	5.32
352.0	0.00	100.00	0.818	1.35	4.83
296.0	0.00	100.00	0.688	2.21	3.48
248.9	0.00	100.00	0.578	1.27	1.27
209.3	0.00	100.00	0.486	0.00	0.00
176.0	0.00	100.00	0.409	0.00	0.00
148.0	0.45	100.00	0.344	0.00	0.00
124.5	0.96	99.55	0.2890	0.00	0.00
104.7	1.49	98.59			
88.00	2.20	97.10			
74.00	3.23	94.90			
62.23	4.72	91.67			
52.33	5.70	86.95			
44.00	5.97	81.25			
37.00	5.93	75.28			
31.11	5.92	69.35			
26.16	6.29	63.43			
22.00	6.57	57.14			
18.50	5.13	50.57			
15.56	4.04	45.44			
13.08	5.17	41.40			
11.00	4.20	36.23			
9.25	2.74	32.03			
7.78	3.80	29.29			
6.54	4.92	25.49			
5.50	4.01	20.57			
4.62	3.39	16.56			
3.89	3.22	13.17			



- Measurement Info -

Title
UNC high SR JR 4-22
Identifiers
4-8-22
4-12-22 taken
Database Record 136
Run Number Avg Of 3
Date4/12/2022
Time 9:30 AM
Acquired Date4/12/2022
Acquired Time 9:30 AM
Serial Number S6309
Sample Cell ID 3151
Calculated Data
Above Residual 0
Below Residual 0
Loading Factor 0.0303
Transmission 0.953
RMS Residual 0.160%
User Defined Calculations
Name Value
Recalculation Status
Live-Meas : : Original :

-SOP Info-

SOP Name: None
Timing
Setzero Time 30 (sec)
Run Time 30 (sec)
Number of Runs 3
Multi-Run Delay 0 (min)
Delay First Meas. Disabled
Analysis
GLASS
Refractive Index 1.51
Transparency Transp
Shape Spherical
WATER
Refractive Index 1.33
Options:
Filter Enabled
Analysis Gain Default(2)
Analysis ModeS3000/3500
Perspective
Progression Standard
Distribution Volume
Upper Edge(um) 1408
Lower Edge(um) 0.243
Residuals Disabled

Summary

Data	Value
MV(um):	25.36
MN(um):	0.680
MA(um):	5.90
CS:	1.017
SD:	21.62
Mz:	23.47
σι:	21.97
Ski:	0.448
Kg:	0.997

Percentiles

%Tile	Size(um)
10.00	3.28
20.00	5.38
30.00	8.13
40.00	12.46
50.00	18.19
60.00	23.77
70.00	31.72
80.00	42.43
90.00	58.22
95.00	74.52

Peaks Summary

Dia(um)	Vol%	Width
32.37	58.6	40.99
10.65	12.1	3.42
4.79	24	3.4
0.644	5.3	0.215

4/12/2022 9:32 AM

FLEX

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- Notes -

mit
final ground product
218 is blue drum

Sample System(Wet)
Number of Rinses 3
Flow Rate (%)55%
Deaeration Cycles 4

Figure A.3: Particle size analysis of JR-3 (High Silica)

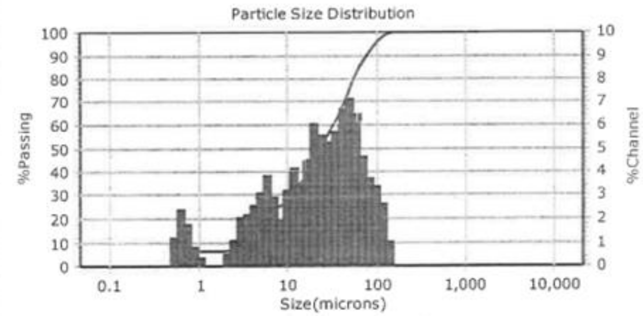
Microtrac

- Particle Size Analysis -

C:\Microtrac\FLEX 11.1.0.4\Databases\MTDatabase.MDB

-Tabular Data -

Size(um)	%Chan	%Pass	Size(um)	%Chan	%Pass
1408	0.00	100.00	3.27	2.08	10.11
1184	0.00	100.00	2.750	1.06	8.03
995.6	0.00	100.00	2.312	0.50	6.97
837.2	0.00	100.00	1.945	0.00	6.47
704.0	0.00	100.00	1.635	0.00	6.47
592.0	0.00	100.00	1.375	0.00	6.47
497.8	0.00	100.00	1.156	0.36	6.47
418.6	0.00	100.00	0.972	0.78	6.11
352.0	0.00	100.00	0.818	1.76	5.33
296.0	0.00	100.00	0.688	2.38	3.57
248.9	0.00	100.00	0.578	1.19	1.19
209.3	0.00	100.00	0.486	0.00	0.00
176.0	0.00	100.00	0.409	0.00	0.00
148.0	1.05	100.00	0.344	0.00	0.00
124.5	2.65	98.95	0.2890	0.00	0.00
104.7	3.36	96.30			
88.00	3.69	92.94			
74.00	4.63	89.25			
62.23	6.44	84.62			
52.33	7.14	78.18			
44.00	6.67	71.04			
37.00	5.71	64.37			
31.11	5.25	58.66			
26.16	5.52	53.41			
22.00	6.03	47.89			
18.50	4.52	41.86			
15.56	3.41	37.34			
13.08	4.14	33.93			
11.00	3.18	29.79			
9.25	1.95	26.61			
7.78	2.90	24.66			
6.54	3.81	21.76			
5.50	3.09	17.95			
4.62	2.56	14.86			
3.89	2.19	12.30			



- Measurement Info -

Title	
UNC ground Gypsum Rox 4-22	
Identifiers	
4-9-22	
4-12-22 taken	
Database Record	140
Run Number	Avg Of 3
Date	4/12/2022
Time	9:37 AM
Acquired Date	4/12/2022
Acquired Time	9:37 AM
Serial Number	S6309
Sample Cell ID	3151
Calculated Data	
Above Residual	0
Below Residual	0
Loading Factor	0.0320
Transmission	0.960
RMS Residual	0.258%
User Defined Calculations	
Name	Value
Recalculation Status	
Live-Meas : : Original :	

-SOP Info-

SOP Name: None	
Timing	
Setzero Time	30 (sec)
Run Time	30 (sec)
Number of Runs	3
Multi-Run Delay	0 (min)
Delay First Meas.	Disabled
Analysis	
GLASS	
Refractive Index	1.51
Transparency	Transp
Shape	Spherical
WATER	
Refractive Index	1.33
Options:	
Filter	Enabled
Analysis Gain	Default(2)
Analysis Mode	S3000/3500
Perspective	
Progression	Standard
Distribution	Volume
Upper Edge(um)	1408
Lower Edge(um)	0.243
Residuals	Disabled

Summary Data Value

MV(um):32.69
MN(um):0.682
MA(um): 5.99
CS:1.001
SD:28.08
Mz:29.84
σi:28.71
Ski:0.436
Kg:0.982

Percentiles

%Tile	Size(um)
10.00	3.24
20.00	6.04
30.00	11.10
40.00	17.35
50.00	23.46
60.00	32.47
70.00	42.88
80.00	54.77
90.00	76.51
95.00	97.63

Peaks Summary

Dia(um)	Vol%	Width
50.48	46.5	52.96
19.53	19.5	8.33
10.75	9.3	3.39
4.83	18.2	3.45
0.671	6.5	0.263

4/12/2022 9:39 AM

FLEX
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- Notes -

mlt
final ground product
216 lbs blue drum

Sample System(Wet)
Number of Rinses 3
Flow Rate (%) 55%
Deaeration Cycles 4

Figure A.4: Particle size analysis of JR-4 (GypRox)

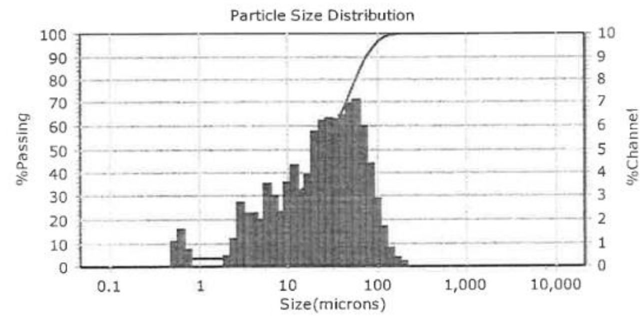
Microtrac
Total Solutions in Particle Characterization

- Particle Size Analysis -

C:\Microtrac\FLEX 11.1.0.4\Databases\MTDatabase.MDB

-Tabular Data -

Size(um)	%Chan	%Pass	Size(um)	%Chan	%Pass
1408	0.00	100.00	3.27	2.73	7.77
1184	0.00	100.00	2.750	1.18	5.04
995.6	0.00	100.00	2.312	0.44	3.86
837.2	0.00	100.00	1.945	0.00	3.42
704.0	0.00	100.00	1.635	0.00	3.42
592.0	0.00	100.00	1.375	0.00	3.42
497.8	0.00	100.00	1.156	0.00	3.42
418.6	0.00	100.00	0.972	0.00	3.42
352.0	0.00	100.00	0.818	0.72	3.42
296.0	0.00	100.00	0.688	1.59	2.70
248.9	0.00	100.00	0.578	1.11	1.11
209.3	0.22	100.00	0.486	0.00	0.00
176.0	0.38	99.78	0.409	0.00	0.00
148.0	0.81	99.40	0.344	0.00	0.00
124.5	1.72	98.59	0.2890	0.00	0.00
104.7	2.91	96.87			
88.00	4.39	93.96			
74.00	6.00	89.57			
62.23	7.15	83.57			
52.33	6.98	76.42			
44.00	6.48	69.44			
37.00	6.31	62.96			
31.11	6.34	56.65			
26.16	6.20	50.31			
22.00	5.76	44.11			
18.50	3.96	38.35			
15.56	3.14	34.39			
13.08	4.34	31.25			
11.00	3.59	26.91			
9.25	2.37	23.32			
7.78	3.02	20.95			
6.54	3.56	17.93			
5.50	2.01	14.37			
4.62	2.28	12.36			
3.89	2.31	10.08			



- Measurement Info -

Title
Gyp-Rox X2 passes#1
Identifiers
11-8-22
2 pm
Database Record 168
Run Number Avg Of 3
Date11/8/2022
Time 2:04 PM
Acquired Date11/8/2022
Acquired Time 2:04 PM
Serial Number S6309
Sample Cell ID 3151
Calculated Data
Above Residual 0
Below Residual 0
Loading Factor 0.0451
Transmission 0.951
RMS Residual 0.185%
User Defined Calculations
Name Value
Recalculation Status
Live-Meas : : Original :

-SOP Info-

SOP Name: None
Timing
Setzero Time 30 (sec)
Run Time 30 (sec)
Number of Runs 3
Multi-Run Delay 0 (min)
Delay First Meas. Disabled
Analysis
GLASS
Refractive Index 1.51
Transparency Transp
Shape Spherical
WATER
Refractive Index 1.33
Options:
Filter Enabled
Analysis Gain Default(2)
Analysis ModeS3000/3500
Perspective
Progression Standard
Distribution Volume
Upper Edge(um) 1408
Lower Edge(um) 0.243
Residuals Disabled

Summary Data	Value
MV(um):	34.17
MN(um):	0.664
MA(um):	7.82
CS:	7.67E-01
SD:	28.49
Mz:	31.62
σι:	27.90
Ski:	0.392
Kg:	0.913

Percentiles %Tile	Size(um)
10.00	3.87
20.00	7.33
30.00	12.42
40.00	19.53
50.00	25.94
60.00	34.12
70.00	44.64
80.00	56.99
90.00	75.13
95.00	92.88

Peaks Summary

Dia(um)	Vol%	Width
39.79	68.8	51.81
10.62	10.3	3.42
6.16	8.6	1.89
3.3	8.9	1.443
0.616	3.4	0.168

11/8/2022 2:05 PM

FLEX
11.1.0.4

- Notes -

Sample System(Wet)
Number of Rinses 3
Flow Rate (%)55%
Deaeration Cycles 4

Figure A.5: Particle size analysis of JR-5 (GypRox)