GUIDANCE FOR USE OF CONSTRUCTION AND INDUSTRIAL WASTE BY-PRODUCTS IN CONCRETE

by

Akshay Bansal

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Approved by:

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Dr. Tara Cavalline

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Dr. Stephanie Pilkington

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Dr. Jake Smithwick

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Dr. Jacelyn Rice-Boayue

ABSTRACT

AKSHAY BANSAL. Guidance for use of construction and industrial waste by-products in concrete. (Under the direction of DR. TARA CAVALLINE)

This thesis presents a study to synthesize the published literature regarding the use of construction and industrial waste by-product as cement or aggregate in concrete, and aims to incorporate this knowledge along with findings of an agency and industry inquiry into development of a protocol for determining the suitability of waste materials for potential use in new concrete pavement construction. The use of construction and industrial waste by-products is beneficial for both environmental and economic reasons because beneficial reuse of waste materials will reduce environmental impacts of new construction as well as prevent the depletion of natural resources.

Construction and industrial byproducts can be used in either bound applications (new concrete) or in unbound applications (base or fill materials) in new construction. Unbound applications are often seen as a lower risk application than bound materials, but minimal standards for physical properties and durability performance must still be met. Additionally, environmental concerns associated with leachate can be an issue. Use of waste byproducts in new concrete can help lower the environmental footprint for this widely used building material. However, performance criteria must still be met. The primary criteria upon which the performance of concrete depends includes fresh properties, mechanical properties, and durability performance. The economics and availability of the materials must also be considered.

In this study, the characteristics of base materials and concrete produced using waste by-products, as well as the potential environmental impacts, were investigated and synthesized through a literature review. The perceived lack of guidance to support agency use of, and specification development for, these materials was explored using an inquiry of selected state highway agencies (SHA) and industry. The results of the inquiry conducted were analyzed to evaluate the barriers to use of construction and industrial waste by-products in concrete, identify needs, and assess risk tolerances. Similarities and differences between SHA and industry perceptions of benefits, required tests, and barriers to use were identified using statistical methods. Findings from the literature review and inquiry results were used to develop a methodology (guidance) for evaluating the suitable uses of construction and industrial waste by-products as unbound materials in concrete pavement construction or in concrete mixtures as either an aggregate or a supplementary cementitious material.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBRIVATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACPA	American Concrete Pavement Association
ASCM	Alternative Supplementary Cementitious Material
ASTM	American Standard for Testing Materials
C&D	Construction and Demolition
CBA	Coal Bottom Ash
CBR	California Bearing Ratio
CGR	Concrete Grinding Residue
DWTPS	Drinking Water Treatment Plant Sludge
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
NCC	National Concrete Consortium
NCPTC	National Concrete Pavement Technology Center
PCC	Portland Cement Concrete
PET	Polythene Terephthalate
PGP	Pozzolanic Glass Powder
PVC	Polyvinyl Chloride
RAP	Recycled Asphalt Pavement
RCA	Recycled Concrete Aggregate
RCPT	Rapid Chloride Permeability Test
RGS	Recycled Glass Sand

RHA	Rice Husk Ash
SCBA	Sugarcane Bagasse Ash
SCMs	Supplementary Cementitious Materials
SHAs	State Highway Agencies
SSA	Sewage Sludge Ash
TTCC	Technology Transfer Concrete Consortium
WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plant

CHAPTER 1: INTRODUCTION

1.1 Background

Natural resources such as rock, river sand, and gravels are diminishing rapidly due to the extensive use of concrete, which has a high demand due to new buildings and infrastructure construction (Kou and Poon 2009). The construction industry consumes 25% of virgin wood and 40% of raw stone, gravel and sand every year globally (Yuan et al. 2012). On the other hand, the volume of waste generated from industries and demolition of old construction which could potentially be used in concrete is high. In the United States, the amount of demolition waste generated has been estimated to be around 143 million metric tons per year (Chini and Bruening 2003). Also, the waste generated from such industries is often disposed of in landfills, which ultimately reduces the available landfill space that could be utilized for other waste and incurs disposal costs.

Concrete is a key component of many types of construction and is required in extensive amounts to build a new structure. The demand for concrete will likely not decrease in this era where development is taking place in most every part of the world. Thus, concrete is required in a variety of types of construction, including infrastructure, commercial, and residential construction to support new development as well as in repair of existing infrastructure. In the United States, use of concrete is estimated to be more than 500 million tons each year (Meyer 2004). Similarly, aggregate materials are utilized as base materials, as fill materials, and as a component of concrete. Use of crushed stone in the United States is estimated to be 1470 million metric tons and sand and gravel is 980 million metric tons in the year 2018 (Bernhardt and Reilly 2019).

Manufacturing or producing products utilizes energy, and also often results in a by-product which is considered a waste. Researchers have shown that these by-products can be beneficial if used in the appropriate manner. Production of concrete requires a binder and has historically been ordinary portland cement. However, after many research studies, ash from several burnt materials (such as coal, wood, sugarcane husk, and rice husk) and some other powdered material obtained as a by-product from some industries (such as slag, silica fumes, and crushed glass) provide pozzolanic activity and can be used as a cement replacement. Also, concrete requires aggregate which is conventionally obtained through mining. Demolition of an existing concrete structure results in an extremely high amount of construction waste which can be used as aggregate in the concrete. These by-products are considered as waste materials and are often disposed of into landfills, which leads to reduction of available landfill space.

Movement towards sustainable design and construction practices is essential for the planet's benefit and to continue the human development and growth of a society. Approximately 12 billion tons of concrete is manufactured annually around the world and this requires high volume of cement and aggregate production (Siddique et al. 2019). Production of portland cement produces more than 5% of carbon dioxide (CO_2) worldwide (Mohit and Sharifi 2019). However, the production of concrete requires cement as an essential constituent and the manufacture of cement releases carbon-di-oxide (CO_2) along with greenhouse gases (GHG) which are very harmful as they cause environmental pollution (Malhotra 2004). Cement production has been expected to rise from 2.5 billion ton in 2006 to about 5 billion ton by 2020 which is almost 100% rise (Naik 2008). The main source of CO_2 and GHG in cement manufacturing (Malhotra 2004) are:

- Calcination of limestone = 50-55%
- Fuel Combustion = 40-50%
- Use of electric power = 0-10%

Thus, to improve the sustainability of concrete, its necessary to reduce the carbon footprint associated with its cement content. One way of doing that is to use supplementary cementitious materials (SCMs) including fly ash, ground granulated blast-furnace slag, rice-husk ash, wood ash, silica fume and other pozzolanic material as a replacement of cement in concrete elements. Replacing cement up to 70% by SCMs in concrete can improve the environmental impact of concrete on air quality, reduction of solid waste along with durability and energy efficiency of concrete if mixed during the cement manufacturing process to reduce the energy required in cement production (Naik et al. 2003).

Construction of new buildings and infrastructure is taking place on a massive scale. Consequently, the worldwide consumption of concrete is increasing consistently every day. This increasing consumption is now causing the depletion of fossil energy resources. Hence, it has become necessary to use the sustainable material in replacement to the conventional materials for concrete production. A sustainable practice to reduce the environmental impacts and increase economic benefits includes reuse of suitable by-products from different industries which are otherwise disposed into landfills by incorporating them in concrete. Availability of industrial by-products for use in concrete is high, thus, they can be beneficially reused in the new infrastructure rather than filling them into the lands as waste (Karim et al. 2011).

Due to the real and perceived risk of using a new material in construction, justification of use of waste products is often required to encourage and support their use.

Life-cycle assessment (LCA) and Life-cycle cost analysis (LCCA) are two ways of evaluating the environmental and economic impacts respectively by using recycled materials in lieu of conventional materials (Carpenter et al. 2007), and can help demonstrate the benefits of using these materials. Using these tools, the sustainability benefits of reusing industrial waste by-products in lieu of conventional material have been shown to include (Karim et al. 2011; Muench and Van Dam 2014):

- Reduction of cement use will lower the energy consumption, as well as the production of greenhouse gasses such as CO_2.
- Use of waste for cement and concrete production reduces the need for use of virgin natural resources.
- Reducing the quantities of materials disposed of will lower landfill costs and conserve space in landfills for other materials.
- Efforts to utilize recovered waste materials supports sustainable development initiatives.
- Use of waste materials that exhibit pozzolanic activity or act as a filler in the hydration process can reduce the amount of portland cement in pavement mixtures
- Use of recycled products can reduce the impacts of transportation by the use of locally available materials over high quality materials without compromising the concrete’s performance
- The environmental damage caused while extracting natural aggregate from the quarries and sand and gravel pits can be mitigated

As an example, an LCA and LCCA study on Wisconsin State Highway 36/83 near Burlington, Wisconsin was conducted to evaluate the environmental and economic benefits of using by-products. As a result, it was found that Greenhouse gas emissions were reduced by 20% with 74% of CO_2 reduction from the heavy equipment, providing significant reductions to global warming associated with this project. It was noted that amount of hazardous waste produced, and amount of water consumed was also reduced about 11%. The total life-cycle cost also reduced by 21% by using recycled materials in lieu of conventional materials (Lee et al. 2010).

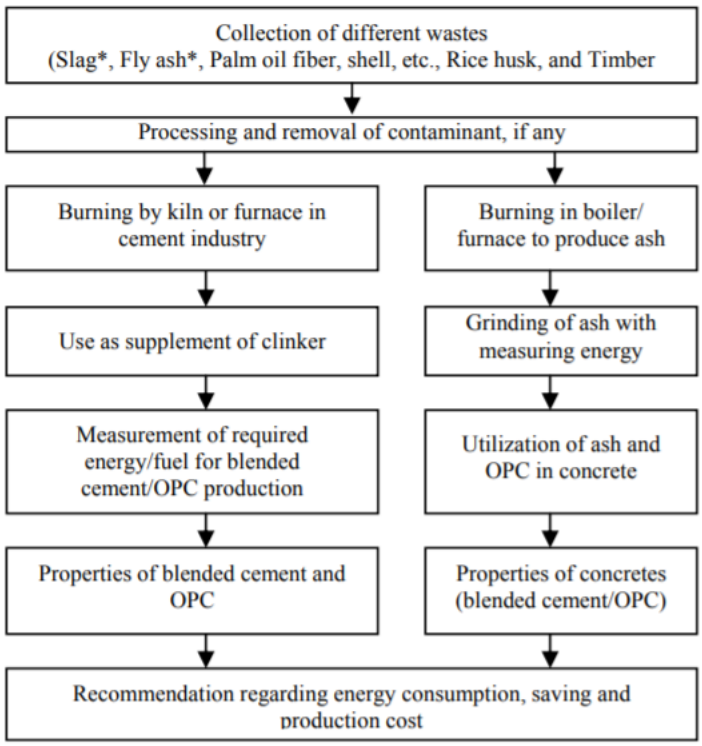

FIGURE 1.1 Utilization of wastes in cement and concrete as an energy saving approach (Karim et al. 2011).

Many construction and industrial waste by-products have the potential to be used in new infrastructure due to the fact that many of their properties are similar to those of conventional materials. The greatest sustainability benefits are generally understood to be highest grade uses (e.g. in new concrete) However, industry is often most motivated to use the lowest risk beneficial use, such as in unbound bases or fill material (Muench and Van Dam 2014).

A variety of industrial waste byproducts have been targeted for use in concrete and in unbound base applications, and published research studies generally provide findings that support consideration of their use. However, a number of limitations continue to exist for reuse of most construction and industrial waste by-products (Tymvios et al. 2019):

- The performance obtained from using by-products in concrete and unbound applications is often unknown.
- Due to the range of chemical compositions and physical characteristics of waste materials, as well as variation in their composition, characterization tests are required prior to use.
- For many waste products, research is still needed to support commercial use.

1.2 Significance

The use of construction and industrial waste by-products can be beneficial in terms of both sustainability and economics. Use of these byproducts can reduce the harmful environmental effects associated with industry while reducing the amount of natural resources depleted due to the heavy demand for concrete throughout the world. Many of these by-products are produced in significant quantities from a variety of different industries. Although some industrial waste by-products are often only available local to an industry, the range and geographic distribution of industries producing potentially beneficial waste provides an opportunity for use of an industrial waste byproduct virtually everywhere.

Due to the range of compositions and variability of the waste materials, most are still not understood well enough to be used efficiently in unbound materials such as base or fill, or in new concrete. These waste materials can be very economical in comparison to the conventional materials used in bases, fill, and concrete production, and shortages of conventional material may drive the demand for increased use of waste byproducts. Also, there may be environmental and financial risks associated with use of these by-products. However, previous, and ongoing research on mitigation of these risks, along with analysis supporting economics benefits of their use, is helping to justify increased usage of construction and industrial waste by-products.

Currently, there is a:

- Lack of synthesized knowledge to support practitioner education and comfort level
- Lack of guidance to support agency specification development
- Lack of a framework to economically justify use of construction and industrial by-products in concrete and demonstrate benefits

Research studies are needed to address the above points and to support the use of construction and industrial by-products which would improve the sustainability of construction.

1.3 Objectives and Scope

The objective of this work is to develop a methodology for determining suitable use(s) for construction and industrial waste by-products in concrete mixtures based upon the results of existing test methods and considering local conditions, including availability and economic considerations. As part of this work, a review of research studies focused on evaluating construction and industrial waste by-products for use in concrete was performed. The review of agency practices, existing guidance, and research findings was extended beyond the United States to other nations. The findings and recommendations were synthesized and summarized. An inquiry of state highway agencies and representatives from the concrete paving industry was performed to identify needs and assess risk tolerances. Best practices, research findings, and the literature inquiry results were synthesized in order to develop a methodology (guidance) for evaluating the suitability of construction and industrial waste by-products for use in concrete pavement applications as either an aggregate or supplementary cementitious material.

CHAPTER 2: LITERATURE REVIEW

2.1 Byproducts Used in Unbound and Bound (Concrete) Materials

2.1.1 Byproducts from the Construction Industry

2.1.1.1 Recycled Concrete Aggregate

2.1.1.1.1 Introduction

The depletion of good quality virgin aggregate along with the demand of raw material makes the availability of materials from permitted quarries more problematic. Also, the transportation cost for hauling those materials increases the overall cost of the construction material (Behera et al. 2014). Thus, there is a need for a substitute for virgin aggregates to fulfill the increasing construction demand without increasing the cost and environmental impact of raw material extraction.

Recycled aggregates are obtained from the demolition of existing infrastructure and they may be of many different types such as demolished concrete structures or pavements, rejected precast concrete members, broken masonry, waste generated from different laboratories, concrete from ready mix plants, asphalt pavement and other types of hardscape materials. Recycled aggregates produced from crushing of existing concrete structures is known as recycled concrete aggregate (RCA) (Chisholm 2011). RCA generally contains of adhered mortar consisting mostly fine aggregates, hydrated and un-hydrated cement particles bound to the residual coarse aggregates from the source concrete (Behera et al. 2014). The volume of residual mortar in recycled concrete aggregate varies from 25% to 60% according to aggregate size (Hansen and Narud 1983), and has been found to be highly influential on the characteristics of the RCA.

To achieve the typical gradation of aggregate used in concrete, primary and secondary crushing is generally required. In primary crushing, hammer and impact crushers are used to reduce the size of the materials to roughly about 50 mm, following which the material passes an electromagnetic separator which removes the metal impurities such as steel reinforcement. Finally, the material moves to a ventilator which uses blasts of air to remove the lightweight particles such as wood and paper. In secondary crushing, the material is further broken into smaller particles of about 14-20 mm size. RCA can be utilized as a substitute for fine aggregate (sand) or coarse aggregate in bound and unbound applications. The fraction of residual mortar contained within fine aggregate is higher than in coarse RCA (Snyder et al. 2018).

2.1.1.1.2 Impact of RCA on Fresh Concrete Properties

The mortar content of RCA has been found to increase the water demand of a concrete mixture required to achieve a desired workability. The workability of fresh concrete incorporating RCA was found to decrease, as the slump is lower as compared to virgin aggregate concrete mixed using the same water/cement ratio (Kou and Poon 2009). It was reported that the water demand increases by 10% for RCA concrete (Tabsh and Abdelfatah 2009). When the replacement increases more than 50%, the workability of recycled aggregate concrete (RAC) concrete is quite prominent (Tavakoli and Soroushian 1996). An increase in slump with increasing RCA was observed when the RCA used was presoaked and mixed while in surface saturated dry (SSD) condition (Poon et al. 2004). Another way to achieve the desired concrete workability when using RCA is by adding 20% fly ash along with superplasticizer as it can increase the workability by 12.5% (Kumar and Dhinakaran 2012).

The loss of capillary moisture, responsible for drying shrinkage, is greater in RCA concrete as compared to conventional concrete (Yang et al. 2008). The lower modulus of elasticity of recycled aggregate also offers less resistance to potential shrinkage of cement paste (Yang et al. 2008). Past studies have shown that the drying shrinkage of RCA concrete was 15-60% higher (Tavakoli and Soroushian 1996) while another study showed that drying shrinkage ranged from 20% on 50% of RCA substitution by mass of coarse aggregate which reached to 70% when the substitution increase to 100% (Domingo-Cabo et al. 2009).

2.1.1.1.3 Impact of RCA on Hardened Concrete Properties

The compressive strength of RCA concrete was found to be reduced by 30% upon replacement of 100% natural virgin aggregates with RCA (Poon et al. 2004; Tam et al. 2005). Other researchers also found significant loss in compressive strength loss ranging from 12-25% with 100% replacement of coarse aggregate with RCA (Etxeberria et al. 2007; Gutiérrez 2004; Hansen 1992). The reason behind the reduction may be due to the lower strength of RCA, increased porosity of the concrete (due to either the increased water required for workability or the porosity of the residual mortar), weak interfacial bonds of aggregates and matrix and presence of microcracks (Xing and Zhou 1998). This has led to many researchers recommended the use of RCA as only a partial replacement of fine and/or coarse aggregate. For example, the optimum replacement of coarse aggregate with RCA suggested by one author is 25-40% (Tam et al. 2007). A contrary statement was given by another author that the compressive strength of RCA concrete is sometimes equal or higher than conventional concrete at high w/c ratio (0.40, 0.55, 0.70) because the excess water absorbed by the aggregates lower the effectiveness of w/c ratio which in turn increase the strength of the concrete (Otsuki et al. 2003).

The splitting tensile strength of RCA concrete shows similar trend as that of compressive strength of the RCA concrete (Behera et al. 2014). It was found that the splitting tensile strength can be reduced up to 24% when 100% substitution of RCA as coarse aggregate is utilized (Rao et al. 2011). In the contrary, some researchers indicated that the splitting tensile strength of RCA concrete is improved over that of conventional concrete because of the improved bond that is formed between the RCA and new mortar, due to the higher water absorption of the residual mortar on the RCA as well as its increased permeability which promotes bond (Etxeberria et al. 2007). High strength concrete derived from RCA has been shown to perform better in splitting tensile strength tests than normal strength concrete (Behera et al. 2014; Rao et al. 2011).

The flexural strength of RCA concrete was found to decrease by 10% upon 100% substitution of RCA as coarse aggregate in concrete (Ajdukiewicz and Kliszczewicz 2002; Hansen 1992; Yang et al. 2008). Another study showed a decrease in the range of 16-23% in flexural strength of RCA concrete (Tavakoli and Soroushian 1996). Some of them found no significant difference in the flexural strength of concrete containing 100% RCA as coarse aggregate (Rao et al. 2011; Sri Ravindrarajah and Tam 1985). One study found that the flexural strength reduced by at most 13% on substitution of 15-50% RCA used as coarse aggregate by mass (Kang et al. 2012).

Concrete’s modulus of elasticity is directly affected by the porosity of aggregate and past matrix, and as such, incorporation of RCA into concrete typically results in a reduction in elastic modulus (Behera et al. 2014). In one study, the authors found a loss of

45% of the elastic modulus on 100% substitution of RCA in place of natural coarse aggregate (Ajdukiewicz and Kliszczewicz 2002; Rao et al. 2011; Yang et al. 2008). However, in another study the reduction was slightly reduced by 20-25% on the same RCA substitution (Bairagi et al. 1993). The author noticed that the failure pattern was indicative of a more brittle failure mode than would be typically observed in conventional concrete (Günçan 1995). The reduction in modulus of elasticity was attributed to the strength characteristics and lower quality of RCA (Limbachiya et al. 2012).

2.1.1.1.4 Impact of RCA on Durability of Concrete

The water absorption characteristics of RCA impose the potential to adversely impact the durability of concrete. The increased porosity of RCA tends to result in greater concrete permeability to water and aggressive ions (Snyder et al. 2018). For example, the chloride ion penetration was found to be 73.2% higher than normal concrete on 100% substitution of RCA as coarse aggregate at 28 days curing period (Olorunsogo and Padayachee 2002). Another study also reported an increase in chloride ion permeability ranging from 32-55% on 100% substitution of RCA as coarse aggregate (Kou et al. 2012). This could be demonstrated using the rapid chloride permeability test (RCPT), passing a charge for 6 hours through concrete cured for 28 days (Kou and Poon 2009).

Concrete containing RCA was found to perform better in freeze and thaw resistance than normal concrete due to its porosity, which likely provides space for water to freeze and reduces freeze-thaw stresses (Gokce et al. 2004). However, it did not perform well in resistance to sulphate attack as the loss in concrete mass increased with the increase of RCA in the sulphate resistance test (Limbachiya et al. 2012).

2.1.1.1.5 Environmental Concerns

Using RCA is a sustainable practice in terms of environmental benefits because it reduces the use of virgin aggregates and landfill facilities, among other advantages. Use of RCA also reduces the fuel consumption and the emissions associated with its combustion. However, there could potentially be some negative impacts associated with the recycling of concrete aggregates on water quality, air quality, waste generation, noise and some other local impacts (Snyder et al. 2018). A description of these is as follows:

Waste:

As, RCA is an inert material, it is not subject to hazardous waste regulation. The waste generated from its production can be solid waste (crusher fines, sealants, reinforced steel) and slurries (from wastewater). They can be mitigated by: -

- Optimizing the crushing operation in such a way to minimize the production of fine particle.
- Reducing the volume of water from RCA's by evaporation techniques.
- Identifying appropriate locations for washing equipment (Snyder et al. 2018).

Air Quality:

The production of RCA can also produce dust and airborne particles (from equipment emission) similar to that produced during construction activities. But the emissions associated with the virgin aggregate production may be greater, and the use of RCA may reduce the greenhouse gases which are emitted by the equipment and the dust from hauling vehicles (Snyder et al. 2018).

There are many ways of mitigating the air quality issues caused due to RCA production. Some of them are (Cavalline 2018):

- Minimizing the haul distance as much as possible.
- Maximizing the fuel efficiency and minimize the emission of a hauling vehicle by properly maintaining them.
- Reducing the speed of hauling vehicle and covering the stockpiles.
- Spraying water during production is an effective way to reduce dust.

Water Quality:

The runoff and leachate from RCA stockpiles may be highly alkaline due to dissolved calcium hydroxide, contaminated with chemicals, and can potentially form deposits of suspended solids in infrastructure components such as drainpipes (Sadecki et al. 1996; Steffes 1999). It may also include some heavy metals like vanadium, chromium, and lead. High pH runoff from the RCA, if not diluted by rainwater, may be harmful for vegetation, zinc-coated and aluminum pipelines, natural water when discharged directly into the streams (Chen et al. 2012; Edil et al. 2012; Sadecki et al. 1996). These effects can be mitigated if the runoff is neutralized by infiltration and exposure to soil and rocks. Thus, use of RCA in construction may reduce some of the impacts on water quality due to leaching. There are many other ways of mitigating the water quality issues (Snyder et al. 2018). Some of them are:

- Selecting the location of the stockpiles away from water bodies such as streams.
- Constructing trenches around the stockpiles and processing equipment for collecting the runoff.
- Mitigating the pH level and solid content of the runoff by using the localized treatment like mechanical catchments and pH logs.

Noise Pollution:

Recycling of concrete causes noise, vibration, as well as dust due to the equipment used. These impacts cannot be completely eliminated, but they can be mitigated using certain techniques. Some of the techniques to mitigate (Snyder et al. 2018) such issues are:

- Recycling operations must be conducted away from sensitive area such as residential and corporate areas.
- Providing noise attenuation barriers.
- Minimizing drop height of the materials.

The environmental impacts of RCA can be reduced through planning and design consideration, use of conventional best management practices (BMP's) and through construction controls which are readily implementable. RCA's are currently used by many state DOTs with good results in sustainability, and appropriate design to mitigate the environment effects can promote the use of RCA as an engineered material for construction (Cavalline 2018; Snyder et al. 2018).

2.1.1.2 Recycled Asphalt Pavement

2.1.1.2.1 Introduction

Reclaimed Asphalt Pavement (RAP) is a mixture of old asphalt binder and the aggregates produced by recycling hot mix asphalt. RAP is a construction by-product which is obtained from milling and removal of old asphalt pavement (Copeland 2011). The United States highway industry generates about 100 million tons of RAP through reconstruction and rehabilitation of existing highway pavements (Topcu and Isikdag 2009). The use of RAP as waste material in pavement construction reduces the emission of greenhouse gases and it behaves as a sustainable material for improving the environment health (Chen and Wang 2018).

2.1.1.2.2 Impacts of RAP on Fresh Concrete Properties

The workability of fresh concrete with RAP as fine aggregate replacement was found to decrease, as evidenced by reduced slump values for constant water contents. At RAP replacement levels of 25%, 50%, 75% and 100% by weight of fine aggregate, the slump value decreased by respectively 29%, 61.3%,74.2% and 100% (zero slump). The reduction in slump was attributed to the angular shape and the higher water absorption of fine RAP aggregate, which was about 204% of the natural aggregate's absorption (Singh et al. 2018).

The density of fresh concrete was constantly found to decrease upon increasing the replacement level of RAP as fine aggregate. The fresh density of the control concrete mixture was 2394 kg/m^3, which upon increasing the RAP replacement level of 25%, 50%, 75% and 100% by weight of fine aggregate reduced by 1.45%, 2.22%, 3.95% and 5.23% respectively. This reduction was attributed to the lower specific gravity of fine RAP compared with fine natural aggregate (Singh et al. 2018).

2.1.1.2.3 Impacts of RAP on Hardened Concrete Properties

The compressive strength of concrete containing RAP aggregate was found to be decreased from that of conventional concrete at 90 days curing period. An almost 70% compressive strength reduction was observed in the concrete mixture containing 100% RAP, while a 60%, 40% and 20% reduction was observed on the replacement of 70%, 40% and 20% aggregate with RAP as compared to the control mixture (Tia et al. 2012). The 28 day compressive strength of concrete was reduced by 6%, 17.5%, 28.8% and 36.3% upon replacement of 25%, 50%, 75% and 100% respectively with RAP fine aggregate by weight (Singh et al. 2018). Another study also observed a reduction of 9%, 16% and 18% of compressive strength on replacing virgin coarse aggregate with 20%, 35% and 50% RAP respectively by weight at 28 days curing period (Brand et al. 2012).

There is a significant reduction in the flexural strength of concrete containing RAP aggregates. The flexural strength was reduced by 50%, 40%, 30% and 20% for the concrete containing 100%, 70%, 40% and 20% RAP as both fine and coarse aggregate by volume respectively (Tia et al. 2012). Another research study also reported a decrease in 28-day flexural strength of concrete containing RAP as fine aggregate replacement. The strength was reduced by 13%, 23.4%, 39.2% and 44.4% respectively for the replacement level of 25%, 50%, 75% and 100% fine RAP respectively by weight (Singh et al. 2018).

2.1.1.2.4 Impacts of RAP on Durability of Concrete

A slight increase in water absorption of 3.5% and 8.1% was observed at 25% and 50% replacement level of fine aggregate with RAP respectively, which drastically increased to 21.3% and 29.4% when the replacement increased by 75% and 100% respectively by weight (Singh et al. 2018). The increase in water absorption was the result of high absorption of water by RAP aggregates. On the other hand, the water absorption for RAP-inclusive concrete was found to increase with a higher amount with the age because after the 91-day curing period, the absorption was noted to increase by 26.1% and 43.1% for the replacement of 25% and 50% fine aggregate respectively by weight (Singh et al. 2018).

The chloride permeability of the concrete containing RAP aggregate was found to be low in several studies. Increasing the substitution level did not impact the chloride permeability to a significant extent (Brand et al. 2012). In a study, the author used surface resistivity method to correlate to the relative chloride permeability through the concrete containing RAP as coarse aggregate. Upon the replacement level of 25% and 30%, the surface resistivity reduced slightly by approximately 5% and 14.5% respectively (Thomas et al. 2018).

2.1.1.3 Concrete Grinding Residual (CGR)

2.1.1.3.1 Introduction

Grinding is done to remove the surface irregularities and change the surface texture which reduces the friction and noise from traffic. Concrete grinding residue is generated during the construction or rehabilitation of PCC slabs. It is the slurry which is collected by adding water to the fugitive dust which is generated while grinding (Kluge et al. 2018). The particles present in the slurry contain partially unreacted cement which when reused may exhibit cementing properties because the physical and chemical composition of CGR is like that of portland cement (Amin et al. 2016; Hanson et al. 2010), thus, it could be used as a cement replacement in concrete. Depending on the particle size of CGR, it could also be used as sand replacement in new concrete (Kluge et al. 2018). CGR also has some other uses other than cement replacement such as, waste-water treatment filters, poultry grit, limestone substitution in SO_2 scrubbers and for stabilization of sewage sludge (Hansen 1992).

2.1.1.3.2 Impacts of CGR on Hardened Concrete Properties

Compressive Strength:

The compressive strength of concrete mortar was found to decrease upon incorporation of concrete grinding residue as portland cement replacement. On comparing with control specimen containing 100% portland cement over 56 days curing period, the compressive strength of 5% replacement by mass showed a reduction of 10-20% while 20% and 35% replacement by mass reduced the strength by 20% and 55% respectively. When the replacement increased to 50%, the reduction of strength was in range of 58% to 72% (Kluge et al. 2018).

2.1.2 Byproducts from Other Industries

2.1.2.1 Coal Bottom Ash (CBA)

2.1.2.1.1 Introduction

Coal Bottom Ash (CBA) is the unburnt matter obtained from coal incineration process (Oruji et al. 2019) which constitute about 10-20% of coal ash (Argiz et al. 2018) and the remaining is fly ash. It is a complex mixture of metal carbonates and oxides and is considered as a waste material (Tian et al. 2020). The CBA generated from coal-fired power plants is usually deposited into a landfill or stored within ponds, which have caused threats to humans and the environment due to its harmful contents leaching into water systems (Singh and Siddique 2016). Disposal of CBA in open air increases the risk of health problems associated to lungs, skin and bladder cancer (Singh et al. 2018). Also, the toxic contaminants present in CBA can pollutes the environment by affecting the air and water quality (Shahbaz et al. 2016). Some of the power plants use a pressure washer to discard bottom ash from the boilers (Bajare et al. 2013) which can dissolve contaminants, which percolate into the ground in the form of leachate and subsequently contaminate the ground water (Goodarzi and Huggins 2001).

The particle size of CBA is on the order of conventional sand, and therefore CBA can be used as a sand replacement in concrete (Singh and Siddique 2015). The chemical composition of CBA particles support pozzolanic behavior when further grinded to make a finer particle size and used in concrete. Thus, CBA has the potential to be used in concrete as cement, sand, or fine aggregate replacement. This will prevent the environment by increasing the landfill space and air exposure of the coal bottom ash.

Chemical Composition:

The components of CBA, along with the associated ranges used in ASTM C618 for use as a pozzolan in concrete, are rare shown in.

TABLE 2.1 Chemical Composition of Coal Bottom Ash
(Singh and Siddique 2015)

Compound	Composition (%)	ASTM C 618-03 requirement (%)
Silicon dioxide SiO_2	56.44	-
Aluminum oxide Al_2O_3	29.24	-
Iron oxide Fe_2O_3	8.44	-
$SiO_2 + Al_2O_3 + Fe_2O_3$	94.12	70 min
Potassium oxide K_2O	1.29	-
Calcium oxide CaO	0.75	-
Magnesium oxide MgO	0.40	5.0 max
Sulphur trioxide SO3	0.24	5.0 max
Titanium oxide TiO3	3.36	-
Sodium oxide Na2 O	0.09	1.5 max
Loss on ignition (%)	0.89	6.0 max

2.1.2.1.2 Impacts of CBA on Fresh Concrete Properties

Workability:

The replacement of sand by CBA in concrete has been proven beneficial in some research studies because the CBA increases the workability of the fresh concrete mixture. One of the studies showed that the workability was found to increase upon replacement percent of 0, 30, 50, 70 and 100% by mass of sand (Bai and Basheer 2003). In another study, the workability was found to increase only up to a 25% replacement level by mass of sand, upon which further replacement percent of 50, 75 and 100% was decreased (Bai et al. 2005; Rafieizonooz et al. 2016). The increase in workability was due to the use of saturated surface dry bottom ash as a sand replacement which tends to improve the workability of fresh concrete due to both the increased moisture content (Rafieizonooz et al. 2016). On the contrary, the workability of concrete decreases when using oven dried CBA, as the slump flow and passing ability of highly workable (self-consolidating) concrete drops when bottom ash is added to the mixture in the range of 10-30% replacement of fine aggregate. This reduction was due to the voids present in the structure of the oven dried CBA, which absorbed the mixing water and reduced the slump value (Singh and Siddique 2016).

The replacement of portland cement with finely ground CBA showed variable results for workability in different studies. In one of the studies, the workability was found decreasing by 10% on incorporation of 10% of grinded CBA as portland cement replacement by mass. The reduction in workability was due to the uneven surface texture of CBA particles which absorbs additional water during mixing (Mangi et al. 2019).

Density:

The dry bulk density of concrete was found to decrease when CBA was incorporated into the mixture. In one research study conducted, the decrease in dry bulk density as compared to that of the control mixture varied between 1.76% and 9.97%, depending on the CBA content in the concrete. On incorporating CBA as 100% replacement of sand by mass, the dry bulk density of concrete mixture decreased by 10%. The reason for the reduction in density was the low specific gravity of coal bottom ash (Singh and Siddique 2016).

2.1.2.1.3 Impacts of CBA on Hardened Concrete Properties

Compressive Strength:

The use of CBA as a sand replacement affects the load bearing capacity of hardened concrete. Some of the studies found that the replacement of sand with CBA enhances the compressive strength. One of the studies found that the replacement of 40% sand by mass of CBA produces some concrete with higher strength concrete compared to the control specimen. Another study found that replacement of sand with 25% and 50% by mass of pre-treated class-F CBA (which is finer and has low carbon content) produces lighter autoclave aerated concrete with enhanced strength which was attributed to the pozzolanic reaction which generates tobermorite (a calcium silicate hydrate mineral).

The replacement of portland cement with finely ground CBA was found to be beneficial in many studies. The authors found a drastic improvement in the compressive strength of concrete until the replacement level of 20% further which due to relatively low reactivity of grinded CBA at early ages, the decrement of compressive strength at 90 days curing was observed (Targan et al. 2003). The compressive strength was found to increase by 5-16% replacement of 5, 10, 15, 20 and 25% of portland cement by weight of grinded CBA at 28 days curing period (Targan et al. 2003). Also, an enhancement in compressive strength of up to 10% was observed on replacement percent of 9, 23, 33 and 41% at constant w/c ratio of 0.55 (Abdulmatin et al. 2018; Jaturapitakkul and Cheerarot 2003; Oruji et al. 2017). The increase in compressive strength is due to the finer size of grinded CBA (i.e. 4.5 μm) which increases the hydration products formed during pozzolanic reaction because of its inherent pore refinement action that fills the pores in the paste (Abdulmatin et al. 2018).

Modulus of Elasticity:

Changes in concrete modulus elasticity appear to be driven by the gradation of the CBA utilized in the mixture. For example, the incorporation of CBA as a sand replacement of fineness modulus 1.97 decreased the modulus of elasticity of concrete. The decrease in 28 days modulus of elasticity varied between 5.2 and 20.7%. Whereas the incorporation of 50% CBA as sand replacement of fineness modulus 2.58 showed comparable results as it was nearly 98% of the control concrete mixture and 100% replacement was about 16% lower than the control mixture. However, the modulus of elasticity of CBA concrete showed a constant increase with age but the respective difference with control mixture remained the same at 90 days curing period (Singh and Siddique 2016).

Abrasion Resistance:

Concrete containing CBA as a sand replacement has been shown to have reduced abrasion resistance compared to conventional concrete. In one study, concrete containing CBA as a 50% by mass sand replacement showed an the abrasion resistance decreased by 27.52, 16.57 and 20.96 at 28, 90 and 365 days respectively compared to the control mixture (Singh and Siddique 2016).

2.1.2.2 Rice Husk Ash (RHA)

2.1.2.2.1 Introduction

Rice Husk Ash (RHA) is an agricultural waste as it is produced by controlled combustion of rice husks which are obtained during rice harvesting. The ash produced through combustion is in the form of non-crystalline or amorphous silica with cellular structure. When the rice husk is properly burned and grinded, it could be used as replacement to portland cement in concrete (Rukzon and Chindaprasirt 2010). RHA could also be produced through open field burning or uncontrolled combustion in industrial furnaces (Mehta and Monteiro 2017). Rice husk is obtained in a large quantity due to the significantly high production of rice around the world. Rice husk is considered as a waste product because it causes environmental pollution. Almost 11% of world's arable land which corresponds to 145 million hectares of land is utilized for rice farming which comprises half of all food consumed by 1.6 billion people (Ahmad et al. 2017).

2.1.2.2.2 Impacts of RHA on Fresh Concrete Properties

RHA possess pozzolanic properties due to its high composition of silica (80-90%). It also includes carbon (0.41-5.91%) and alkali oxides (0.95-4.61%). RHA is beneficial for increasing compressive strength, workability, bending strength and lowering the hydration temperature, permeability, and bleeding of a concrete mix. Its chemical and physical composition is shown in Table 2.2.

TABLE 2.2 Chemical and Physical Compositions of Rice Husk Ash
(Arel and Aydin 2018)

Analysis %	Composition
SiO_2	88.4%
Al_2O_3	0.21%
Fe_2O_3	1.1%
CaO	1.3%
MgO	0.2%
SO_3	0.4%
Na_2O	0.4%
K_2O	1.77%
Loss on ignition	2.8%
Specific Surface Area (ft^2/lb.)	118,155
Mean Particle Size (μm)	4.12

2.1.2.2.3 Impacts of RHA on Hardened Concrete Properties

Cement replaced by mass of RHA by 30% increases almost 60.5% in 28 days compressive strength with about 6.74% decrease in pore volume, when compared to a control mixture (Qing-ge et al. 2004). On the other hand, a 15% replacement increased setting time, 28-day compressive strength (35%), flexural strength (19.9%), tensile strength (15%). and 20% gave comparatively higher compressive strength (14.6%) (Venkatanarayanan and Rangaraju 2015). The primary drawback of replacing cement with RHA is that it tends to decrease the slump and workability of a fresh concrete mixture (Arel and Aydin 2018).

2.1.2.3 Sugarcane Bagasse Ash (SCBA)

2.1.2.3.1 Introduction

Sugarcane bagasse Ash (SCBA) is obtained from the burning of sugarcane's husk (also known as bagasse) in cogeneration plants of sugarcane industries at temperature levels between 500 and 550 ºC. It is one of the major by-products from the agriculture industry - every 10 tons of crushed sugarcane produces about 3 tons of bagasse (Gar et al. 2017) which is generally non-usable and is landfilled, causing environmental pollution. According to research published in 2014 (Fig 2.1), United States produces about 2% of sugarcane bagasse, while its largest producers in the world are Brazil and India with a hold of 50% of world's production volume.

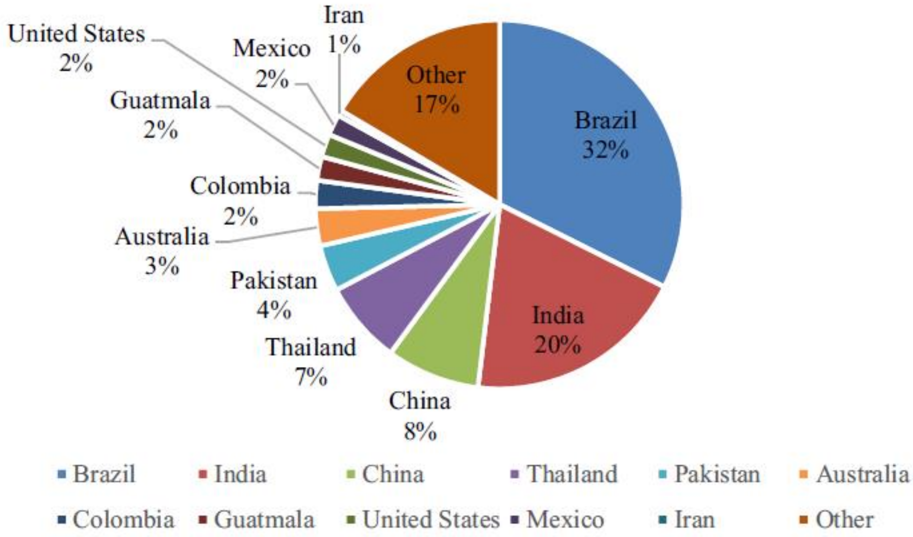

FIGURE 2.1 World production of sugarcane bagasse (thousand metric tons) in 2014 (Zareei et al. 2018).

Chemical composition:

TABLE 2.3 Oxide compositions of SCBA obtained from XRF test (Gar et al. 2017)

Oxide	Average (Wt.%)
SiO_2	69.94
MgO	6.68
P_2O_5	6.12
K_2O	5.83
Al_2O_3	3.34
CaO	2.27
Na_2O	1.49
Fe_2O_3	1.25
SO_3	0.42
TiO_2	0.088
Cr_2O_3	0.078
MnO	0.059
SrO	0.03
CuO	0.02
ZrO_2	0.02
ZnO	0.01
Rb_2O	0.01
Ni_2O_3	0.01
LOI	2.35

From the chemical composition shown in Table 2.3, it can be noted that the grains of SCBA show potential pozzolanic properties due to high amount of silica (70%). The ash produced by combustion consists of high amount of amorphous silica which could react with free lime produced during cement hydration and form new silicate hydrate, which significantly improves the durability along with the mechanical properties of concrete (Payá et al. 2002). The particle size distribution of SCBA is similar to that of portland cement (Zareei et al. 2018), and maximum size is typically below 100 µm (Gar et al. 2017). Initially, the particle size of raw bagasse ash is large and highly porous which requires more water and lowers the compressive strength of concrete. However, these particles when finely grounded up results in increasing the compressive strength due to greater reactivity as a result of larger surface area (Zareei et al. 2018).

2.1.2.3.2 Impacts of SCBA on Concrete Properties

The mechanical properties of concrete containing SCBA were evaluated by Chusilp et al. (2009), who found that portland cement replaced by 3-10% bagasse ash by weight of binder included in the concrete improves the strength compared to the reference sample (Chusilp et al. 2009). The optimum percentage of SCBA utilized to increase compressive strength and lower water permeability at 28 and 90 days was determined to be 30% (Chusilp et al. 2009). In another study, the optimum SCBA replacement of cement for increasing the compressive strength was 20% by weight of cement which if further increased to 25% or 30% results in a reduction of the compressive strength (Amin 2011).

A more recent study was performed by Zareei et al. (2018). Some of the tests performed by Zareei et al. to determine the properties of concrete with bagasse ash in fresh and hardened states are listed in the Table 2.4.

TABLE 2.4 Standard test to determine concrete properties in fresh and hardened states (Zareei et al. 2018)

Test	Standard	Age
Slump test	ASTM C143/C143M-12	Fresh concrete
Fresh density	ASTM C138/C138M-14	Fresh concrete
Water absorption	ASTM C642-13	28 Day
Compressive strength	ASTM C39/C39M-14	28 Day
Splitting tensile strength	ASTM C496/C496M-11	28 Day
Impact resistance test	ASTM G544	28 Day
Ultrasonic pulse velocity	ASTM C 137/C 597–16	28 Day

From the tests, it was found that (Zareei et al. 2018):

1. The slump value increases with an increase in SCBA content. The fresh density of the mixture will also increase with an increase in SCBA content because SCBA has lower density as that of cement. Thus, the optimum value of cement replacement was determined to be 20% to obtain the desired workability of the mixture (a slump of 4 inches), while additional SCBA added can result in excessive slumps of the mixture.
2. Increasing replacement of cement by 20% by weight of SCBA resulted in a reduction of tensile strength of the concrete mixture by 29%.
3. Incorporating SCBA when tested in low weight concrete (LWC) and self-compacting concrete (SCC) at a 5% replacement rate of cement by weight significantly increased the impact resistance of LWC and SCC by 36% and 53% respectively which suddenly reduced by 37% and 53% respectively while increasing the percentage of SCBA to 10%. Further, when the percentage was increased to 25%, the impact resistance increased up to 27% and 16% respectively in LCC and SCC.

4. The water permeability measured via the ASTM C642 test increased with increasing SCBA content. For cement replacement of 25% by weight of SCBA water permeability increased by 72% compared to the control mixture, this could be due to the carbon content and the increasing void content in the sample which produced more porous concrete.

Based on the results obtained, Zareei et al. concluded that SCBA in general improves the performance of concrete when cement is replaced with SCBA by 5% by weight.

2.1.2.4 Crumb Rubber

2.1.2.4.1 Introduction

The increase in number of vehicles has led the amount of waste tires to increase around the world. Around 1000 million tires which are completely used are discarded every year which will reach to 1200 million tires by the year 2030 (Pacheco-Torgal et al. 2012). The waste rubber generated from used tires is considered as one of the major environmental problems faced by every country around the globe due to the disposal problems as well as health hazards (Al-Tayeb et al. 2012). Rubber particles obtained from used tires can be reused in many ways which are environmentally friendly and one of those practice is to reuse them in concrete as cement or aggregate replacement to reduce the high demand of natural resources which is considered as unsustainable practice. The usable rubber can be extracted from tire through shredding process with the help of electromagnet to separate out the steel fibers (Aiello and Leuzzi 2010).

Rubber aggregates from used tires increase the energy absorption capacity of concrete, protecting it from damage due to impact. This is because the rubber aggregates possess a relatively low elastic modulus which allows displacement upon impact, reducing the damage due to collisions (Topçu and Avcular 1997). For this reason, rubber aggregates their use has primarily been in concrete jersey barriers and (outside of the United States) in road pavements (Bravo and De Brito 2012). It is also suggested to use waste tire rubberized concrete as vibration dampers in foundation pads for rotating machinery and railway stations (Fattuhi and Clark 1996), sound barriers in highway construction, earthquake shock-wave absorber in buildings (Avcular 1997). From the ultrasonic echo technique conducted on rubberized concrete, it was found that concrete is an effective absorber of shaking energy and sound (Khaloo et al. 2008). The presence of rubber in concrete can offer better protection to the steel reinforcement from corrosion because it is capable of reducing water absorption and avoid water propagation (Aiello and Leuzzi 2010).

The unit weight of tire rubber particle has been reported as 1.15 g/cm^3 (Khaloo et al. 2008), 0.84 g/cm^3 (Hernández-Olivares and Barluenga 2004) and 0.9 g/cm^3 (Bignozzi and Sandrolini 2006). These variations could be probably due to the origin, type (car, truck, motorbike etc.) of the rubber.

Chemical Composition:

The Table 2.5 shows different chemical found in the rubber which is obtained from used tires.

TABLE 2.5 Chemical Composition of Discarded Tire Rubber
(Thomas et al. 2014)

Test	Results
Ash content, %	5.11
Carbon black content, %	28.43
Acetone extract, %	9.85
Volatile matter, %	0.56
Hydrocarbon content, %	56.05
Polymer analysis	SBR

2.1.2.4.2 Impact of Crumb Rubber on Fresh Concrete Properties

Workability:

The workability of a fresh concrete mixture increases on partially substituting the fine or coarse aggregates with rubber shreds. It was found that when coarse aggregates are replaced by 25, 50 and 75% of rubber by volume, the respective slump increased by 22, 19.5 and 19.5%. Also the replacement of fine aggregate with rubber showed similar result for slump with slight variations (Aiello and Leuzzi 2010).

Density:

The density of crumb rubber decreases with an increase the rubber content. It was reported that on replacing the coarse aggregate or fine aggregate 50% by volume of rubber, a density decay of 5.8% and 6.0% respectively was observed. Similarly, for 75% replacement by volume, the corresponding density decay is 8.8% and 8.3%. This confirms that the density or unit weight of concrete decreases on increasing the rubber content (Aiello and Leuzzi 2010). This change in density is a result of differences in density of normal aggregate and rubber aggregates (Bravo and De Brito 2012).

2.1.2.4.3 Impact of Crumb Rubber on Hardened Concrete Properties

Compressive Strength:

The compressive strength of crumb rubber concrete was evaluated by comparison of conventional concrete with different types of replacements of cement and aggregates with different percentage replacements by volume, it was found that: -

- When sand is replaced with 5, 10, and 20% by volume of fine crumb rubber (0.4-1.0mm), the compressive strength reduced by 13, 21, and 28% respectively. Similarly, for the same percent replacement of sand by crumb rubber (1.0mm), compressive strength again reduced by 11, 15, and 19%. When cement is replaced with the same percent by rubber powder (0.15-0.6mm) the respective reductions were 19, 32 and 53% (Al-Tayeb et al. 2012).
- When coarse aggregates are replaced with 50% and 75% of rubber shreds by volume, the compressive strength reduced by 54% and 62% respectively. Whereas for same replacement percent of fine aggregate with rubber shreds, the compressive strength reduced by 28% and 37% (Aiello and Leuzzi 2010). Further, if both the aggregates together are replaced by 50% and 75% then the compressive strength is respectively decreased by 57% and 70% (Toutanji 1996).

In one study conducted, it was found that varying the crumb rubber replacement percent in the concrete mixture's fine aggregates may reduce the compressive strength, tensile strength and modulus of elasticity of the concrete, but it can be compensated by changing the water-cement ratio, cement content and cement to aggregate ratio of the mixture. The reduced strength from the addition of crumb rubber was mitigated by using extra cement which eventually increased the cost of producing the mix by approximately 5-12% of the normal concrete (Mendis et al. 2017).

Impact Resistance:

The impact resistance of concrete was reported to increase with the increase in rubber content in the concrete. The replacement of cement by 5% and 10% of crumb rubber powder by volume increased the first crack resistance by 26% and 68% respectively, which was reduced to 46% when replacement increased to 20%. An increase of ultimate failure impact resistance by 6% and 13% was observed when cement is replaced similarly by 5% and 10%, which reduced to 2% when replacement increased by 20% (Al-Tayeb et al. 2012).

When sand was replaced with crumb rubber by 5, 10 and 20% by volume, the first crack impact resistance increased by 31, 78 and 105% respectively and ultimate failure impact resistance increased by 5, 21 and 34% respectively with fine rubber (0.4-1.0mm) and 16, 25 and 50% respectively with crumb rubber (1.0-5.0mm). In case of impact energy, the replacement of coarse aggregate with chipped rubber up to 50% increased the impact energy of the concrete and beyond 50% it started to decline (Al-Tayeb et al. 2012).

2.1.2.4.4 Impacts of Crumb Rubber on Durability of Concrete

In a durability study conducted on high performance concrete with partial replacement of sand with waste tires, it was reported that when 5% sand was replaced with rubber and cement was replaced by 15% fly ash and 15% metakaolin had similar resistance to sulphuric acid attack as of actual concrete without replacement. While the replacement of cement with 45% fly ash and 15% metakaolin shows a high resistance to sulphuric acid resistance independently of the rubber waste content (Azevedo et al. 2012).

2.1.2.5 Crushed Glass

2.1.2.5.1 Introduction

A municipal solid waste report published by Environmental Protection Agency stated that 11.5 million tons of waste glass was generated in the United States in the year 2013 among which the maximum proportion was of soda-lime bottles. Out of the glass waste generated, 26% was recovered for recycling in 2013 whereas 74% of waste glass collected was landfilled (Afshinnia and Rangaraju 2016). Glass powder obtained by crushing waste glass to the desired shape has been proven to have pozzolanic characteristics according to ASTM C618 which states that the sample containing glass powder must provide at least 75% of the strength of the control sample at both 7 days and 28 days of age. The strength index found out to be 83.38% and 87.12% at 7 days and 28 days of age which meets the requirements of ASTM C618 and can be considered as class C and class F pozzolanic materials (Aliabdo et al. 2016).

In order to be used in concrete, the glass needs to follow seven procedures which includes, washing, crushing, milling, sieving (wet and dry), sedimentation and uniformity control to be obtained in powdered form with size range of 63-75 mm and 0-25 mm.

Chemical Compositions:

Typical chemical compositions of recycled glass sand and glass powder are shown in Table 2.6.

TABLE 2.6 Chemical Compositions of Crushed Glass
(Taha and Nounu 2009)

Chemical Compounds	Recycled Glass Sand	Glass Powder
CaO	10.63	8.61
SiO_2	72.13	72.26
Al_2O_3	1.78	1.04
Fe_2O_3	0.36	0.17
MgO	1.26	3.89
Na_2O	12.4	13.31
K_2O	0.64	0.52
TiO_2	0.06	<0.05
Mn_3O_4	<0.05	<0.05
SrO	<0.05	<0.05
P_2O_5	<0.05	<0.05
V_2O_5	<0.05	<0.05
Cr_2O_3	0.09	<0.05
BaO	<0.05	<0.05

2.1.2.5.2 Impact of Crushed Glass on Fresh Concrete Properties

Consistency and Homogeneity:

Addition of glass as a sand replacement caused several changes in the properties of fresh concrete, including:

- The consistency was reduced due to lack of fines the recycled crushed glass
- Wet density was reduced due to the lower density of the recycled crushed glass
- Segregation and bleeding occurred due to the smooth surface and negligible water absorbing property of glass which reduced the cohesive forces inside the concrete.

The consistency of the mixture was also reduced as a result of sharp edges of the recycled crushed glass which increased the frictional forces inside the concrete during handling and mixing. On the other hand, when cement was replaced by pozzolanic glass powder (PGP), no significant changes in the slump was observed while the wet density of the mix dropped due to the lower density of PGP (Taha and Nounu 2009).

Workability:

The slump of fresh concrete was found to increasing with the addition of glass powder in the mixture. There was a systematic increase in slump from 40 mm to 160mm when 40% of glass powder by weight passing through 300 mm sieve was added into the mix (Kumarappan 2013). The enhancement of slump was also reported in a research study on replacement of cement by weight up to 40% of glass powder of size 600 mm (Chikhalikar and Tande 2012). The workability of concrete mixture decreased by using the crushed glass particles as coarse aggregates. The slump value of the mixture containing coarse glass aggregate decreased by 50% compared to the one containing normal aggregates (Afshinnia and Rangaraju 2016). On using angular shaped glass powder of about 75 mm size, there is a negative effect on the workability of mix (Vandhiyan et al. 2013). From the test conducted on the water requirement of the mix, it was found that the water demand decrease by 0.4% on 5% of cement replacement by weight with glass powder (Aliabdo et al. 2016).

2.1.2.5.3 Impact of Crushed Glass on Hardened Concrete properties

Compressive Strength:

In one study (Aliabdo et al. 2016), the compressive strength of a mortar sample at 3 days and 7 days was found to increase by about 4.45% on cement replacement up to 10% of glass powder by weight, which gradually decreased on increasing the replacement percentage. It was observed that on increasing the percentage of cement replacement by

15%, 20% and 25% the compressive strength at 28 days age was reduced by 9.4%, 11.1% and 12.5% respectively for 45MPa concrete grade. The author suggested a reduction in water-cement ratio to eliminate the strength reduction as they found an increase in compressive strength from 40 MPa to 45 MPa for 15% replacement of cement by reducing the W/C ratio from 0.35 to 0.32. While using the glass powder as cement addition, it was found that the compressive strength increased by 4.7%, 14.6% and 16.8% with 5%,10% and 15% addition of glass powder by weight of the cement respectively (Aliabdo et al. 2016).

Splitting Tensile Strength:

The 28-day splitting tensile strength has been reported to decrease on addition of glass aggregates as compared to normal aggregate, it was 20% less. On the other hand, addition of glass powder as sand to concrete at a 20% replacement by weight increased the tensile strength by 21%. When used as 20% cement replacement by weight it reduced the splitting tensile strength by 12% (Afshinnia and Rangaraju 2016). Replacement of natural sand by recycled glass sand did not result in much difference in tensile and flexural strength of the concrete up to 20% replacement by weight. However, a decrease in tensile strength of about 15% was observed on increasing the replacement to 60% (Tamanna et al. 2020).

2.1.2.5.4 Impacts of Crushed Glass on Durability of Concrete

Concrete’s durability is mostly affected by chloride ion penetration into the hardened concrete. When natural sand was replaced with recycled glass as sand, an improvement in chloride ion penetration was observed. Use of a 20% replacement of sand reduced the permeability by 56 days and was exhibited as moderately permeable, while increasing the replacement level to 40% was found to have lowest chloride ion penetration with an improvement of 29% and 32% at 28 days and 56 days respectively and 60% replacement showed 20% and 19% resistant at 28 days and 56 days respectively (Tamanna et al. 2020).

Environmental Impacts:

The reduction of conventional aggregates and increasing the glass aggregate significantly reduced the CO_2 emission by about 17%. The figure below shows the reductions of CO_2 foot prints on different replacements of normal or conventional aggregates with glass waste (Rashid et al. 2018).

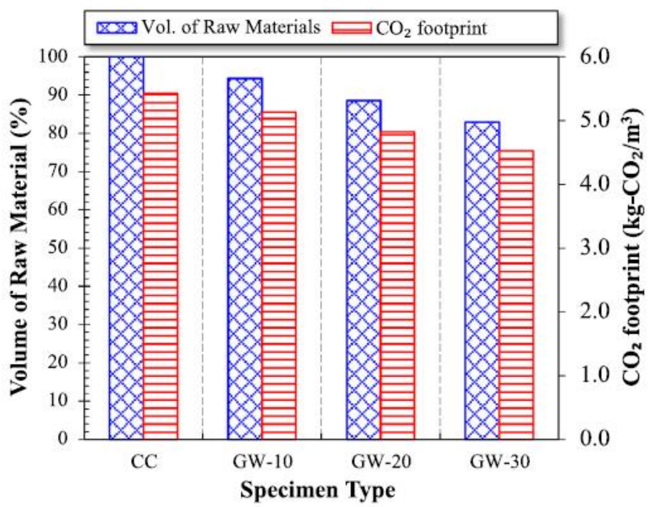

FIGURE 2.2 Environmental impact evaluation of mixture containing Glass Waste (Rashid et al. 2018).

2.1.2.6 Brick Waste

2.1.2.6.1 Introduction

According to several research studies, it has been found that bricks obtained from demolition of existing construction has the potential to be used as a material for replacements of conventional materials in concrete. It has been estimated that brick will be the most significant material in construction after concrete over the next 50 years (AGO

2006). It has been estimated that approximately 75% of the construction and demolition waste for a construction site is contributed by concrete and brick. The landfilling of concrete and brick costs up to $136/ton, while if they are recycled it may cost only around $21/ton (Lennon 2005). The total production of clay brick around the world is $6.25*10^8$ tons out of which $7*10^6$ tons of brick are landfilled each year (Lalchandani and Maithel 2013). Thus, the use of waste brick needs to be optimized to reduce the extreme landfilling, one way of doing is by using them as a replacement in concrete.

Chemical Composition:

Table 2.7 shows the various chemical compositions of waste clay bricks which could be used in concrete.

TABLE 2.7 Chemical Composition of Clay Brick
(Adamson et al. 2015)

Chemical analysis (%)	Clay brick
SiO_2	69.43
Al_2O_3	17.29
Fe_2O_3	6.4
CaO	0.51
SO_3	2.54
MgO	1.14
Loss on ignition	0.17

2.1.2.6.2 Impact of Brick Waste on Fresh Concrete Properties

Workability:

The workability of concrete mix containing brick as a replacement to coarse aggregates at constant water-cement ratio was found to increase compared to the control mix. This is often due to the porosity of brick which holds more amount of water as compared to natural aggregate and in return improves the workability of fresh concrete (Adamson et al. 2015). On the other hand, on replacing cement with brick powder of different grades affected workability differently. It was noted that only minor reduction of about 13% in slump took place when the replacement level of brick powder (200mm) was kept to 10% by volume of cement which slightly reduced on increasing the percentage to 20% but further increase in replacement percentage to 30% caused a drastic reduction in slump value from about 6 inches to about 1.2 inches (almost 80%) (Ge et al. 2015).

Density:

The density of normal concrete on replacement of brick as coarse aggregate was found decreasing on increasing the substitution level due to the lower density of brick aggregate. One of the studies found the reduction in density was below 5% on 50% replacement of coarse aggregate and on increasing the replacement to 100% the loss of density was 22% for fresh concrete and 16% for hardened concrete (González et al. 2017). The variation in density can be seen in Table 2.8 where the increase in replacement percent by 25% and 50% reduced the density of hardened concrete (Adamson et al. 2015).

TABLE 2.8 Density of hardened concrete containing brick aggregate (Adamson et al. 2015)

Sample type	Bulk density, dry(g/mm3)	Bulk density after immersion (g/mm3)	Bulk density after boiling (g/mm3)	Apparent density(g/mm3)
Control	2.24	2.40	2.41	2.68
25% brick	2.16	2.31	2.32	2.55
50% brick	2.11	2.27	2.28	2.53

The density of light weight concrete was found to increase upon increasing the replacement of coarse aggregate with waste brick aggregate. The density increased by 1% on replacement of 25% by volume of coarse aggregate which kept on increasing and when the replacement increased by 100% the density increased by about 6.5%. This increase in density was attributed to the water absorption capacity of bricks during curing process

(Ibrahim et al. 2013). On the contrary the density of normal concrete was found to decrease upon increasing the waste brick as replacement of coarse aggregate (Adamson et al. 2015).

2.1.2.6.3 Impacts of Brick Waste on Hardened Concrete Properties

Compressive Strength:

The incorporation of brick waste as aggregate in concrete has resulted in lower early age strength which could be attributed to its higher water absorption compared to less porous conventional natural aggregates. However, with time the strength was found to increase due to the pozzolanic characteristics of finely grounded brick powder from the brick aggregate (Khalaf and DeVenny 2005). When waste brick powder was used as cement replacement, it showed good results when the replacement level is 15% by volume of cement as compressive strength increased by 6.5% (Letelier et al. 2017).

It was noted that the compressive strength of the mixture increases upon increasing the amount of brick content, as determined by the L.A. abrasion test. This could be due to the high strength of brick aggregate compared to the natural aggregate (Adamson et al. 2015). On the contrary, the compressive strength was found to decrease at w/c ratio of 0.35 by 22%, 25%, 47% and 60% upon increasing the replacement levels to 25%, 50%, 75% and 100% respectively by volume of natural aggregate (Cai et al. 2012). The reduction in compressive strength was attributed to the porosity of the brick aggregates. The more porous the brick aggregate, the greater the anticipated reduction in compressive strength and vice-versa (Khalaf and DeVenny 2005).

Modulus of Elasticity:

Concrete with waste brick powder as a substitute of cement has been found to result in a gradual decrease in the modulus of elasticity up to a 10% replacement of cement by volume. However, when the replacement increased to 15%, there a slight positive increase in modulus of elasticity was observed. However, the measured modulus of elasticity was still about 3.6% below the conventional mix (Letelier et al. 2017).

The use of brick waste as a replacement for coarse aggregate in concrete strongly affects the modulus of elasticity. For example, it was found that 100% replacement of coarse aggregate with brick waste by weight reduces the modulus of elasticity by 60% (González et al. 2017), 50% (Debieb and Kenai 2008) and 45% (Cabral et al. 2010) in three different studies. In another study, the modulus of elasticity was reduced by 30% (Alves et al. 2014) and the dynamic modulus of elasticity was reduced by 15%(Khatib 2005)for 100% replacement of coarse aggregate with brick aggregate by mass for concrete of strength less than 50MPa. The reduction of elastic modulus is due to the lower rigidity of brick aggregate than natural aggregate (González et al. 2017).

2.1.2.6.4 Impacts of Brick Waste on Durability of Concrete

Chloride Penetration:

Concrete made utilizing brick waste exhibited satisfactory results when tested for chloride ion permeability (Cavalline 2012). However, the chloride ion permeability of concrete containing brick was increased compared to the control mix with natural aggregates (Kibriya and Speare 1996). The chloride penetration was found to increase with an increase in brick content. From ages 0 to 6 month, the chloride penetration increased by 16% and 24% for brick replacement of 25% and 50% respectively by weight of aggregate. The primary reason behind this increase in chloride permeability is the porosity of brick, which may increase the permeability of the concrete (Adamson et al. 2015). The chloride ion permeability performance of brick aggregate concrete showed better results upon use of high-range water-reducing admixture (Cavalline and Weggel 2013). Thus, use of chemical admixtures could be a convenient solution for increasing the durability of concrete utilizing waste products.

One of the major advantage of the incorporation of brick as a replacement to fine aggregate is that it can perform well in resisting the freeze and thaw cycle of the concrete due to the high porosity of the mix contributed by bricks (Litvan and Sereda 1978).

Shrinkage:

The shrinkage of concrete mixtures containing waste brick aggregate was found to increase with the increase of replacement percentage. Up to 50% of replacement, the shrinkage value stabilizes at the end of the test period but when the replacement exceeds 50%, the shrinkage gradually increased overtime which could be due to high volume of water retained in the pores of brick aggregates (Gayarre et al. 2019).

2.1.2.6.5 Impacts of Brick Waste on Pervious Concrete

The properties of pervious concrete were tested by varying the percentage of RCA and crushed brick in the mixture. The author noticed a significant loss in the compressive strength of the concrete. The concrete containing 50% of crushed brick by weight showed 37.1% compressive strength (28 days) from the normal concrete while for 15% incorporation it was around 80%. Thus, the author recommends 15% of crushed brick along with RCA (for the remaining fraction) to be used for the pavement bases with moderate traffic. For high traffic roads, the incorporation of crushed brick is not recommended. The water permeability of concrete 15% and 0% crushed brick was found to have the highest water permeability, with a value of 0.69 cm/s and 0.66 cm/s respectively while the one with 50% crushed brick was the lowest with a value of 0.18 cm/s, the reason being the increase in water absorption at high ratio. The use of crushed brick in pervious concrete has some adverse effects on the drying shrinkage of the permeable concrete as the rate of water loss 50% substitution was 9.35% which was 4.5 time of the concrete with 0% crushed bricks. However, the deformation of pervious concrete with 50% crushed brick was 0.53 mm, which was not much as compared to the dense concrete. Due to the presence of free water inside the voids of permeable concrete, the loss of free water does not cause the concrete to shrink. Thus, the presence of crushed brick does not much affect the shrinkage of base layer (Cai et al. 2020).

2.1.2.6.6 Uses of Crushed Brick in Pavement Foundation

Crushed brick obtained from the demolition of existing structure can also be used in permeable concrete for the road base. A study conducted in China (Cai et al. 2020) suggested the use of crushed bricks along with recycled concrete aggregate (RCA) in different proportions affects the properties of the resultant permeable concrete in different way due to the differences in individual properties. The properties of coarse recycled aggregate (i.e. the mixture of various proportions of RCA with crushed brick) is shown in the Table 2.9. Table 2.9 shows that as the ratio of crushed brick increased, the density of the recycled aggregate decreased while the water absorption and crushing values increased (Cai et al. 2020).

TABLE 2.9 Properties of the Coarse Recycled Aggregate
(Cai et al. 2020)

Mixed type	Technical indicators					
	Apparent density/kgm−3	Crushing value (%)	Water absorption (%)	Content of partials <0.075 mm (%)	The needle-shape particle content (%)	light component (%)
100% RCA	2673.0	23.3	4.35	1.8	0.7	0.7
85% RCA+15% CB	2438.1	27	6	1.7	0.9	0.6
70% RCA+30% CB	2228.3	30.3	7.4	2.2	0.6	0.6
50% RCA+50% CB	2044.2	38.7	10.4	1.6	0.5	1.3
100% CB	1561.1	42.7	15.4	1.3	–	2.5

Note: The % of CB is the weight of the coarse aggregates. The aggregates of each particle size were sorted and then proportionally blended to fit the test gradation according to the density and volume conversion.

2.1.2.7 Mixed Rubble

2.1.2.7.1 Introduction

The cost for disposing of construction and demolition (C&D) wastes has been increasing gradually over recent years. One cause of this increased cost is due to the increasing amount of waste generated from the construction industry which has led to the decrease in readily accessible disposal sites around major cities. The United States is one of the biggest producers of construction and demolition waste with a total of around 500 million tons per year (Akhtar and Sarmah 2018).

The aggregates to be used in concrete need to be well graded before use and therefore the debris obtained from demolition has to be crushed and sieved accordingly to obtain the required size of the aggregate. The contaminants in mixed rubble are highly dependent on the source structure and the demolition process, and may include materials such as mortar, bitumen, glass, chloride and sulphates, soils and filler materials, gypsum, organic matter, tiles, and other types of debris depending on the structure from which the rubble is obtained. One range of suggested maximum amounts of impurities that can be accepted in the recycled aggregates are given in the Table 2.10 in which three types of aggregates are displayed. Type 1 aggregate consists of 100% recycled brick, Type 2 aggregate consists of 100% recycled concrete and Type 3 aggregate consists of a blend of natural and recycled aggregates (Khalaf and DeVenny 2004).

TABLE 2.10 Maximum Allowable Values for Impurities in Recycled Aggregate (Khalaf and DeVenny 2004)

	Type of aggregate		
Mandatory requirements	1	2	3
Minimum dry particle density (kg/m^3)	1,500	2,000	2,400
Maximum water absorption (%)	20	10	3
Maximum content of material with SSD < 2,200 kg/m^3 (%)	—	10	10
Maximum content of material with SSD < 1,800 kg/m^3 (%)	1	1	1
Maximum content of material with SSD < 1,000 kg/m^3 (%)	1	0.5	0.5
Maximum content of foreign materials (glass, bitumen, soft materials, etc.)	5	1	1
Maximum content of metals (%)	1	1	1
Maximum content of organic material (%)	1	0.5	0.5
Maximum content of filler (<0.063 mm) (%)	3	2	2
Maximum content of sand (<4 mm) (%)	5	5	5
Maximum content of sulfate (%)	1	1	1
Note: SSD = Saturated dry density			

Economics of Mixed Rubble:

The economics of recycling the mixed rubble depends upon the cost of sorting, crushing, screening, transportation to the crushing plant and transportation to site. While on the other hand, the cost incurred in obtaining natural aggregate includes extraction through dredging or quarrying, and transportation to the site. There are various environmental factors that are affected during the extraction process of both the natural and recycled aggregates such as, landscape scarring, vibration, dust, visual intrusion and the factors associated with the transportation of the final product (Khalaf and DeVenny 2004).

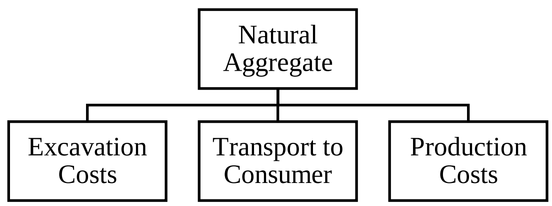

FIGURE 2.3 Cost Factors for Natural Aggregate
(Khalaf and DeVenny 2004)

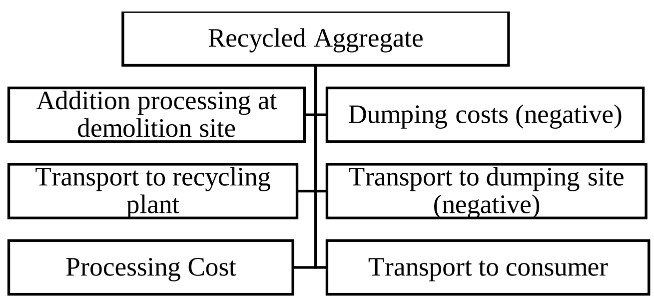

FIGURE 2. 4 Cost Factor for recycled Aggregate
(Khalaf and DeVenny 2004)

2.1.2.7.2 Impact of Mixed Rubble on Fresh Concrete Properties

Use of mixed rubble in concrete is viewed as difficult, due to its variability and properties such as increased absorption. In one study, the water absorption of mixed rubble was observed to be 6.2-13% which was far greater than the 1.8% absorption for natural aggregate, showing that the mixed rubble particles from this study were observed to be seven times more porous in nature than natural aggregate (Sabai et al. 2013).

Workability:

In one research study, the workability of concrete containing mixed rubble aggregate at a 100% replacement level was found to increase, with the slump value increasing by 12.82% compared to conventional concrete. While 60%, 30% and 25% replacement by mass reduced the slump value by 15.4%,7.7% and 15.4% respectively (Hoffmann et al. 2012). The higher workability is a result of increasing water demand of mixed rubble in comparison to natural aggregate, due to its porosity the total water-cement ratio increased significantly (Hoffmann et al. 2012). The increasing water demand may decrease the strength and increase the permeability of the concrete which may be mitigated using suitable water reducing admixture (Hover 1998).

2.1.2.7.3 Impacts of Mixed Rubble on Hardened Concrete Properties

Compressive Strength:

The compressive strength of concrete decreases with an increase in water-cement ratio. Since the w/cm ratio of a mixture with 100% mixed rubble needs to be much higher than the w/cm of a control mixture achieving the same slump, the compressive strength will be significantly lower. However, in one study, the strength was comparatively higher than the conventional concrete. The reason behind the strength increase could be the initial water absorption of the aggregates. The increased absorption of the mixed rubble aggregates does not initially support cement hydration and causes relatively denser paste in relation to w/b present. However, the aggregates release soaked water with ongoing time, providing internal curing to the concrete and increasing the quality of cement paste which increased its strength (Hoffmann et al. 2012). In another research study, it was found that concrete manufactured with the incorporation of recycled mixed rubble aggregate reduced the compressive strength of the mixture by 20% compared to the conventional concrete (Zieliński 2017).

A study conducted on properties of concrete incorporating mixed rubble as aggregate replacement indicated that the mean compressive strength of concrete containing mixed rubble as coarse aggregate was 8.8 MPa which was lower than the concrete with natural aggregate as the strength of natural aggregate which was 14.2 MPa (Sabai et al. 2013). On the other hand, replacing cement with the recycled powder obtained from mixed rubble also decreases the compressive strength of the concrete. When 15%, 13% and 45% of cement was replaced by recycled powder by weight, the 28 day strength was found to be reduced by 2.5%, 7.7%, and 21.1%, respectively (Xiao et al. 2018).

Elastic Modulus:

The elastic modulus of concrete containing mixed rubble decreases with increasing the content of recycled mixed rubble. The decrease in elastic modulus is a result of higher volume of paste as compared to conventional concrete. Concrete with 100% crushed concrete as coarse aggregate and natural sand showed an elastic modulus of up to 30% lower than conventional concrete (Hoffmann et al. 2012).

Chloride Penetration:

The chloride penetration of a mixture with mixed rubble as aggregate is higher than conventional concrete due to the porosity of the aggregates. The chloride conductivity depends on the percentage of porous aggregate in the mix. It was shown by the author that a batch of mixed rubble containing minimum amount of porous aggregate when incorporated in concrete as coarse aggregate at 25% replacement rate showed lowest chloride ion conductivity (Hoffmann et al. 2012).

Environmental Impact:

The replacement of cement with recycled powder obtained from mixed rubble can reduce the energy consumption as well as carbon emissions associated with concrete production. The production of 1 ton of recycled powder consumes 18 kwh of energy which is significantly lower than 105 kwh energy consumption for cement production (Xiao et al. 2018).

2.1.2.7.4 Uses of Mixed Rubble in Pavement Foundation

A mixture of mixed rubble and portland cement has been found to be suitable for stabilizing certain sub-base soils. In one study, the author found that use of 50% mixed rubble and 2% cement by weight allowed the sub-base soil to reach the limit strength of cement-modified soil for sub-base layer with a compressive strength ranging from 1.20 to 2.10 MPa. It was also found that different combinations of cement and mixed rubble such as 25% and 50% mixed rubble and 4% and 6% cement is suitable for both base and sub-base layers of the pavement (Reis et al. 2015). In another study it was found that when measured using the California bearing ratio (CBR) value, mixed rubble recycled aggregate provides a gain in bearing capacity due to the pozzolanic reactions between the various mineral phases that make up such type of granular material (Vegas et al. 2011). The mixed rubble recycled aggregate would be viable to use in unbound structural layer of road if the ceramic content is below 35%, organic content is below 0.8% and soluble sulphate content below 0.4% (Vegas et al. 2011).

2.1.2.8 Plastic Waste

2.1.2.8.1 Introduction

Plastic is one of the most used materials in the world. The production of plastic in year 2017 was approximately 348 million tons around the globe (Europe 2015). The disposal of such plastic waste through incineration is inappropriate, harmful and non-economical because the process cost is high and it produces dangerous gases in the environment which can adversely affect living beings (Ghernouti et al. 2015). According to the United Nation Environment Programme, there are 46,000 pieces of floating plastic at every square mile of ocean in the year 2006 which can account for the death of about 100,000 sea mammals and more than 1 million sea birds each year.

Plastic waste accounts for 10.62 ± 5.12% amongst the total wastes that are stored in the landfills in which the percent of plastic bags is about 69.13% and the rest 30.87% is other plastics like PVC (Zhou et al. 2014). Polythene terephthalate (PET) is one of the most manufactured plastics and it is the second most discarded form of plastic in world (de Mello et al. 2009; Foti 2013). It is used in food packaging, soft-drink bottles, water bottles, etc.

Plastic is a non-biodegradable material and thus its landfilling can be hazardous as it may pollutes the soil due to the presence of toxic substances like lead and cadmium (Faraj et al. 2020). Thus, the recycling of plastic waste in an ecofriendly way in the best possible solution for the environment. One of those possible solution is to use it in concrete as aggregate replacement as it is very economical and ecofriendly.

2.1.2.8.2 Impacts of Plastic Waste on Fresh Concrete Properties

Workability:

In one study on use of plastic waste as aggregate in concrete, the workability of fresh concrete was measured using the slump value of concrete incorporating various types of plastic waste as aggregate replacement. It was found that the slump decreased by 25% upon replacement of 20% plastic aggregate by mass as compared to the conventional concrete. The decrease in slump was attributed to the sharp edges and angular particle size of the plastic aggregate (Batayneh et al. 2007). On the other hand, the slump value of concrete was found to increase with an increasing in the plastic aggregate due to the non-water absorbing nature and smooth surface of plastic which leaves more free water in the mix (Al-Manaseer and Dalal 1997).

The workability of concrete changes with different shapes of plastic waste as the concrete containing pellet plastic aggregate (which has a smooth surface and spherical nature) requires a lower water-cement ratio compared to flaky plastic aggregate with different sizes, which required a much higher water-cement ratio due to the sharper edges and angular nature of the flaky aggregates (Saikia and De Brito 2012).

Density:

The fresh and dry densities of concrete were found to decrease on incorporation of plastic waste in the concrete mixture due to the relatively light weight of the plastic aggregates (Choi et al. 2009; Saikia and de Brito 2014). The replacement of sand with plastic aggregate by 10%, 15% and 20% by weight reduced the fresh density of concrete by 5%, 7% and 8.7% respectively compared to conventional mixture which was due to the lower density of waste plastic compared to natural sand by 69.7% (Ismail and Al-Hashmi 2008). Similarly in another research also the fresh density of concrete was found to decrease by 2.5%, 6% and 13% on plastic content of 10%, 30% and 50% respectively (Al-Manaseer and Dalal 1997).

Concrete containing polyethylene terephthalate (PET) waste and polycarbonate (PC) waste as aggregate tends to reduce the fresh and dry densities of the mixture. The result obtained by Hannawi et al. (2010) showed that the dry densities reduced to 1755 and 1643 kg/m^3 respectively for 50% replacement of PET and PC plastic aggregates compared to the reference concrete mixture containing 0% plastic with density of 2173 kg/m^3. The dry density of a mixture containing 50% replacement of fine aggregate by PET waste and PC waste reduced by 19% and 24% respectively compared to normal concrete due to the lower specific weight of the plastic (Hannawi et al. 2010).

2.1.2.8.3 Impact of Plastic Waste on Hardened Concrete Properties

Compressive Strength:

The compressive strength of concrete was found to be decrease upon incorporation of plastic waste in the mixture (Hannawi et al. 2010; Kou et al. 2009; Saikia and de Brito 2014). The lower strength was attributed to the low bond strength between the cement paste and surface of plastic waste and the hydrophobic nature of plastic waste can inhibit the cement hydration reaction by restricting the movement of water (Saikia and De Brito 2012).

In a study where a partial substitution of plastic was used as a fine aggregate at rates of 5% and 20% by mass, the compressive strength was noted to be reduced by 23% and 72% respectively of the original strength of normal concrete (Batayneh et al. 2007). In another study, the author states that the replacement of fine natural aggregate with 10%, 15% and 20% by mass of PET, even though the strength was not as high as companion natural aggregate concrete mixtures. However, the strength achieved by the plastic waste mixtures fulfilled the minimum strength required for the concrete structure which was 17.24 MPa (Ismail and Al-Hashmi 2008). A similar statement related to strength was given in another study which stated that the standard strength values of concrete with moderate strength of 21 and 30 MPa at 28 days of curing age, could be achieved by incorporating 10% of PET into the mixture as natural aggregate replacement. The factors identified contributors to the lower compressive strength were, the failure and formation of honeycombs, particle size and low workability (Albano et al. 2009). On the other hand, the replacement of fine natural aggregate with PET plastic waste by 5% of mass can significantly increase the compressive strength of concrete by 8.86% and 11.97% at w/c ratio of 0.42 and 0.52 respectively (Rahmani et al. 2013). The abrasion resistance of concrete also increased when the pellet PET aggregate content is increased.

When fine aggregates are replaced by PVC (polyvinyl chloride) granules derived from scraped PVC pipes, the compressive strength decreased in comparison to the control mixture by 9.1%, 18.6%, 21.8% and 47.3% respectively at the replacement percent of 5%, 15%, 30% and 45% (Kou et al. 2009).

Modulus of Elasticity:

The modulus of elasticity was found (by the ultrasonic method) to decrease when the fine natural aggregate was replaced with 50% by mass of plastic aggregate. This decrease was attributed to the reduction of bulk density of mortar and the plastic aggregate that disturbed the ultrasonic wave propagation and decreased the velocity of wave (Marzouk et al. 2007). In a few different studies, the modulus of elasticity of concrete was also found to decrease upon increasing the plastic content in the mixture. According to these studies, the reason behind this reduction is the lower modulus of elasticity of plastic than natural aggregate and high porosity in concrete which generates due to the higher w/c value (Hannawi et al. 2010; Saikia and de Brito 2014).

The incorporation of polyvinyl chloride (PVC) as a fine aggregate replacement significantly reduced the modulus of elasticity. It was found that the elastic modulus was reduced by 6.1%, 13.8%, 18.9% and 60.2% on replacement percent of 5%,15%, 30% and 45% respectively by volume of fine aggregates. The reduction of elastic modulus was due to the lower compressive strength of concrete incorporating PVC waste and lower modulus of elasticity of PVC granules.(Kou et al. 2009).

2.1.2.8.4 Impacts of Plastic Waste on Durability of Concrete

Concrete containing PET plastic as aggregate replacement tended to exhibit increased water absorption characteristics as the replacement percent, size of PET, and w/c ratio increases. This increase in water absorption was attributed to the difference in the size distribution and shape of plastic aggregate as compared to fine aggregate (Albano et al. 2009). In another study, the author observed 0% water absorption in cement mortar containing 100% polyurethane plastic as fine aggregate than the control mixture (Choi et al. 2009). Further, if the polyurethane aggregates are pre-wetted before incorporation in the mix can increase the porosity which could be controlled by the addition of super plasticizer (Frigione 2010).

The resistance of concrete to chloride ion penetration was found to increase upon incorporation of polyvinyl chloride (PVC) into the concrete in place of fine aggregate. RCPT test results indicated a reduction of 11.9%, 19.0%, 26.9% and 36.2% in total charge passed on samples utilizing a 5%, 15%, 30% and 45% replacement of fine aggregate with

PVC plastic aggregate by volume. This reduction in chloride ion penetration was attributed to the impervious PVC granules that block the passage of the chloride ion (Kou et al. 2009).

Concrete containing polystyrene foam as partial replacement of both fine and coarse aggregates was found to provide good resistance to freeze-thaw stresses using standard method ASTM 666 procedure B, providing improved durability to the concrete. This improvement in concrete is likely because polystyrene foam is highly susceptible to distress due to freeze-thaw cycles as compared to natural aggregate due to the presence of 20-50% voids with any air entrainment (Kan and Demirboğa 2009).

2.1.2.9 Waste from Water Treatment Plants and Wastewater Treatment Plants

2.1.2.9.1 Introduction

The chemical clumps and non-portable particles which are collected through filtration are hazardous wastes known as sludge. These materials often constitute approximately 1% of the total volume of the treated wastewater (de Almeida Lima and Zulanas 2016). The sediments obtained by mechanical and biological treatment of wastewater which includes microorganisms and potentially harmful organic and inorganic substance are known as excess sludge (Peccia and Westerhoff 2015).

Drinking water treatment plant sludge (DWTPS) is a by-product which is obtained from the coagulation-flocculation process when aluminum or iron-based salts are used to precipitate colloidal particles, algae, clay, and humic substances from water resources (Abo-El-Enein et al. 2017). The sludge obtained from DWTP in mostly inorganic and can be used without the need to burn the organic matter.

After processing, typically by thermal methods, sludge produced from the wastewater treatment processes has the potential to be used as an alternative material in concrete, a soil amendment, an unbound base material or fill. Use of sludge in construction could impact the cost of construction while also reducing the environmental concerns regarding sludge disposal and its associated landfilling costs. Using sludge would also provide additional value due to the fact that it doesn’t require any additional resources to be produced (de Almeida Lima and Zulanas 2016). In addition to its use in concrete, sludge can also be used for the production of bricks, tiles, and other ceramic materials (Hamood et al. 2017; Rahman et al. 2017).

There are some effects of incorporating sludge into concrete on its physical properties because its increasing content can produce excess heat during curing, potentially increasing the chances of crack generation. Thus, the use of sludge incorporated into concrete should be restricted to low-grade concrete where less strength is required (such as sidewalks, barrier walls, etc.), and it should not be used in structural elements in which high cracking resistance is important (such as buildings and bridges). According to one research study, using 5% of sludge in concrete has no significant effect on the structure’s integrity, so it can be used in the construction of the structures where the requirement of high cracking resistance of concrete is not required such as sidewalks (Costa 2011).

The various end-use methods for sewage worldwide are shown in Figure 2.5. These statistics show that the USA produces almost 6.540 million tons of sewage every year, most of which is utilized in the agriculture industry, while an almost equal amount is incinerated or utilized in other applications. Also, a relatively small amount of sewage (about 8%) is landfilled in USA (Christodoulou and Stamatelatou 2016; Drechsel et al. 2015).

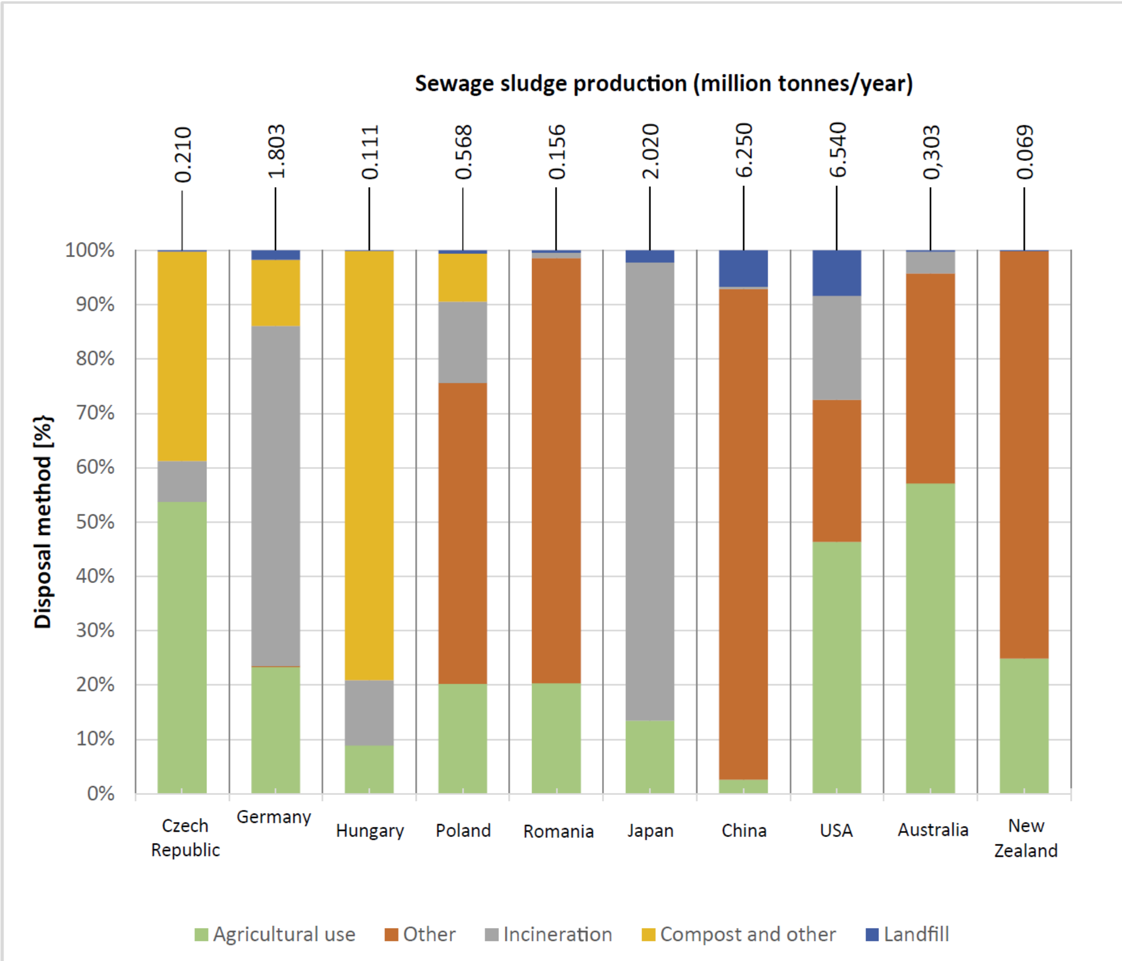

FIGURE 2. 5 Worldwide excess sewage sludge utilization methods (Christodoulou and Stamatelatou 2016; Drechsel et al. 2015)

Chemical and physical Composition:

The various chemicals that are present in WWTP sludge ash and drinking water treatment plant sludge (DWTPS) which are responsible for its pozzolanic properties are shown in the Table 2.11 along with the physical properties of sewage sludge ash shown in Table 2.12.

TABLE 2.11 Chemical Composition of WWTPS Ash and DWTPS
(Cyr et al. 2007)(Dahhou et al. 2018)

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	P_2O_5	SO_3	Na_2O	K_2O	TiO_2	MgO	MnO	LOI
SSA%	34.2	12.6	4.7	20.6	14.8	2.8	1.0	1.7	0.9	1.9	0.06	5.5
DWTPS	33.08	48.94	4.46	4.67	0.21	0.17	0.0	2.53	0.36	0.7	0.24	4.45

Note: LOI=Loss on Ignition

TABLE 2.12Physical Properties of Sewage Sludge Ash
(Chen et al. 2013)

Moisture Content	0% fresh mass
Apparent Density	0.66 kg/m^3
Real Density	2.7 kg/m^3
Porosity	76%

2.1.2.9.2 Impacts of Sewage Sludge on Fresh Concrete Properties

Workability:

The workability of concrete mixtures containing coarse aggregate derived from the incineration of sludge was found to decrease, which could be attributed to the angular, rough surface texture and low unit weight of the derived sludge aggregates (Yip and Tay 1990). The reduction in workability was also observed in another study, in which the cement was replaced by sewage sludge ash (SSA). The results showed that the measured slump decreased from 114.2 mm to 102.5 mm upon increasing the replacement percent of SSA from 0% to 30% respectively. This loss in slump was due to the irregular morphology of SSA particles (Monzó et al. 2003). The average rate of decrease in workability as calculated came out to be 6% for every 10% replacement of SSA with an equivalent slump reduction of 12% for every 10% replacement (Chang et al. 2010; Pinarli 2000; Tay 1987).

Setting Time:

The setting time of fresh concrete mixtures increased upon increasing the SSA content. The average setting time (both initial and final) increased 35% on the replacement of 10% SSA by weight (Lynn et al. 2015).

2.1.2.9.3 Impacts of Sewage Sludge on Hardened Concrete Properties

Compressive Strength:

The various research studies conducted on the partial replacement of sand by water treatment plant (WTP) aluminum-based sludge showed varying results. In one of the studies, the author evaluated that substitution of 4-8% sand by weight of wet sludge from the WTP in concrete resulted in a compressive strength greater than 27 MPa at a 28-day curing period. This suggests that the concrete containing 4-8% of wet sludge could be used in non-structural applications such as sidewalks, subfloor, concrete blocks, and architectural purposes (Hoppen et al. 2005). In a similar study, the author found that the replacement of sand with up to 5% of wet WTP aluminum-based sludge by weight gives a satisfactory result of 15.5 MPa compressive strength which was 11% less than the compressive strength of the reference mixture. The incorporation of wet sludge also increased the water absorption by 12% and 32% on the replacement of 5% and 10% respectively (Tafarel et al. 2016). On the contrary, the replacement of sand even with 5% of aluminum based wet sludge by weight led to a decrease in compressive strength by 50% and increase in water absorption by 45% (Ramirez et al. 2017).

When cement was replaced with 10% by weight of sewage sludge ash from a WWTP, the results showed a decrease in compressive strength by about 25% as compared to the conventional concrete. This shows that the activity index of the concrete was more than 75%. The results obtained by the author showed that the compressive strength of concrete incorporating sewage sludge ash was as high as 27.1 MPa after 28 days curing which would satisfy the technical requirements for residential and light commercial buildings (Chen et al. 2013).

Modulus of Elasticity:

The replacement of natural sand with wet WTP sludge showed significant negative impacts on the elastic modulus of the concrete mix. The author used three different water-cement ratios to determine the modulus of elasticity of concrete containing wet sludge. The first reference sample had an elastic modulus of 36 GPa at w/c of 0.45. With the sludge replacement rates of 5, 7 and 10%, a reduction in elastic modulus of 35.19%, 47.68% and 88.18% respectively was observed. When w/c was increased to 0.55, the reference sample had modulus of elasticity of 33 GPa, which was reduced by 39.47%, 55.59% and 86.61% upon replacement of 5, 7 and 10% respectively. Finally, with a w/c ratio of 0.65, the modulus of elasticity of reference sample was 34 GPa, which became reduced by 46.52%, 65.63% and 100% with replacement rates of 5% ,7% and 10% respectively (Ramirez et al. 2017).

2.1.2.9.4 Impacts of Sewage Sludge on Durability of Concrete

Corrosion Resistance:

Concrete’s resistance to corrosion has been found increasing on partial replacement of cement by WWTP sludge ash up to 20% by weight. This could be due to the overriding influence of aluminum content of SSA at lower replacement which has positive effects on the chemical binding of chlorides. Upon increasing the replacement level to 60%, the corrosion resistance of concrete was found to decrease. This is because the porosity is increased due to the continuous weakening of pore structure and reduction in hydration rate which eventually has negative effect on the durability of concrete (Alcocel et al. 2006).

Leaching of Ash Material:

In one study, results of chemical tests of leachate obtained by submerging concrete cylinders in water showed that except for Mo and Se, the leachate obtained from concrete produced with a range of ashes for all the tested elements (Al, B, Ba, Co, Cr, Cu, Sr, V, Zn) were far below the limits. The results obtained were similar to results obtained from conventional concrete without sewage sludge ash (SSA). Thus, mixing SSA with cement stabilizes Mo and Se in the concrete and it can be considered as good treatment of ashes rather than disposing in landfills (Chen et al. 2013).

2.1.2.10 Porcelain Waste

2.1.2.10.1 Introduction

Porcelain is a material that is generally used to produce tiles, mugs, cookware, and other goods due to its high durability and hardness. Porcelain is also known synthetic stone. Porcelain products are comprised exclusively of white and refined clay. Porcelain also contains kaolin and feldspar. The soil used to produce porcelain has lower impurities as compared to ceramic, which ultimately makes it more durable (Keshavarz and Mostofinejad 2020).

Porcelain is a non-biodegradable material, and thus its disposal into landfills could occupy the land space The production of porcelain helps in the reduction of CO_2 emission as production on 1 ton of porcelain clay tile powder emits 0.07 tons of CO_2 while the production on 1-ton portland cement emits 0.343 tons of CO_2 in the environment which is responsible for global warming (Morris 2018). Using porcelain as a substitute material in concrete provides not only environment benefits, but also economic benefits. Upon replacing 20% of portland cement by mass of porcelain powder the cost of concrete can be reduced by almost 15.2%, where the cost of other materials such as sand, aggregate etc. remains constant (Morris 2018). The engineering properties of porcelain used in one study are shown in the Table 2.13

TABLE 2.13 Engineering Properties of Porcelain
(Morris 2018)

Water absorption	0.34%
Apparent Porosity	0.84%
Bulk Density	2.48 g/cm^3
Linear Shrinkage	12.2%
Modulus of rupture	46 MPa

Chemical Composition:

The various chemicals present in porcelain that makes it suitable to be used as a substitute material in concrete is shown in Table 2.14.

TABLE 2.14 Chemical Composition of Porcelain
(El-Abidi et al. 2020)

Compositions	Porcelain (%)
SiO_2	62.29
Al_2O_3	28.89
Fe_2O_3	0.21
CaO	0.0524
MgO	0.32
P_2O_5	0.0072
K_2O	2.05
SO_3	0.068
TiO_2	–
MnO	0.0176
LOI	5.88

Note: LOI=loss on ignition

2.1.2.10.2 Impacts of Porcelain on Fresh Concrete Properties

Workability:

The workability of concrete decreases upon increasing the porcelain content in the concrete, when the porcelain is used as a cement substitution. It was found that on 5%, 10%, 15%, 20%, 25%, and 30% replacement of cement by mass of porcelain in concrete, the workability was reduced by 3.33%, 8.33%, 16.67%, 18.33%, 23.33%, and 26.67% respectively as compared to the control mixture (Morris 2018). This reduction in workability was the result of increasing volume of mixture as the density of porcelain powder is lower than that of cement which eventually increased the water demand by absorbing more water and reduced the workability (Morris 2018).

Density:

The fresh and dry densities of concrete were found to increase upon increasing the substitution of porcelain as fine aggregate replacement in concrete. The bulk density of concrete also increased when replacement of cement by porcelain. When the porcelain replacement of cement was increased from 0% to 5%, 15% and 30%, the bulk density increased by 5.05, 6.73 and 1.68% respectively as compared to the control mixture at a 28 day curing period (El-Abidi et al. 2020).

2.1.2.10.3 Impacts of Porcelain Waste on Hardened Concrete Properties

Compressive Strength:

The compressive strength of concrete increased with the introduction of porcelain waste as a fine aggregate replacement. The best results for increased compressive strength were obtained by a partial substitution of 75% fine aggregate by weight of porcelain. At this substitution rate, the compressive strength was increased by 50% when tested on concrete cubes and 23% when tested on concrete cylinders as compared to control concrete mixtures. Concrete produced with a substitution percent of 25% also showed similar results, as the strength of concrete cubes was increased by 47% (Kobbekaduwa and Perera 2019). The increase in compressive strength was attributed to the lower absorption of porcelain waste. The strength of concrete was also found to increase upon replacement of coarse aggregate with porcelain. At 100% replacement of coarse aggregate by mass of porcelain, the compressive strength increased by 41% (Keshavarz and Mostofinejad 2019).

The replacement of natural sand with porcelain has been found to have a positive effect on the compressive strength of concrete. In one study, it was found that the 28-day compressive strength for a concrete mixture produced with a 30% substitution by mass of sand slightly increased by 0.8%. However, when the substitution rate of porcelain for sand increased to 40% and 50%, the 60-day strength increased by 16.42% and 15.38% respectively (Jamal et al. 2018).

On the other hand, when porcelain powder is substituted for portland cement as an SCM, the strength was found to increase at substitution rate up to 10% compared to control mixture. The highest strength was obtained from mixtures produced at a 5% replacement by mass of porcelain powder (compressive strengths increased by 9%). In this study, the target compressive strength was achieved at substitution rates up to 20% replacement of cement. Beyond this substitution rate, further addition of porcelain reduced the concrete's compressive strength (Morris 2018).

Flexural Strength:

The flexural strength was found to increase when porcelain waste was utilized in place of fine aggregate in concrete. In one study, the flexural strength increased gradually on each substitution rate used within a range from 25% to 75%, and then it started to decrease upon greater substitution (however, it was still higher than the control mixture). The highest flexural strength was found when porcelain waste was used as a 75% replacement by mass of fine aggregate. At this substitution rate, the flexural strength was found to be 54% higher than the control concrete. The flexural strength was also found to increase when porcelain was substituted as coarse aggregate in concrete. It was found that the flexural strength increased up to 67% on replacement of 100% coarse aggregate (Keshavarz and Mostofinejad 2019).

2.1.2.10.4 Impacts of Porcelain Waste on Durability of Concrete

Water Absorption:

In one study, the water absorption of concrete reduced upon increasing the content of porcelain as cement replacement up to a certain limit, after which it started to increase. In this study the control mixture exhibited showed 5.71% water absorption using water absorption test method. When the porcelain replacement level was 5% of mass of cement, the water absorption reduced to 3.5%, and on further increase in replacement to 15% and 30%, the absorption increased to 6.23% and 11.7% respectively. Ultimately, this study showed that replacement of 5% cement by porcelain can perform better in water absorption of concrete (El-Abidi et al. 2020).

Chloride Penetration:

There were not many studies found on the chloride ion penetration for the concrete containing porcelain. In one study identified, the researchers found that the total chloride ion permeability was reduced for concrete mixtures on increasing the replacement of cement by porcelain. The best results were found for 15% replacement level as the penetration value was almost 50% lower than that of control concrete at 28-days curing period (Patel and Shah 2015).

2.1.2.10.5 Uses of Porcelain/Ceramic Waste in Pavement Foundation

Only a limited amount of literature was found on the properties of unbound base layers stabilized using porcelain. However, some studies were conducted on the stabilization of soil properties using ceramic waste material. From these studies, it can be seen that ceramic waste can be used to stabilize the soil properties in the sub-base layer of the pavement (Deboucha et al. 2020). It was found that the maximum dry density of the soil was obtained when the addition of ceramic waste was in the range of 5-10% after which it slightly decreased. The maximum dry density obtained for addition of 0, 5%, 10%, and 15% ceramic waste by dry weight was 19.4kN/m^3, 19.5kN/m^3, 19.9kN/m^3, and 19.5kN/m^3 respectively (Deboucha et al. 2020). On the other hand, the California bearing ratio (CBR) values of soil mixtures containing 0%, 5%, 10%, and 15% ceramic waste by weight were 51.64%, 75.26%, 94.05% and 73.24% of the control mix respectively in un-soaked condition. The study also showed that the following properties of soil stabilization could be further increased on little incorporation of ordinary portland cement to the mixture (Deboucha et al. 2020).

2.2 Tests to Determine Suitability for Use in Concrete

2.2.1 Tests for Use as Aggregates

The various ASTM tests that are needed to be performed on any construction or industrial waste by-product to determine its suitability in different construction applications are shown in Figure 2.6.

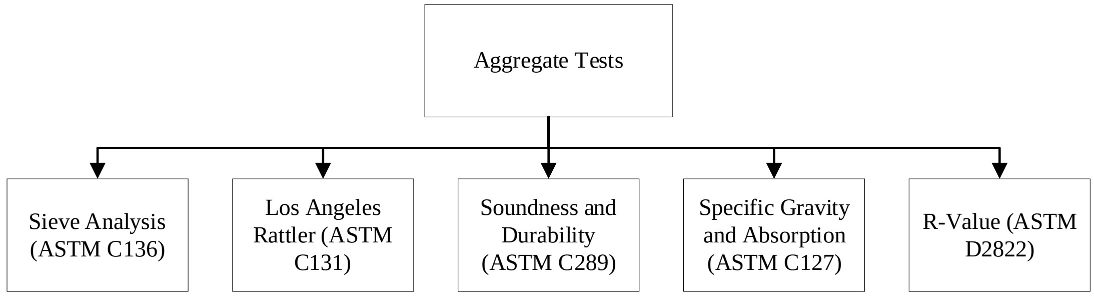

FIGURE 2. 6 Standard Test for evaluating the suitability of aggregate in concrete.

2.2.2 Tests for Use as Supplementary Cementitious Material

The standard guide for evaluation of alternative supplementary cementitious materials (ASCM) for use in concrete (ASTM C1709-18) provides a technical approach for the evaluation of ASCM like hydraulic materials and pozzolans that are outside the scope of the guides provided for conventional SCMs (ASTM C618, C989 and C1240) such as fly ash, slag cement, silica fumes and calcined clays. This guide suggests five different stages which are to be followed for the evaluation of performance ASCM in concrete mixture. They are:

Stage I – Characterization of Material – In this stage I, the chemical analysis of the material is to be conducted to trace the quality of all the major and minor elements present using x-ray fluorescence, atomic absorption spectroscopy, inductively coupled plasma spectroscopy, and the various test methods according to ASTM C114, C311, and D4326. Among the elements identified using the methods specified, most consideration must be given to those which could be injurious to cement hydration or concrete properties. Suitable tests are needed to be conducted to determine the availability of those compounds to particulate the hydration reactions.

Stage II – Determination of Suitable Fineness – Fineness of an SCM plays a major role in affecting the performance of concrete. So, if the production process of ASCM involves or requires crushing or grinding then the guidance for the selection of suitable fineness can be obtained from workability, durability and compressive strength tests on the mortar made with ASCM along with hydraulic cement. The fineness can be tested according to the procedures mentioned in ASTM C311, C204 and C430. The determination of particle size distribution could be done using laser diffraction particle size analyzer.

Stage III – Testing to Specification – The potential SCM material is required to be tested to meet the chemical, physical, and uniformity requirements specified in ASTM C618, C989 or C1240 along with the additional test such as chlorides test (C1218), free calcium oxide test (C114, section 28), leachable heavy metals test (D3987), soluble alkalis test (C114) and air void stability (as described in C1709-18).

Stage IV – Concrete Performance Tests – The suitability of alternative SCM on concrete performance can be verified by performing various tests on the fresh and hardened concrete to find the effects of SCMs on its physical, mechanical and durability properties. Such tests are shown in Figure 2.7 below.

FIGURE 2.7 Standard tests for evaluating the suitability of ASCM on concrete (ASTM C1709-18)

Stage V – Field Trials and Long-Term Performance and Durability – These tests are needed to be performed only when acceptable test results from the laboratory have been demonstrated. Some field evaluation methods are also recommended, out of which at least three are needed to be performed in such a way that the short term and long-term evaluation should be relevant to the intended use. These include:

1. Effects of ASCM on the finishing characteristics of the concrete

2. Variations on fresh properties of concrete such as air content, slump and setting time
3. Compatibility with admixture
4. Performance characteristics of concrete including parameters of strength and durability
5. Determine the environmental impacts on the concrete's performance specific to SCMs use.

There are some specifications mentioned in ASTM C311 to test the chemical and physical properties of alternative SCMs for use in concrete which are show in Figure 2.8.

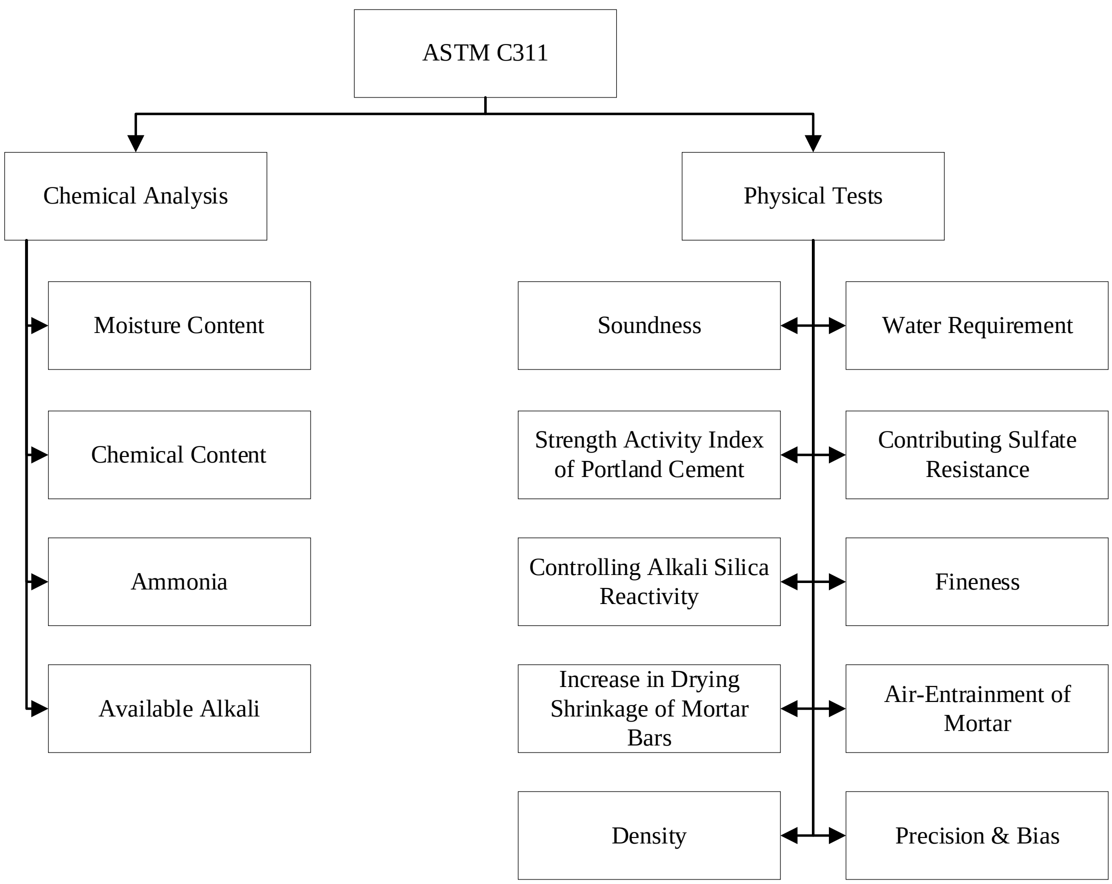

FIGURE 2.8 Standard Tests for Testing Fly Ash or Natural Pozzolans for Use in PCC.

2.3 Economic Considerations in Recycling

Life Cycle Cost Analysis (LCCA) is a process of evaluating the total cost that would be incurred in a project by the analysis of initial cost and future discounted cost like cost of, maintenance, reconstruction, user cost, restoring, rehabilitation, and resurfacing, throughout the complete lifespan of the project (Van Dam et al. 2015).

The determination of the potential economic and environmental benefits of using recycled waste materials in road construction was done by different case studies performed in Wisconsin using the LCA and LCCA. One of the studies was performed on 1-mile highway construction project at Interstate 94 (I-94) in Kenosha county. The project included a multi-year reconstruction, modernization, and expansion of I-94 mainline, ramps, resurfacing of State highway 142 (STH 142) and embankments for the portion of I-94 (approx. 180,000 cubic meters). The highway was constructed using recycled materials including fly ash, bottom ash, foundry sand, recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP). The cost savings from using such material in substitution to conventional materials were calculated from the differences of the actual quantity of recycled materials versus the hypothetical cost of conventional materials which were replaced. The authors found that the project saved over $770,000 in which the largest savings were due to the use of bottom ash (over $410,000) as the unit cost of bottom ash was very low and the amount of bottom ash used in construction of was high. The various environmental and economical savings for this project is shown in Table 2.15 (Bloom et al. 2016).

TABLE 2.15 Results of savings from I-94 highway construction project (Bloom et al. 2016)

Criteria	**Reference**	**Actual**	**Percent Improved**
Energy Use (TJ)	141,000	89,000	37%
GWP (Mg)	9,500	5,800	39%
Water Consumption (kg)	38,000	28,000	25%
SCC ($)	$ 654,000	$ 398,000	39%
Hazardous Waste (kg)	237,000	151,000	36%
In Situ Recycling (m^3)	0	19,100	7%
Total Recycling (m^3)	0	154,000	57%
Life Cycle Cost Savings [$]:	$771,000		

This case study showed that by using recycled materials in road construction, the environmental and econimical benefits could be achieved as the amount of energy, water consumption, CO_2 emission and hazardous waste generated were significantly decreased (Bloom et al. 2016).

CHAPTER 3: INQUIRY OF AGENCY AND INDUSTRY USE OF BY-PRODUCTS IN CONCRETE PAVEMENT APPLICATIONS

3.1 Approach and Limitations

A two-part benchmarking inquiry was developed to evaluate the utilization of construction and industrial waste by-products in the United States concrete paving industry and the potential barriers associated with the use of these by-products in new concrete or in pavement foundations. The inquiries was developed by the research team, approved by the technical lead on the project at Iowa State University, and responses were solicited from state highway agencies and industry stakeholders with the help of American Concrete Pavement Association (ACPA) and National Concrete Pavement Technology Center (NCPTC).

Inquiry questions that aimed to gather information from the State Highway Agencies (SHAs) are provided in Appendix A, inquiry questions used gather information from the contractors or the Industry people who are involved in designing sustainable pavements using construction or industrial waste by-product are provided in Appendix B. A summary of the agency and industry inquiries is provided in Figures 3.1 and 3.2.

FIGURE 3.1 Agency Inquiry

Respondent Information:

Name of firm	
Address	
Name of Inquiry respondent	
Phone number	
Email address	

1) Which of the following construction and/or industrial by-products are you allowing (or considering allowing) in **concrete pavement applications?**

Construction and/or Industrial by-product	Allowable uses	
	Allow in pavement foundations? (Yes/Considering/No)	Allow in new concrete? (Yes/Considering/No)
Bottom ash		
Off-specification fly ash		
Rice husk ash		
Sugar cane ash		
Water treatment residuals		
Recycled concrete aggregate		
Mixed rubble (recycled aggregates from mixed sources)		
Recycled asphalt pavement		
Concrete grinding slurry and fines		
Hydro-demolition residual material		
Brick waste		
Crushed glass		
Crumb rubber		
Porcelain		
Plastics		
Other (please identify)		

1) For what reasons are you allowing (or considering allowing) the construction and/or industrial by-products **in concrete pavement applications**? (select all that apply)

Construction and/or Industrial by-product	Reason			
	Lack of availability of other products (supplementary cementitious materials and/or aggregates)	Cost savings over other products (supplementary cementitious materials and/or aggregates)	Economic benefits of recycling these materials from a project (or sourcing from a local industry or project)	Other reason (please describe)
Bottom ash				
Off-specification fly ash				
Rice husk ash				
Sugar cane ash				
Water treatment residuals				
Recycled concrete aggregate				

Construction and/or Industrial by-product	Reason			
	Lack of availability of other products (supplementary cementitious materials and/or aggregates)	Cost savings over other products (supplementary cementitious materials and/or aggregates)	Economic benefits of recycling these materials from a project (or sourcing from a local industry or project)	Other reason (please describe)
Mixed rubble (recycled aggregates from mixed sources)				
Recycled asphalt pavement				
Concrete grinding slurry and fines				
Hydro-demolition residual material				
Brick waste				
Crushed glass				
Crumb rubber				
Porcelain				
Plastics				
Other (please identify)				

2) On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers within your agency to using construction or industrial by-product **in pavement foundations. Foundation applications include bound bases/subbases, unbound bases/subbases, and natural/stabilized soils.**

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

Barrier	**Rating (please score each barrier on 1 to 5 scale)**
Specifications currently restrict use	
Concerns regarding the material supply being consistently available	
Concerns regarding foundation strength and/or stability	
Concerns regarding durability of the by-product in service	

Barrier	Rating (please score each barrier on 1 to 5 scale)
Concerns regarding variability in material properties	
Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials)	
Ready availability of good, inexpensive SCM and natural aggregate sources	
Regulatory barriers (permitting, environmental regulations)	
Concerns regarding environmental impacts (e.g. runoff, leachate, etc.)	
Other (please describe)	

3) On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to **using construction or industrial by-products as supplemental cementitious materials (SCMs) in new concrete.**

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

Barriers	Rating (please score each barrier on 1 to 5 scale)
Specifications currently restrict use	
Concerns regarding the material supply being consistently available	
Concerns regarding variability in material properties	
Concerns regarding performance of fresh concrete – setting time, workability, etc.	
Concerns regarding the strength of the new concrete	
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)	
Concerns regarding the durability of the new concrete	
Lack of guidance on conducting concrete mixture designs and proportioning using these materials	
Economics (costs of producing/procuring by-product vs. cost of conventional materials)	
Ready availability of conventional materials that are suitable and inexpensive	
Regulatory barriers (permitting, environmental regulations)	
Other (please describe)	

4) On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to **using construction or industrial by-products as aggregates or inert fillers in new concrete.**

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

Barriers	Rating (please score each barrier on 1 to 5 scale)
Specifications currently restrict use	
Concerns regarding the material supply being consistently available	
Concerns regarding variability in material properties	
Concerns regarding performance of fresh concrete – setting time, workability, etc.	
Concerns regarding the strength of the new concrete	
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)	
Concerns regarding the durability of the new concrete	
Lack of guidance on conducting concrete mixture designs and proportioning using these materials	
Economics (costs of producing/procuring by-product vs. cost of conventional materials)	
Ready availability of conventional materials that are suitable and inexpensive	
Regulatory barriers (permitting, environmental regulations)	
Other (please describe)	

5) What characterization tests of the by-product materials listed above would provide your agency confidence in their use **as a supplementary cementitious material (SCM) in pavement foundations or in new concrete.**

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

Characteristics and Tests	Rating (please score each on a 1 to 5 scale)
Tests of By-product Materials:	----------------------------
Chemical composition	
Carbon content	
Other contaminants	
Incompatibility with certain cements	
Fineness	
Specific gravity	
Strength activity index	
Water requirement	
Soundness (autoclave expansion or other)	
Density	
Uniformity	
Tests of Base Materials Stabilized with By-Products:	----------------------------
Shear strength	
Elastic modulus (stiffness)	
Permeability	
Tests of Concrete Incorporating By-Products:	----------------------------
Workability	
Initial and final set	
Heat of hydration of concrete	
Strength	

Characteristics and Tests	Rating (please score each on a 1 to 5 scale)
Permeability	
Resistance to freezing and thawing	
Resistance to deicing salts	
Susceptibility to ASR	
Susceptibility to sulfate attack	
Other Tests (please describe):	----------------------------

6) What characterization tests of the by-product materials listed above would provide your agency confidence in their use **as an aggregate or filler material in pavement foundations or new concrete** (1 = not significantly important, 5 = critical characterization test of very high importance).

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

Characteristics and Tests	Rating (please score each on a 1 to 5 scale)
Tests of By-Product Aggregate or Filler Materials:	----------------------------
Specific gravity	
Absorption	
Gradation	
Percent passing #200	
Soundness of Unconfined Freeze-Thaw	
Abrasion resistance (L.A., Micro-Deval or Other)	
Tests of Unbound Base Material Incorporating Recycled or By-Product Aggregate:	----------------------------
Density	
Strength (Shear, CBR or Other)	
Permeability	
Leachate potential and composition	
Tests of Stabilized Base Material Incorporating Recycled or By-Product Aggregate:	----------------------------
Strength (Compressive, Flexural or Other)	
Stiffness (Elastic or Resilient Modulus or Other)	
Permeability	
Tests of Concrete Incorporating Recycled or By-Product Aggregate:	----------------------------
Workability – Quality and Duration	
Strength (Compressive, Flexural, or Other)	
Permeability	
Resistance to Freezing and Thawing	
Resistance to Deicing Salts (Salt Scaling, Formation Factor, or Other)	
Susceptibility to ASR	
Susceptibility to Sulfate Attack	
Other Tests (please describe):	----------------------------

7) Please rate the importance of the following potential benefits associated with the use of construction and industrial by-products in your transportation infrastructure.

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

Potential benefit of use of construction and industrial by-products in transportation infrastructure	**Rating (please score each on a 1 to 5 scale)**
Conserving natural materials	
Conserving landfill space and reducing the need for new landfill	
Reducing project costs through use of recycled materials	
Increasing strategic business opportunities and business competitiveness	
Reducing the environmental impacts of cement and aggregate production	
Enhancing foundation material and/or concrete quality	
Other (please describe):	

8) Do you have any additional information that you could share regarding your agency's consideration of use of construction and industrial by-products in new transportation applications?

FIGURE 3.2 Industry Inquiry

Respondent Information:

Name of firm	
Address	
Name of Inquiry respondent	
Phone number	
Email address	

1) Which of the following construction and/or industrial by-product are you using (or interested in using) **in concrete pavement applications?**

Construction and/or Industrial by-product	Uses	
	Using in pavement foundations? (Yes/Interested/No)	Using in new concrete? (Yes/Interested/No)
Bottom ash		
Off-specification fly ash		
Rice husk ash		
Sugar cane ash		
Water treatment residuals		
Recycled concrete aggregate		
Mixed rubble (recycled aggregates from mixed sources)		
Recycled asphalt pavement		
Concrete grinding slurry and fines		
Hydro-demolition residual material		
Brick waste		
Crushed glass		
Crumb rubber		
Porcelain		
Plastics		
Other (please identify)		

1) For what reasons are you using (or interested in using) the construction and/or industrial by-products **in concrete pavement applications?** (select all that apply)

Construction and/or Industrial by-product	Reason			
	Lack of availability of other products (supplementary cementitious materials and/or aggregates)	Cost savings over other products (supplementary cementitious materials and/or aggregates)	Economic benefits of recycling these materials from a project (or sourcing from a local industry or project)	Other reason (please describe)
Bottom ash				

Construction and/or Industrial by-product	Reason			
	Lack of availability of other products (supplementary cementitious materials and/or aggregates)	Cost savings over other products (supplementary cementitious materials and/or aggregates)	Economic benefits of recycling these materials from a project (or sourcing from a local industry or project)	Other reason (please describe)
Off-specification fly ash				
Rice husk ash				
Sugar cane ash				
Water treatment residuals				
Recycled concrete aggregate				
Mixed rubble (recycled aggregates from mixed sources)				
Recycled asphalt pavement				
Concrete grinding slurry and fines				
Hydro-demolition residual material				
Brick waste				
Crushed glass				
Crumb rubber				
Porcelain				
Plastics				
Other (please identify)				

2) On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products **in pavement foundations. Foundation applications include bound bases/subbases, unbound bases/subbases, and natural/stabilized soils.**

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

Barrier	Rating (please score each barrier on 1 to 5 scale)
Specifications currently restrict use	
Concerns regarding the material supply being consistently available	
Concerns regarding foundation strength and/or stability	
Concerns regarding durability of the by-product in service	
Concerns regarding variability in material properties	
Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials)	
Ready availability of conventional materials that are suitable and inexpensive	
Regulatory barriers (permitting, environmental regulations)	
Concerns regarding environmental impacts (e.g. runoff, leachate, etc.)	
Other (please describe)	

3) On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to **using construction or industrial by-products as supplemental cementitious materials (SCMs) in new concrete.**

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

Barriers	Rating (please score each barrier on 1 to 5 scale)
Specifications currently restrict use	
Concerns regarding the material supply being consistently available	
Concerns regarding variability in material properties	
Concerns regarding performance of fresh concrete – setting time, workability, etc.	
Concerns regarding the strength of the new concrete	
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)	
Concerns regarding the durability of the new concrete	
Lack of guidance on conducting concrete mixture designs and proportioning using these materials	
Economics (costs of producing/procuring by-product vs. cost of conventional materials)	
Ready availability of conventional materials that are suitable and inexpensive	
Other (please describe)	

4) On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to **using construction or industrial by-products as aggregates or inert fillers in new concrete.**

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

Barriers	**Rating (please score each barrier on 1 to 5 scale)**
Specifications currently restrict use	
Concerns regarding the material supply being consistently available	
Concerns regarding variability in material properties	
Concerns regarding performance of fresh concrete – setting time, workability, etc.	
Concerns regarding the strength of the new concrete	
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)	
Concerns regarding the durability of the new concrete	
Lack of guidance on conducting concrete mixture designs and proportioning using these materials	
Economics (costs of producing/procuring by-product vs. cost of conventional materials)	
Ready availability of conventional materials that are suitable and inexpensive	
Other (please describe)	

5) Rate the importance of the following potential benefits associated with the use of construction and industrial by-products in your transportation infrastructure (1 = not significantly important, 5 = of very high importance).

Potential benefit of use of construction and industrial by-products in transportation infrastructure	**Rating (please score each on a 1 to 5 scale)**
Conserving natural materials	
Conserving landfill space and reducing the need for new landfill	
Reducing project costs through use of recycled materials	
Increasing strategic business opportunities and business competitiveness	
Reducing the environmental impacts of cement and aggregate production	
Enhancing foundation material and/or concrete quality	

6) Do you have any additional information that you could share regarding your firm's consideration of use of construction and industrial by-products in new transportation applications?

Both inquiries were intended to reveal the potential barriers that restrict the use of construction and industrial waste by-product in highway construction. The inquiries requested input on the use (either actual or desired) of construction and/or industrial waste by-products including:

- Bottom ash
- Off-specification fly ash
- Rice husk ash
- Sugar cane ash
- Water treatment residuals
- Recycled concrete aggregate
- Mixed rubble (recycled aggregates from mixed sources)
- Recycled asphalt pavement
- Concrete grinding slurry and fines
- Hydro-demolition residual material
- Brick waste
- Crushed glass
- Crumb rubber

- Porcelain
- Plastics

3.2 Findings

3.2.1 Agency Inquiry

The Agency inquiries was sent to the states participating in the Technology Transfer Concrete Consortium (TTCC) pooled fund and the National Concrete Consortium (NCC) with the support of National CP Tech center. It began with the information of the respondents following the various questions that were drafted addressing:

1. If the agency allows, does not allow, or is considering allowing the use of construction and/or industrial waste by product in the concrete pavements. Information supporting the reason behind allowance (or considering allowing) is also requested).
2. The potential barrier(s) hindering the use of such materials in pavement foundation or as an SCM or aggregate in new concrete. These questions regarding challenges and barriers were based on the Likert scale from 1 to 5, where 1 means no significant barrier or importance and 5 means critical barrier or very high importance.
3. The characterization tests that would provide confidence in use of these materials as aggregate or SCM in pavement foundation or in new concrete. These questions were based on the Likert scale from 1 to 5, where 1 means no significant barrier or importance and 5 means critical barrier or very high importance.
4. The potential benefits associated with construction and/or industrial waste by product in transportation infrastructure. The benefit questions were also based on

the Likert scale from 1 to 5, where 1 means no significant importance and 5 means very high importance.

5. Lastly, a free answer box was provided for the respondents to provide any additional information regarding the agency's consideration for the use of construction and/or industrial waste by-products in new transportation applications.

3.2.2 Industry Inquiry

The industry inquiries were sent to ACPA representatives to be further disseminated to contractors and other industry stakeholders to gather input. The industry inquiry questions were similar to the agency inquiry questions, although questions regarding the characterization tests was not included. The inquiry began with the information of the respondents following the various questions that were drafted addressing:

1. If their company ever used, not used, or interested in using the construction and/or industrial waste by product in the concrete pavements along with the reason behind allowance.
2. The potential barriers preventing the use of such materials in pavement foundation or as an SCM or aggregate in new concrete. The barrier questions were based on the Likert scale from 1 to 5, where 1 means no significant barrier or importance and 5 means critical barrier or very high importance.
3. The potential benefits associated with use of construction and/or industrial waste by-products in transportation infrastructure. The benefit questions were also based on the Likert scale from 1 to 5, where 1 means no significant importance and 5 means very high importance.

4. Lastly, a free answer box was provided for the respondents to provide any additional information regarding the firm's consideration for the use of construction and/or industrial waste by product in new transportation applications.

CHAPTER 4: RESULTS OF INQUIRIES ON USE OF CONSTRUCTION AND WASTE BY-PRODUCTS IN CONCRETE PAVEMENT APPLICATIONS

4.1 Introduction:

The data collected for the inquiry from various State Highway Agencies (SHAs) and contractors was summarized in tabular and graphical format, from which the various results (such as current utilization, barriers and benefits associated with construction and industrial by-products in concrete pavement) were analyzed. The analysis included three stages:

1. Analysis of responses from Agency Inquiry (SHAs)
2. Analysis of responses from Industry Inquiry (Contractors)
3. Evaluating risk tolerance by comparison of inquiry responses from both the Industry and SHAs.

Stage 1: The responses from the agencies were used to evaluate the awareness and use of by-products for use, reasons supporting the use (or consideration of use), and barriers and benefits of using construction and industrial by-products in concrete pavement applications. Characterization tests that would provide confidence to an agency considering allowing such products in pavement applications were also identified and tabulated. Methods utilized to evaluate these responses included summary tables with descriptive statistics (such as total, percent of total, mean, and standard deviation), and graphical plots of the data. A summary of analysis methods for each question of the inquiry is presented in Table 4.1 below:

TABLE 4.1 Summary of analysis methods for data received from agency inquiry

Question	Topic	Type of Response	Graphical summary	Statistical measure
1	Types of byproducts used type of use	Yes/No	Table, bar chart	• Total agencies using each type • Total number of agencies using each byproduct for each type of use
1	Reason for use	Yes/No	Table, (Mauriya 2019) bar chart	• Total agencies using for each reason • Total reason for each type of byproduct
2	Barriers for use in pavement foundation	Likert Scale (1 to 5)	Table, bar chart	• Total number of agency respondents for each Likert scale value with percent • Average Rating of total responses for each barrier
3	Barriers for use as SCMs in new concrete	Likert Scale (1 to 5)	Table, bar chart	• Total number of agency respondents for each Likert scale value with percent • Average Rating of total responses for each barrier
4	Barriers for use as aggregate in new concrete	Likert Scale (1 to 5)	Table, bar chart	• Total number of agency respondents for each Likert scale value with percent • Average Rating of total responses for each barrier
5	Test of by-product materials	Likert Scale (1 to 5)	Table, bar chart	• Total number of agency respondents for each Likert scale value with percent • Average Rating of total responses for each test
5	Test of base materials stabilized with by-products	Likert Scale (1 to 5)	Table, bar chart	• Total number of agency respondents for each Likert scale value with percent • Average Rating of total responses for each test
5	Test of concrete incorporating by-products	Likert Scale (1 to 5)	Table, bar chart	• Total number of agency respondents for each Likert scale value with percent • Average Rating of total responses for each test
6	Test of by-product aggregate or filler materials	Likert Scale (1 to 5)	Table, bar chart	• Total number of agency respondents for each Likert scale value with percent • Average Rating of total responses for each test
6	Test of unbound base material incorporating recycled or by-product aggregate	Likert Scale (1 to 5)	Table, bar chart	• Total number of agency respondents for each Likert scale value with percent • Average Rating of total responses for each test
6	Tests of stabilized base material incorporating recycled	Likert Scale (1 to 5)	Table, bar chart	• Total number of agency respondents for each Likert scale value with percent • Average Rating of total responses for each test

TABLE 4.1(Cont.) Summary of analysis methods for data received from

Question	Topic	Type of Response	Graphical summary	Statistical measure
	or by-product aggregate:			
6	Test of concrete incorporating recycled or by-product aggregate	Likert Scale (1 to 5)	Table, bar chart	• Total number of agency respondents for each Likert scale value with percent • Average Rating of total responses for each test
7	Benefits from use in transportation infrastructure	Likert Scale (1 to 5)	Table, bar chart	• Total number of agency respondents for each Likert scale value with percent • Average Rating of total responses for each benefit
8	Additional Information	Open Response		

Stage 2: The responses from the contractors were used to identify whether they allowed the use (or desired to use) construction and industrial by-products. Also, the barriers to use of by-products and benefits of use of these materials were tabulated. Methods utilized to evaluate these responses included summary tables with descriptive statistics (such as total, percent of total, mean, and standard deviation), and graphical plots of the data. A summary of analysis methods for each question of the inquiry is presented in Table 4.2 below:

TABLE 4.2 Summary of analysis methods for data received from industry inquiry

Question	Topic	Type of Response	Graphical summary	Statistical measure
1	Types of byproducts used type of use	Yes/No	Table, bar chart	• Total number of industry respondents using each type • Total number of industry respondents using each byproduct for each type of use
1	Reason for use	Yes/No	Table, bar chart	• Total number of industry respondents using for each reason • Total reason for each type of byproduct

TABLE 4.2(Cont.) Summary of analysis methods for data received from industry

Question	Topic	Type of Response	Graphical summary	Statistical measure
2	Barriers for use in pavement foundation	Likert Scale (1 to 5)	Table, bar chart	• Total number of industry respondents for each Likert scale value with percent • Average Rating of total responses for each barrier
3	Barriers for use as SCMs in new concrete	Likert Scale (1 to 5)	Table, bar chart	• Total number of industry respondents for each Likert scale value with percent • Average Rating of total responses for each barrier
4	Barriers for use as aggregate in new concrete	Likert Scale (1 to 5)	Table, bar chart	• Total number of industry respondents for each Likert scale value with percent • Average Rating of total responses for each barrier
5	Benefits from use in transportation infrastructure	Likert Scale (1 to 5)	Table, bar chart	• Total number of industry respondents for each Likert scale value with percent • Average Rating of total responses for each benefit
6	Additional Information	Open Response		

Stage 3: A comparison of risk tolerance between agencies and industry stakeholders was performed by statistically comparing selected results from industry and agency inquiries. The Mann-Whitney U test (McKnight and Najab 2010) was used to compare the results between both the inquiries. The various comparisons were:

- Comparison of potential barriers associated with the use of construction and industrial byproduct in pavement foundation
- Comparison of potential barriers associated with the use of construction and industrial byproduct as SCM or aggregate in new concrete

- Comparison of perceived benefits of concrete recycling using construction and industrial byproduct

4.2 Summary of Key Findings

The Figure 4.1 shows the states represented by the inquiry findings, which included input from 21 DOTs plus the Illinois Tollway Authority (total 22) and 20 contractor/industry firms. As a reminder, most state agencies that responded are members of the National Concrete Consortium (NCC). Typically, respondents are State Materials Engineers, State Pavement Engineers, State Concrete Engineers, Pavement Construction Engineers, or their designee within the agency's central office. The Industry survey respondents were primarily prime contractors involved in concrete paving, all contractors from paving companies capable of bidding/securing interstate concrete pavement projects. Typical respondents are Project Managers, Senior Project Managers, or Executives along with two material suppliers whose respondents' roles are Area Managers Director of Market Development.

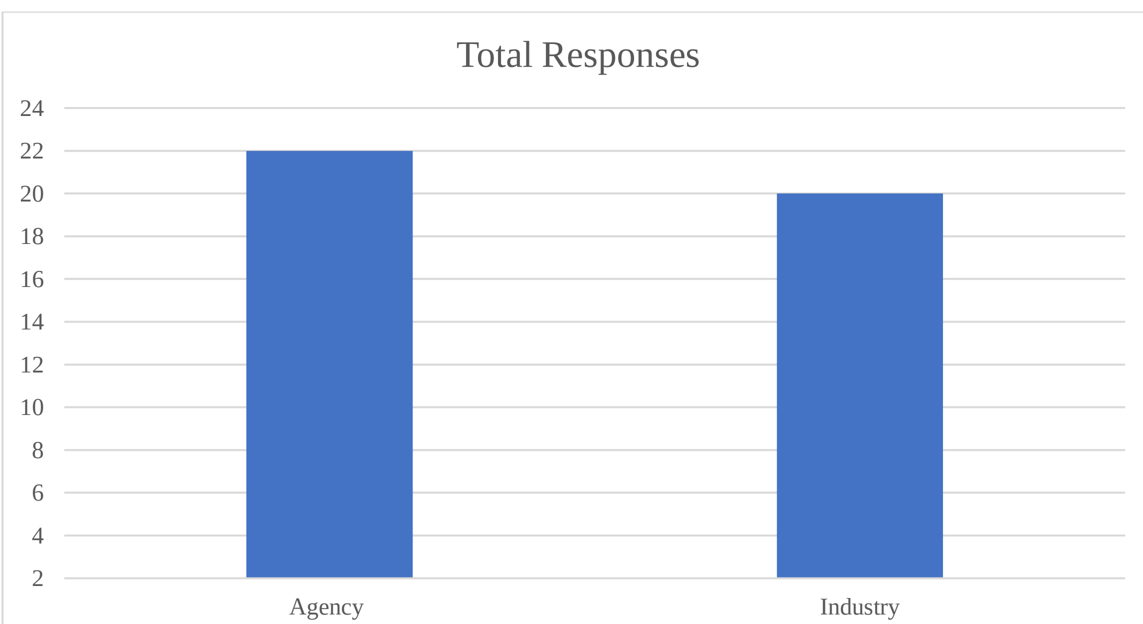

FIGURE 4.1 Graph showing total responses from SHAs and Industries

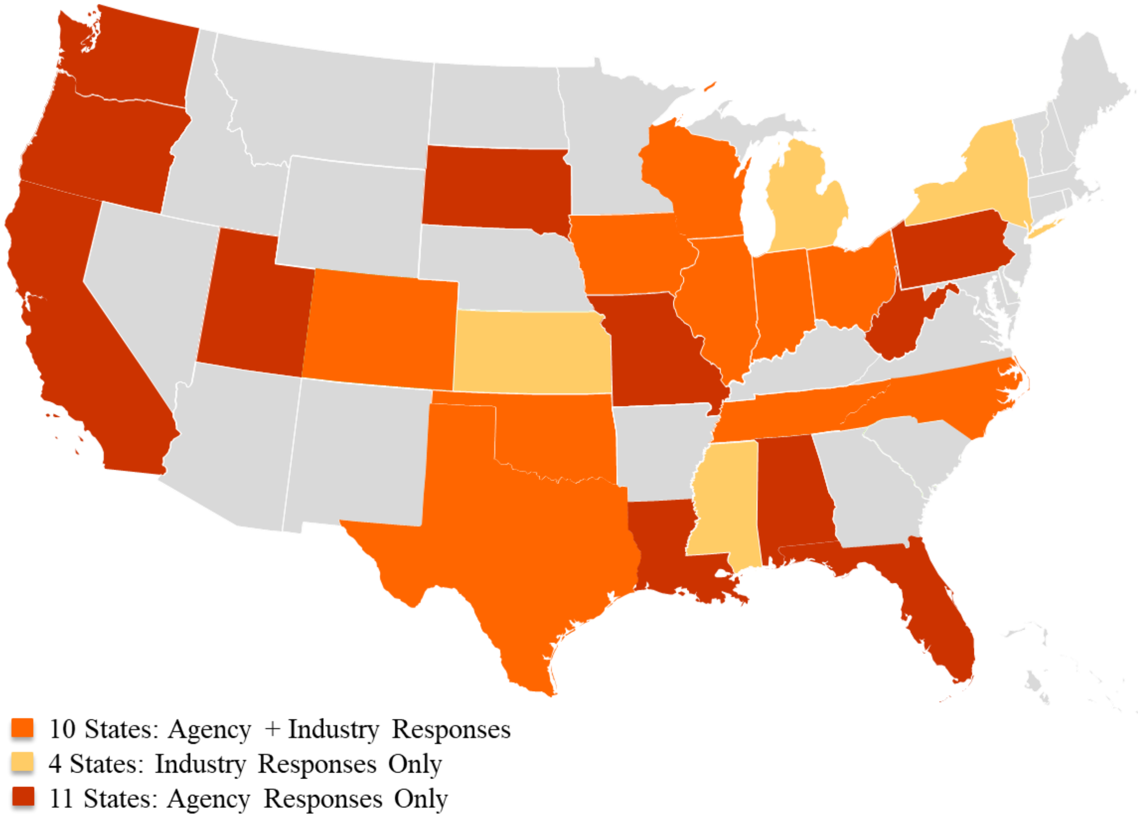

FIGURE 4.2 States represented by the SHAs (n = 21) and Industries (n = 20) that responded to the inquiry questions

The US map shown in Figure 4.2 highlights of the states from where the SHAs and industries responded to the survey. It can be seen that there are 10 common states, 4 states for industry responses only and 11 states for agency responses only.

4.3 State Highway Agencies Responses:

A total of 22 responses were received from the different state highway agencies (Figure 4.3).

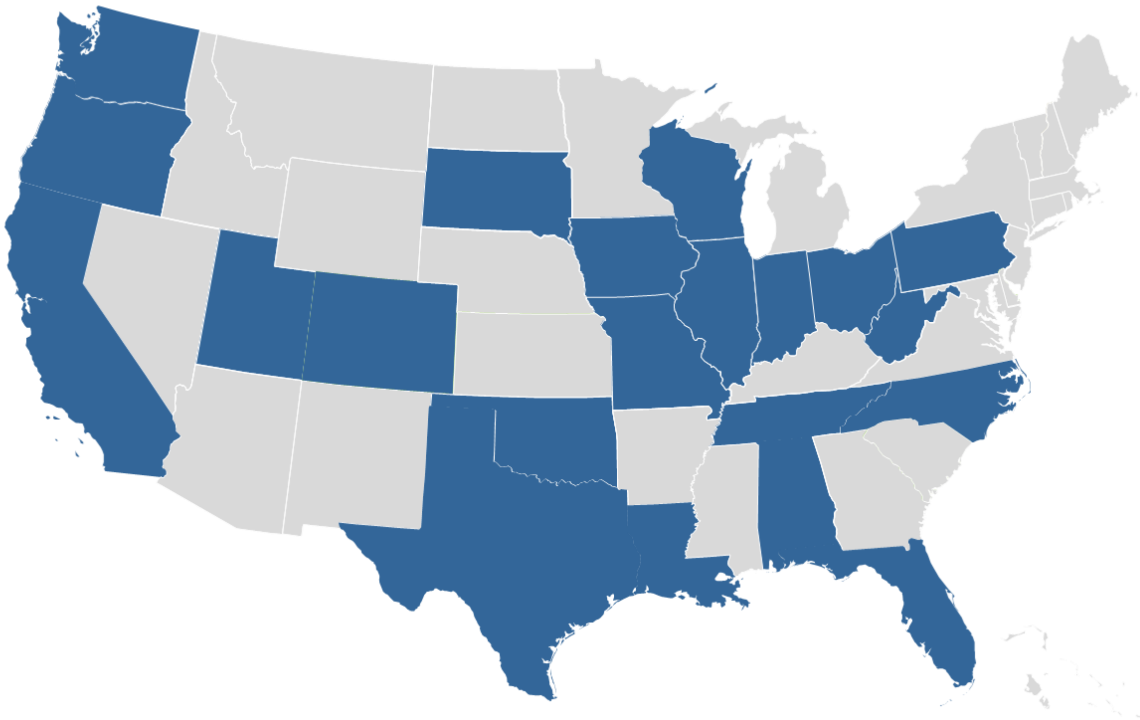

FIGURE 4.3 States represented by the SHAs that responded to the inquiry questions

Key Findings:

Key findings of the study indicated that the most used by-product is recycled concrete aggregate in pavement foundation and in new concrete. The materials such as water treatment residuals, concrete grinding slurry and fines, hydro-demolition residual material, brick waste and plastics are not at all allowed by the agencies to date in pavement foundations. Along with the materials not used in pavement foundation, crumb rubber and porcelain are also not used in new concrete.

The utilization of rest of the materials are as follows:

4.3.1 Pavement Foundation:

Table 4.3 Shows the number of SHA respondents using each type of material in pavement foundation. It can be seen that most of the responders use RCA and RAP in pavement foundation as a substitute material.

TABLE 4.3 Responses for Question 2 of Agency Inquiry

Q2. Which of the following construction and/or industrial by-products are you allowing (or considering allowing) in concrete pavement applications?	Pavement Foundation		
	Yes	**Considered**	**No**
Bottom ash	2	2	18
Off-specification fly ash	3	7	12
Rice husk ash	0	1	21
Sugar cane ash	0	1	21
Water treatment residuals	0	0	22
Recycled concrete aggregate	17	1	4
Mixed rubble (recycled aggregates from mixed sources)	6	2	14
Recycled asphalt pavement	14	1	7
Concrete grinding slurry and fines	0	0	22
Hydro-demolition residual material	0	0	22
Brick waste	0	0	22
Crushed glass	3	1	18
Crumb rubber	2	0	20
Porcelain	1	0	21
Plastics	0	0	22

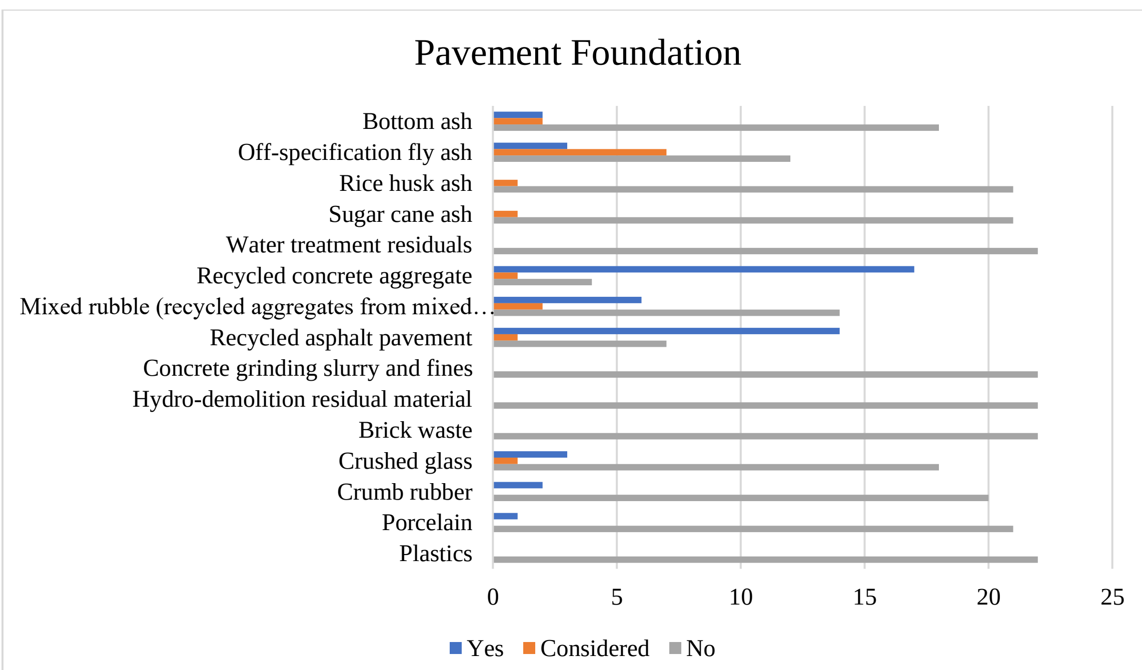

FIGURE 4.4 Responses for Question 2 of Agency Inquiry

4.3.2 Barriers of using by-products in pavement foundation:

From the Table 4.4, it can be surmised that the most critical barrier for agencies that likely hindering the use of by-products in pavement foundation is the perceived durability of by-product with a high average rating (4.4). Potential environmental impacts and availability of the material does not seem to be as great of a barrier as other barriers. Economic barriers to use of the by-products were viewed as far less important to the SHAs (2.6).

TABLE 4.4 Responses for Question 4 of Agency Inquiry

Q4. On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers within your agency to using construction or industrial by-product in pavement foundations. Foundation applications include bound bases/subbases, unbound bases/subbases, and natural/stabilized soils.	**No Import ance (%)**	**Some Import ance (%)**	**Impor tant (%)**	**High Import ance (%)**	**Very High Import ance (%)**	**Aver age Ratin g**
	1	**2**	**3**	**4**	**5**	
Concerns regarding durability of the by-product in service	0	0	3	7	12	**4.4**
Concerns regarding variability in material properties	0	1	2	10	9	**4.2**
Concerns regarding foundation strength and/or stability	0	2	5	10	5	**3.8**
Ready availability of good, inexpensive SCM and natural aggregate sources	1	4	5	4	8	**3.6**
Concerns regarding environmental impacts (e.g. runoff, leachate, etc.)	2	2	7	7	4	**3.4**
Concerns regarding the material supply being consistently available	0	4	9	6	3	**3.4**
Specifications currently restrict use	4	7	4	1	6	**2.9**
Regulatory barriers (permitting, environmental regulations)	2	6	9	4	1	**2.8**
Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials)	4	5	9	3	1	**2.6**

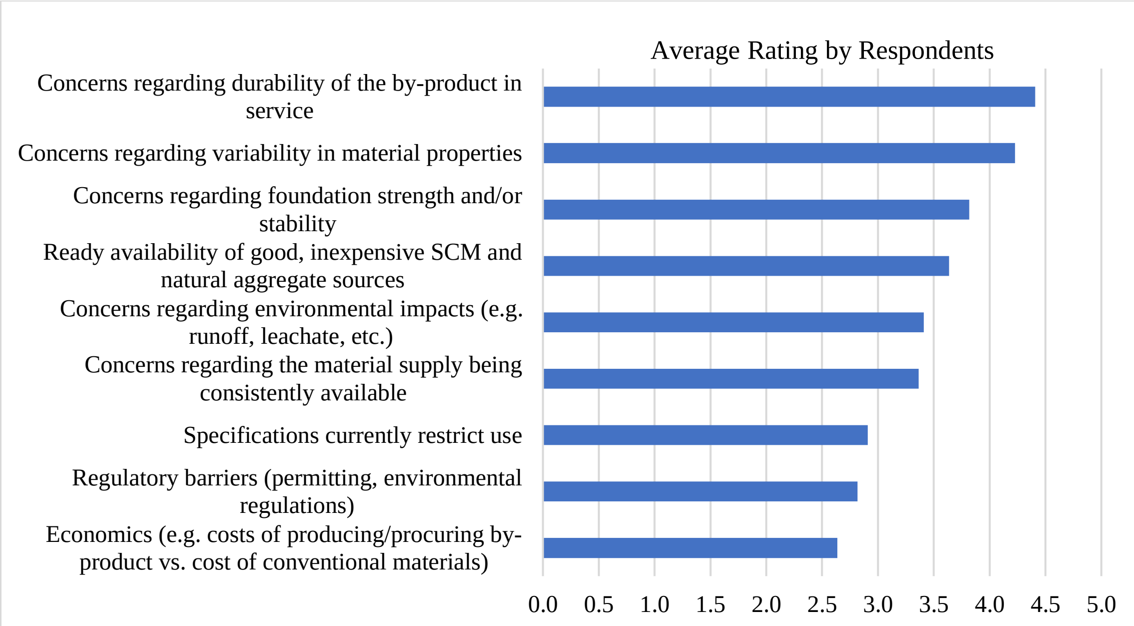

FIGURE 4.5 Responses for Question 4 of Agency Inquiry

4.3.3 New Concrete:

Table 4.5 shows the number of SHA respondents using each type of material in new concrete. The table shows that most of the agencies have not used most of the byproduct materials in new concrete. The most often used byproduct material in new concrete is RCA. Other than RCA, bottom ash, off-specification fly ash, mixed rubble and RAP are the only materials have been used by few agency respondents.

TABLE 4.5 Responses for Question 2 of Agency Inquiry

Q2. Which of the following construction and/or industrial by-products are you allowing (or considering allowing) in concrete pavement applications?	**New Concrete**		
	Yes	**Considered**	**No**
Bottom ash	2	1	19
Off-specification fly ash	1	6	15
Rice husk ash	0	3	19
Sugar cane ash	0	2	20
Water treatment residuals	0	0	22
Recycled concrete aggregate	8	6	8
Mixed rubble (recycled aggregates from mixed sources)	1	2	19
Recycled asphalt pavement	1	2	19
Concrete grinding slurry and fines	0	0	22

TABLE 4.5(Cont.) Responses for Question 2 of Agency Inquiry

Q2. Which of the following construction and/or industrial by-products are you allowing (or considering allowing) in concrete pavement applications?	New Concrete		
	Yes	Considered	No
Hydro-demolition residual material	0	0	22
Brick waste	0	0	22
Crushed glass	0	2	20
Crumb rubber	0	0	22
Porcelain	0	0	22
Plastics	0	0	22

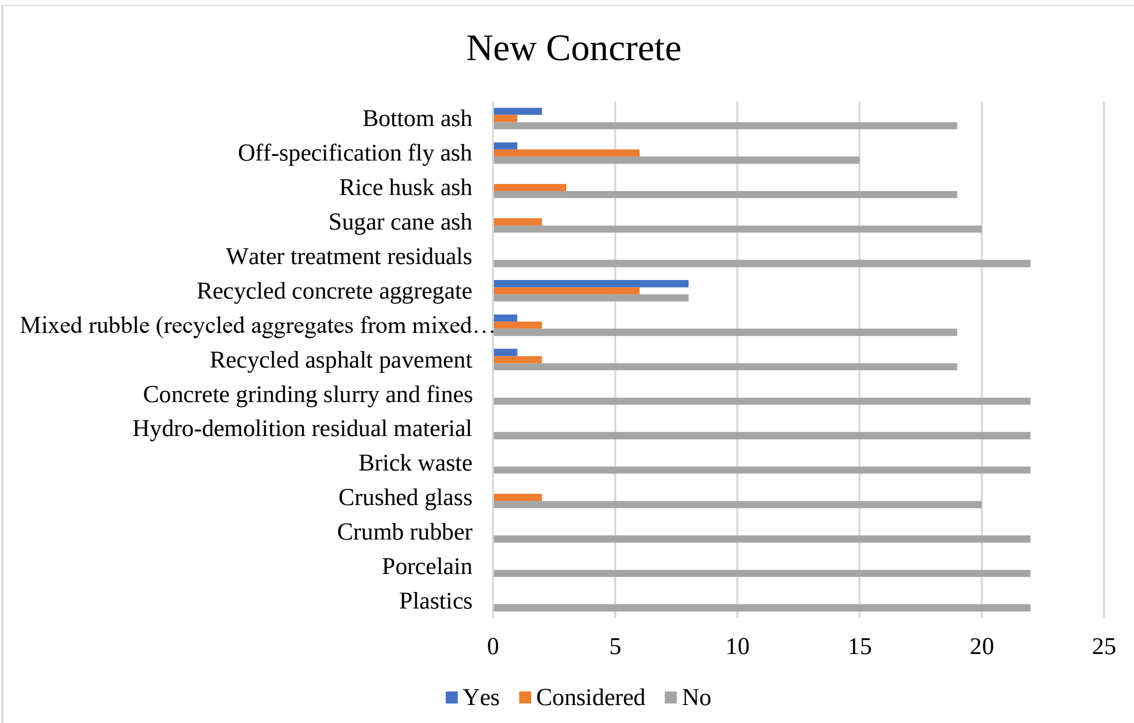

FIGURE 4.6 Responses for Question 2 of Agency Inquiry

4.3.4 Barriers of using by-products in new concrete as SCM:

It was seen from Table 4.6 that the actual or perceived durability of the new concrete is a major concern for the agencies that makes them unconfident in using new by-products as SCM in concrete. This barrier had a score (4.5) significantly higher than the next greatest barrier, variability in the material properties (4.2). The actual or perceived variability in materials properties also has a high rating by agencies. Economics and regulatory barriers are of least importance to the agencies. The availability of the materials is also important to the SHAs.

TABLE 4.6 Responses for Question 5 of Agency Inquiry

Q5. On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products as supplemental cementitious materials (SCMs) in new concrete.	**No Importance (%)**	**Some Importance (%)**	**Important (%)**	**High Importance (%)**	**Very High Importance (%)**	**Average Rating**
	1	**2**	**3**	**4**	**5**	
Concerns regarding the durability of the new concrete	0	1	1	6	14	**4.5**
Concerns regarding variability in material properties	0	1	2	10	9	**4.2**
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)	0	2	5	7	8	**4.0**
Concerns regarding performance of fresh concrete – setting time, workability, etc.	0	1	7	7	7	**3.9**
Concerns regarding the strength of the new concrete	0	4	1	12	5	**3.8**
Concerns regarding the material supply being consistently available	1	2	8	8	3	**3.5**
Ready availability of conventional materials that are suitable and inexpensive	1	4	8	6	3	**3.3**
Specifications currently restrict use	2	7	6	3	4	**3.0**
Lack of guidance on conducting concrete mixture designs and proportioning using these materials	3	3	11	3	2	**2.9**
Economics (costs of producing/procuring by-product vs. cost of conventional materials)	3	2	13	3	1	**2.9**
Regulatory barriers (permitting, environmental regulations)	2	6	11	2	1	**2.7**

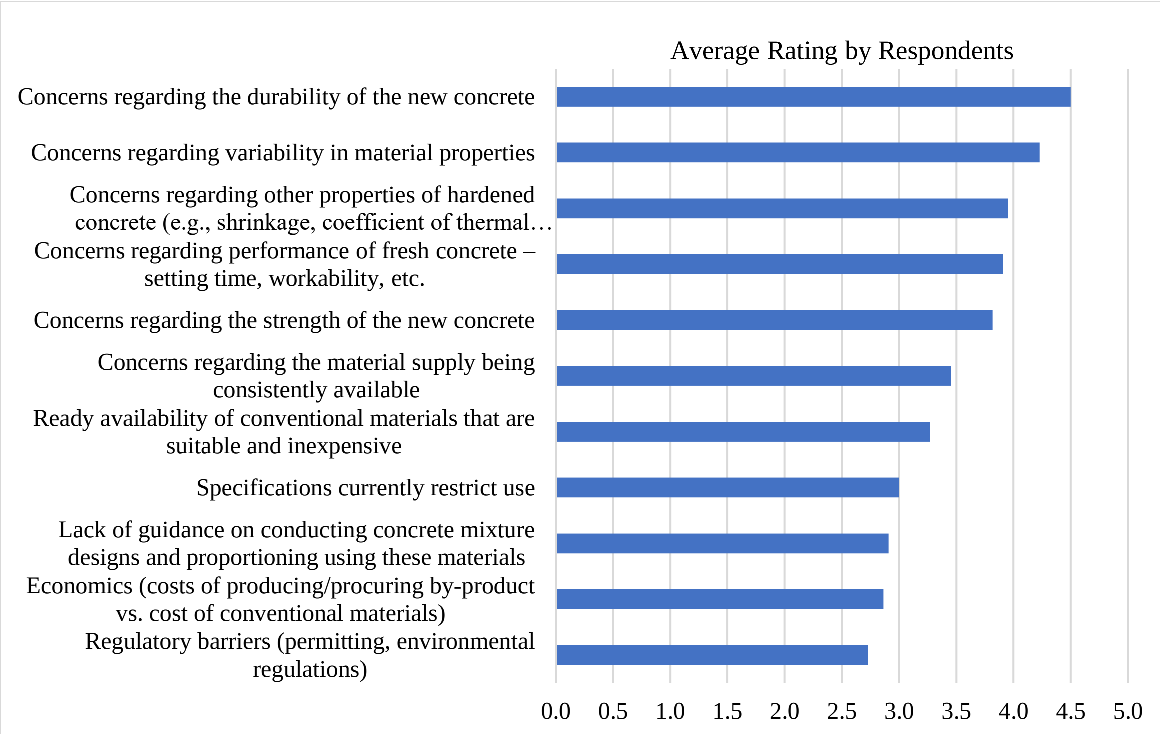

FIGURE 4.7 Responses for Question 5 of Agency Inquiry

4.3.5 Barriers of using by-products in new concrete as aggregate or filler material:

Similar to the barriers of using the by-products as SCM, the most critical barrier identified is the durability of new concrete with a rating (4.5) which dropped significantly (to 4.1) for the next three consecutive barriers. The three barriers that have same rating, variability in material properties, performance of fresh concrete and properties of hardened concrete properties are also of very high importance to most of the agencies. Regulatory barriers and specifications that currently restrict the use of by-products are viewed to have less importance to many agencies. Of note, regulatory barriers were rated significantly lower (2.6) than the next two least important barriers specification restrictions and lack of guidance (3.0).

TABLE 4.7 Responses for Question 6 of Agency Inquiry

Q6. On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products as aggregates or inert fillers in new concrete.	**No Importance (%)**	**Some Importance (%)**	**Important (%)**	**High Importance (%)**	**Very High Importance (%)**	**Average Rating**
	1	**2**	**3**	**4**	**5**	
Concerns regarding the durability of the new concrete	0	1	1	6	14	**4.5**
Concerns regarding variability in material properties	0	1	4	9	8	**4.1**
Concerns regarding performance of fresh concrete – setting time, workability, etc.	0	0	6	8	8	**4.1**
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)	0	3	2	7	10	**4.1**
Concerns regarding the strength of the new concrete	0	2	3	13	4	**3.9**
Concerns regarding the material supply being consistently available	1	3	5	9	4	**3.5**
Ready availability of conventional materials that are suitable and inexpensive	2	3	7	5	5	**3.4**
Economics (costs of producing/procuring by-product vs. cost of conventional materials)	2	2	12	4	2	**3.1**
Lack of guidance on conducting concrete mixture designs and proportioning using these materials	1	4	12	3	2	**3.0**
Specifications currently restrict use	2	8	6	0	6	**3.0**
Regulatory barriers (permitting, environmental regulations)	3	7	9	2	1	**2.6**

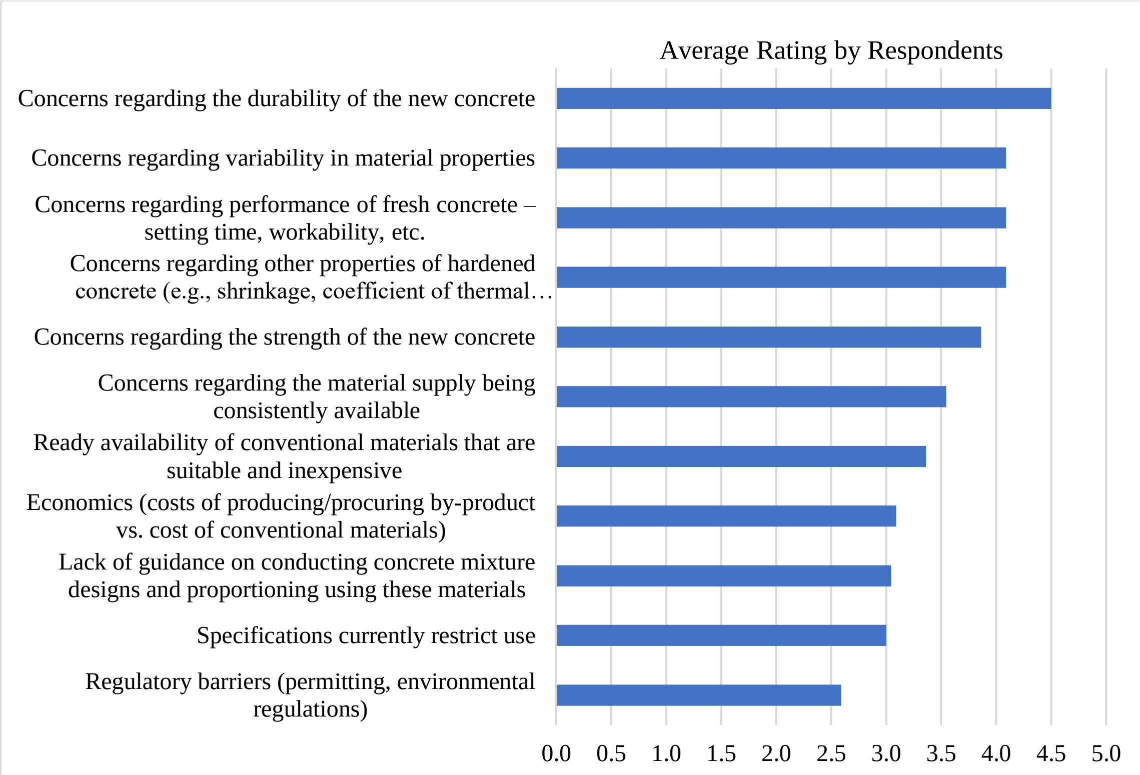

FIGURE 4.8 Responses for Question 6 of Agency Inquiry

4.3.6 Reasons for allowing the use of by-products in concrete pavement:

From the Table 4.8 and Figure 4.9, economic benefits of recycling RCA was identified as a major reason to support increased use, with 14 responses for which the agencies are considering allowing it in the pavement applications. Other than that, lack of availability of other by-products seems to be the reason for use of most of the by-products listed in the Table 4.8. There are few other reasons of interest that some of the respondents mentioned in the comments such as:

1. "Recycled concrete aggregate from mixed sources is allowed and new concrete pavement as a result of legislation to reduce stockpiles of waste concrete. Crushed glass is allowed but is not currently being used".
2. "RCA is currently not allowed for use as subbase due to environmental issues. We are looking at ways to mitigate these issues so that it can be used again. As

for the rest of the products, we have not been asked to look at them as far as I know".

3. "Off-specification fly ash: Specifically looking at it for a blended fly ash product Recycled Asphalt Pavement: Probably wouldn't consider since it is already used extensively in HMA; we may have tried in the lab to no avail. Crumb Rubber: We may have tried in the lab to no avail".

TABLE 4.8 Responses for Question 3 of Agency Inquiry

Q3. For what reasons are you allowing (or considering allowing) the construction and/or industrial by-products in concrete pavement applications?	Lack of availability of other products (supplementary cementitious materials and/or aggregates)	Cost savings over other products (supplementary cementitious materials and/or aggregates)	Economic benefits of recycling these materials from a project (or sourcing from a local industry or project)	Other
Bottom ash	3	3	1	7
Off-specification fly ash	6	5	2	8
Rice husk ash	5	0	0	3
Sugar cane ash	4	0	0	3
Water treatment residuals	2	0	0	4
Recycled concrete aggregate	3	6	14	5
Mixed rubble	1	2	4	6
Recycled asphalt pavement	1	6	4	4
Concrete grinding slurry and fines	0	1	0	5
Hydro-demolition residual material	0	1	0	5
Brick waste	1	0	0	5
Crushed glass	2	0	1	5
Crumb rubber	0	2	0	5
Porcelain	1	0	0	5
Plastics	1	0	0	5

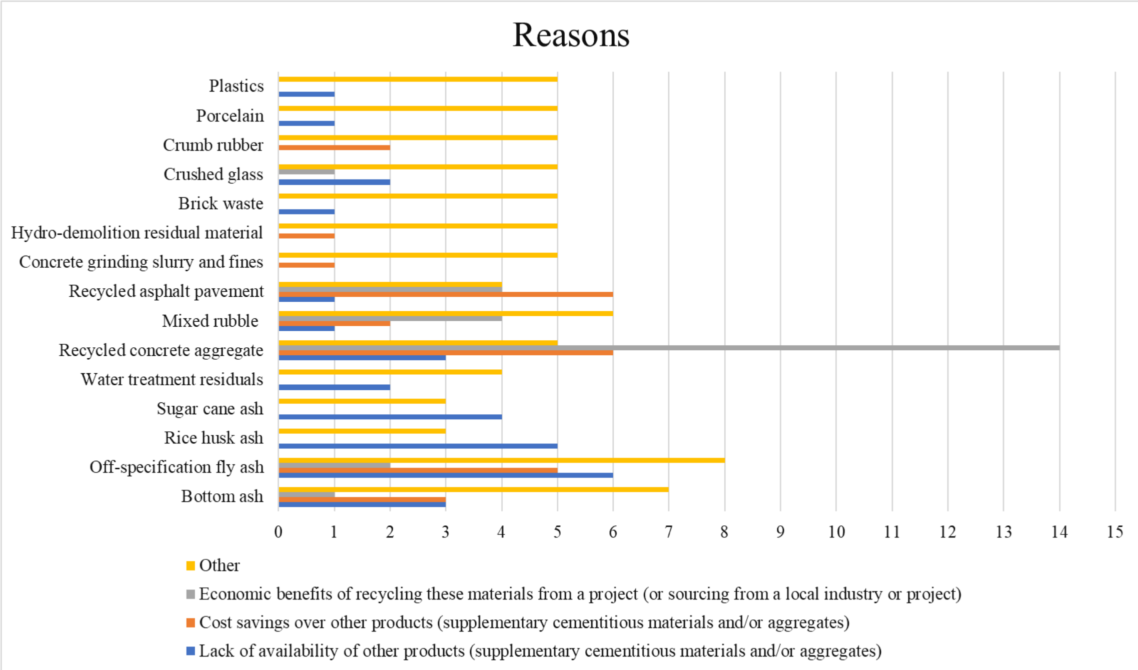

FIGURE 4.9 Responses for Question 3 of Agency Inquiry

4.3.7 Benefits of using construction and industrial by-products:

Most agencies appear to believe that use of by-product in transportation infrastructure enhances foundation material and/or concrete quality. Thus, it is a benefit with high importance to the agencies. They also appear to believe that it conserves natural materials, reduces projects cost along with the reduction of environmental impacts of producing cement and aggregate. The benefit ranked least important is the increasing strategic business opportunities and business competitiveness. With a relatively high average rating (3.0), business opportunities/competitiveness offered by use of byproducts can be considered important benefits.

TABLE 4.9 Responses for Question 14 of Agency Inquiry

Q14. Please rate the importance of the following potential benefits associated with the use of construction and industrial by-products in your transportation infrastructure.	No Importance (%)	Some Importance (%)	Important (%)	High Importance (%)	Very High Importance (%)	Total	Average Rating
	1	2	3	4	5		
Enhancing foundation material and/or concrete quality	0	0	5	10	7	22	**4.1**
Reducing project costs through use of recycled materials	0	1	6	10	5	22	**3.9**
Conserving natural materials	1	3	5	6	7	22	**3.7**
Reducing the environmental impacts of cement and aggregate production	2	3	3	10	4	22	**3.5**
Conserving landfill space and reducing the need for new landfill	1	4	6	6	5	22	**3.5**
Increasing strategic business opportunities and business competitiveness	2	5	9	4	2	22	**3.0**

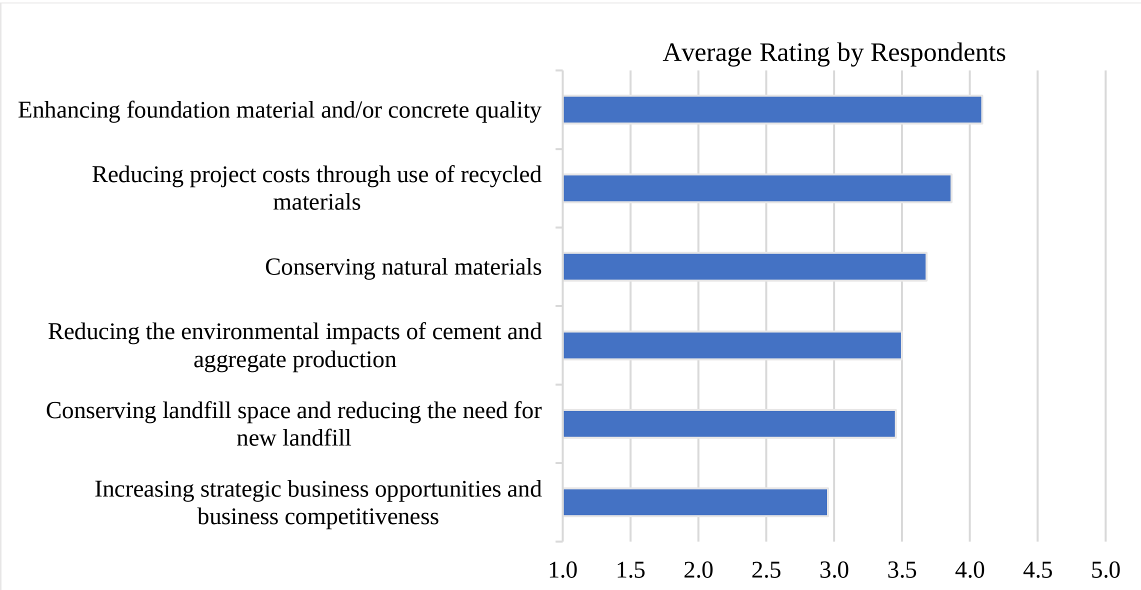

FIGURE 4.10 Responses for Question 14 of Agency Inquiry

4.3.8 Characterization Tests:

4.3.8.1 Supplementary Cementitious Material:

4.3.8.1.1 Characterization Tests of By-product Materials:

The most important characterization test(s) identified by the agencies are those to determine the incompatibility of by-products with certain cements that could lead to failure of the concrete with a significant high score (4.4) which reduced (to 4.1) in the next important test of uniformity. Eleven agencies indicated that water requirements associated with use of the by-product as an SCM is of high importance, and for most of them density of the by-product material does not seems to hold much importance. Other characteristics appeared to have significant importance (scoring >3).

TABLE 4.10 Responses for Question 7 of Agency Inquiry

Q7. What characterization tests of the by-product materials listed above would provide your agency confidence in their use as a supplementary cementitious material (SCM) in pavement foundations or in new concrete?	**No Importance (%)**	**Some Importance (%)**	**Important (%)**	**High Importance (%)**	**Very High Importance (%)**	**Total**	**Average Rating**
	1	**2**	**3**	**4**	**5**		
Incompatibility with certain cements	0	1	1	9	11	22	**4.4**
Uniformity	0	1	5	7	9	22	**4.1**
Other contaminants	0	1	6	10	5	22	**3.9**
Soundness (autoclave expansion or other)	1	2	5	7	7	22	**3.8**
Strength activity index	1	0	8	9	4	22	**3.7**
Chemical composition	2	2	5	6	7	22	**3.6**
Water requirement	1	1	6	11	3	22	**3.6**
Carbon content	3	0	10	4	5	22	**3.4**
Fineness	3	2	10	5	2	22	**3.0**
Specific gravity	4	4	8	5	1	22	**2.8**
Density	4	4	9	4	1	22	**2.7**

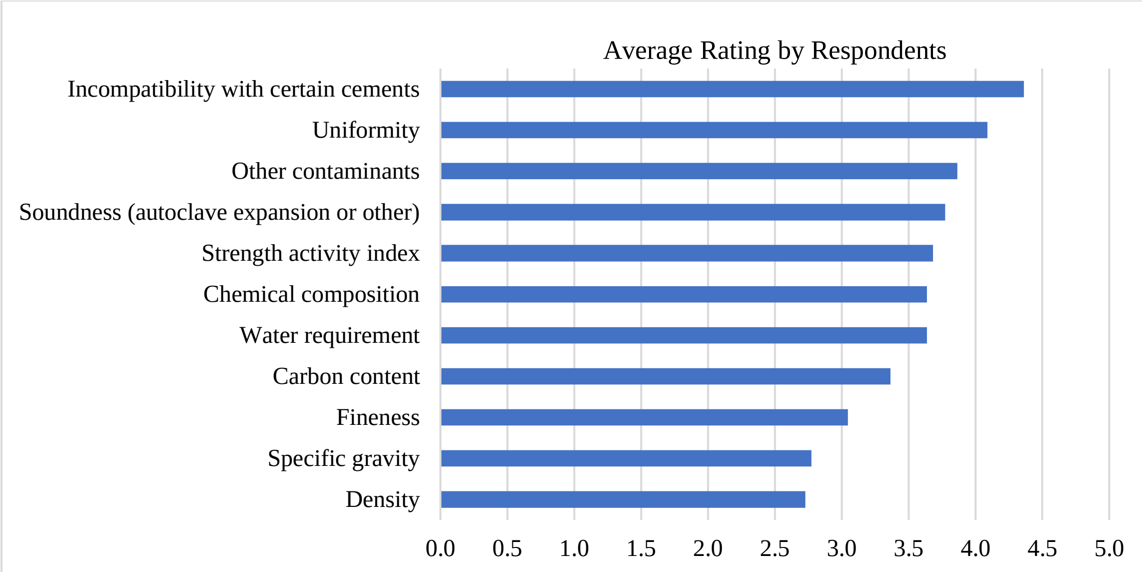

FIGURE 4.11 Responses for Question 7 of Agency Inquiry

4.3.8.1.2 Characterization Tests of Base Materials Stabilized with By-products:

The agencies tended to indicate all the three tests (elastic modulus, permeability, and shear strength) important, with each test scoring an average rating between 3 and 4. Amongst the three tests, permeability was identified as highly important by many (9) agencies.

TABLE 4.11 Responses for Question 8 of Agency Inquiry

Q8. What characterization tests of base materials stabilized with a by-product would provide your agency confidence in the by-product's use as a supplementary cementitious material (SCM) in pavement foundations or in new concrete?	**No Importance (%)**	**Some Importance (%)**	**Important (%)**	**High Importance (%)**	**Very High Importance (%)**	**Total**	**Average Rating**
	1	**2**	**3**	**4**	**5**		
Elastic modulus (stiffness)	0	0	11	6	5	22	**3.7**
Permeability	0	3	5	9	5	22	**3.7**
Shear strength	0	1	11	7	3	22	**3.5**

FIGURE 4.12 Responses for Question 8 of Agency Inquiry

4.3.8.1.3 Characterization Tests of Concrete Incorporating By-products:

Most of the agencies indicated that tests to confirm low permeability, resistance to freezing and thawing, and resistance to deicing salts are viewed as very critical to use by-products as SCM. For some agencies, resistance to deicing salts does not appear to be viewed important at all. This is likely a function of geographical location of the agency/respondent. The average rating for heat of hydration of concrete as an important test was slightly lower than other results (>3) but it is still of high importance of many agencies.

TABLE 4.12 Responses for Question 9 of Agency Inquiry

Q9. What characterization tests of the concrete incorporating a by-product would provide your agency confidence in the by product's use as a supplementary cementitious material (SCM) in pavement foundations or in new concrete?	**No Importance (%)**	**Some Importance (%)**	**Important (%)**	**High Importance (%)**	**Very High Importance (%)**	**Total**	**Average Rating**
	1	**2**	**3**	**4**	**5**		
Permeability	0	1	2	7	12	22	**4.4**
Strength	0	1	5	8	8	22	**4.0**
Resistance to freezing and thawing	1	2	5	3	11	22	**4.0**
Resistance to deicing salts	3	1	4	1	13	22	**3.9**

TABLE 4.12(Cont.) Responses for Question 9 of Agency

Q9. What characterization tests of the concrete incorporating a by-product would provide your agency confidence in the by product's use as a supplementary cementitious material (SCM) in pavement foundations or in new concrete?	No Importance (%)	Some Importance (%)	Important (%)	High Importance (%)	Very High Importance (%)	Total	Average Rating
	1	2	3	4	5		
Susceptibility to ASR	2	4	3	5	8	22	**3.6**
Workability	0	2	9	9	2	22	**3.5**
Initial and final set	0	3	10	5	4	22	**3.5**
Susceptibility to sulfate attack	1	6	4	4	7	22	**3.5**
Heat of hydration of concrete	0	4	8	8	2	22	**3.4**

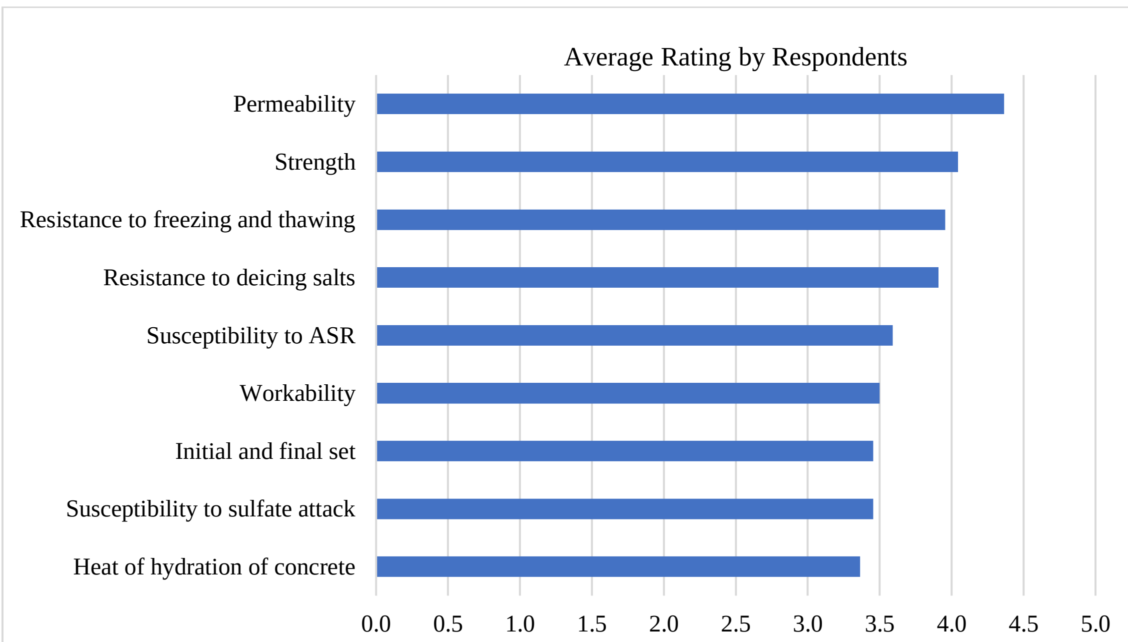

FIGURE 4.13 Responses for Question 9 of Agency Inquiry

4.3.8.2 Aggregate or Filler Material:

4.3.8.2.1 Characterization Tests of By-product Aggregate or Filler Materials:

The abrasion resistance test was cited as the most critical of the tests that many agencies believe are of high importance. The specific gravity appears to be of least importance to many (5) agencies, while gradation appears to be of high importance to 9 of them. Abrasion resistance is a key performance measure of concrete used in paving applications, which is likely the targeted use of byproducts for many agencies, as opposed to structural uses with greater safety implications.

TABLE 4.13 Responses for Question 10 of Agency Inquiry

Q10. What characterization tests of the by-products listed above would provide your agency confidence in their use as an aggregate or filler material in pavement foundations or new concrete?	**No Importance (%)**	**Some Importance (%)**	**Important (%)**	**High Importance (%)**	**Very High Importance (%)**	**Total**	**Average Rating**
	1	**2**	**3**	**4**	**5**		
Abrasion resistance (L.A., Micro-Deval or Other)	0	1	3	10	8	22	**4.1**
Percent passing #200	0	3	5	8	6	22	**3.8**
Soundness OR Unconfined Freeze-Thaw	2	1	5	6	8	22	**3.8**
Gradation	1	1	8	9	3	22	**3.5**
Absorption	1	4	7	7	3	22	**3.3**
Specific gravity	5	2	9	4	2	22	**2.8**

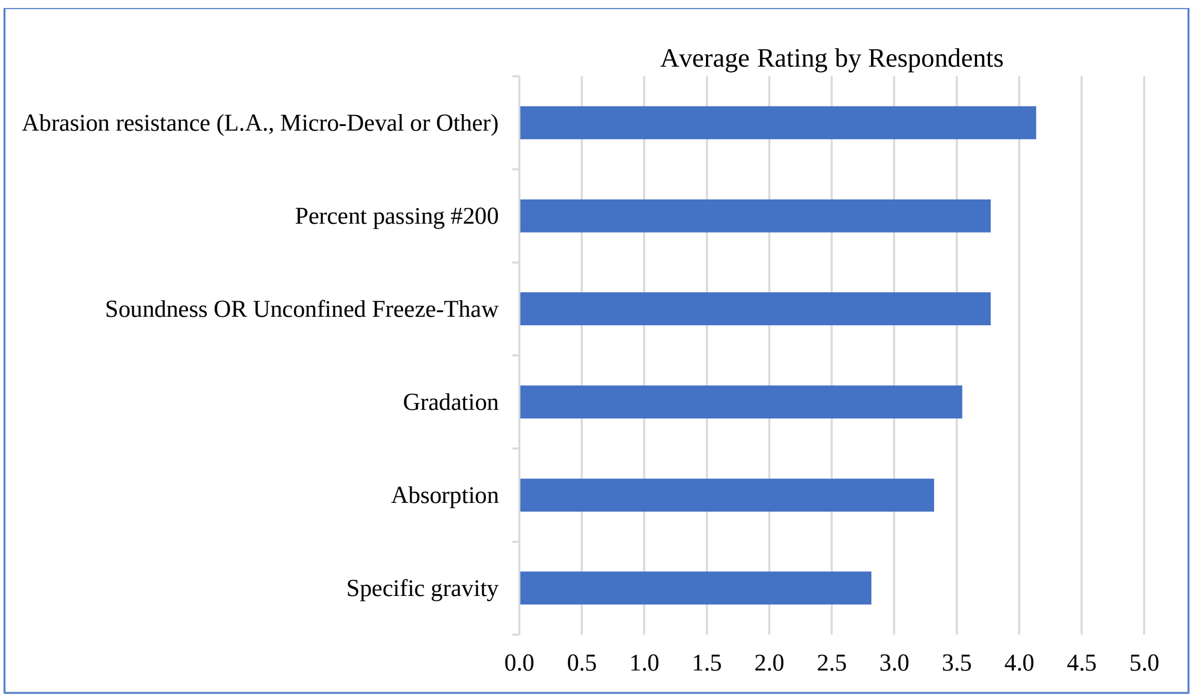

FIGURE 4.14 Responses for Question 10 of Agency Inquiry

4.3.8.2.2 Characterization Tests of Unbound Base Material:

Half of the agencies indicated that they believe that suitably low permeability is highly important. However, the highest rating was achieved by strength of concrete as for 8 agencies it is highly important and for 5 it has very high importance. Nine agencies indicated that the leachate potential of the material is of very high importance. While for 2 of them, density is of no importance.

TABLE 4.14 Responses for Question 11 of Agency Inquiry

Q11. What characterization tests of unbound base material incorporating recycled or by-product aggregates would provide your agency confidence in their use as an aggregate or filler material in pavement foundations or new concrete?	**No Importance (%)**	**Some Importance (%)**	**Important (%)**	**High Importance (%)**	**Very High Importance (%)**	**Total**	**Average Rating**
	1	**2**	**3**	**4**	**5**		
Strength (Shear, CBR or Other)	0	1	8	8	5	22	**3.8**
Leachate potential and composition	1	4	4	4	9	22	**3.7**
Permeability	0	1	8	10	3	22	**3.7**
Density	2	3	9	6	2	22	**3.1**

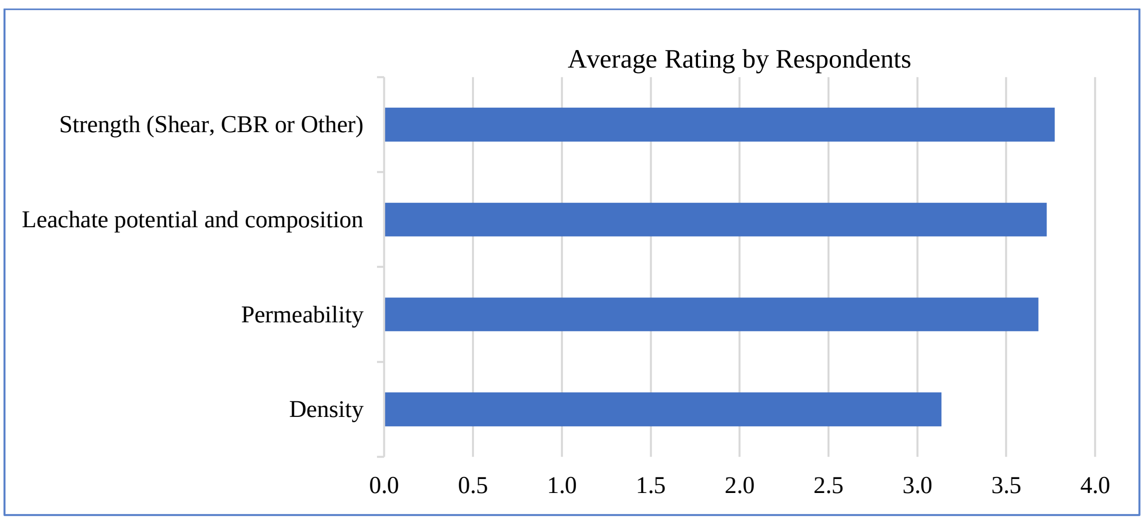

FIGURE 4.15 Responses for Question 11 of Agency Inquiry

4.3.8.2.3 Characterization tests of Stabilized Base:

All the three tests for the stability of base materials are judged to be important for the agencies. Although the average rating for stiffness was higher (3.8 vs. 3.7 and 3.6) than the other two tests, more agencies appeared to believe that strength and permeability are highly important.

TABLE 4.15 Responses for Question 12 of Agency Inquiry

Q12. What characterization tests of stabilized base material incorporating recycled or by-product aggregate would provide your agency confidence in their use as an aggregate or filler material in pavement foundations or new concrete?	**No Importance (%)**	**Some Importance (%)**	**Important (%)**	**High Importance (%)**	**Very High Importance (%)**	**Total**	**Average Rating**
	1	**2**	**3**	**4**	**5**		
Stiffness (Elastic or Resilient Modulus or Other)	0	0	10	7	5	22	**3.8**
Strength (Compressive, Flexural or Other)	0	3	5	9	5	22	**3.7**
Permeability	0	3	6	9	4	22	**3.6**

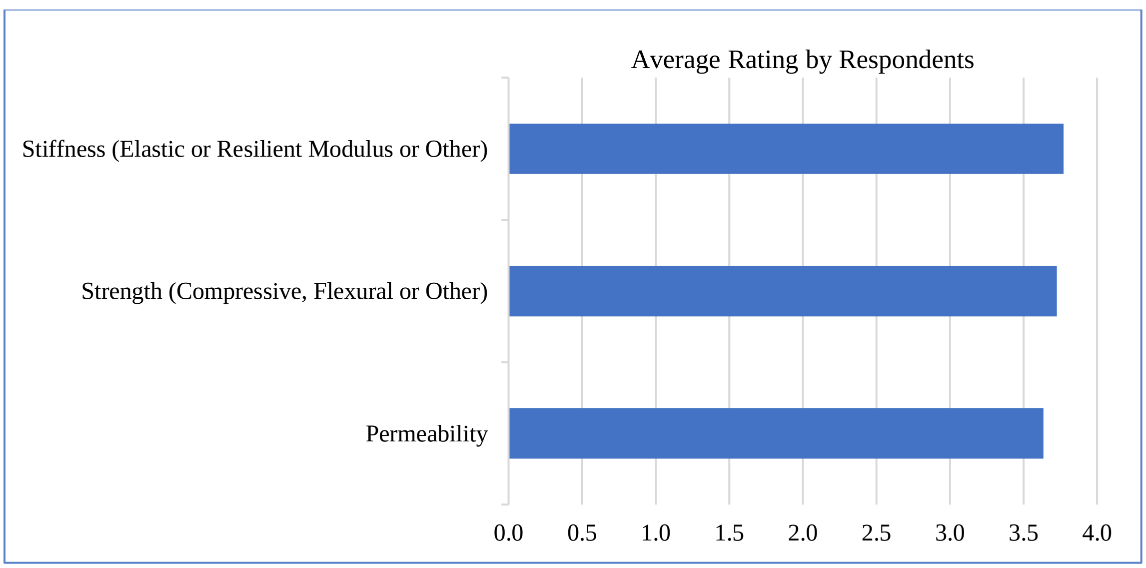

FIGURE 4.16 Responses for Question 12 of Agency Inquiry

4.3.8.2.4 Characterization Tests of Concrete:

For this question, the greatest number of agencies indicated that they believe that permeability, resistance to freeze/thaw distress, and resistance to deicing salts is of very high importance to be incorporated in concrete as aggregate. Some believe that resistance to deicing salts and susceptibility to ASR is of no importance, although this may be a function of geographic location and the presence/absence of ASR-susceptible aggregates respectively. While strength and workability are viewed as highly important, the least important test was reported to be susceptibility to sulfate attack.

TABLE 4.16 Responses for Question 13 of Agency Inquiry

Q13. What characterization tests of concrete incorporating recycled or by-product aggregate would provide your agency confidence in their use as an aggregate or filler material in pavement foundations or new concrete?	**No Importance (%)**	**Some Importance (%)**	**Important (%)**	**High Importance (%)**	**Very High Importance (%)**	**Total**	**Average Rating**
	1	**2**	**3**	**4**	**5**		
Permeability	0	1	1	7	13	22	**4.5**
Strength (Compressive, Flexural, or Other)	0	0	6	11	5	22	**4.0**
Workability – Quality and Duration	0	1	6	9	6	22	**3.9**
Resistance to Freezing and Thawing	1	3	3	5	10	22	**3.9**
Resistance to Deicing Salts (Salt Scaling, Formation Factor, or Other)	3	3	1	3	12	22	**3.8**
Susceptibility to ASR	3	4	2	4	9	22	**3.5**
Susceptibility to Sulfate Attack	1	4	6	4	7	22	**3.5**

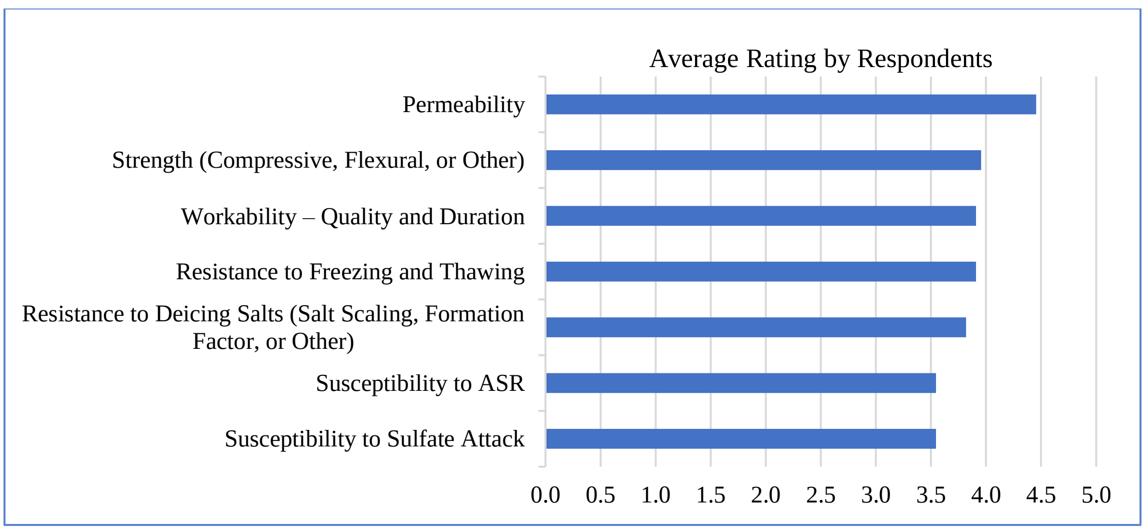

FIGURE 4.17 Responses for Question 13 of Agency Inquiry

4.4 Industry Responses:

A total of 20 responses were received from the contractors or the industry stakeholders (Figure 4.18). The figure shows that responses were received from industry respondents in 14 different states from which 20 contractors responded to the inquiry. Single response was received from each state except Texas (3 responses), Illinois (4 responses) and Colorado (2 responses).

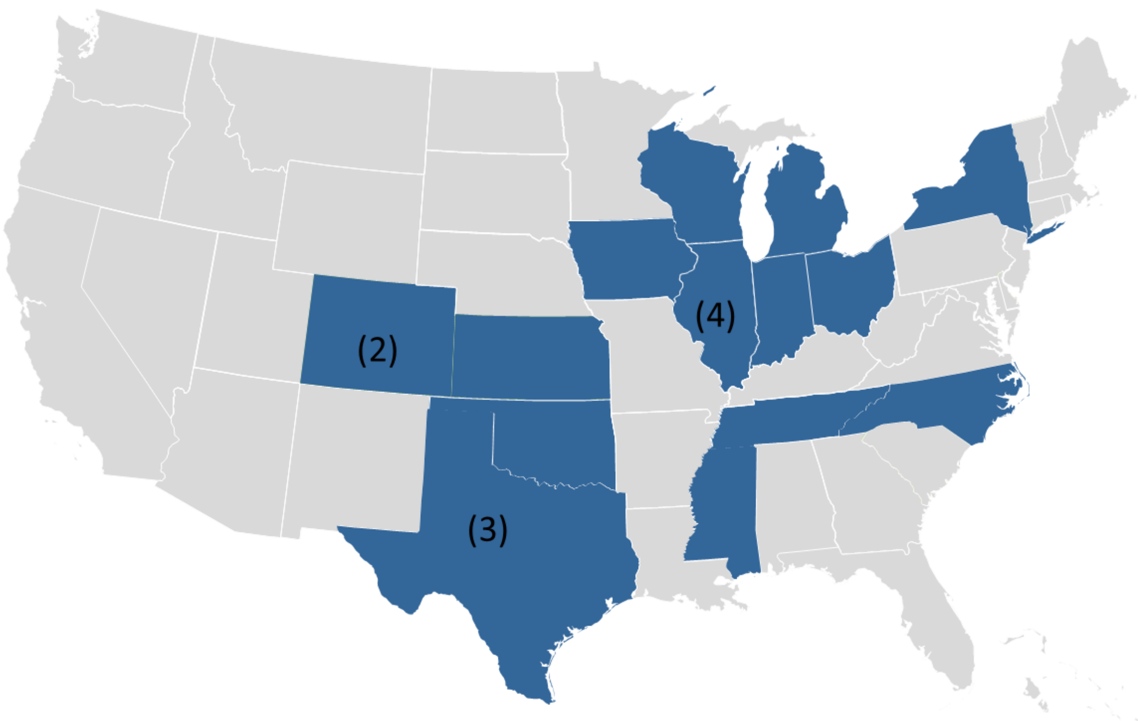

FIGURE 4.18 States represented by the contractor that responded to the inquiry questions

Key Findings:

It can be seen that most of the respondents are currently using RCA in pavement foundations as well as in new concrete. Rice husk ash, sugar cane husk, water treatment residue, brick waste, crushed glass and porcelain are the materials which are not used in either of the applications by any of the industry respondents, but many of them are interested in using these materials. Most of them are interested in using crushed glass and concrete grinding slurry and fines in both pavement foundations and in new concrete.

The utilization of the remaining byproduct materials are as follows:

4.4.1 Pavement Foundation:

Table 4.17 shows the number of Industry respondents using each type of material in pavement foundation. It can be seen that most of the respondents are using RCA and RAP in pavement foundations as a substitute material, and most of them are interested in using other the materials included in this study.

TABLE 4.17 Responses for Question 2 of Industry Inquiry

Q2. Which of the following construction and/or industrial by-products are you allowing (or considering allowing) in concrete pavement applications?	**Pavement Foundation**		
	Yes	**Interested**	**No**
Bottom ash	3	7	10
Off-specification fly ash	4	9	7
Rice husk ash	0	8	12
Sugar cane ash	0	8	12
Water treatment residuals	0	4	16
Recycled concrete aggregate	12	6	2
Mixed rubble (recycled aggregates from mixed sources)	3	9	8
Recycled asphalt pavement	7	8	5
Concrete grinding slurry and fines	2	11	7
Hydro-demolition residual material	1	9	10
Brick waste	0	8	12
Crushed glass	0	10	10
Crumb rubber	1	4	15
Porcelain	0	4	16
Plastics	1	5	14

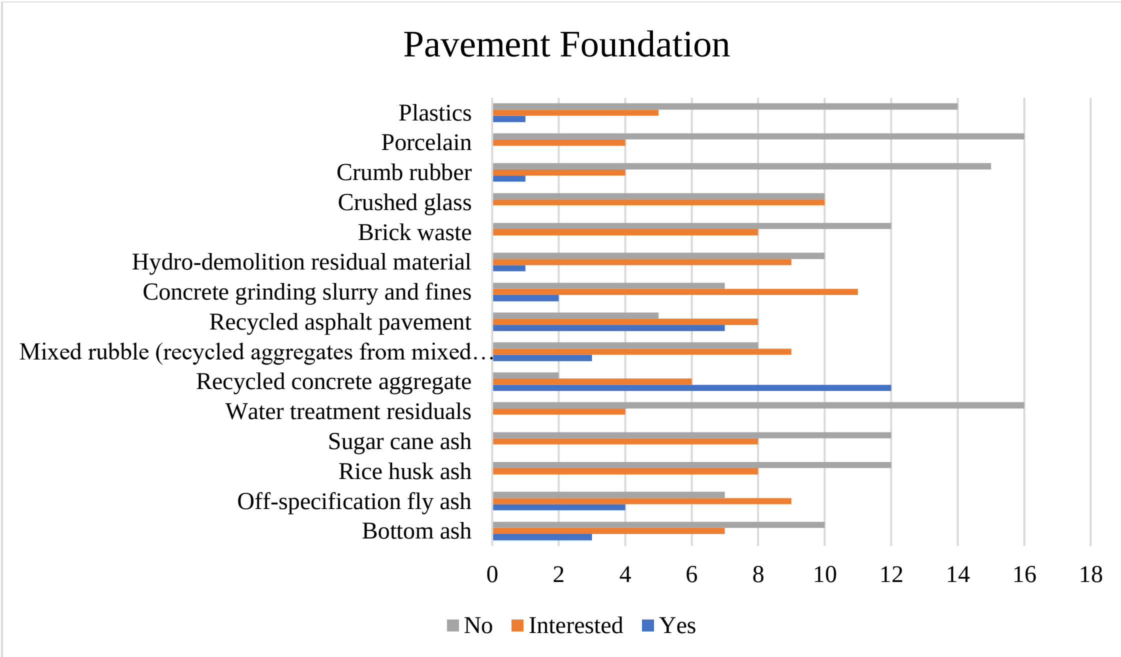

FIGURE 4.19 Responses for Question 2 of Industry Inquiry

4.4.2 Barriers of using by-products in pavement foundation:

From the Table 4.18, it can be surmised that most contractors feel they are restricted by the specifications for the use of by-products in pavement foundation applications. This barrier had a score (4.2) significantly higher than the next greatest barrier which is economics and availability of the materials (3.7) thus specification restrictions appear to be highly important as per the contractor’s perspective. It is noted that 2 respondents indicate that the specifications are of no importance as a barrier to use. The regulatory barriers and environmental impacts are highly important to many respondents though their average rating is not much high. The least important barrier for the industries as per the Table 4.18 is the concern regarding foundation strength and/or stability and the variability in material properties, but they still hold some importance with rating above 3.

TABLE 4.18 Responses for Question 4 of Industry Inquiry

Q4. On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers within your agency to using construction or industrial by-product in pavement foundations. Foundation applications include bound bases/subbases, unbound bases/subbases, and natural/stabilized soils.	**No Importance (%)**	**Some Importance (%)**	**Important (%)**	**High Importance (%)**	**Very High Importance (%)**	**Total**	**Average Rating**
	1	**2**	**3**	**4**	**5**		
Specifications currently restrict use	2	0	3	3	12	20	**4.2**
Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials)	2	2	3	7	6	20	**3.7**
Ready availability of good, inexpensive SCM and natural aggregate sources	1	3	5	4	7	20	**3.7**
Regulatory barriers (permitting, environmental regulations)	2	1	4	9	4	20	**3.6**
Concerns regarding the material supply being consistently available	3	1	6	5	5	20	**3.4**
Concerns regarding durability of the by-product in service	2	4	4	6	4	20	**3.3**
Concerns regarding environmental impacts (e.g. runoff, leachate, etc.)	2	4	4	8	2	20	**3.2**
Concerns regarding foundation strength and/or stability	4	1	6	7	2	20	**3.1**
Concerns regarding variability in material properties	2	3	9	3	3	20	**3.1**

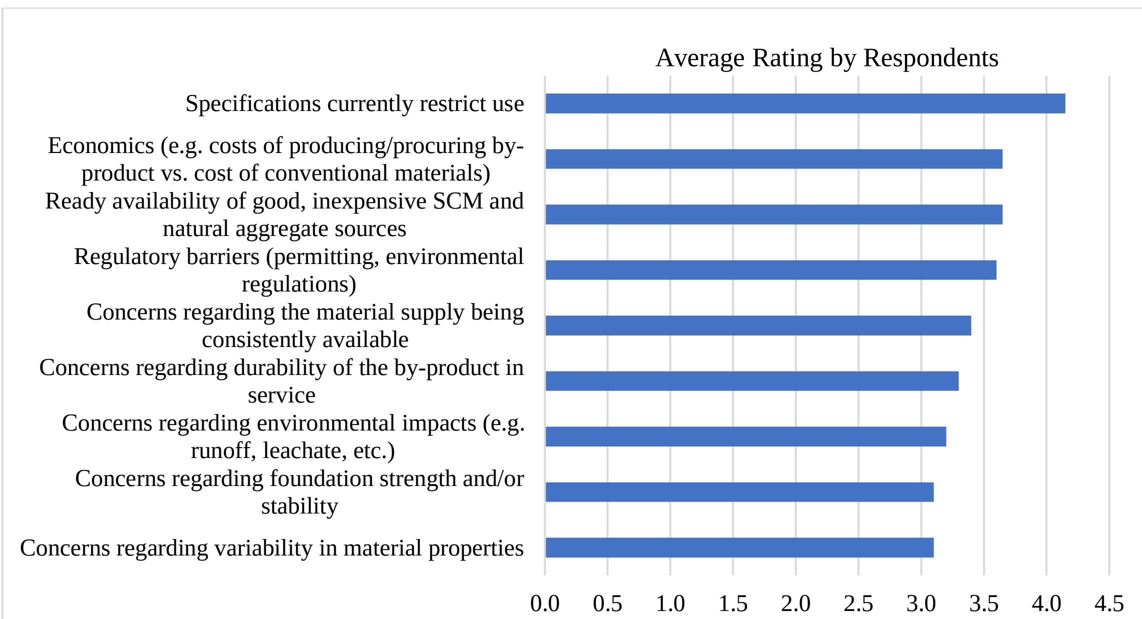

FIGURE 4.20 Responses for Question 4 of Industry Inquiry

4.4.3 New Concrete:

Table 4.19 shows the number of Industry respondents using each type of material in new concrete. The table shows that most of the people have not used many of the materials in new concrete. The most commonly used material is RCA. Many of the contractors are interested in using all the materials listed as a substitute material in new concrete.

TABLE 4.19 Responses for Question 2 of Industry Inquiry

Q2. Which of the following construction and/or industrial by-products are you allowing (or considering allowing) in concrete pavement applications?	**New Concrete**		
	Yes	**Interested**	**No**
Bottom ash	1	8	11
Off-specification fly ash	3	9	8
Rice husk ash	0	7	13
Sugar cane ash	0	8	12
Water treatment residuals	0	4	16
Recycled concrete aggregate	8	8	4
Mixed rubble (recycled aggregates from mixed sources)	1	7	12
Recycled asphalt pavement	1	7	12
Concrete grinding slurry and fines	1	11	8
Hydro-demolition residual material	0	7	13
Brick waste	0	7	13
Crushed glass	0	10	10
Crumb rubber	1	4	15
Porcelain	0	4	16
Plastics	1	5	14

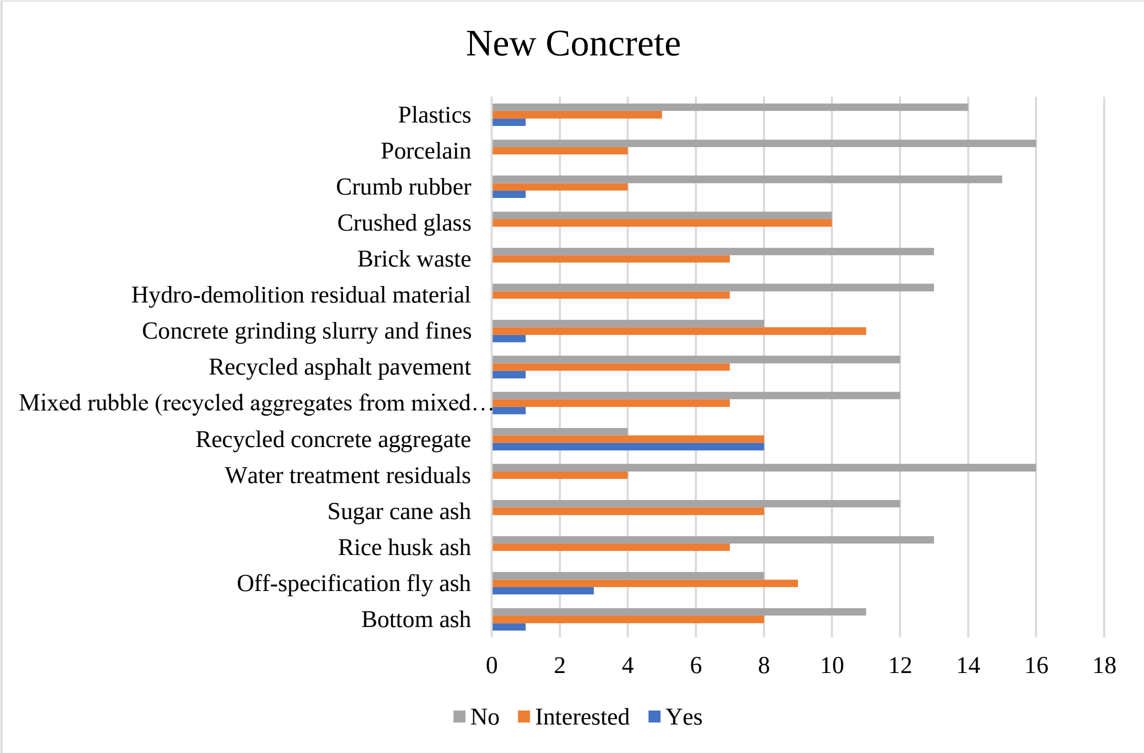

FIGURE 4.21 Responses for Question 2 of Industry Inquiry

4.4.4 Barriers of using by-products in new concrete as SCM:

Similar to the barriers cited by industry for use of these materials in pavement foundations, respondents appear to feel restricted by the specifications, and find specifications to be the most important barrier amongst all the listed barriers with a high rating (4.3). The availability and economics of the by-products, strength, performance, and durability of concrete are factors that most of the industry respondents are concerned about. The remainder of the barriers are also perceived to have high importance for most of the industry respondents with regards to use of the by-products as SCM in new concrete.

TABLE 4.20 Responses for Question 5 of Industry Inquiry

Q5. On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products as supplemental cementitious materials (SCMs) in new concrete.	**No Importance (%)**	**Some Importance (%)**	**Important (%)**	**High Importance (%)**	**Very High Importance (%)**	**Total**	**Average Rating**
	1	**2**	**3**	**4**	**5**		
Specifications currently restrict use	1	1	2	4	12	20	**4.3**
Concerns regarding the material supply being consistently available	0	1	4	5	10	20	**4.2**
Concerns regarding the strength of the new concrete	2	0	3	3	12	20	**4.2**
Concerns regarding performance of fresh concrete – setting time, workability, etc.	1	2	1	6	10	20	**4.1**
Economics (costs of producing/procuring by-product vs. cost of conventional materials)	0	3	2	5	10	20	**4.1**
Concerns regarding the durability of the new concrete	2	0	3	5	10	20	**4.1**
Concerns regarding variability in material properties	2	2	0	9	7	20	**3.9**
Lack of guidance on conducting concrete mixture designs and proportioning using these materials	1	2	4	5	8	20	**3.9**
Ready availability of conventional materials that are suitable and inexpensive	0	4	4	3	9	20	**3.9**
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)	1	2	5	5	7	20	**3.8**

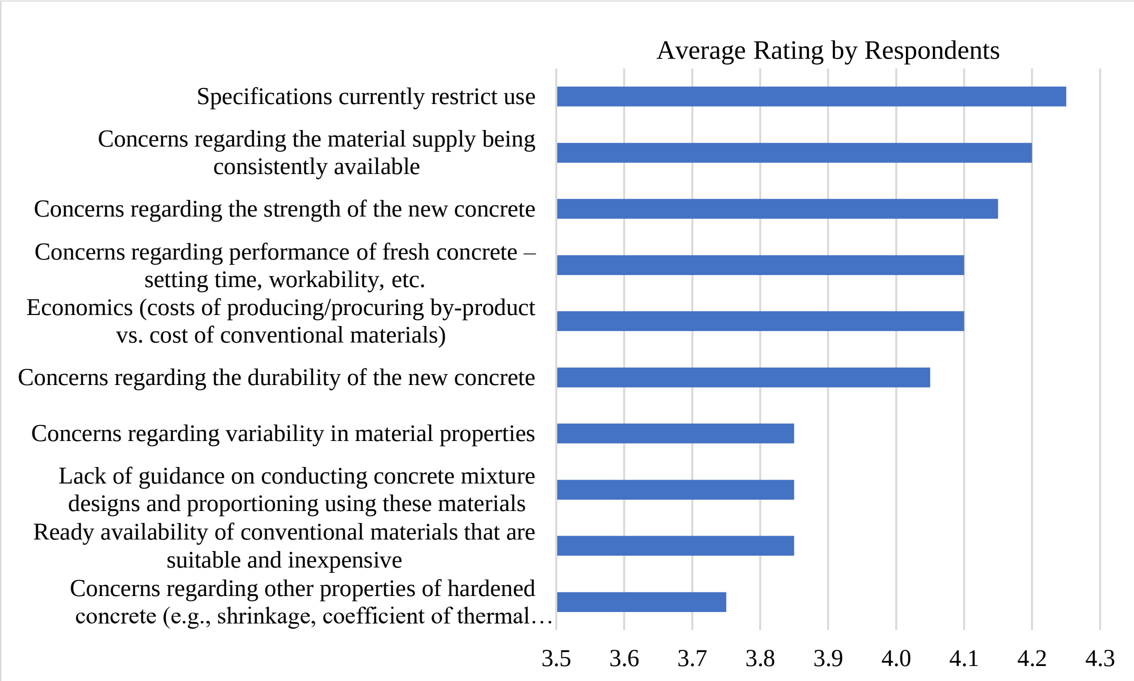

FIGURE 4.22 Responses for Question 5 of Industry Inquiry

4.4.5 Barriers of using by-products in new concrete as Aggregate or filler material:

It can be surmised that the highest number of respondents seems to find that specifications currently restrict the use of by-products the most important barrier with a high average rating (4.5) which dropped significantly (to 4.0) for the next two consecutive important barriers, which are durability concerns and the lack of guidance for conducting mixture designs and proportioning using these materials. Strength of the concrete is also very important for 10 contractors, for some it is not important. Concerns for the properties of hardened concrete seems highly important to 9 contractors but it has the lowest average rating (3.5).

TABLE 4.21 Responses for Question 6 of Industry Inquiry

Q6. On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products as aggregates or inert fillers in new concrete.	**No Importance (%)**	**Some Importance (%)**	**Important (%)**	**High Importance (%)**	**Very High Importance (%)**	**Total**	**Average Rating**
	1	**2**	**3**	**4**	**5**		
Specifications currently restrict use	0	1	1	5	13	20	**4.5**
Concerns regarding the durability of the new concrete	2	0	2	9	7	20	**4.0**
Lack of guidance on conducting concrete mixture designs and proportioning using these materials	1	1	4	6	8	20	**4.0**
Concerns regarding variability in material properties	1	1	5	5	8	20	**3.9**
Concerns regarding performance of fresh concrete – setting time, workability, etc.	2	2	0	9	7	20	**3.9**
Concerns regarding the strength of the new concrete	2	1	5	2	10	20	**3.9**
Economics (costs of producing/procuring by-product vs. cost of conventional materials)	2	1	5	4	8	20	**3.8**
Ready availability of conventional materials that are suitable and inexpensive	1	2	6	4	7	20	**3.7**
Concerns regarding the material supply being consistently available	1	2	5	7	5	20	**3.7**
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)	2	1	5	9	3	20	**3.5**

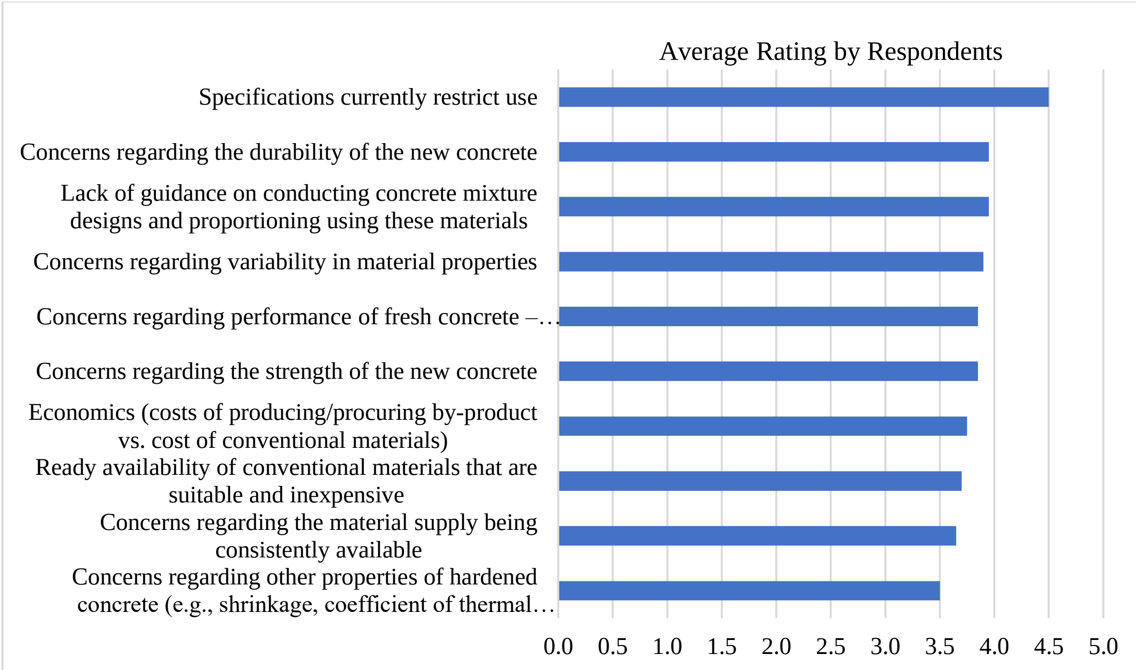

FIGURE 4.23 Responses for Question 6 of Industry Inquiry

4.4.6 Reasons for using by-products in pavement applications:

Most of the industry respondents seem to believe that the use of RCA, RAP and mixed rubble provide cost savings over use of other conventional products, and also have economic advantages. Many industry respondents indicated they are interested in using RHA, SCBA and off-specification fly ash due to the lack of availability of other products. The remainder of the other materials included in this study appear to be of interest to most of the industry respondents. Some respondents also listed some other reasons in the comment section, such as:

1. “Many of these materials are by products or waste from other processes. Incorporating them into the highway pavement system as useful materials eliminates the need to otherwise dispose of them. It also helps to conserve virgin material sources - which are depleting in some areas - and generally seems more sustainable than producing new material. Finally, I expect it would bring cost savings to the owner in the form of lower prices on materials from standard sources, due to the increased competition”.

2. “Slag and Fly Ash offer High Performance and heat hydration control. Bottom Ash not suitable cementitious material”.
3. “Other responses are there is considerable potential waste, and it needs a place to go besides landfills Crumb rubber & Plastics - better used as a whole tire and fuel source for cement kilns”.

TABLE 4.22 Responses for Question 3 of Industry Inquiry

Q3. For what reasons are you using (or interested in using) the construction and/or industrial by-products in concrete pavement applications?	Lack of availability of other products (supplementary cementitious materials and/or aggregates)	Cost savings over other products (supplementary cementitious materials and/or aggregates)	Economic benefits of recycling these materials from a project (or sourcing from a local industry or project)	Other
Bottom ash	10	10	5	7
Off-specification fly ash	12	10	7	7
Rice husk ash	13	8	5	6
Sugar cane ash	12	7	5	7
Water treatment residuals	8	4	5	7
Recycled concrete aggregate	6	15	14	4
Mixed rubble (recycled aggregates from mixed sources)	5	12	10	7
Recycled asphalt pavement	6	11	13	5
Concrete grinding slurry and fines	6	10	7	7
Hydro-demolition residual material	7	7	5	7
Brick waste	7	6	6	7
Crushed glass	8	7	8	8
Crumb rubber	7	6	6	7
Porcelain	6	5	5	8
Plastics	7	5	5	8

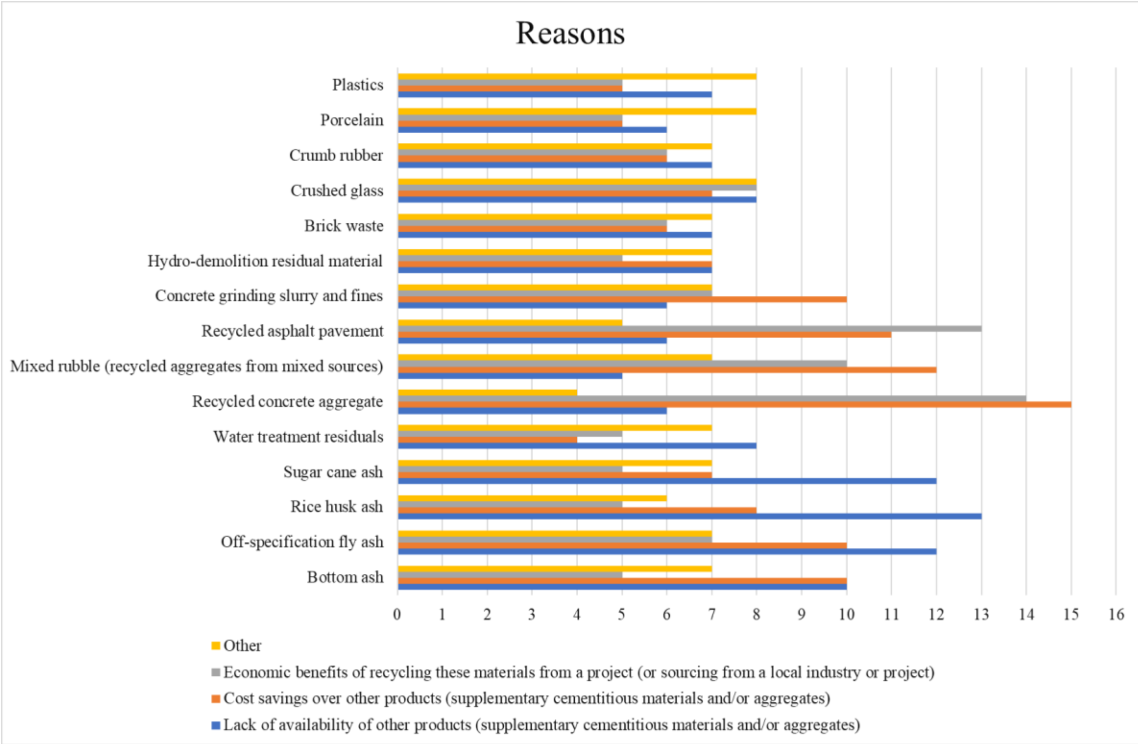

FIGURE 4.24 Responses for Question 3 of Industry Inquiry

4.4.7 Benefits of using construction and industrial by-products:

From the Table 4.23, it can be surmised that most contractors appear to believe that use of these byproducts reduces project costs and increases strategic business opportunities and business competitiveness. It may also conserve natural materials according to many contractors. The benefit ranked least important is that use of these byproducts enhances foundation material and/or concrete quality. It is noted that although being ranked lowest, these this benefit still received a relatively important ranking for 10 of the industry respondents.

TABLE 4.23 Responses for Question 7 of Industry Inquiry

Q7. Rate the importance of the following potential benefits associated with the use of construction and industrial by-products in your transportation infrastructure.	No Importance (%)	Some Importance (%)	Important (%)	High Importance (%)	Very High Importance (%)	Total	Average Rating
	1	2	3	4	5		
Reducing project costs through use of recycled materials	0	0	3	7	10	20	**4.4**
Increasing strategic business opportunities and business competitiveness	0	1	4	5	10	20	**4.2**
Conserving natural materials	0	1	4	6	9	20	**4.2**
Conserving landfill space and reducing the need for new landfill	0	1	6	6	7	20	**4.0**
Reducing the environmental impacts of cement and aggregate production	0	2	5	6	7	20	**3.9**
Enhancing foundation material and/or concrete quality	2	2	1	10	5	20	**3.7**

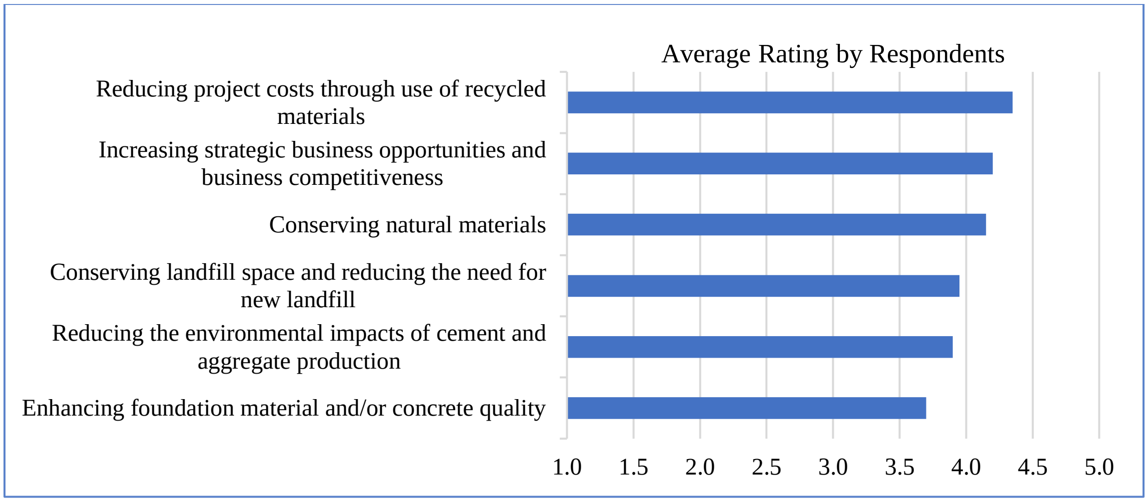

FIGURE 4.25 Responses for Question 7 of Industry Inquiry

4.5 Comparison of responses between Agency and Industry Stakeholders:

The statistical comparison between the responses from both the population was done using the Mann-Whitney U Test, due to the data being non-parametric and ordinal. The significance level was considered to be 5% and the corresponding *p*-value was calculated using the IBM SPSS software. The weighted averages (average rating) of the Likert scale data was also calculated to identify the major differences between the responses from the industry and the agency stakeholders. It was observed that most of the factors received similar responses from both the industry and agency, but there were some factors for which the responses were significantly different. The various comparisons are as follows:

4.5.1 Comparison of potential barriers for use in pavement foundation:

From the Table 4.24, it can be surmised that there are 5 barriers which had a significant difference in ratings between industry and agency respondents. Industry respondents appeared to believe that specifications restrict them from using the by-products while for agencies indicated that they believe that specifications are not a major barrier. Durability and variability concerns were ranked to be more important to agencies than to the industry respondents, while economics and regulatory barriers were ranked as more important to the industry respondents than agencies. The remaining barriers include in the inquiry received similar responses from both agencies and industry stakeholders.

TABLE 4.24 Comparison of Responses for Question 4

Q4. On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-product in pavement foundations. Foundation applications include bound bases/subbases, unbound bases/subbases, and natural/stabilized soils.	**Average Rating (Agency)**	**Average Rating (Industry)**	**Significance Level**	**Mann-Whitney U Test (*p*-value)**	**Significantly Different (Yes/No)**
Specifications currently restrict use	2.9	4.2	0.05	**0.010**	**Yes**
Concerns regarding the material supply being consistently available	3.4	3.4	0.05	**0.685**	**No**
Concerns regarding foundation strength and/or stability	3.8	3.1	0.05	**0.069**	**No**
Concerns regarding durability of the by-product in service	4.4	3.3	0.05	**0.003**	**Yes**
Concerns regarding variability in material properties	4.2	3.1	0.05	**0.001**	**Yes**
Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials)	2.6	3.7	0.05	**0.008**	**Yes**
Ready availability of good, inexpensive SCM and natural aggregate sources	3.6	3.7	0.05	**0.979**	**No**
Regulatory barriers (permitting, environmental regulations)	2.8	3.6	0.05	**0.014**	**Yes**
Concerns regarding environmental impacts (e.g. runoff, leachate, etc.)	3.4	3.2	0.05	**0.602**	**No**

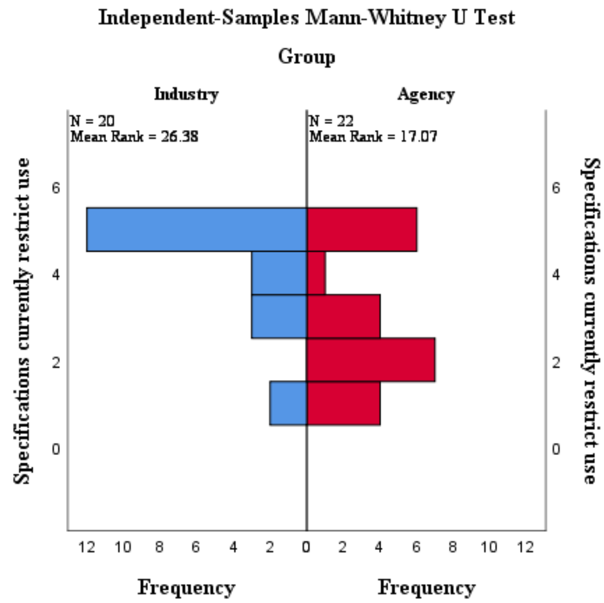

FIGURE 4.26 Comparison of responses for "Specifications currently restrict use"

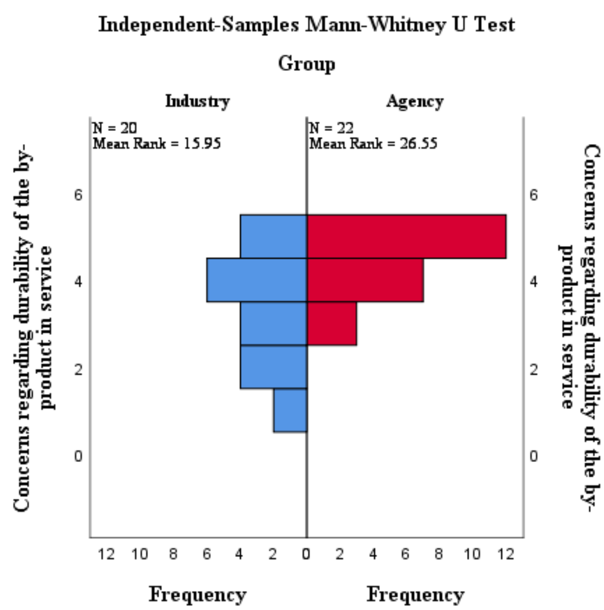

FIGURE 4.27 Comparison of responses for "Concerns regarding durability of the by-product in service"

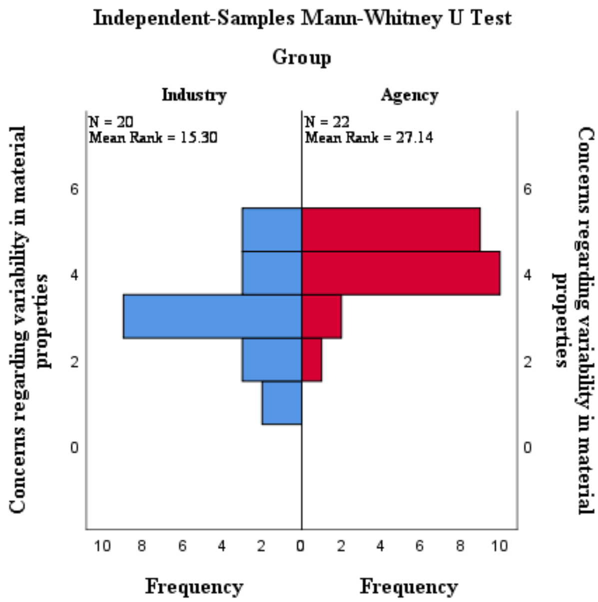

FIGURE 4.28 Comparison of responses for “Concerns regarding variability in material properties”

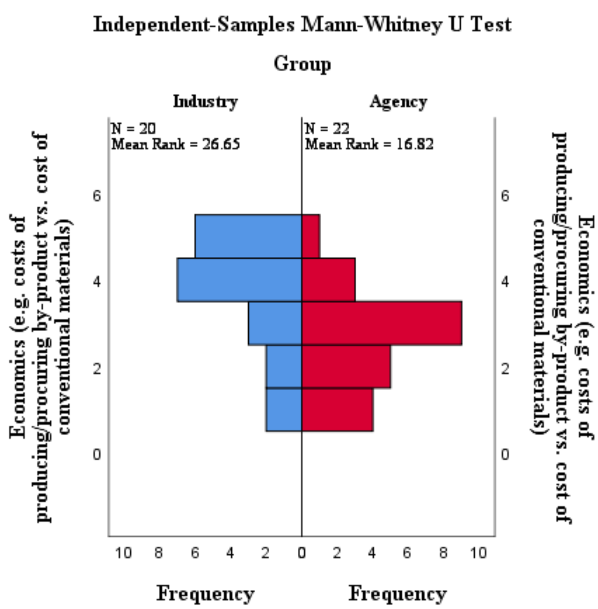

FIGURE 4.29 Comparison of agency and industry responses for “Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials)”

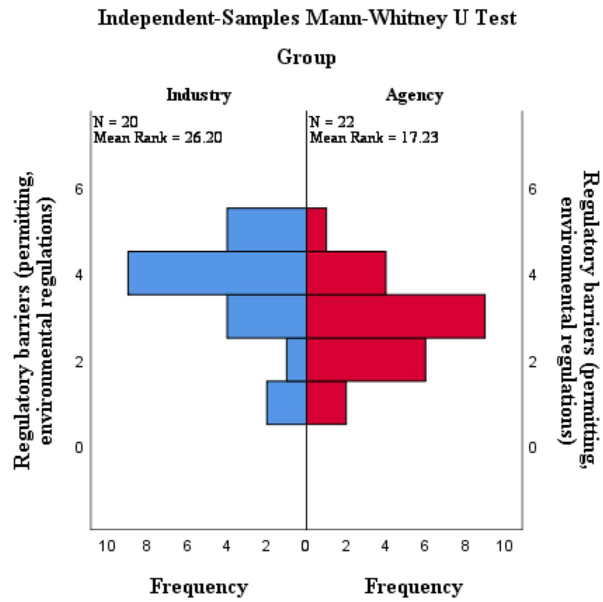

FIGURE 4.30 Comparison of agency and industry responses for "Regulatory barriers (permitting, environmental regulations)"

4.5.2 Comparison of potential barriers for use as SCM in new concrete:

As can be seen in the Table 4.25, four barriers are identified as showing differences in the opinion between the industry and agency respondents. The biggest difference was seen in the specifications that restrict the use and the economics of the material, as industry finds it highly important and agency finds it less important. The concerns for material supply and lack of guidance were also significantly different with industry having more concern than the agencies. It is noted that no responses were requested from industry regarding regulatory barriers, and therefore the statistical test could not be performed.

TABLE 4.25 Comparison of Responses for Question 5

Q5. On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products as supplemental cementitious materials (SCMs) in new concrete.	**Average Rating (Agency)**	**Average Rating (Industry)**	**Significance Level**	**Mann-Whitney U Test (*p*-value)**	**Significantly Different (Yes/No)**
Specifications currently restrict use	3.0	4.3	0.05	**0.002**	Yes
Concerns regarding the material supply being consistently available	3.5	4.2	0.05	**0.018**	Yes
Concerns regarding variability in material properties	4.2	3.9	0.05	**0.504**	No
Concerns regarding performance of fresh concrete – setting time, workability, etc.	3.9	4.1	0.05	**0.294**	No
Concerns regarding the strength of the new concrete	3.8	4.2	0.05	**0.106**	No
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)	4.0	3.8	0.05	**0.655**	No
Concerns regarding the durability of the new concrete	4.5	4.1	0.05	**0.253**	No
Lack of guidance on conducting concrete mixture designs and proportioning using these materials	2.9	3.9	0.05	**0.011**	Yes
Economics (costs of producing/procuring by-product vs. cost of conventional materials)	2.9	4.1	0.05	**0.001**	Yes
Ready availability of conventional materials that are suitable and inexpensive	3.3	3.9	0.05	**0.116**	No
Regulatory barriers (permitting, environmental regulations)	2.7	-	-	-	-

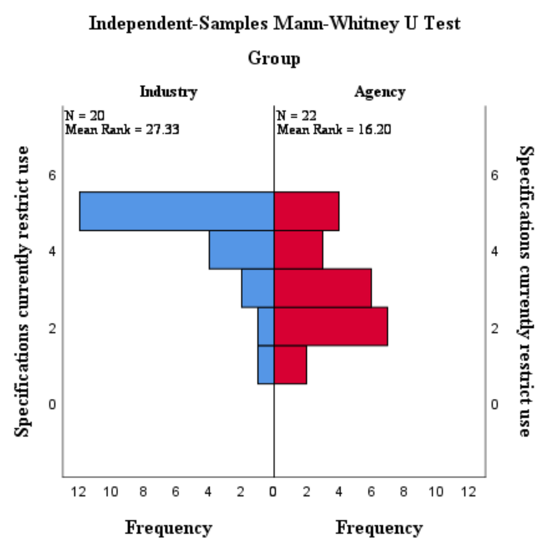

FIGURE 4.31 Comparison of agency and industry responses for “Specifications currently restrict use”

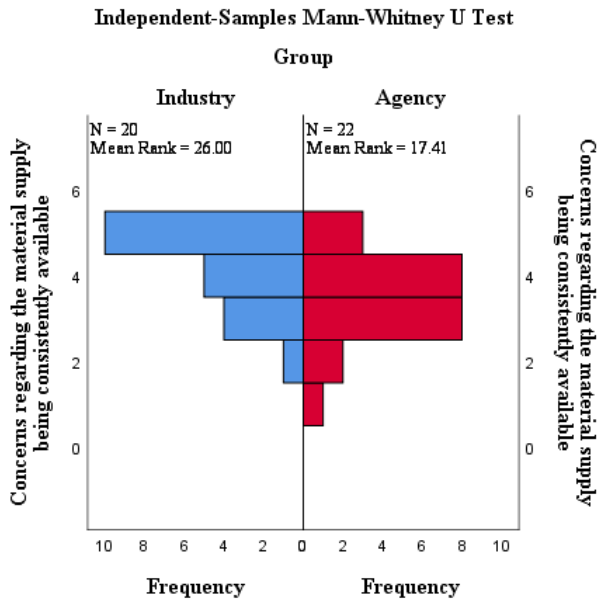

FIGURE 4.32 Comparison of agency and industry responses for "Concerns regarding the material supply being consistently available"

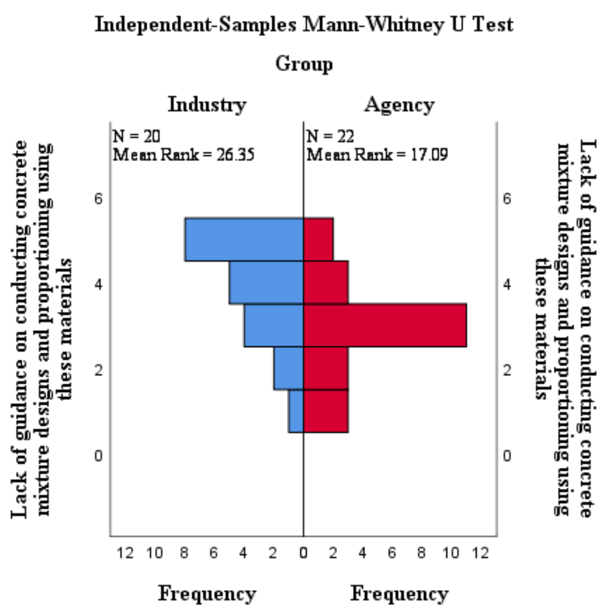

FIGURE 4.33 Comparison of agency and industry responses for "Lack of guidance on conducting concrete mixture designs and proportioning using these materials"

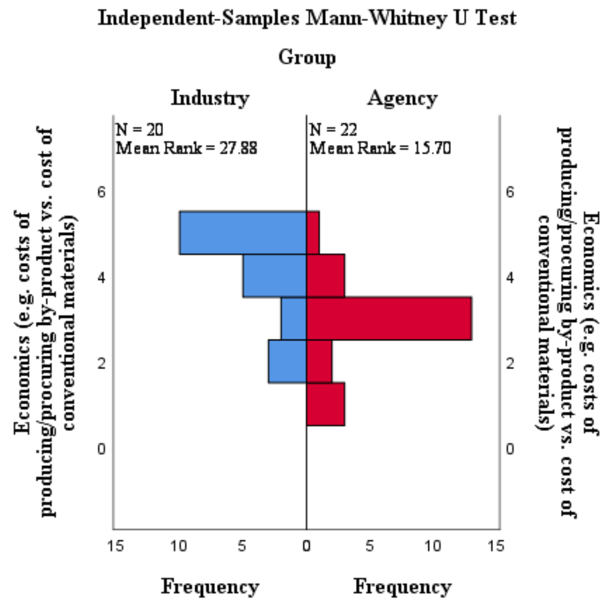

FIGURE 4.34 Comparison of agency and industry responses for “Economics (costs of producing/procuring by-product vs. cost of conventional materials)”

4.5.3 Comparison of potential barriers for use as Aggregate/fill in new concrete:

From the Table 4.26, it can be seen that specifications that restricts the use had a huge difference in the opinion of the industry and agencies with a very low *p*-value (0.001). Other than that, lack of guidance and economics also had significantly high difference between agency and industry respondents, in that the responses from industry indicate that they believe these barriers are very important, but agencies find them less important. It is again noted that regulatory barriers were not included on the industry survey, and therefore the statistical test was not performed.

TABLE 4.26 Comparison of Responses for Question 6

Q6. On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products as aggregates or inert fillers in new concrete.	**Average Rating (Agency)**	**Average Rating (Industry)**	**Significance Level**	**Mann-Whitney U Test (*p*-value)**	**Significantly Different (Yes/No)**
Specifications currently restrict use	3.0	4.5	0.05	**0.001**	Yes
Concerns regarding the material supply being consistently available	3.5	3.7	0.05	**0.743**	No
Concerns regarding variability in material properties	4.1	3.9	0.05	**0.730**	No
Concerns regarding performance of fresh concrete – setting time, workability, etc.	4.1	3.9	0.05	**0.915**	No
Concerns regarding the strength of the new concrete	3.9	3.9	0.05	**0.570**	No
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)	4.1	3.5	0.05	**0.061**	No
Concerns regarding the durability of the new concrete	4.5	4.0	0.05	**0.064**	No
Lack of guidance on conducting concrete mixture designs and proportioning using these materials	3.0	4.0	0.05	**0.005**	Yes
Economics (costs of producing/procuring by-product vs. cost of conventional materials)	3.1	3.8	0.05	**0.048**	Yes
Ready availability of conventional materials that are suitable and inexpensive	3.4	3.7	0.05	**0.383**	No
Regulatory barriers (permitting, environmental regulations)	2.6	-	-	-	-

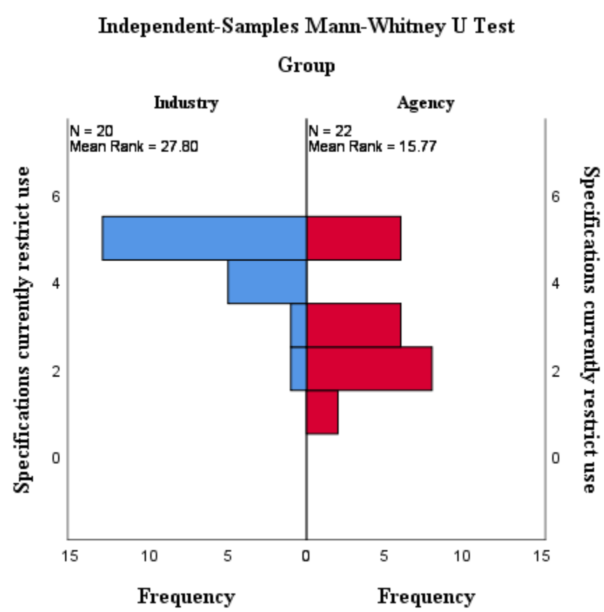

FIGURE 4.35 Comparison of agency and industry responses for “Specifications currently restrict use”

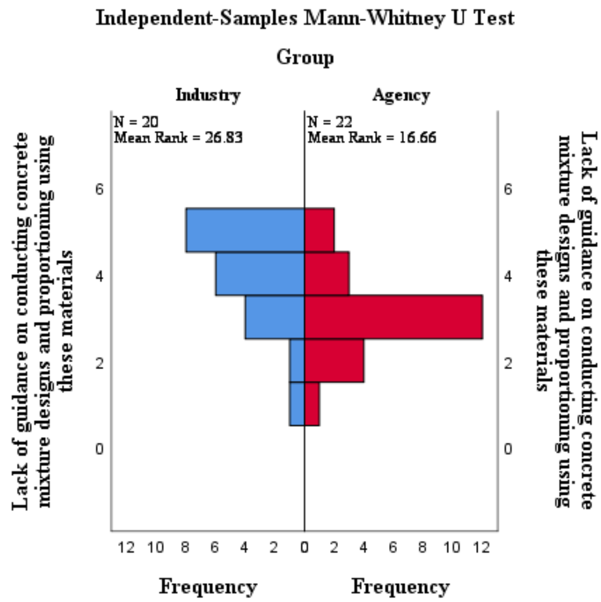

FIGURE 4.36 Comparison of agency and industry responses for "Lack of guidance on conducting concrete mixture designs and proportioning using these materials"

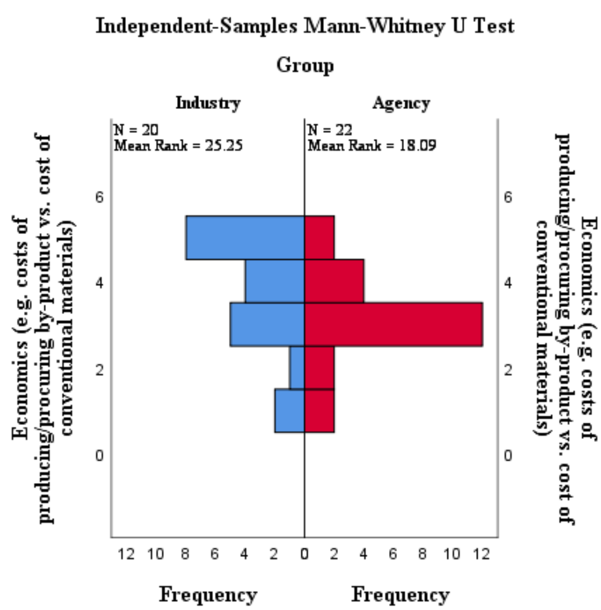

FIGURE 4.37 Comparison of agency and industry responses for "Economics (costs of producing/procuring by-product vs. cost of conventional materials)"

4.5.4 Comparison of perceived benefits of concrete recycling byproducts:

There is only one benefit identified to have very significant differences in the responses from the agencies and industry. Industry respondents indicated they strongly feel that use of byproducts increases the strategic business opportunities and business competitiveness, while agency finds the strategic business opportunities and business competitiveness comparatively less important of a benefit. Other than the differences in opinion evident for this reason, is also a difference of opinion for the benefit use of by products may reduce project cost, a difference of 0.5 (3.9 vs. 4.4) between agency and industry. The difference in rating was not enough to be rejected, however, since the *p*-value was too close to the significance level.

TABLE 4.27 Comparison of Responses for Question 7 and 14

Q7/14. Rate the importance of the following potential benefits associated with the use of construction and industrial by-products in your transportation infrastructure.	**Average Rating (Agency)**	**Average Rating (Industry)**	**Significance Level**	**Mann-Whitney U Test (*p*-value)**	**Significantly Different (Yes/No)**
Conserving natural materials	3.7	4.2	0.05	**0.215**	No
Conserving landfill space and reducing the need for new landfill	3.5	4.0	0.05	**0.178**	No
Reducing project costs through use of recycled materials	3.9	4.4	0.05	**0.056**	No
Increasing strategic business opportunities and business competitiveness	3.0	4.2	0.05	**0.001**	Yes
Reducing the environmental impacts of cement and aggregate production	3.5	3.9	0.05	**0.324**	No
Enhancing foundation material and/or concrete quality	4.1	3.7	0.05	**0.499**	No

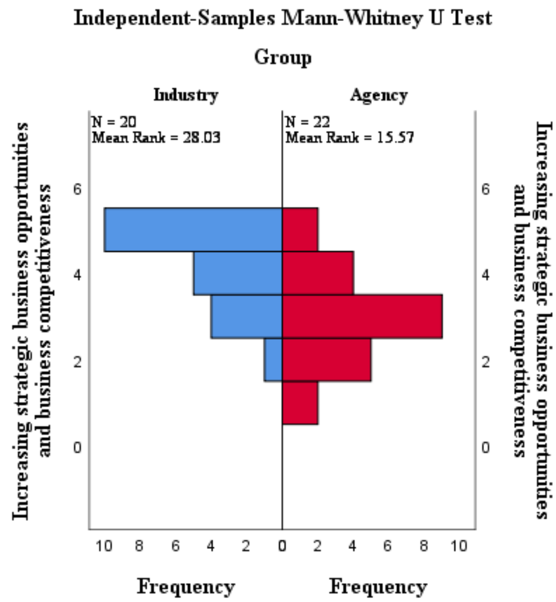

FIGURE 4.38 Comparison of agency and industry responses for "Increasing strategic business opportunities and business competitiveness"

4.6 Comparison of Results from States with Both Agency and Industry Responses Against Results of States with Only One Type of Response

As noted previously, for some states, a response was received from both the agency and one or more contractors, while other states had only one type of respondent (either agency or industry) but not both. Given that agency preferences, regional differences, and local markets vary across the United States, it was of interest to see if there would have been a significantly different outcome to the results if only data from states with both types of respondents (agency and industry) was used. Therefore, Table 4.28, Table 4.29, Table 4.30, and Table 4.31 were constructed to compare the averages of the responses to each question between those received from states with both types of respondents and the averages computed using all data. These tables are shown below. The red color in the cells represents the response with higher rating and the green color in the cells represents response with lower rating.

As can be observed from these tables, the difference between the average for states with both industry and agency responses and the average for all data did not exceed 0.5 in any question. For most questions, the difference in average is less than 0.3. Therefore, it can reasonably be said that if this analysis were performed including only data from states in which both agency and industry responses were received, the results would not be substantially different than those obtained from analysis of the data from all responses.

TABLE 4.28 Comparison of responses for states with both agency and industry respondents (Q4)

RESPONDING STATES	Specifications currently restrict use		Concerns regarding the material supply being consistently available		Concerns regarding foundation strength and/or stability		Concerns regarding durability of the by-product in service		Concerns regarding variability in material properties		Economics		Ready availability of good, inexpensive SCM and natural aggregate sources		Regulatory barriers (permitting, environmental regulations)		Concerns regarding environmental impacts	
	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry
IA	2	1	3	1	5	1	5	1	4	3	3	5	3	5	2	1	4	5
IN	5	3	5	3	3	3	3	2	5	3	3	3	5	4	5	4	5	2
NC	3	5	4	3	4	1	4	2	5	2	3	5	3	5	3	5	4	2
OH	4	5	3	4	3	4	3	5	4	4	3	4	2	4	3	5	4	5
OK	2	5	4	3	4	5	4	5	5	3	1	4	5	5	3	4	3	2
TN	3	5	4	4	2	4	2	4	4	3	3	3	4	3	2	4	3	4
WI	1	5	3	4	3	4	3	3	5	2	1	4	1	4	3	4	5	1
CO	1	5	4	3	4	2	4	4	4	3	5	3	5	3	3	3	1	4
		5		1		1		1		1		1		1		1		1
TX	5	5	5	1	2	4	2	4	5	5	1	4	5	3	1	3	3	4
		3		5		3		3		3		5		5		5		4
		4		5		4		4		5		4		5		4		4
IL	5	3	2	2	5	3	5	2	3	2	2	2	2	2	1	4	1	4
		4		4		5		5		3		5		3		4		4
		1		5		1		2		4		5		5		3		3
		5		5		4		4		3		4		5		4		3
Average for states with both industry and agency respondents	3.10	4.00	3.70	3.31	3.50	3.06	3.50	3.19	4.40	3.06	2.50	3.81	3.50	3.88	2.60	3.63	3.30	3.25
Average for all data	2.91	4.15	3.36	3.40	3.82	3.10	4.41	3.30	4.23	3.10	2.64	3.65	3.64	3.65	2.82	3.60	3.41	3.20
Difference	0.19	0.15	0.34	0.09	0.32	0.04	0.91	0.11	0.17	0.04	0.14	0.16	0.14	0.23	0.22	0.02	0.11	0.05
Difference >0.5?	NO	NO	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

TABLE 4.29 Comparison of responses for states with both agency and industry respondents (Q5)

RESPONDING STATES	Specifications currently restrict use		Concerns regarding the material supply being consistently available		Concerns regarding variability in material properties		Concerns regarding performance of fresh concrete – setting time, workability, etc.		Concerns regarding the strength of the new concrete		Concerns regarding other properties of hardened concrete		Concerns regarding the durability of the new concrete		Lack of guidance on conducting concrete mixture designs and proportioning using these materials		Economics		Ready availability of conventional materials that are suitable and inexpensive	
	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry
IA	2	5	4	5	4	4	4	5	2	3	4	3	5	5	4	1	3	5	3	5
IN	5	5	5	5	5	5	5	5	5	5	4	3	5	5	3	5	3	5	4	5
NC	3	5	4	4	4	4	4	4	4	1	4	1	4	1	4	2	4	5	3	5
OH	4	5	4	4	4	5	4	5	4	5	3	4	4	5	4	4	3	4	3	3
OK	3	5	5	3	5	5	3	5	2	5	4	5	4	5	3	5	5	5	5	5
TN	4	5	4	4	4	4	4	5	4	5	2	4	4	4	3	5	3	4	4	5
WI	3	5	3	4	5	4	3	4	5	5	3	4	5	3	1	3	1	2	1	3
CO	3	2	3	3	5	2	5	4	5	3	5	2	5	4	1	3	3	3	3	2
		5		5		5		5		5		5		5		5		5		5
TX	3	5	5	3	4	4	2	3	2	3	2	4	2	4	2	5	1	4	4	3
		3		5		2		4		5		3		3		4		3		5
		4		5		4		5		4		5		5		5		5		5
IL	5	3	2	2	3	1	3	1	4	1	5	2	5	1	1	2	3	2	2	2
		4		4		4		5		5		5		5		3		4		4
		1		5		1		2		4		4		4		3		5		4
		5		5		4		4		5		5		5		5		5		4
Average for states with both industry and agency respondents	3.50	4.19	3.90	4.13	4.30	3.63	3.70	4.13	3.70	4.00	3.60	3.69	4.30	4.00	2.60	3.75	2.90	4.13	3.20	4.06
Average for all data	3.00	4.25	3.45	4.20	4.23	3.85	3.91	4.10	3.82	4.15	3.95	3.75	4.50	4.05	2.91	3.85	2.86	4.10	3.27	3.85
Difference	0.50	0.06	0.45	0.08	0.07	0.23	0.21	0.03	0.12	0.15	0.35	0.06	0.20	0.05	0.31	0.10	0.04	0.03	0.07	0.21
Difference >0.5?	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

TABLE 4.30 Comparison of responses for states with both agency and industry respondents (Q6)

RESPONDING STATES	Specifications currently restrict use		Concerns regarding the material supply being consistently available		Concerns regarding variability in material properties		Concerns regarding performance of fresh concrete – setting time, workability, etc.		Concerns regarding the strength of the new concrete		Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)		Concerns regarding the durability of the new concrete		Lack of guidance on conducting concrete mixture designs and proportioning using these materials		Economics (costs of producing/procuring by-product vs. cost of conventional materials)		Ready availability of conventional materials that are suitable and inexpensive	
	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry
IA	2	5	4	4	4	4	4	4	2	3	4	4	5	4	4	5	3	5	3	5
IN	5	5	5	5	5	5	5	5	5	5	4	3	5	5	3	5	3	5	4	5
NC	3	5	4	4	4	4	4	4	4	3	4	3	4	3	4	3	4	5	3	5
OH	4	5	4	4	4	5	4	4	4	5	3	4	4	5	4	4	3	3	3	3
OK	3	5	5	3	5	5	3	5	2	5	4	5	4	5	3	5	5	5	5	5
TN	4	5	4	4	4	4	4	4	4	5	2	4	4	4	3	5	3	5	4	4
WI	3	5	3	4	5	4	3	4	5	4	3	4	5	4	1	4	1	3	1	3
CO	3	4	3	3	5	3	5	2	5	3	5	3	5	4	1	3	3	3	3	3
		3		1		1		1		1		1		1		1		1		1
TX	3	5	5	3	4	3	2	4	2	3	2	4	2	4	2	5	1	3	4	3
		4		4		3		5		5		3		4		4		4		5
		2		2		5		4		2		4		3		3		3		3
IL	5	4	2	2	3	2	3	1	4	1	5	1	5	1	1	2	3	1	2	2
		4		4		3		5		5		3		5		3		4		4
		4		5		5		4		5		4		4		5		4		4
		5		5		5		5		5		4		4		5		5		4
Average for states with both industry and agency respondents	3.50	4.38	3.90	3.56	4.30	3.81	3.70	3.81	3.70	3.75	3.60	3.38	4.30	3.75	2.60	3.88	2.90	3.69	3.20	3.69
Average for all data	3.00	4.50	3.55	3.65	4.09	3.90	4.09	3.85	3.86	3.85	4.09	3.50	4.50	3.95	3.05	3.95	3.09	3.75	3.36	3.70
Difference	0.50	0.13	0.35	0.09	0.21	0.09	0.39	0.04	0.16	0.10	0.49	0.13	0.20	0.20	0.45	0.08	0.19	0.06	0.16	0.01
Difference >0.5?	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

TABLE 4.31 Comparison of responses for states with both agency and industry respondents (Q7/14)

RESPONDING STATES	Conserving natural materials		Conserving landfill space and reducing the need for new landfill		Reducing project costs through use of recycled materials		Increasing strategic business opportunities and business competitiveness		Reducing the environmental impacts of cement and aggregate production		Enhancing foundation material and/or concrete quality	
	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry	Agency	Industry
IA	3	5	3	4	3	5	3	5	3	4	3	5
IN	5	4	5	4	3	5	4	5	5	4	4	5
NC	4	5	4	5	3	5	3	5	4	5	3	5
OH	3	4	4	4	4	5	4	4	4	4	4	4
OK	3	4	3	5	4	5	2	3	1	3	4	1
TN	4	5	3	4	4	4	3	4	4	5	4	4
WI	5	4	5	3	3	4	1	5	5	3	5	4
CO	1	3	1	3	4	5	1	4	1	3	4	4
		5		3		5		5		5		4
TX	2	5	2	4	4	4	2	3	4	5	4	3
		4		5		5		5		5		4
		4		4		4		4		4		4
IL	4	2	3	2	5	3	4	3	3	2	5	2
		3		3		4		5		3		4
		3		3		3		5		3		4
		3		3		4		5		2		5
Average for states with both industry and agency respondents	3.40	3.94	3.30	3.69	3.70	4.38	2.70	4.38	3.40	3.75	4.00	3.88
Average for all data	3.68	4.15	3.45	3.95	3.86	4.35	2.95	4.20	3.50	3.90	4.09	3.70
Difference	0.28	0.21	0.15	0.26	0.16	0.03	0.25	0.18	0.10	0.15	0.09	0.18
Difference >0.5?	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

CHAPTER 5: EVALUATION FOR THE USE OF CONSTRUCTION AND INDUSTRIAL BY-PRODUCTS

5.1 Introduction:

Some construction and industrial waste by-products could be beneficially reused in many ways for concrete pavement applications, as well as other areas of the highway industry, if suitable results in the different characterization tests are achieved and tests for performance of the foundation or concrete indicate that the by-product is suitable for use in concrete or as a base material.

From the literature review, analysis of the responses to the agency and industry inquiry, and review of FHWA recommendations, there are several tests that should be helpful to determine of the suitability of by-products for beneficial reuse in both bound and unbound concrete pavement applications.

Tests are identified based on the type for which the by-product will be used such as SCM or aggregate. A flowchart (Figure 5.1) is designed to briefly show the different tests of, by-product material, base or fill incorporating by-product and by-product material for use in concrete. There are two different stages in which the tests are needed to be performed. These stages, which are both points at which other conventional material characterization and performance tests are performed are:

- Preconstruction stage
- Construction stage

Preconstruction Stage:

The purpose of preconstruction tests is to assess the suitability of proposed materials to perform acceptably in its intended use and environment. Preconstruction testing allows assessment and selection of materials before construction activities begin. Preconstruction testing also allows an opportunity for exploration of differences between field-based tests and lab-based tests, allows for adjustments to be made, and provides direction on the appropriate thresholds for the materials to be utilized and performance likely to be experienced (Taylor et al. 2006)

Construction Stage:

Construction stage testing allows stakeholders to assess variation in properties that can occur based on differences in the material source, construction methods, and the environment. Field tests that support confirmation of uniformity and constructability can provide rapid results (often within 24 hours) in ideal conditions. However, tests to support the decisions acceptancy may need additional tests at later ages. For concrete, a suite of construction stage tests can be considered useful if the information gathered from the tests provide enough confidence to change the mixture proportions to sidestep problems (Taylor et al. 2006).

5.2 Characterization Tests:

There are many characterization tests that should be performed on any new material to assess its suitability of use as aggregate or supplementary cementitious material in new concrete and/or as a fill or SCM material in bound or unbound base applications. The by-product should be characterized using certain specified testing standards according to ASTM and AASHTO during preconstruction stage to get approved and qualified by the SHA for its use. The recommended characterization tests that needs to be performed are described in the following sections.

5.2.1 Characterization Tests for use of by-products as aggregate or fill material:

These tests are used to determine the suitability of by-product material in bound or unbound base and in concrete applications when used as aggregate. Characterization tests include those typically performed to determine the various properties of aggregate, and to evaluate the base/fill and concrete incorporating aggregates. The results obtained may indicate if the aggregate requires further processing or if there are chemicals such as silica or alumina are present in the material so that it could be further grinded into finer granules to be used as SCM. The various tests are as follows:

- Tests of By-product Material:

  It is important to know the initial properties of the by-product before deciding its application as an aggregate or fill material. A material could be suitable if it qualifies the following preconstruction tests:

  1. **Gradation** of the material needs to be determined according to AASHTO T 27 (Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates)
  2. **Contaminants** that could be present in the material should be identified by visual analysis of according to AASHTO M 319 (Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course)
  3. **Abrasion resistance** test is needed to be performed as per AASHTO T 96 (Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine)
  4. **Soundness** test should be performed to analyze the resistance to disintegration of the aggregate as per AASHTO T 103 (Standard Method of Test for Soundness of Aggregates by Freezing and Thawing)

5. The **chemical composition** of the by-product needs to be determined using XRF or XRD to identify the presence any substance that could adversely affect its performance

Once the material passed the preconstruction test, then it qualifies for the construction stage tests. The tests that are recommended for the by-product as construction stage are:

1. **Gradation** of the material needs to be determined according to AASHTO T 27 (Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates)
2. **Contaminants** that could be present in the material needs to be identified by visual analysis of according to AASHTO M 319 (Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course)
3. **Uniformity** should be evaluated by reviewing the variability of the characterization test results. The agency will need to consider the sampling frequency and allowable variability that provides confidence in the uniformity.

- Tests of Base or Fill Incorporating By-product:

  The by-product needs to test to evaluate some of the important properties that would determine its suitability when used in base or fill applications. The recommended by-product tests for qualifying are:

1. **General specifications** of the material as per AASHTO M 147 (Standard Specification for Materials for Aggregate and Soil-Aggregate Subbase, Base, and Surface Courses)

2. **Particle shape** needs to be determined as per ASTM D4791 (Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate)
3. **Unit weight** of the material should be known according to AASHTO T 19M/T19 (Standard Method of Test for Bulk Density (Unit Weight) and Voids in Aggregate)
4. **Deleterious components** should be identified according to ASTM D2419 (Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregate)

Materials that are finer and are more like soils than aggregate needs different tests similar to the soil tests, for determining it suitability. The recommended tests of base or fill incorporating by-product are:

1. **Consolidation tests** according to ASTM D2435 (Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading)
2. **Vertical free swell tests** as per ASTM D4546 (Standard Test Methods for One-Dimensional Swell or Collapse of Soils)
3. **Liquid and plastic limit** determination as per ASTM D4318 (Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity)
4. **Resilient modulus**, to measure the stiffness of material under different conditions according to AASHTO T 307 (Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials)

5. **Shear strength** of the material needs to be determined at optimal moisture content and saturated condition under static triaxial and repeated triaxial loading.

After the preconstruction stage tests, the tests that should be performed during the construction stage are:

1. **Optimal moisture and maximum dry density** as per AASHTO T 134 (Standard Method of Test for Moisture-Density Relations of Soil-Cement Mixtures)
2. **Compacted density** as per AASHTO T 310 (Standard Method of Test for In-Place Density and Moisture Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)), AASHTO T 191 (Standard Method of Test for Density of Soil In-Place by the Sand-Cone Method) and ASTM D2167 (Standard Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method)

- Tests of Byproduct Material for Use in Concrete:

Amongst all the tests for aggregate, the most important ones are those which determines the suitability of the material when incorporated in concrete. Following are some of the recommended tests for qualification or preconstruction stage:

1. The **standard specifications** of concrete particularly associated with **deleterious substance** should be met according to ASTM C33 (Standard Specification for Concrete Aggregates)
2. **Alkali aggregate resistivity** needs to be assessed using AASHTO R 80 (Standard Practice for Determining the Reactivity of Concrete Aggregates and

Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction)

3. The materials susceptibility of **D-cracking** which is caused by freeze/thaw deterioration of aggregate needs to be assessed using ASTM C666 (Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing)

If the by-product qualifies the preconstruction tests, then the following tests needs to be performed to assess the suitability of by-product material in concrete during construction stage:

1. **Workability** tests should be performed according to AASHTO T 119 (Standard Method of Test for Slump of Hydraulic Cement Concrete) or TP 129 (Standard Method of Test for Vibrating Kelly Ball Penetration in Fresh Portland Cement Concrete)
2. **Air content** of the concrete should be determined using AASHTO T 152 or T 156 (Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method)
3. **Super Air Meter (SAM)** number should be known as per AASHTO TP 118 (Standard Method of Test for Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method)
4. **Strength** of the concrete should be assessed according to AASHTO T 22/ T 97 (Standard Method of Test for Flexural Strength of Concrete Using Simple Beam with Third-Point Loading)

5.2.2 Characterization Tests for use of by-products as SCM:

If byproduct materials are ground to a fine powder and possess components such as silica and alumina, the byproduct may potentially be used as an SCM. To evaluate the potential for a byproduct to be used as an SCM, there are certain tests that are recommended to confirm its suitability for use in base/fill or concrete in paving applications. The tests that are recommended to be performed are:

- Tests of By-product Material:

  The by-products that can potentially be used as SCM are usually processed using heat and ground to an appropriate fineness. It is important to analyze the basic chemical composition and physical properties of the by-product to know if it has the potential to support pozzolanic reactions and can replace cement from the concrete. Tests should be performed to confirm the byproduct meets the minimum requirements of ASTM C1709. Additionally, the suitability of such materials could be assessed using following:

  1. The **chemical composition** of the material should be identified using XRF or XRD to assess the potential effects of certain chemicals that could adversely affect the performance such as carbonates (for unbound applications), sulfates, aluminate (for concrete)
  2. **Contaminants** that could be present in the material should be identified visually or using XRF
  3. **Particle size and fineness** using ASTM C311 (Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete) and C430 (Standard Test Method for Fineness of Hydraulic

Cement by the 45-m (No. 325) Sieve) is necessary to know the fineness of the material and whether additional (or less) grinding should be performed.

4. **Strength activity index** should be assessed to understand the byproducts potential pozzolanicity in concrete or unbound applications

The recommended tests for construction stage include two tests that are similar to those recommended for use in the preconstruction stage. Those are:

1. **Contaminants** as per AASHTO M 319 (Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course) or assessed visually
2. **Uniformity** should be evaluated by reviewing the variability of the characterization test results. The agency will need to consider the sampling frequency and allowable variability that provides confidence in the uniformity

- Tests of Base or Fill Incorporating By-products:

The by-products that do not shows potential for use as an SCM and/or are not fine enough to be used in concrete as cement replacement can be used as fill in concrete and in base applications. The recommended tests of base or fill that contains by-product material will allow comparison of their properties to those of conventional materials. Following are the recommended tests for preconstruction stage:

1. **Compressive strength** is one of the most important properties that need to be tested according to ASTM C593 (Standard Specification for Fly Ash and Other Pozzolans for Use With Lime for Soil Stabilization) and/or D1632 (Standard

Practice for Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory)

2. **Freeze-thaw durability** should be tested as per ASTM C593 (Standard Specification for Fly Ash and Other Pozzolans for Use with Lime for Soil Stabilization) and/or D560 (Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures)
3. **Maximum dry density and optimum moisture** content should be assessed using ASTM D698 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort) or D1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort)
4. **Compact density** needs to be measured according to ASTM D1556 (Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method) and/or D3877 (Standard Test Methods for One-Dimensional Expansion, Shrinkage, and Uplift Pressure of Soil-Lime Mixtures)
5. **Volumetric stability** should be analyzed as per ASTM D3877 (Standard Test Methods for One-Dimensional Expansion, Shrinkage, and Uplift Pressure of Soil-Lime Mixtures)
6. **Resilient modulus** for measuring the stiffness of material under different conditions should be performed using AASHTO T 307 (Standard Method of Test for Determining the Resilient Modulus of Subgrade Soils)

After the qualification process, the construction stage tests that are needed to be performed to confirm the suitability of a by-product material in base or fill applications are:

1. **Optimum moisture** content and maximum **dry density** according to AASHTO T 134 (Standard Method of Test for Moisture-Density Relations of Soil-Cement Mixtures)
2. **Compact density** according to the test procedures given in AASHTO T 310 (Standard Method of Test for In-Place Density and Moisture Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)), AASHTO T 191 (Standard Method of Test for Density of Soil In-Place by the Sand-Cone Method), ASTM D2167 (Standard Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method)

- Tests of By-product Material for Use in Concrete:
    1. **Setting time** of fresh concrete should be observed according to the procedures given in ASTM C191 (Standard Test Methods for Time of Setting of Hydraulic Cement by VICAT Needle)
    2. **Strength development** should be checked with time as per given in AASHTO T 22 (Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens) or T 97 (Standard Method of Test for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading))
    3. **Unrestrained volume change** should be measured using AASHTO T 160 (Standard Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete) or T 334 (Standard Method of Test for Estimating the

Cracking Tendency of Concrete) and **restrained volume change** should be measured using AASHTO T 363 (Standard Method of Test for Evaluating Stress Development and Cracking Potential due to Restrained Volume Change Using a Dual Ring Test)

4. **Temperature development** due to heat of hydration should be measured using ASTM C 186 (Standard Test Method for Heat of Hydration of Hydraulic Cement) or calorimetry

The tests on concrete that are needed to be performed on site during construction which confirms the suitability of by-product material for use as cement replacement in new concrete are as follows:

1. **Workability** should be measured by checking on the slump of the concrete following the procedures given in AASHTO T 119 (Standard Method of Test for Slump of Hydraulic Cement Concrete) or TP 129 (Standard Method of Test for Vibrating Kelly Ball Penetration in Fresh Portland Cement Concrete) or TP 137 (Standard Method of Test for Box Test in Slip Form Paving of Fresh Portland Cement Concrete)
2. **Air content** should be measured using AASHTO T 152 (Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method)
3. **Super Air Meter (SAM)** number should be performed as per AASHTO TP 118 (Standard Method of Test for Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method)
4. **Strength** of hardened concrete should be measured according to AASHTO T 22 (Standard Method of Test for Compressive Strength of Cylindrical Concrete

Specimens) or T 97 (Standard Method of Test for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading))

5.3 Recommendations on Environmental Impact Testing:

Certain chemicals that may be contained in various by-product materials from different sources may be susceptible to leaching, particularly in unbound applications where water is free to move through the material. Some chemical components may impact water quality, and these should be identified during the qualification/preconstruction testing. Thus, agencies need to submit the material's chemical characterization results to their department of environmental quality personnel and seek approval using methods that prevent water quality issues. Required testing to support assessment of environmental impacts varies greatly from agency to agency. Tests utilized include the paint filter test, the Toxicity Characteristic Leaching Procedure (TCLP) and other tests. The potential users of by-product materials should consult with agencies to determine the appropriate procedures, requirements, and regulations that would guide environmental testing, if deemed appropriate for approval of use of the product.

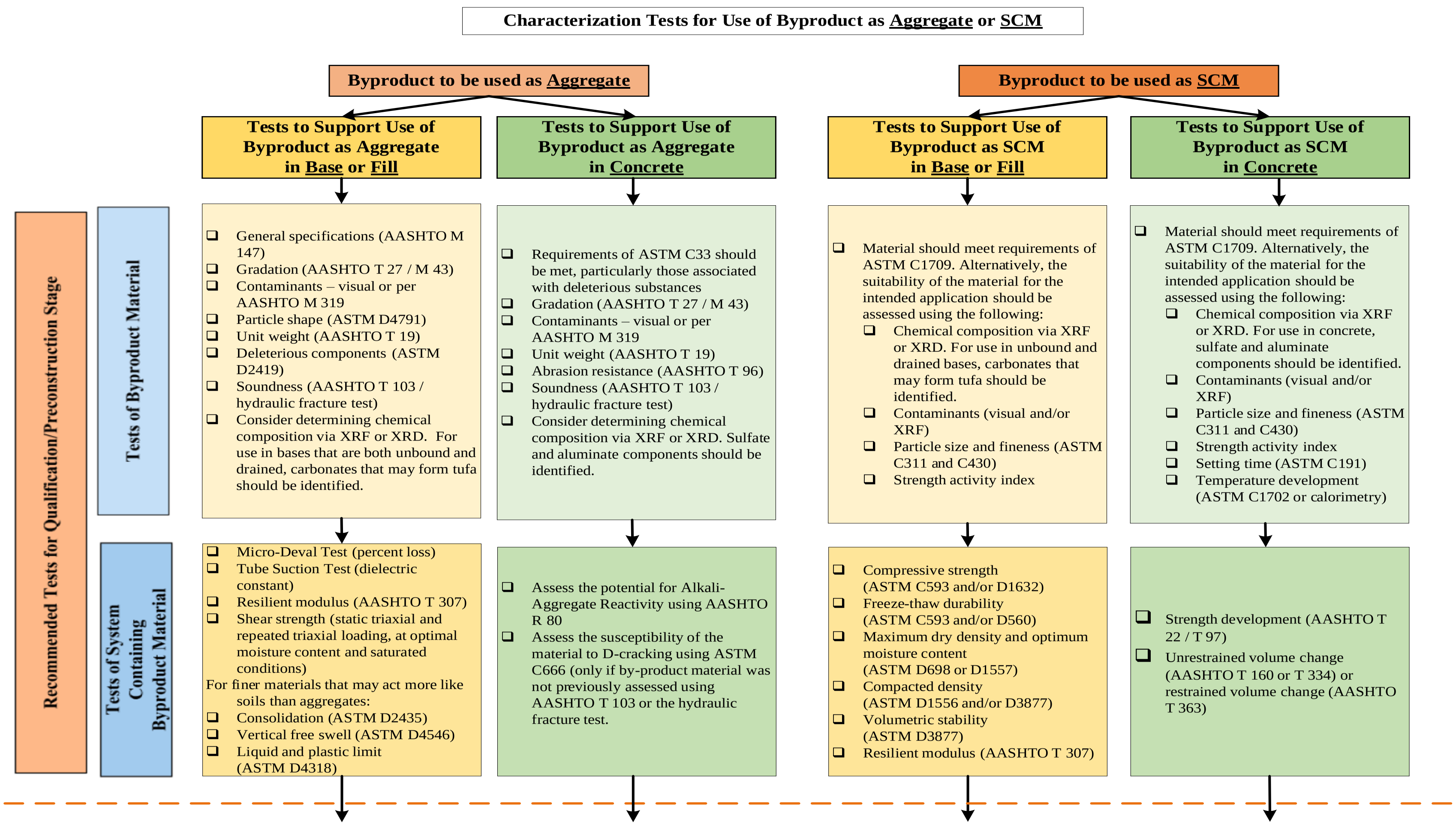

FIGURE 5.1 Flowchart representing the characterization tests for use of by-product as Aggregate or SCM

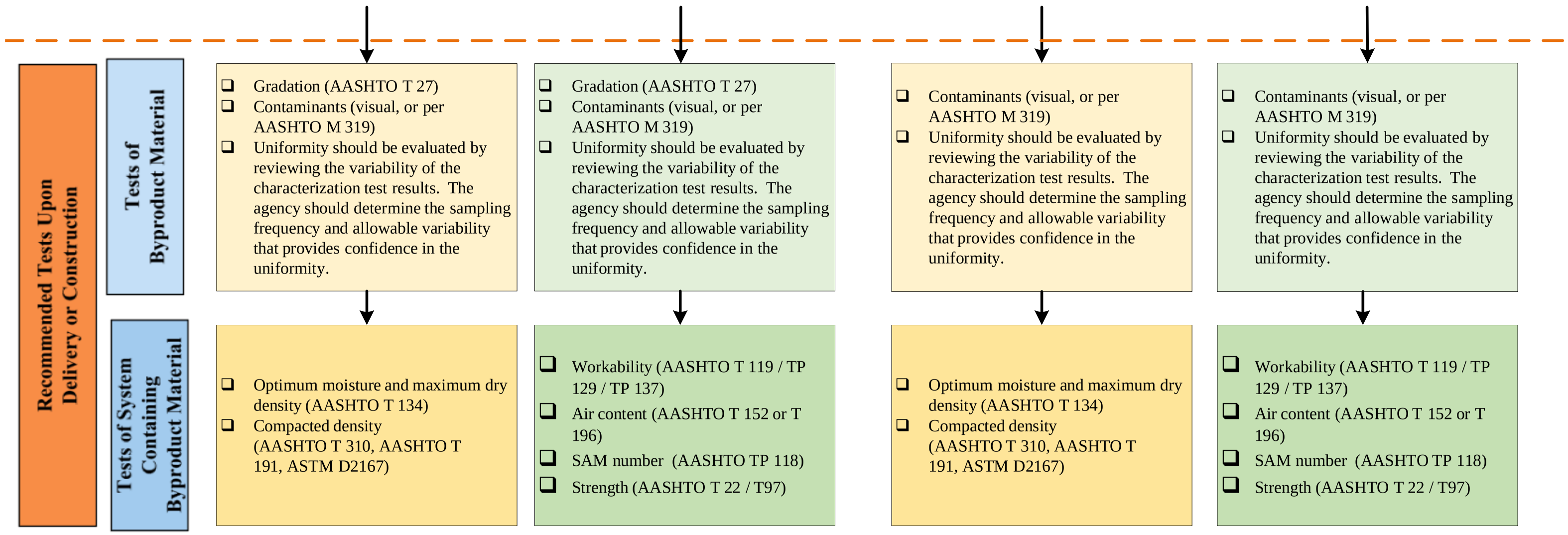

FIGURE 5.1 (cont.) Flowchart representing the characterization tests for use of by-product as Aggregate or SCM

CHAPTER 6: CONCLUSIONS

6.1 Conclusions from Agency and Industry Inquiries:

Based on the inquires that were conducted in this study from the 22 State Highway Agencies (SHAs) and 20 Contractor firms (Industries). The following conclusions were drawn:

6.1.1 Agency Inquiry:

- Most of the agencies use RCA and RAP in pavement foundation as a substitute material for conventional aggregates
- The most critical barrier for agencies for the use of by-products in pavement foundations is the potential reduced durability of the base in service
- The most used byproduct material by the agencies in new concrete is RCA
- The most critical barrier for agencies for the use of by-products in new concrete is the potential for reduced durability of the new concrete
- The most critical barrier identified for the use of by-products in new concrete as aggregate or filler material is the potential for reduced durability of new concrete
- The most important reason for allowing the by-products in pavement applications is the anticipated economic benefits of recycling
- The most important benefit of using construction and industrial by-products is the enhancement of foundation material and concrete quality
- The most important characterization tests for use of by-products as SCM are:
    - Characterization Tests of By-product Materials: **Incompatibility with certain cements**

  - Characterization Tests of Base Materials Stabilized with By-products: **Elastic Modulus and Permeability**
  - Characterization Tests of Concrete Incorporating By-products: **Permeability**

- The most important characterization tests for use of by-products as aggregate or filler material are:
  - Characterization Tests of By-product Aggregate or Filler Materials: **Abrasion Resistance**
  - Characterization Tests of Unbound Base Material Incorporating Recycled or By-product Aggregate: **Strength**
  - Characterization tests of Stabilized Base Material Incorporating Recycled or By-Product Aggregate: **Stiffness**
  - Characterization Tests of Concrete Incorporating Recycled or By-Product Aggregate: **Permeability**

6.1.2 Industry Inquiry:

- Most of the industry stakeholders responding to the inquiry use RCA and RAP in pavement foundation as a substitute material for conventional aggregates
- The most critical barrier for the use of by-products in pavement foundation are the specifications that restrict the use
- The most used byproduct material in new concrete by the industry respondent is RCA
- The most critical barrier for agencies for the use of by-products in new concrete as SCM is the specifications that restrict the use

- The most critical barrier identified for the use of by-products in new concrete as aggregate or filler material is the specifications that restrict the use
- The most important reason for allowing the by-products in pavement applications is that it will likely save cost over other product and should also provide economic advantages
- The most important benefit of using construction and industrial by-products is the likely reduction in project costs through use of recycled materials

6.1.3 Comparison between agency and industry inquiries:

- The barriers for use of by-products in pavement foundation with significant measured differences in responses between agencies and industry respondents are:
    - Specifications currently restrict use
    - Concerns regarding durability of the by-product in service
    - Concerns regarding variability in material properties
    - Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials)
    - Regulatory barriers (permitting, environmental regulations)
- The barriers for use of by-products as SCM in new concrete with significant measured differences in responses between agencies and industry respondents are:
    - Specifications currently restrict use
    - Concerns regarding the material supply being consistently available
    - Lack of guidance on conducting concrete mixture designs and proportioning using these materials

    - Economics (costs of producing/procuring by-product vs. cost of conventional materials)

- The barriers for use of by-products as aggregate or filler material in new concrete with significant measured differences between agency and industry respondents are:
    - Specifications currently restrict use
    - Lack of guidance on conducting concrete mixture designs and proportioning using these materials
    - Economics (costs of producing/procuring by-product vs. cost of conventional materials)
- The benefit of using construction and industrial byproduct with a significant measured difference between agency and industry respondents is:
    - Increasing strategic business opportunities and business competitiveness

6.2 Economics and Environmental Factors:

The use of by-products from constructions and industries are mostly dependent on the economic and environmental factors which act as drivers and barriers that can shape the supply and demand for their beneficial reuse in construction. The various economic and environmental factors are as follows:

6.2.1 Economic Factors:

1. Geographical Distribution:

    The locations of different byproduct generator facilities and end users accounts for the transportation costs as the distance and access to transportation corridors are considered as important factors which affect the overall cost of the by-product.

2. Relative Convenience and Lower Cost of Landfilling:

   The market value of material needs to be higher than the cost of landfilling for the convenience of byproduct generator to arrange and transport the by-product for beneficial reuse rather than disposing of it in the closest landfill. If the tipping fee charged for waste disposal exceeds a certain limit, it becomes expensive enough for the byproduct generator to seek reuse of the materials as an alternative option to disposal. Thus, restrictions or higher tipping fees for the use of landfills would promote the reuse of by-products by the potential end users.

3. Inconsistent Quantities and Composition of By-products:

   The feasibility of using a by-product depends upon the availability of a minimum quantity for consistent use in a project (or projects) along with its favorable composition/physical characteristics and consistency. Thus, the volume of by-products that are produced by the generators needs to be sufficient enough for the end user to fulfill the demand in specific projects. Also, transportation of large shipments is much more cost efficient than transportation of multiple small shipments.

4. Awareness and Marketing:

   The manufacturers of the by-products need to be aware of the consumers nearby that could potentially use their by-product beneficially in bound or unbound concrete pavement applications. A lack of awareness of potential beneficial reuses can result in the increased costs associated with hiring a broker to connect the manufacturer to the consumer.

5. Standards and Specifications:

   The specifications developed by the different state agencies for the beneficial reuse of by-products in concrete need to be crafted in a manner that enables flexibility and economic feasibility in reuse of such materials.

6. Core Competency:

   Lack of information about the by-products hinders industry stakeholders and agencies from investigating the reuse of such by-product material in highway applications. A combined effort of agencies along with the openness of industries to the potential beneficial reuses of these byproducts could lead to find more supporting evidence for the use of by-products in highway applications.

6.2.2 Environmental Impacts:

The various environmental impacts that could be eliminated by the reuse of construction and industrial waste by-products in highway infrastructure include:

1. The need to harvest virgin materials would be reduced by the increased use of these by-products
2. The replacement of cement with byproducts as SCMs could reduce the greenhouse gas emissions associated with cement and cementitious products
3. The impacts due to transportation will be reduced along with the energy consumption
4. Use of land for landfills would be reduced

6.3 Recommendations

Tests to characterize byproducts for use in unbound and bound applications in concrete paving were presented in Figure 5.1. This suite of tests focuses on both preconstruction and construction phases of the work and includes testing of both the byproduct material and the systems (base, fill, or concrete) constructed using the byproducts. Due to the potential for leaching of components of the byproducts (particularly in unbound applications), additional environmental testing may be required during the qualification/preconstruction stage. Environmental testing approaches vary greatly from agency to agency. Potential users of byproducts should consult with agency requirements and regulations to determine the appropriate testing for each byproduct.

Future Work:

More work is recommended in future to find the variations in material properties obtained from different areas and weather conditions. Also, the variations in the concrete properties incorporating materials from different region should be assessed.

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APPENDIX A: FHWA RECYCLING AND REUSE OF WASTE PRODUCTS IN CONCRETE PAVEMENT APPLICATIONS: AGENCY INQUIRY

Inquiry objectives:

Information gathered through this inquiry will be used to identify the current and potential uses of construction and industry by-products in concrete pavement applications across the United States. Once compiled, this information will be available for sharing with agencies, consulting engineers, and contractors. Ultimately, this information will be utilized to develop tools to promote evaluation and effective use of these by-product materials in pavement construction. All inquiries responses will be held in the strictest confidence and remain anonymous in all reports.

1) Respondent Information:

Name:	
Name of Firm:	
Address:	
City:	
State:	
Zip:	
Email Address:	

2) Which of the following construction and/or industrial by-products are you allowing (or considering to allow) in concrete pavement applications?

By-products	Allow in pavement foundations?	Allow in new concrete?
Bottom ash	Select one...	Select one...
Off-specification fly ash	Select one...	Select one...
Rice husk ash	Select one...	Select one...
Sugar cane ash	Select one...	Select one...
Water treatment residuals	Select one...	Select one...
Recycled concrete aggregate	Select one...	Select one...
Mixed rubble (recycled aggregates from mixed sources)	Select one...	Select one...
Recycled asphalt pavement	Select one...	Select one...
Concrete grinding slurry and fines	Select one...	Select one...
Hydro-demolition residual material	Select one...	Select one...
Brick waste	Select one...	Select one...
Crushed glass	Select one...	Select one...
Crumb rubber	Select one...	Select one...
Porcelain	Select one...	Select one...
Plastics	Select one...	Select one...

Other (please describe)

Comments:

1. “Soil Cement and Blended Calcium Sulfate for pavement foundations”.

2. “Waste to energy ash from residential garbage”.

3) For what reasons are you allowing (or considering to allow) the construction and/or industrial by-products in concrete pavement applications? (select all that apply)

	Lack of availability of other products (supplementary cementitious materials and/or aggregates)	Cost savings over other products (supplementary cementitious materials and/or aggregates)	Economic benefits of recycling these materials from a project (or sourcing from a local industry or project)	Other (please describe in the box below)
Bottom ash	☐	☐	☐	☐
Off-specification fly ash	☐	☐	☐	☐
Rice husk ash	☐	☐	☐	☐
Sugar cane ash	☐	☐	☐	☐
Water treatment residuals	☐	☐	☐	☐
Recycled concrete aggregate	☐	☐	☐	☐
Mixed rubble (recycled aggregates from mixed sources)	☐	☐	☐	☐
Recycled asphalt pavement	☐	☐	☐	☐
Concrete grinding slurry and fines	☐	☐	☐	☐
Hydro-demolition residual material	☐	☐	☐	☐
Brick waste	☐	☐	☐	☐
Crushed glass	☐	☐	☐	☐
Crumb rubber	☐	☐	☐	☐
Porcelain	☐	☐	☐	☐
Plastics	☐	☐	☐	☐

Other (please describe)

Comments:

1. "Reduce GHG emission".
2. "Recycled concrete aggregate from mixed sources is allowed n new concrete pavement as a result of legislation to reduce stockpiles of waste concrete. Crushed glass is allowed but is not currently being used".
3. "Improved durability of concrete".
4. "Supplements allow for high LOI ash to be used provided mitigation procedures are in place. We also have a recycled concrete aggregate supplement, but folks are Leary to use it".
5. "N/A".
6. "Environmental benefit".

7. “RCA is currently not allowed for use as subbase due to environmental issues. We are looking at ways to mitigate these issues so that it can be used again. As for the rest of the products, we have not been asked to look at them as far as I know”.
8. “Not interested”.
9. “Not interested or using, just forced to answer”.
10. “Off-specification fly ash: Specifically looking at it for a blended fly ash product Recycled Asphalt Pavement: Probably would not consider since it is already used extensively in HMA; we may have tried in the lab to no avail. Crumb Rubber: We may have tried in the lab to no avail”.
11. “not interested”.

4) On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers within your agency to using construction or industrial by-product in pavement foundations. Foundation applications include bound bases/subbases, unbound bases/subbases, and natural/stabilized soils.

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

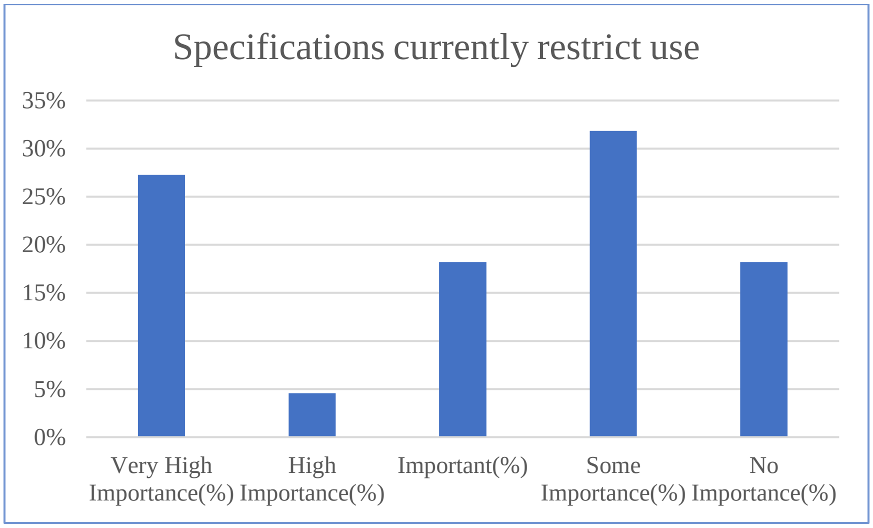
	1	2	3	4	5
Specifications currently restrict use	○	○	○	○	○
Concerns regarding the material supply being consistently available	○	○	○	○	○
Concerns regarding foundation strength and/or stability	○	○	○	○	○
Concerns regarding durability of the by-product in service	○	○	○	○	○
Concerns regarding variability in material properties	○	○	○	○	○
Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials)	○	○	○	○	○
Ready availability of good, inexpensive SCM and natural aggregate sources	○	○	○	○	○
Regulatory barriers (permitting, environmental regulations)	○	○	○	○	○
Concerns regarding environmental impacts (e.g. runoff, leachate, etc.)	○	○	○	○	○

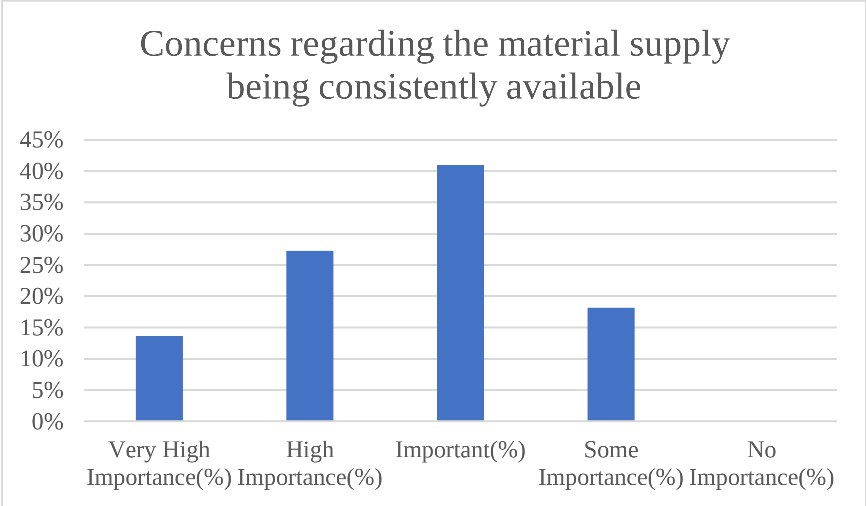
Other (please describe)

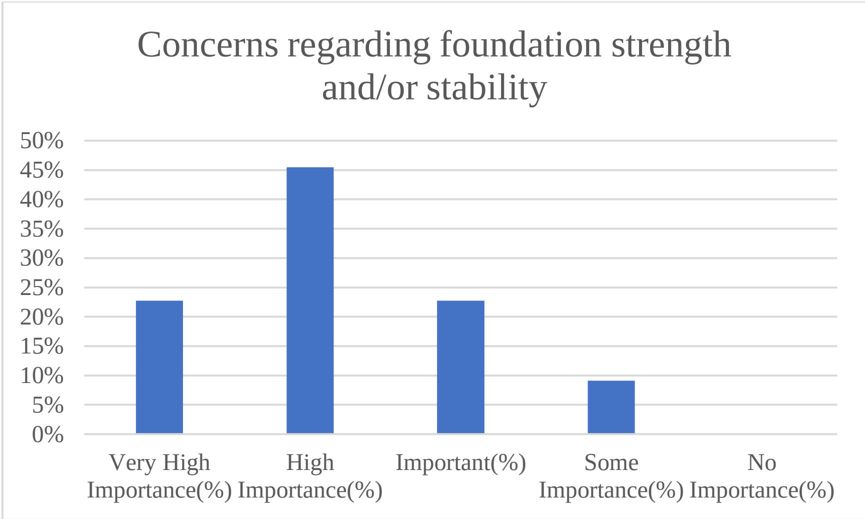
Comments:

1. “The cost depends on transportation cost. Waste materials can be efficiently use only in a certain distance from the source”.

2. “Some of these materials will impact the drain ability of the subbase”.






Concerns regarding foundation strength and/or stability
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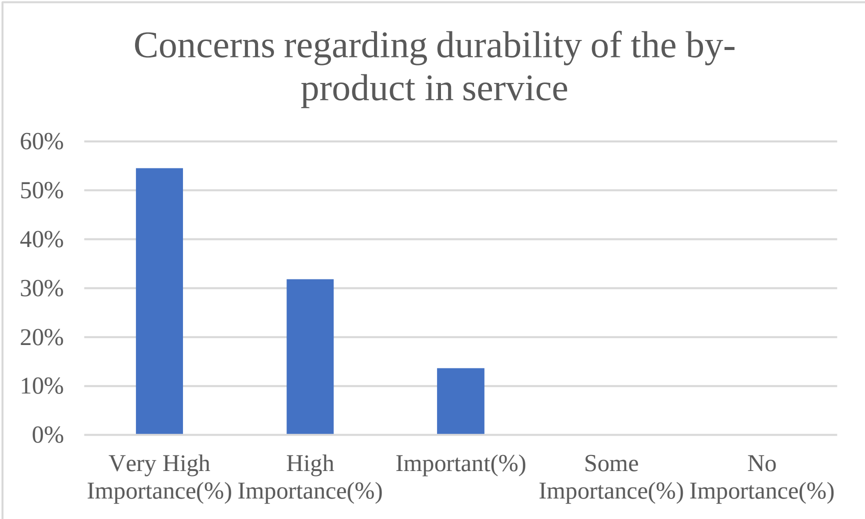
Concerns regarding durability of the by-product in service
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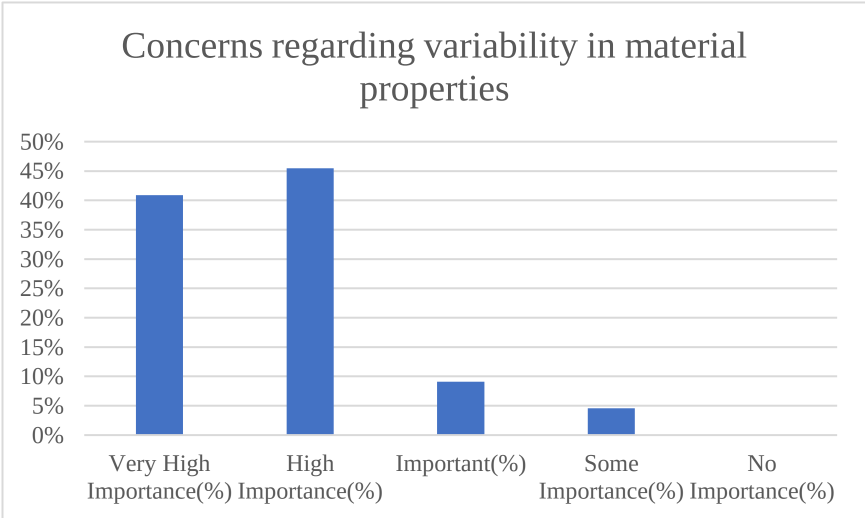
Concerns regarding variability in material properties
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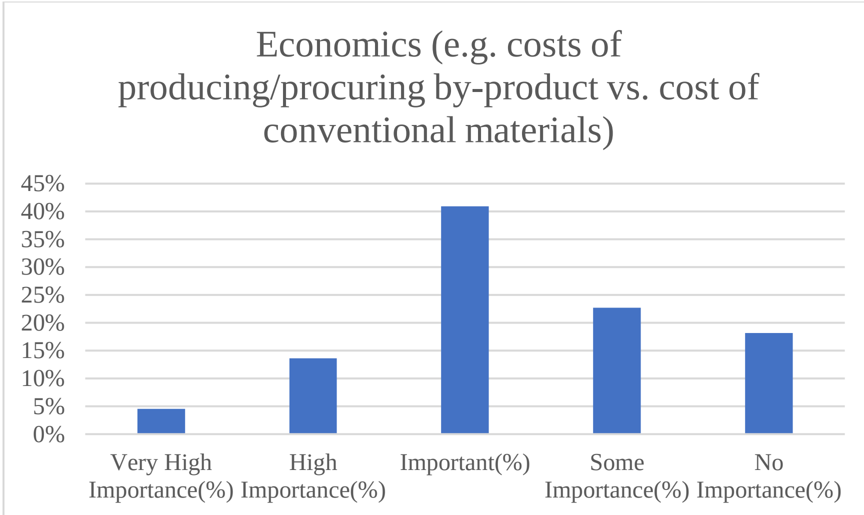
Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials)
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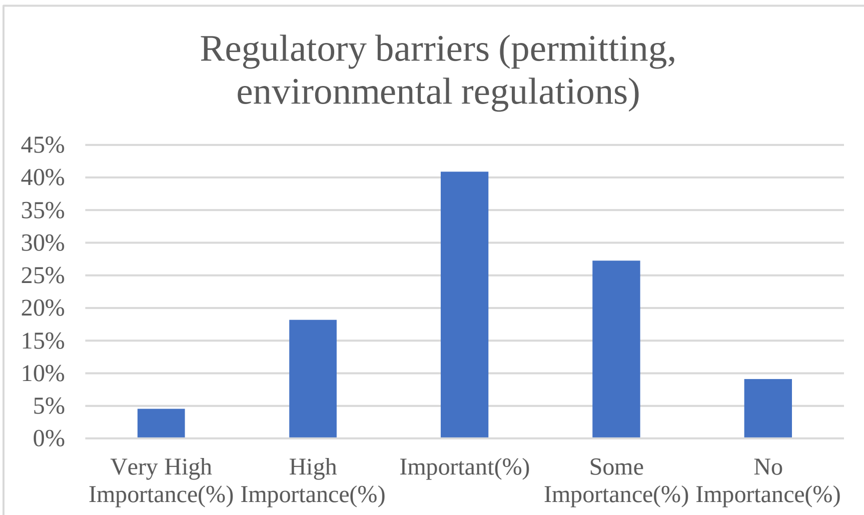
Regulatory barriers (permitting, environmental regulations)
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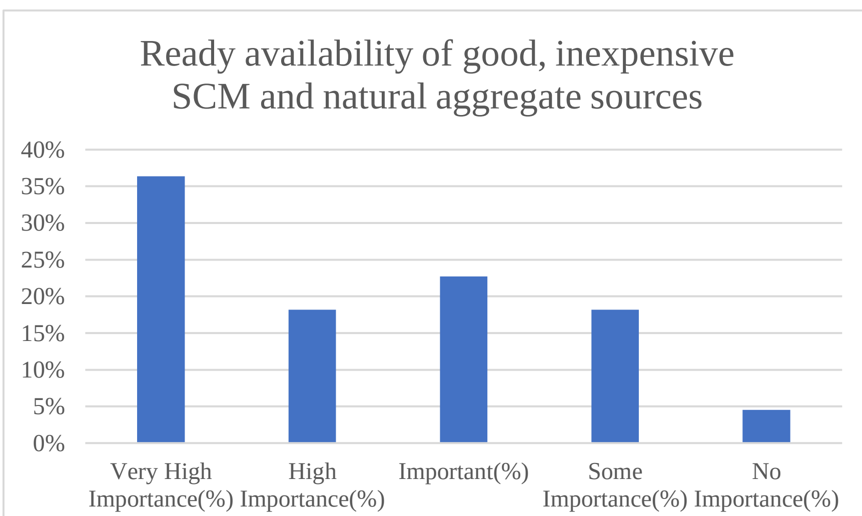
Ready availability of good, inexpensive SCM and natural aggregate sources
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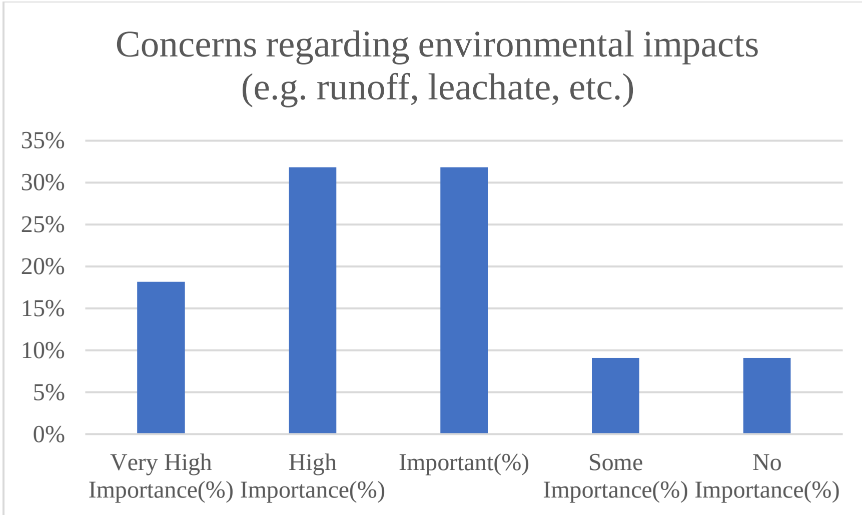
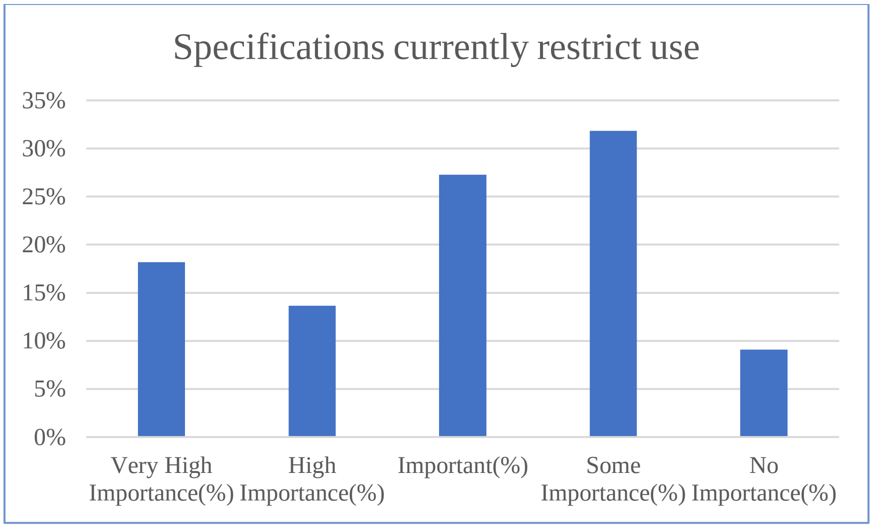


5) On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products as supplemental cementitious materials (SCMs) in new concrete.

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

	1	2	3	4	5
Specifications currently restrict use	○	○	○	○	○
Concerns regarding the material supply being consistently available	○	○	○	○	○
Concerns regarding variability in material properties	○	○	○	○	○
Concerns regarding performance of fresh concrete – setting time, workability, etc.	○	○	○	○	○
Concerns regarding the strength of the new concrete	○	○	○	○	○
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)	○	○	○	○	○
Concerns regarding the durability of the new concrete	○	○	○	○	○
Lack of guidance on conducting concrete mixture designs and proportioning using these materials	○	○	○	○	○
Economics (costs of producing/procuring by-product vs. cost of conventional materials)	○	○	○	○	○
Ready availability of conventional materials that are suitable and inexpensive	○	○	○	○	○
Regulatory barriers (permitting, environmental regulations)	○	○	○	○	○

Other (please describe)


Specifications currently restrict use
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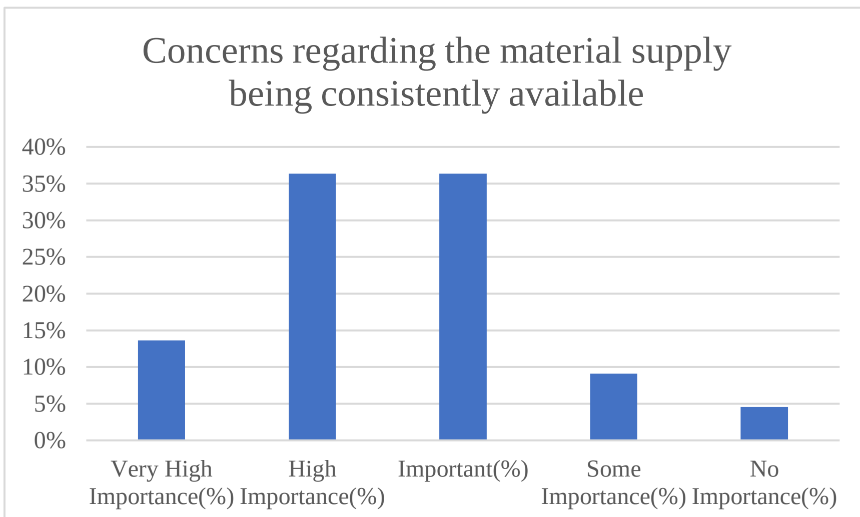
Concerns regarding the material supply being consistently available
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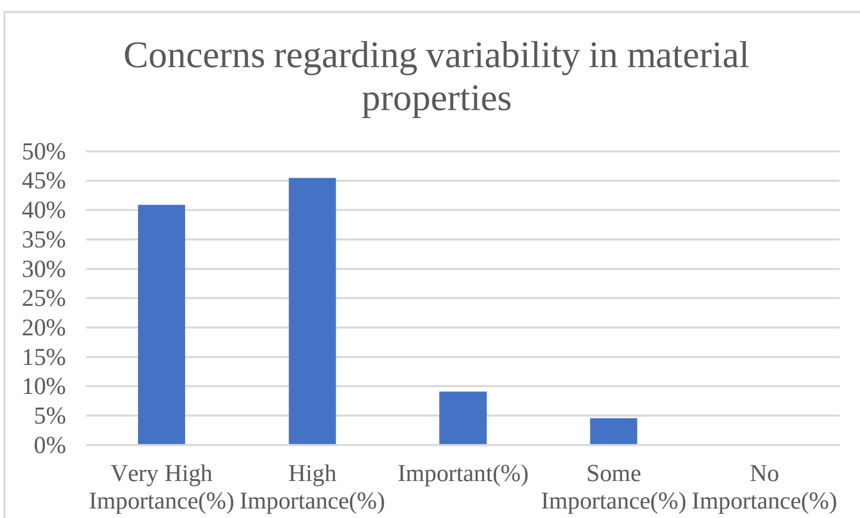
Concerns regarding variability in material properties
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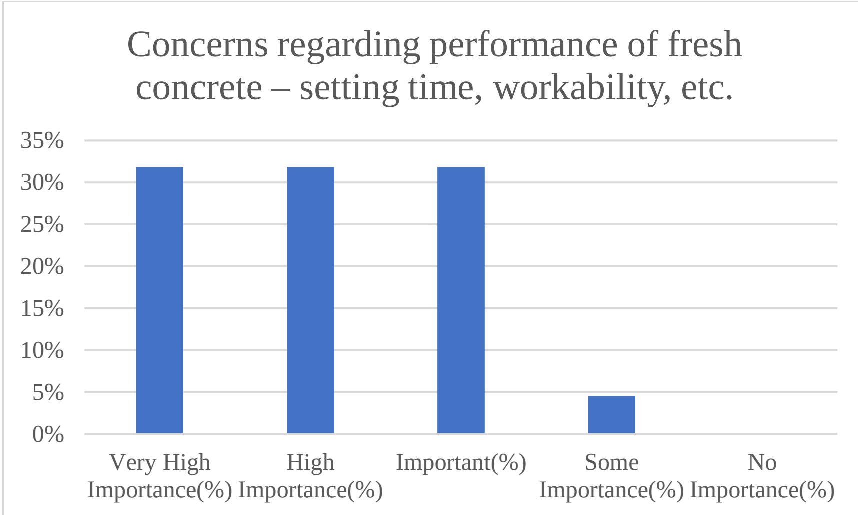
Concerns regarding performance of fresh concrete – setting time, workability, etc.
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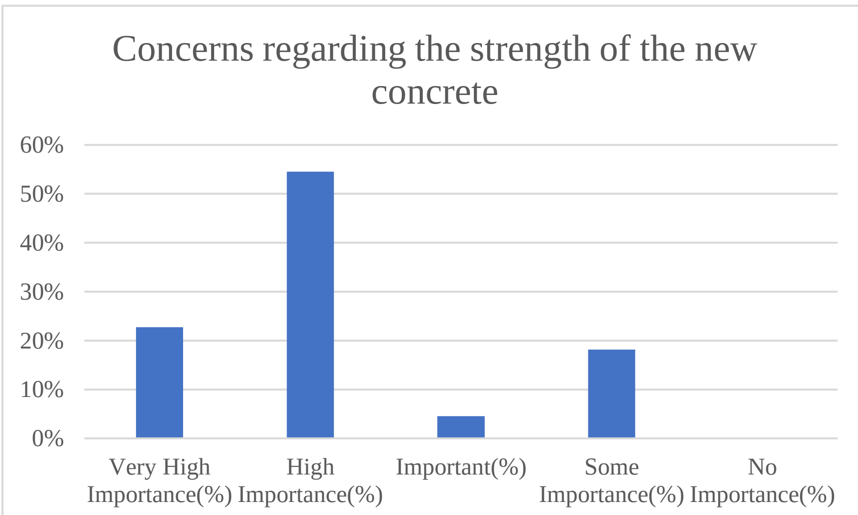
Concerns regarding the strength of the new concrete
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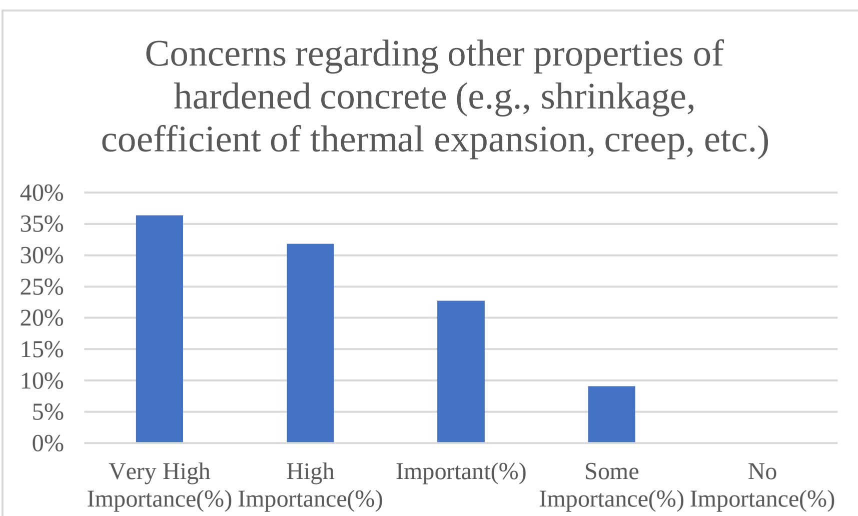
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)
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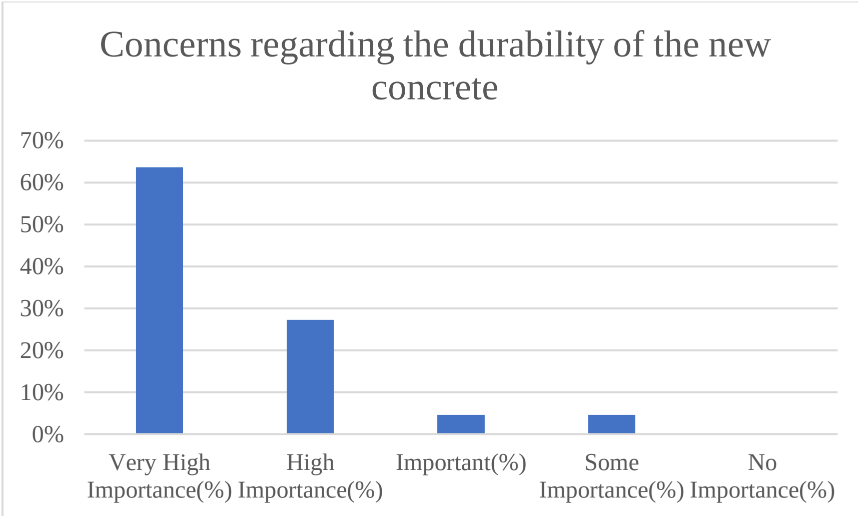
Concerns regarding the durability of the new concrete
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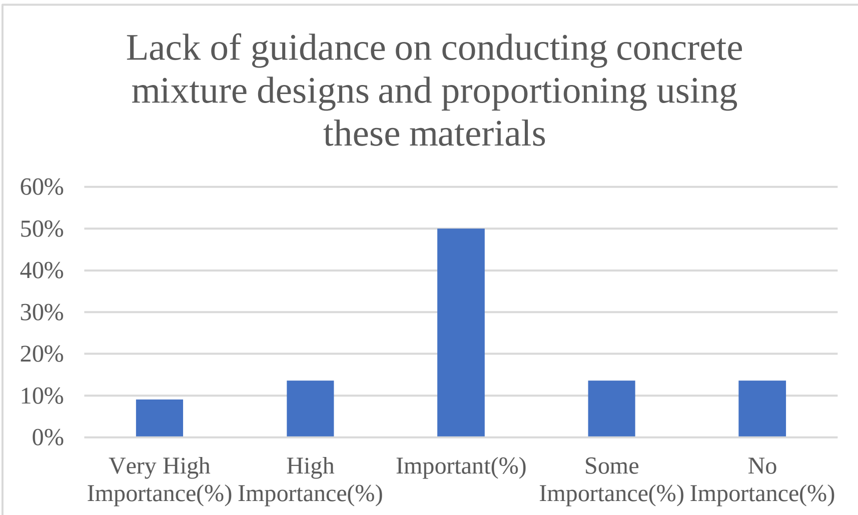
Lack of guidance on conducting concrete mixture designs and proportioning using these materials
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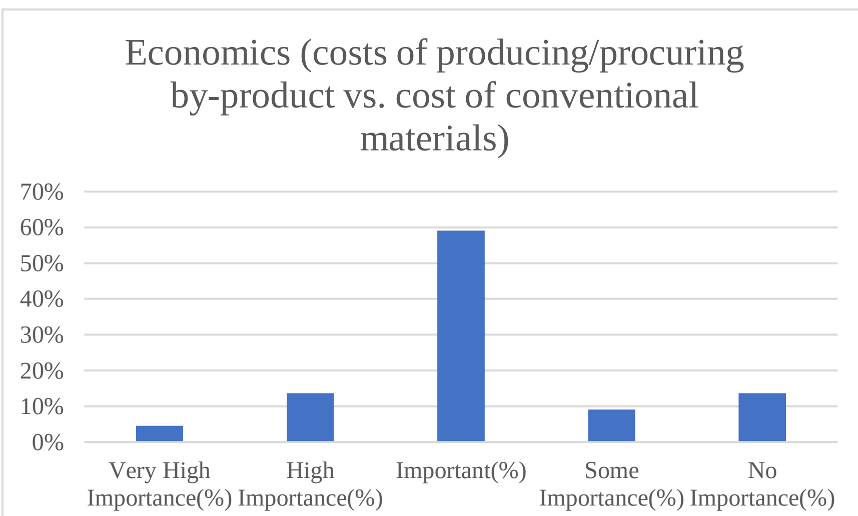
Economics (costs of producing/procuring by-product vs. cost of conventional materials)
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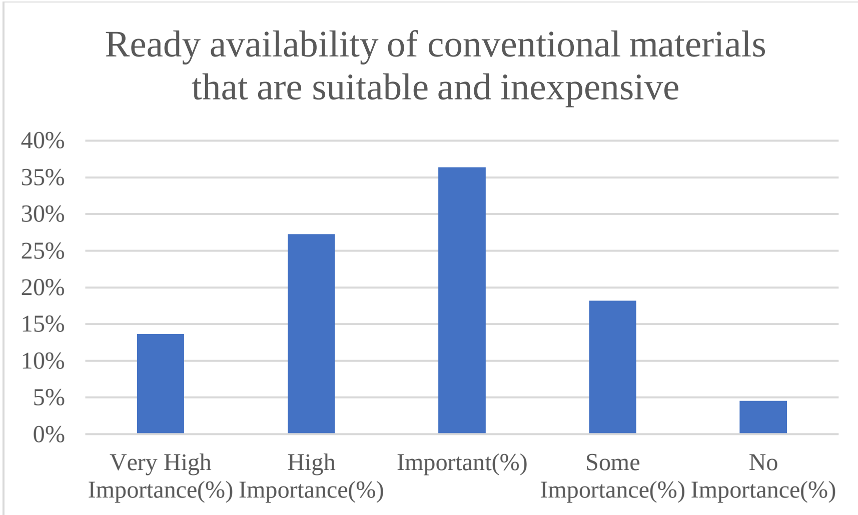
Ready availability of conventional materials that are suitable and inexpensive
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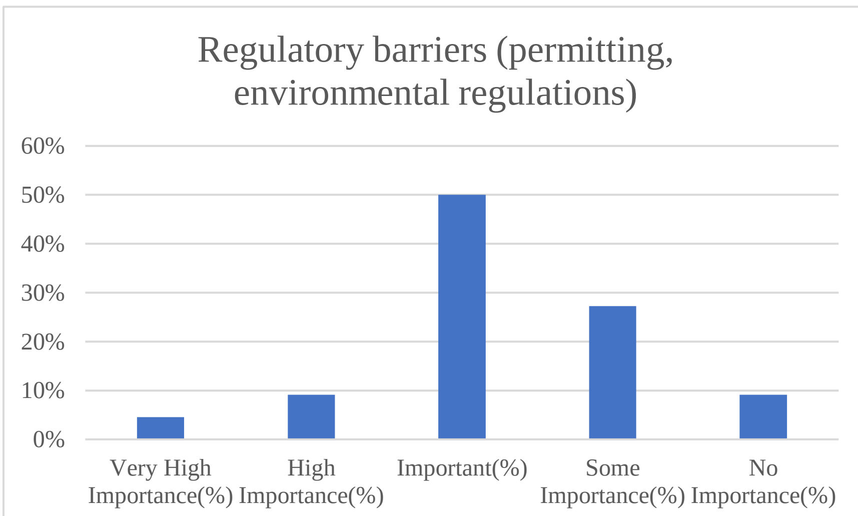
Regulatory barriers (permitting, environmental regulations)
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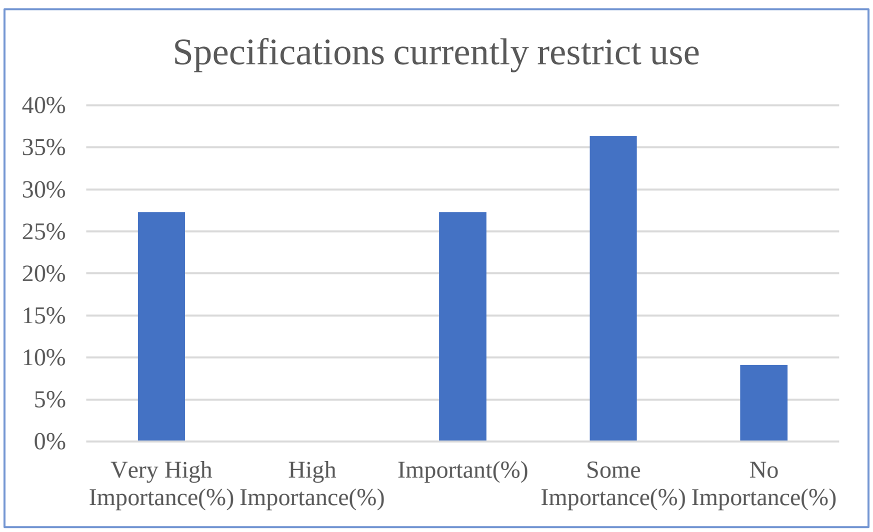
No Importance(%)

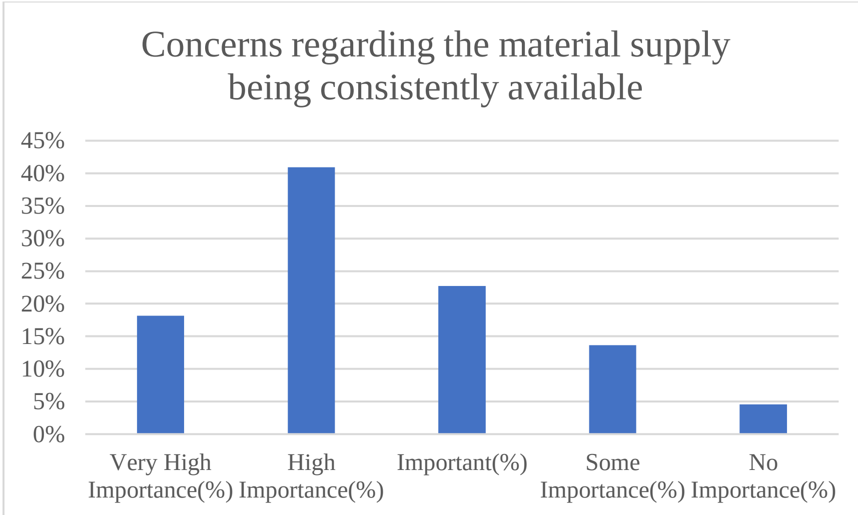
6) On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products as aggregates or inert fillers in new concrete.

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

	1	2	3	4	5
Specifications currently restrict use					
Concerns regarding the material supply being consistently available					
Concerns regarding variability in material properties					
Concerns regarding performance of fresh concrete – setting time, workability, etc.					
Concerns regarding the strength of the new concrete					
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)					
Concerns regarding the durability of the new concrete					
Lack of guidance on conducting concrete mixture designs and proportioning using these materials					
Economics (costs of producing/procuring by-product vs. cost of conventional materials)					
Ready availability of conventional materials that are suitable and inexpensive					
Regulatory barriers (permitting, environmental regulations)					

Other (please describe)




Concerns regarding the material supply being consistently available
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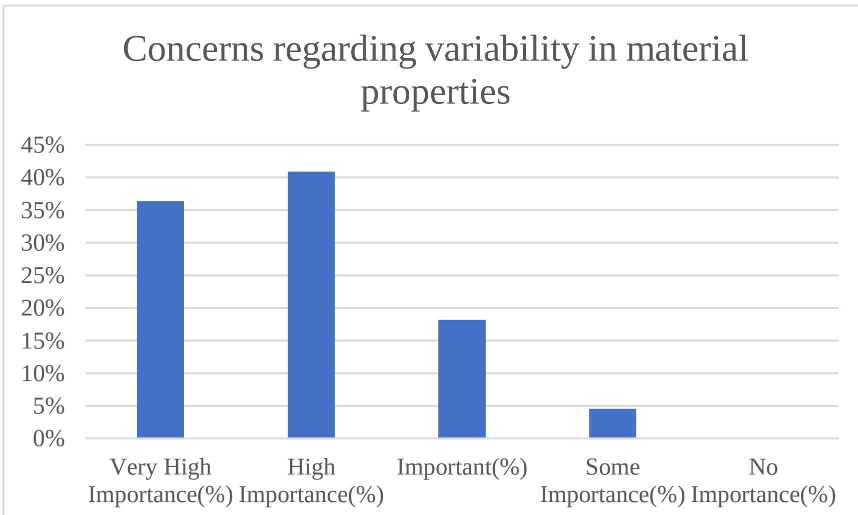
Concerns regarding variability in material properties
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Very High Importance(%)
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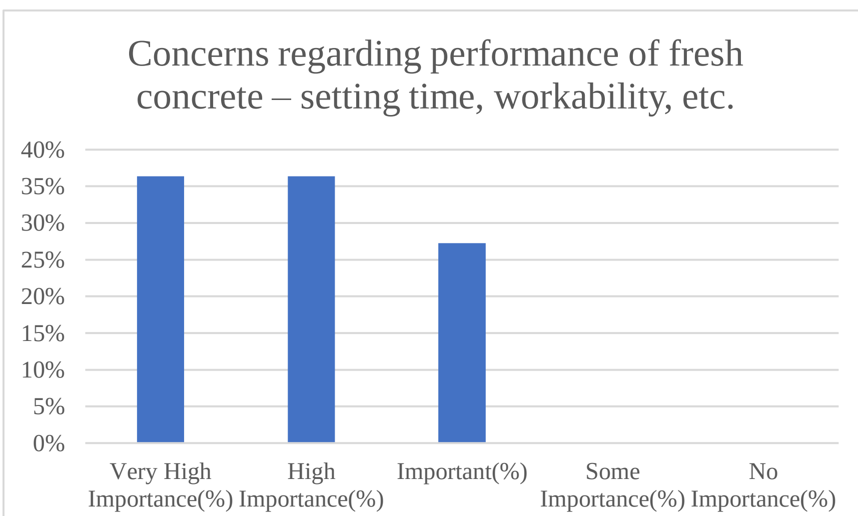
Important(%)
Some Importance(%)
No Importance(%)


Concerns regarding performance of fresh concrete – setting time, workability, etc.
40%
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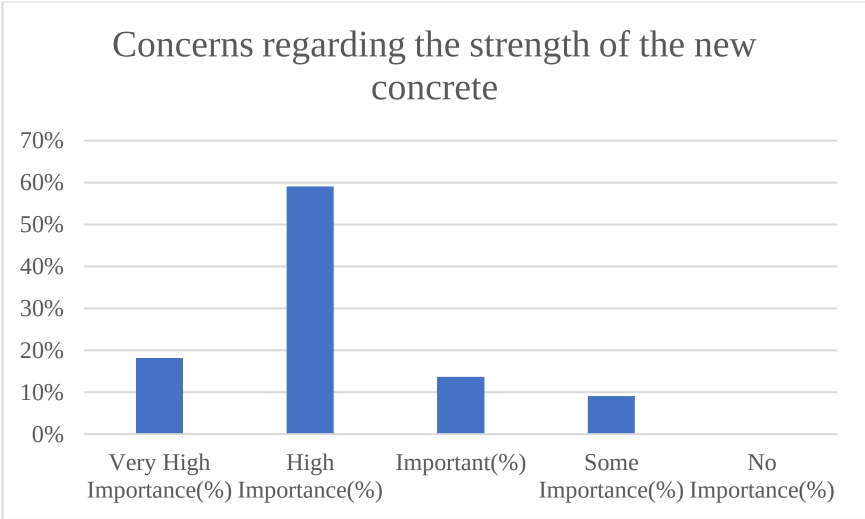
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Concerns regarding the strength of the new concrete
70%
60%
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Very High Importance(%)
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Important(%)
Some Importance(%)
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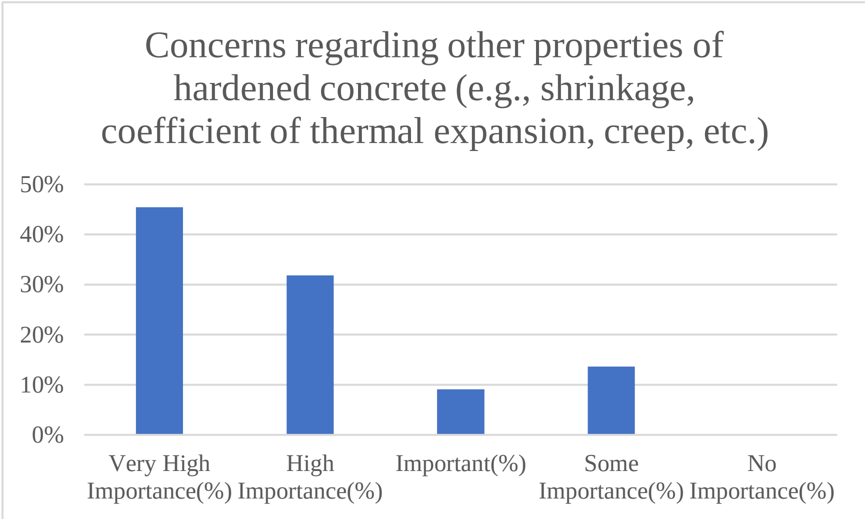
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)
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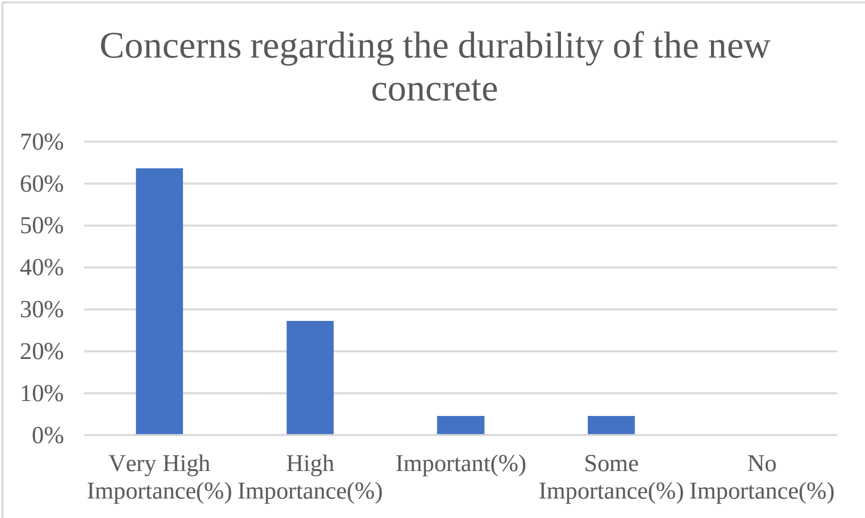
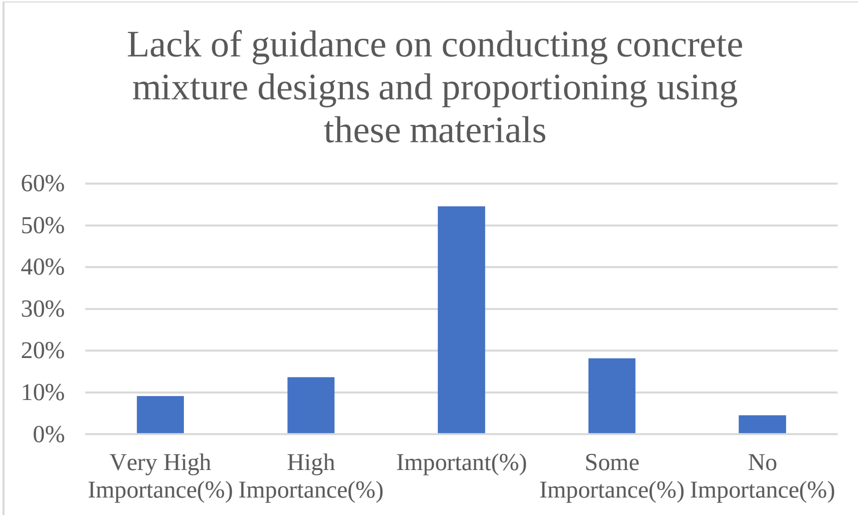
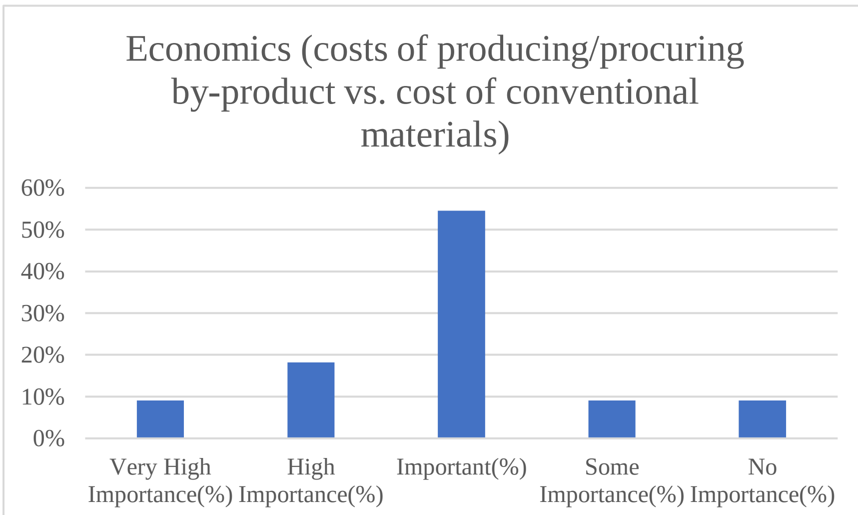
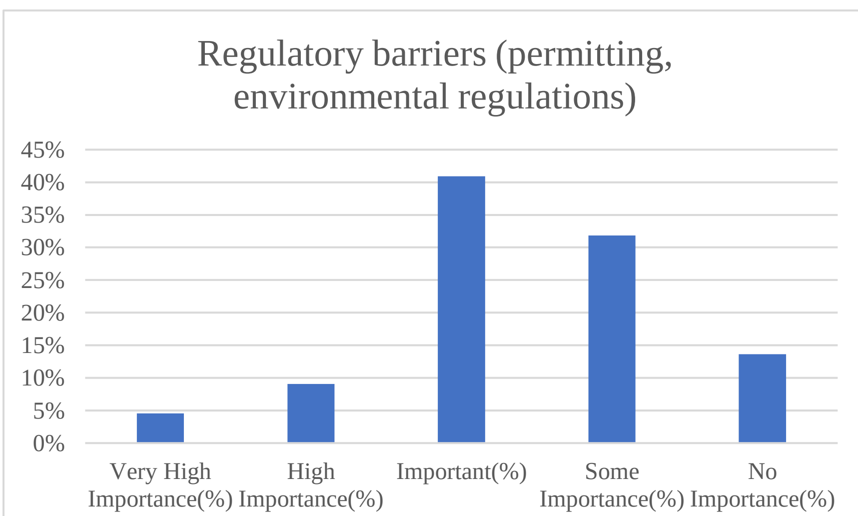
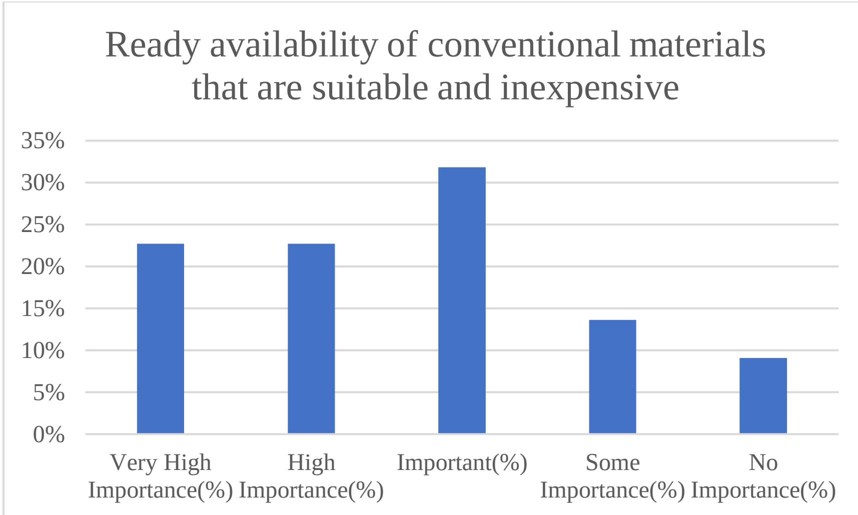
No Importance(%)


Concerns regarding the durability of the new concrete
70%
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Lack of guidance on conducting concrete mixture designs and proportioning using these materials
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Economics (costs of producing/procuring by-product vs. cost of conventional materials)
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Regulatory barriers (permitting, environmental regulations)
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)



7) What characterization tests of the by-product materials listed above would provide your agency confidence in their use as a supplementary cementitious material (SCM) in pavement foundations or in new concrete?

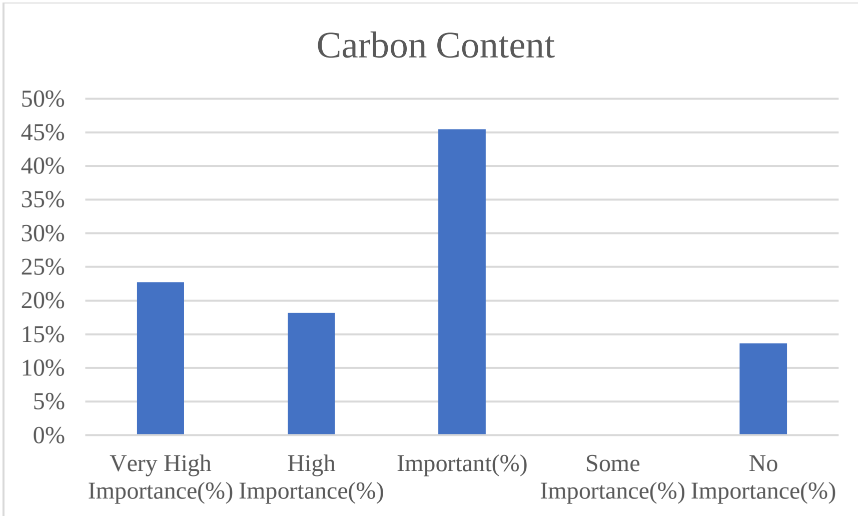
Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

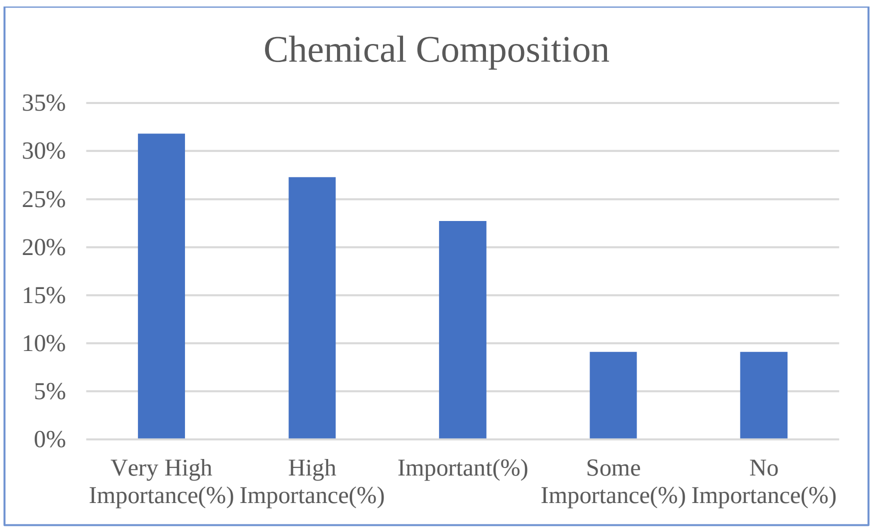
	1	2	3	4	5
Chemical composition	○	○	○	○	○
Carbon content	○	○	○	○	○
Other contaminants	○	○	○	○	○
Incompatibility with certain cements	○	○	○	○	○
Fineness	○	○	○	○	○
Specific gravity	○	○	○	○	○
Strength activity index	○	○	○	○	○
Water requirement	○	○	○	○	○
Soundness (autoclave expansion or other)	○	○	○	○	○
Density	○	○	○	○	○
Uniformity	○	○	○	○	○

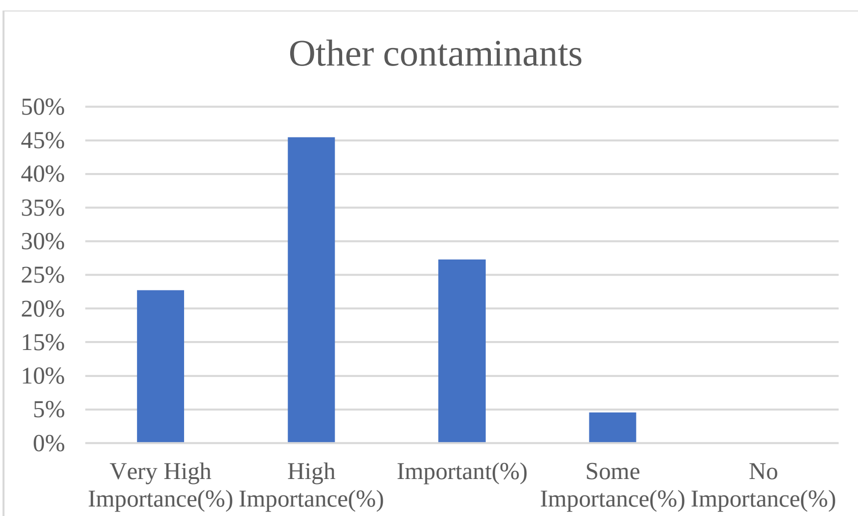
Other Tests (please describe):

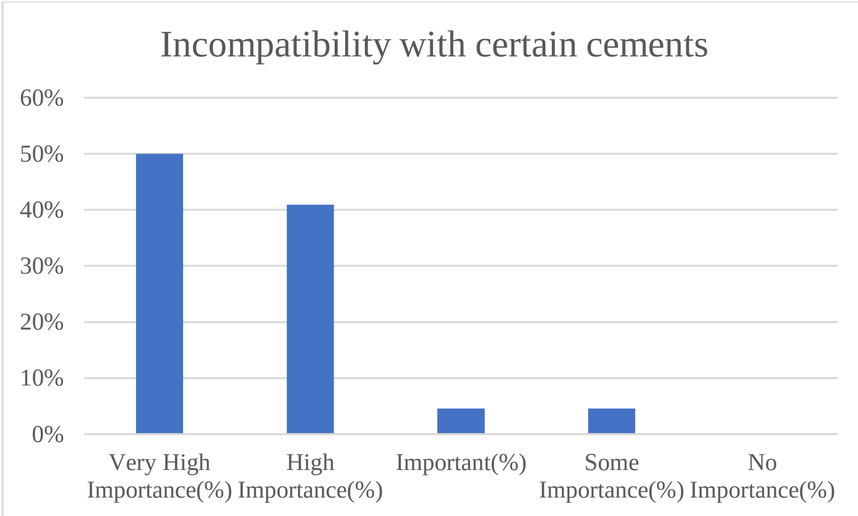
Comments:

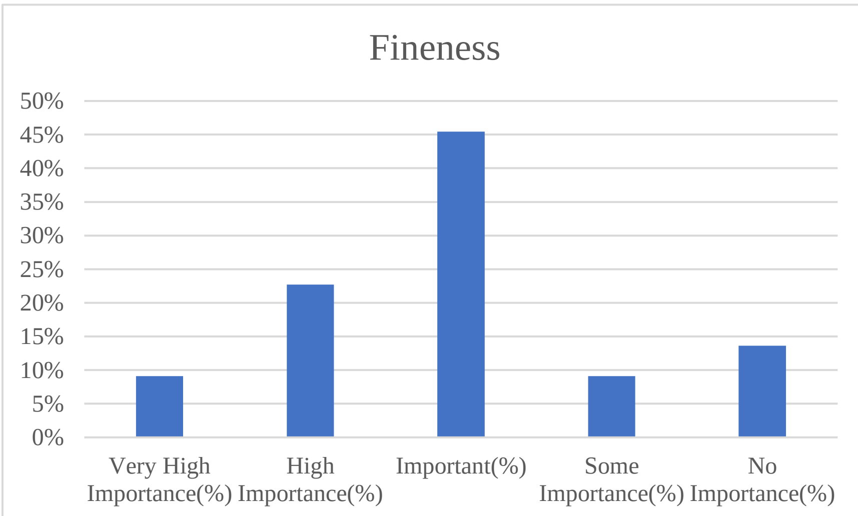
1. "Chloride Diffusion Coefficient: 5".

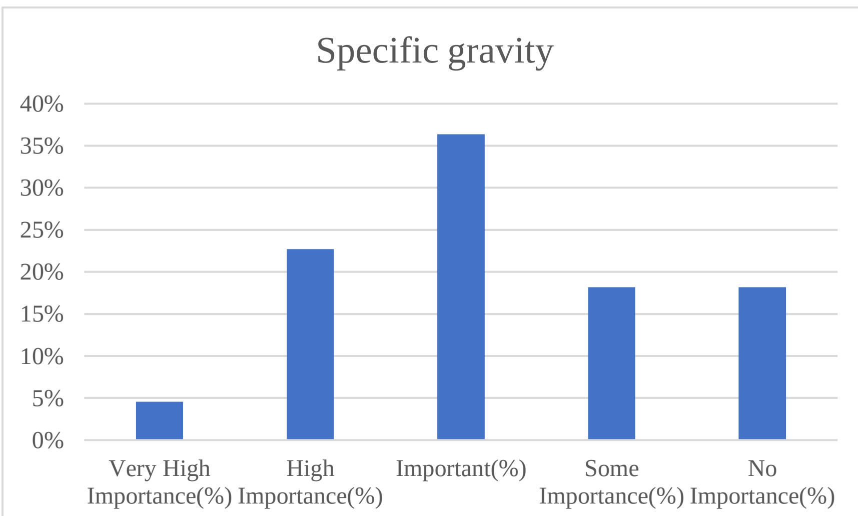

Carbon Content
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

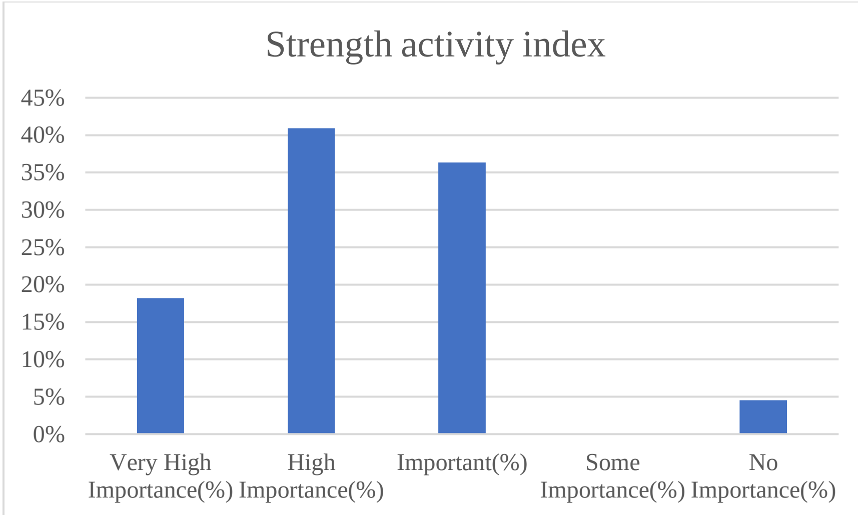

Chemical Composition
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

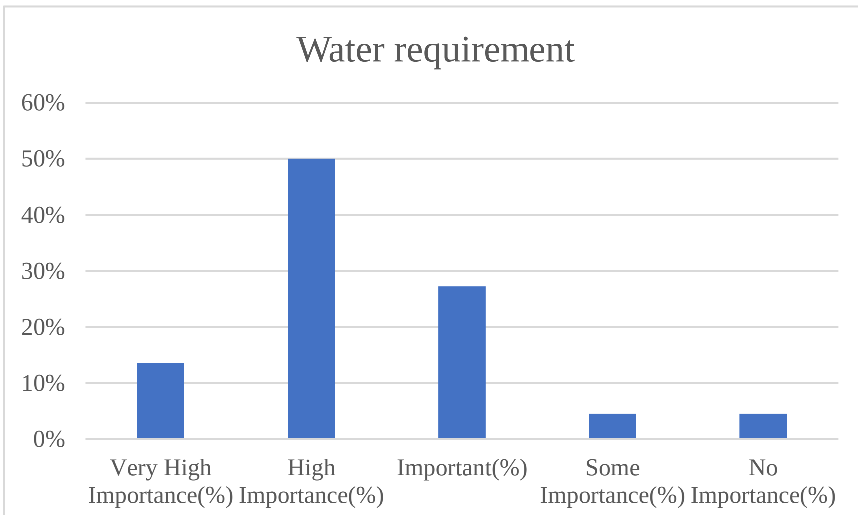

Other contaminants
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

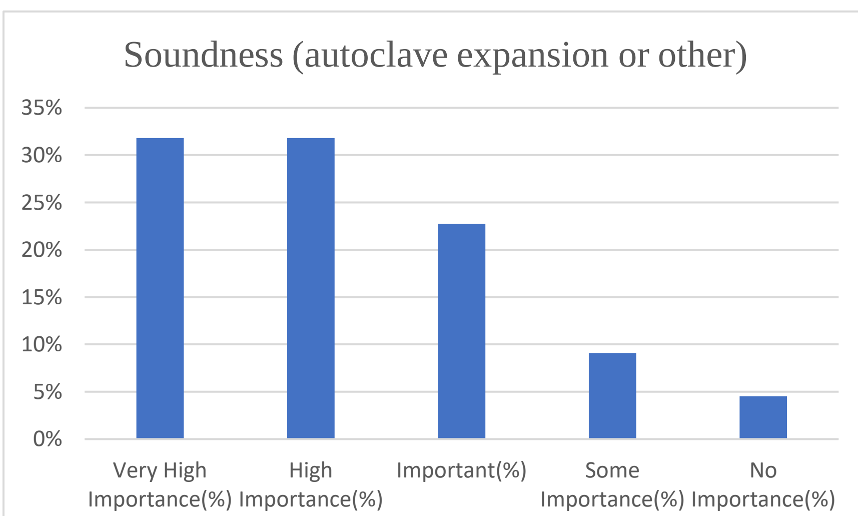

Incompatibility with certain cements
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

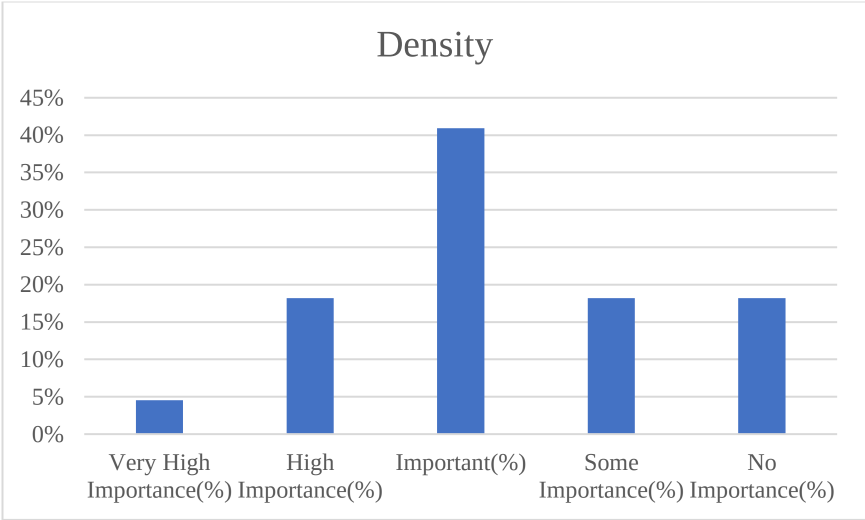

Fineness
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

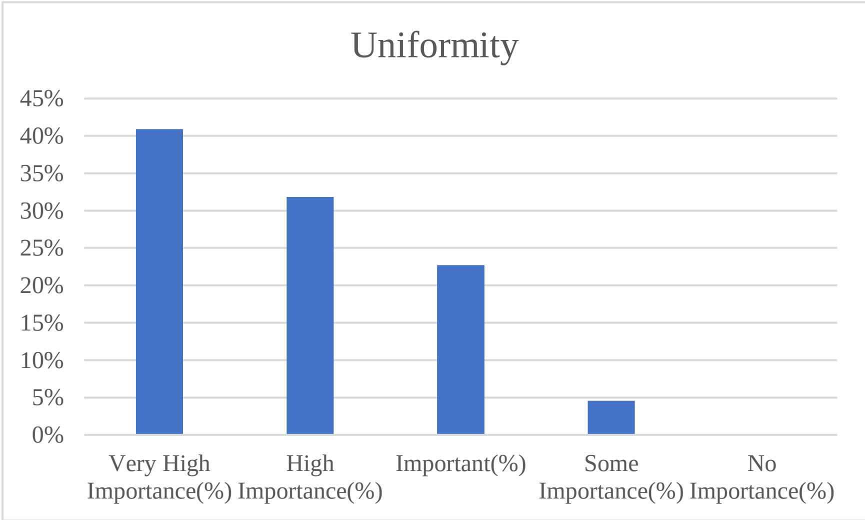

Specific gravity
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Strength activity index
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Water requirement
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Soundness (autoclave expansion or other)
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Density
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

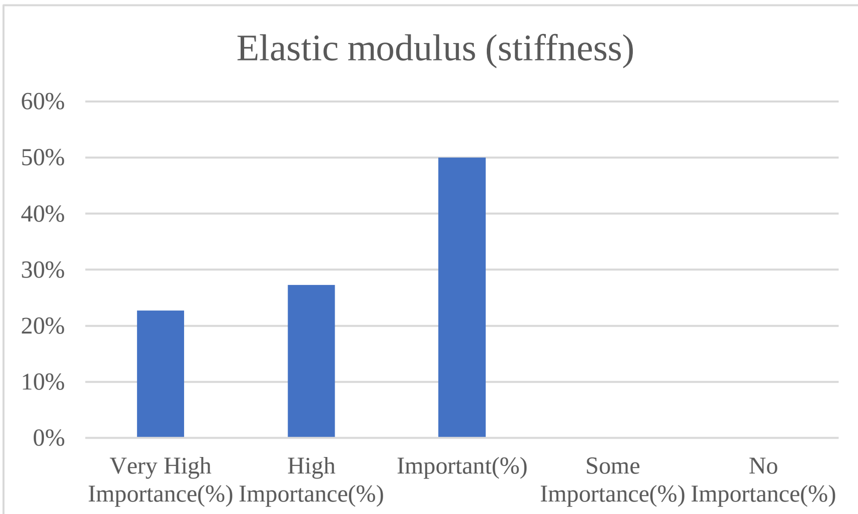

Uniformity
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

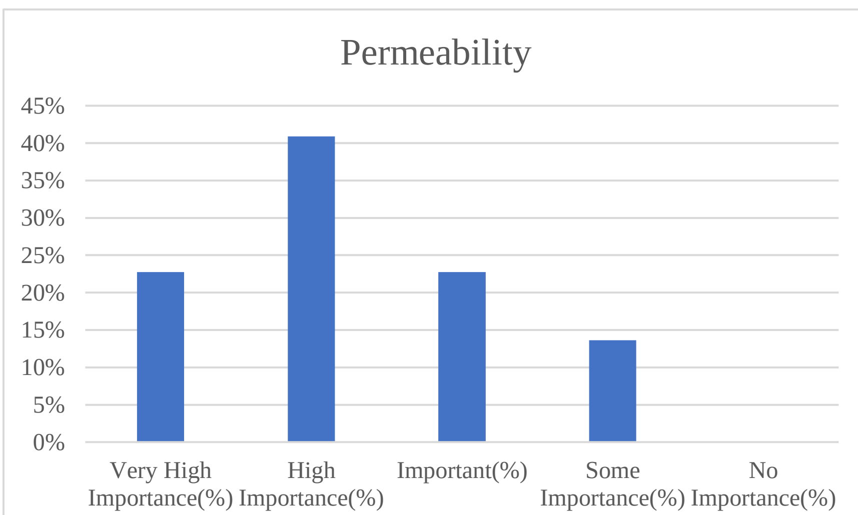
8) What characterization tests of base materials stabilized with a by-product would provide your agency confidence in the by-product's use as a supplementary cementitious material (SCM) in pavement foundations or in new concrete?

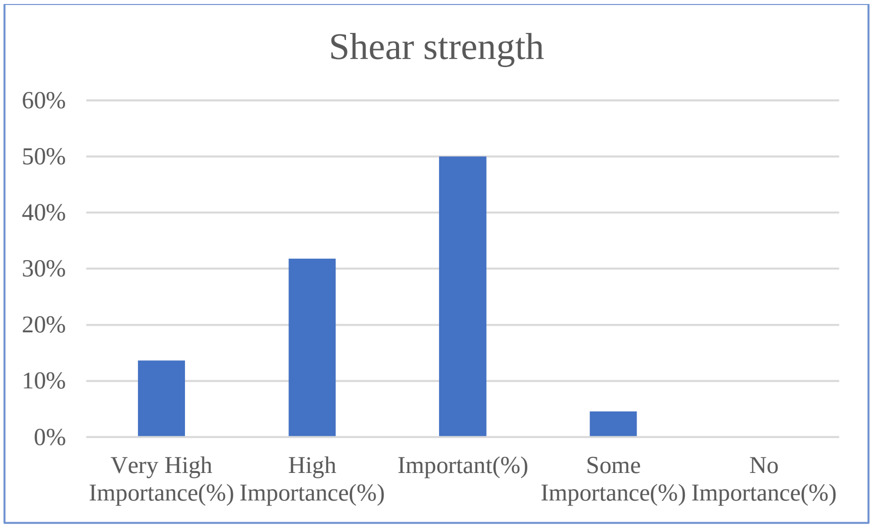
Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

	1	2	3	4	5
Shear strength	○	○	○	○	○
Elastic modulus (stiffness)	○	○	○	○	○
Permeability	○	○	○	○	○

Other Tests (please describe):





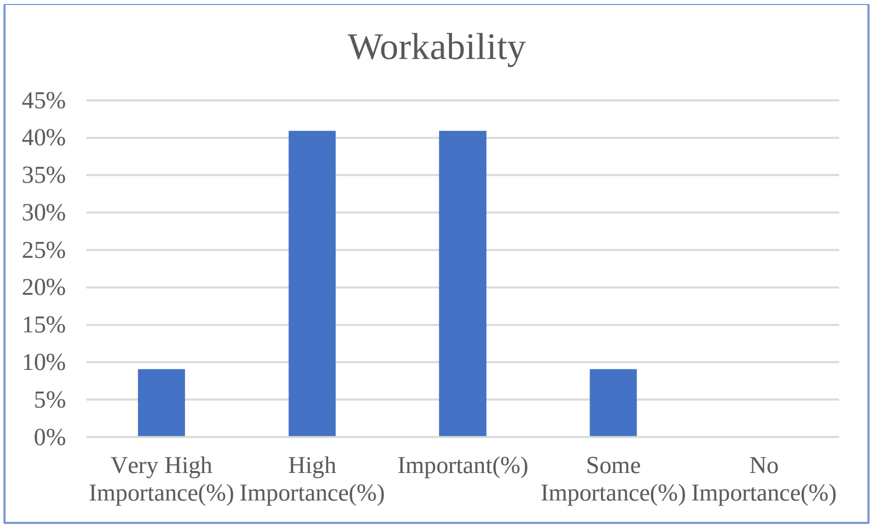


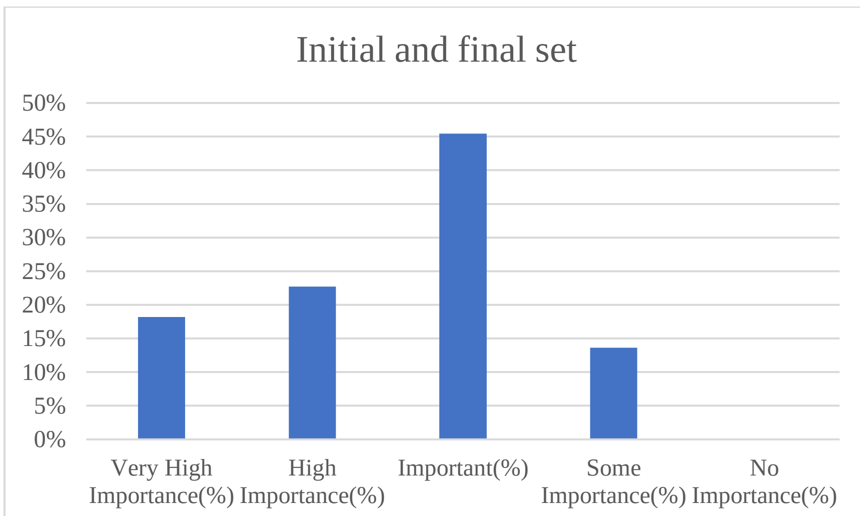
9) What characterization tests of the concrete incorporating a by-product would provide your agency confidence in the by product's use as a supplementary cementitious material (SCM) in pavement foundations or in new concrete?

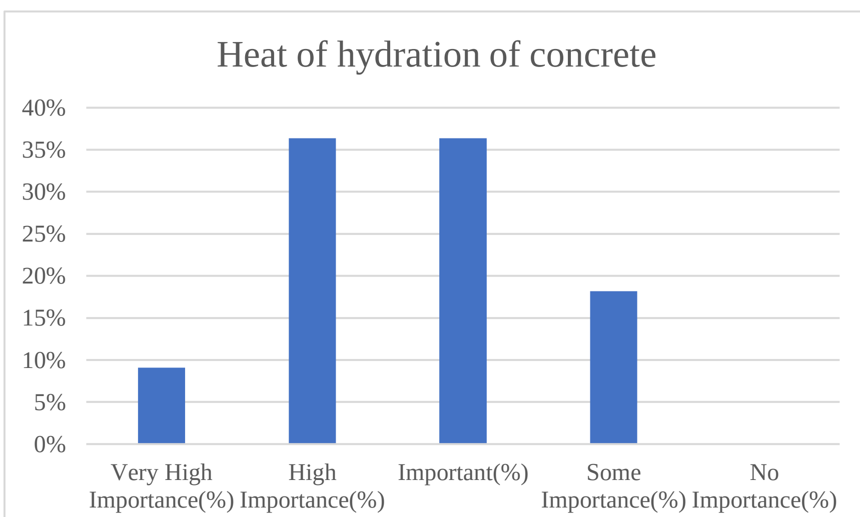
Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

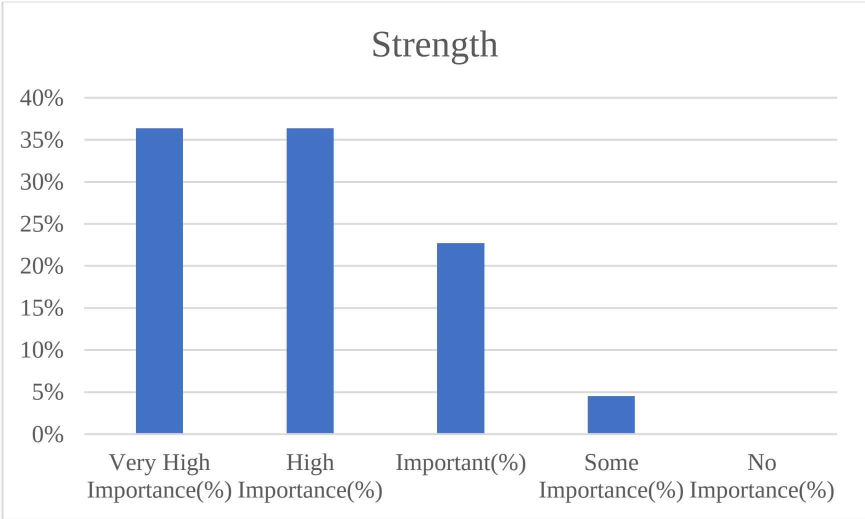
	1	2	3	4	5
Workability	○	○	○	○	○
Initial and final set	○	○	○	○	○
Heat of hydration of concrete	○	○	○	○	○
Strength	○	○	○	○	○
Permeability	○	○	○	○	○
Resistance to freezing and thawing	○	○	○	○	○
Resistance to deicing salts	○	○	○	○	○
Susceptibility to ASR	○	○	○	○	○
Susceptibility to sulfate attack	○	○	○	○	○

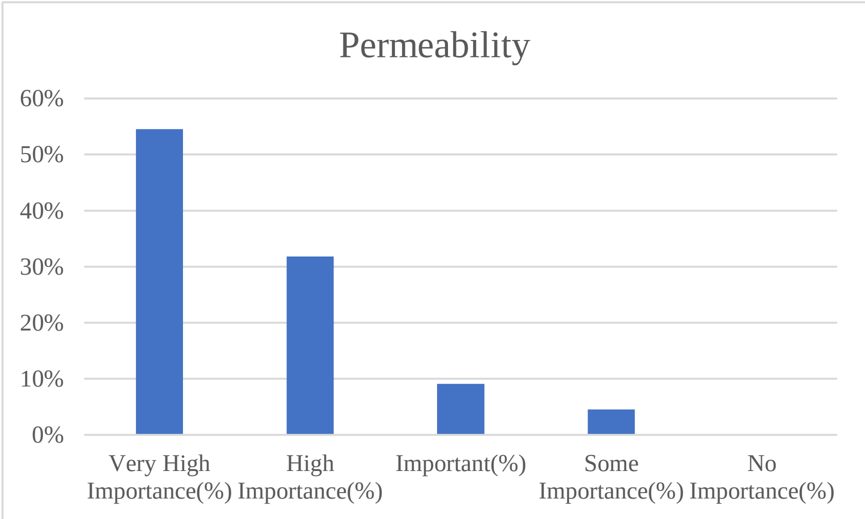
Other Tests (please describe):

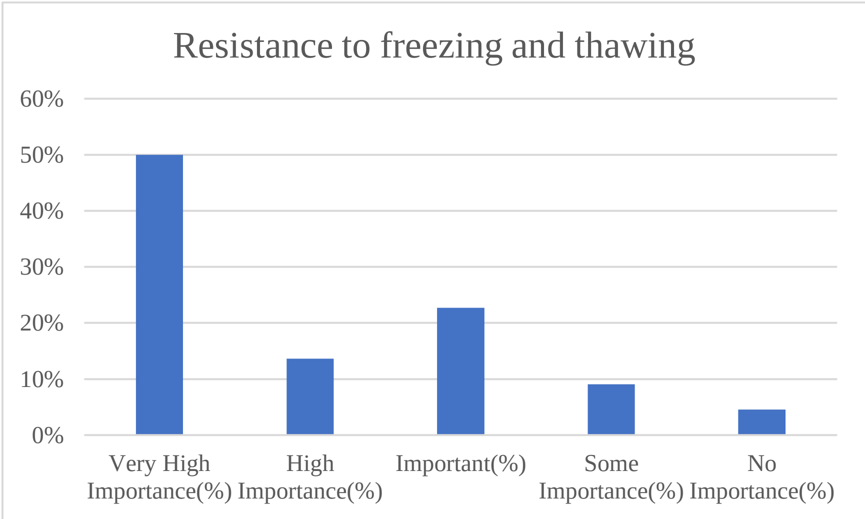

Workability
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

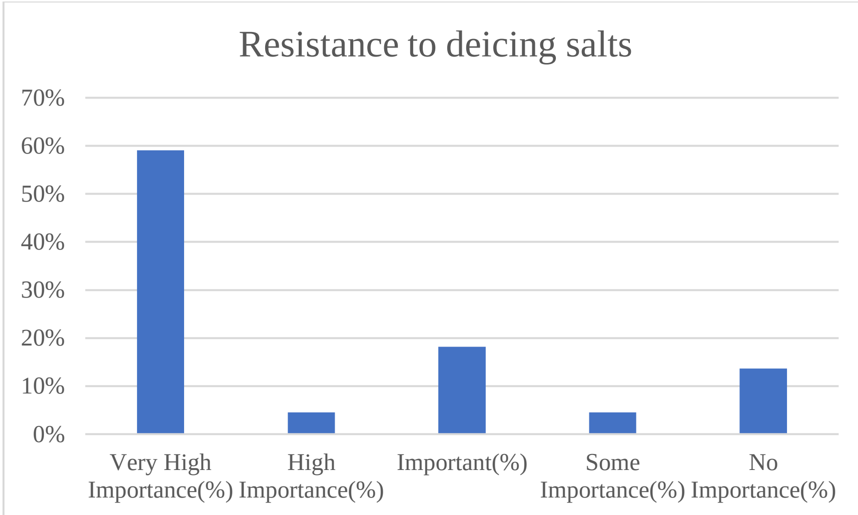

Initial and final set
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

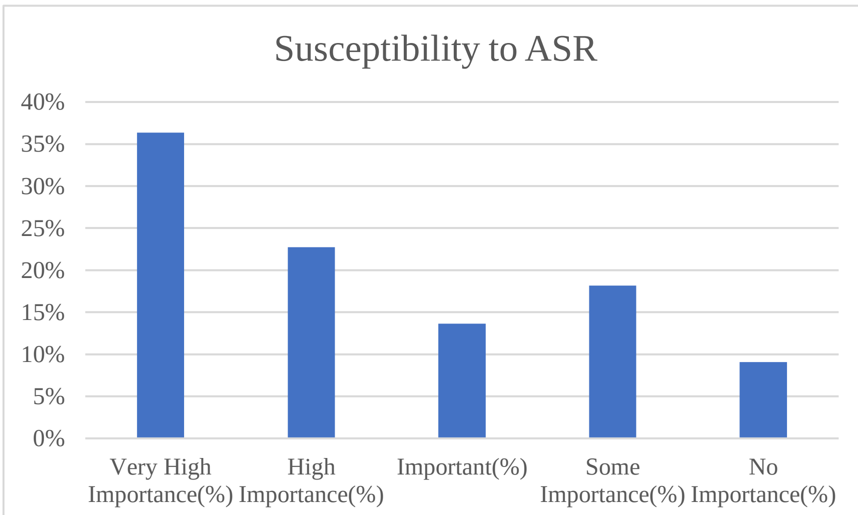

Heat of hydration of concrete
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

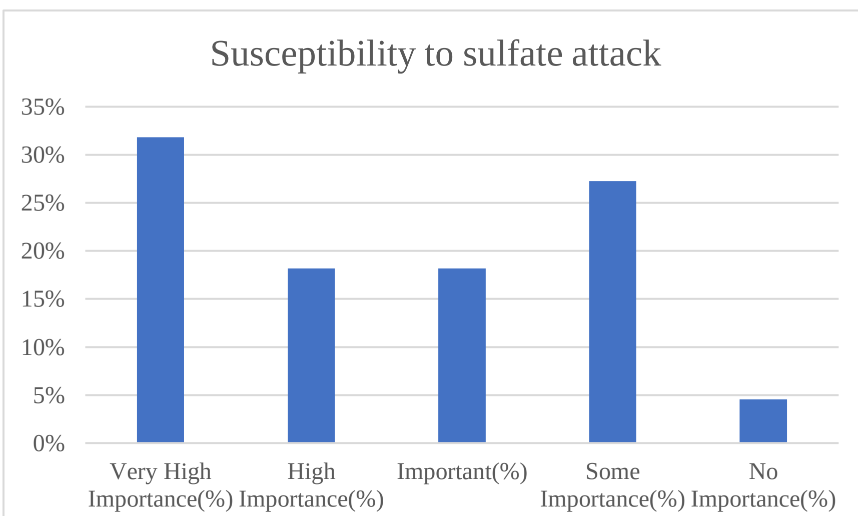

Strength
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Permeability
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Resistance to freezing and thawing
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Resistance to deicing salts
70%
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Susceptibility to ASR
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

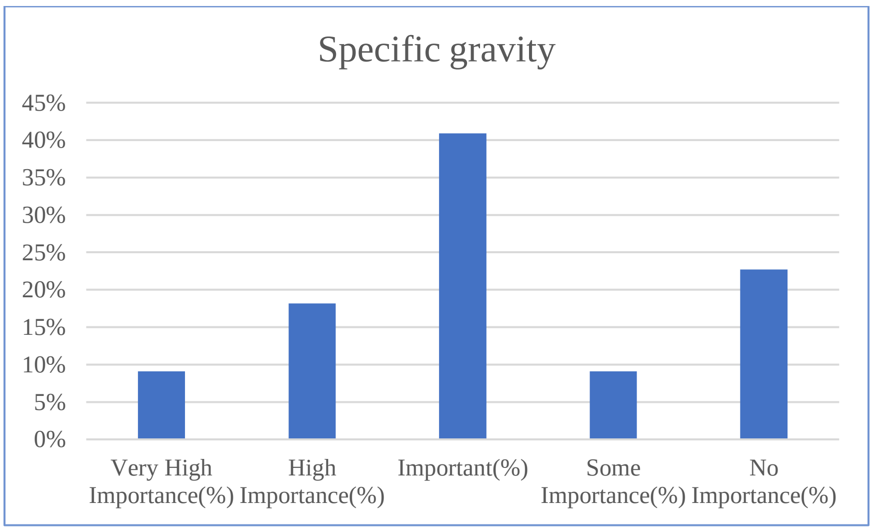

Susceptibility to sulfate attack
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

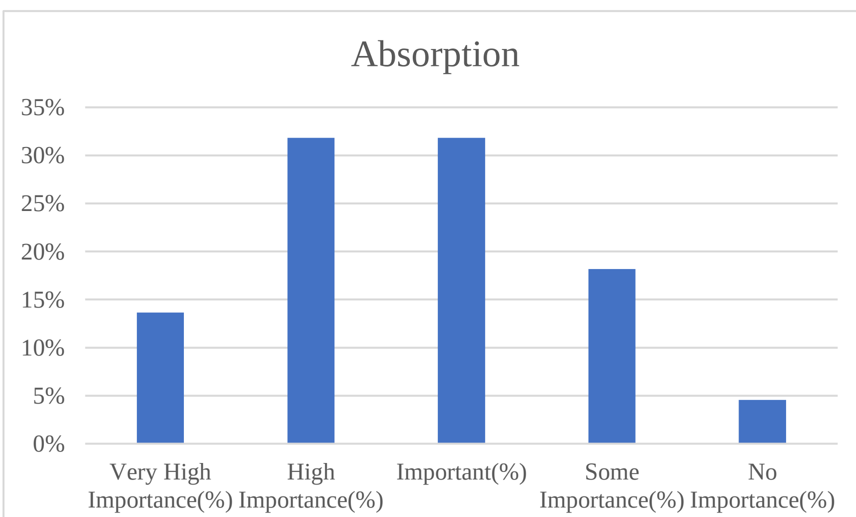
10) What characterization tests of the by-products listed above would provide your agency confidence in their use as an aggregate or filler material in pavement foundations or new concrete?

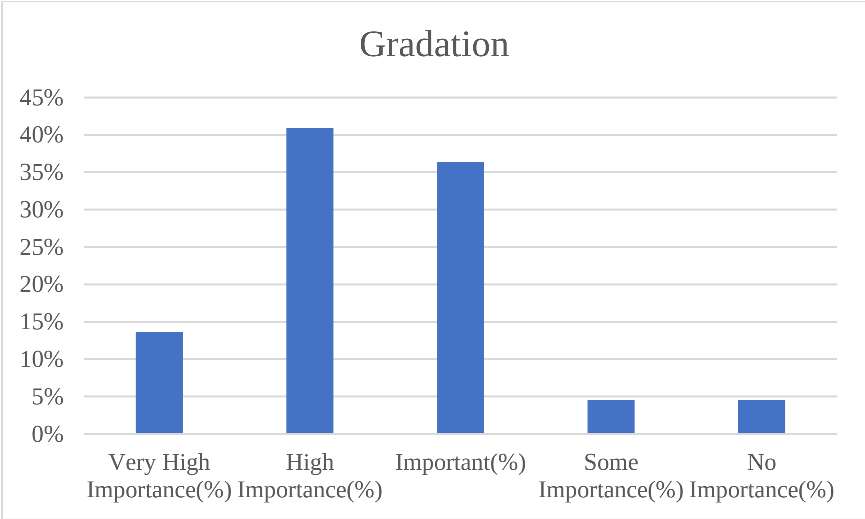
Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

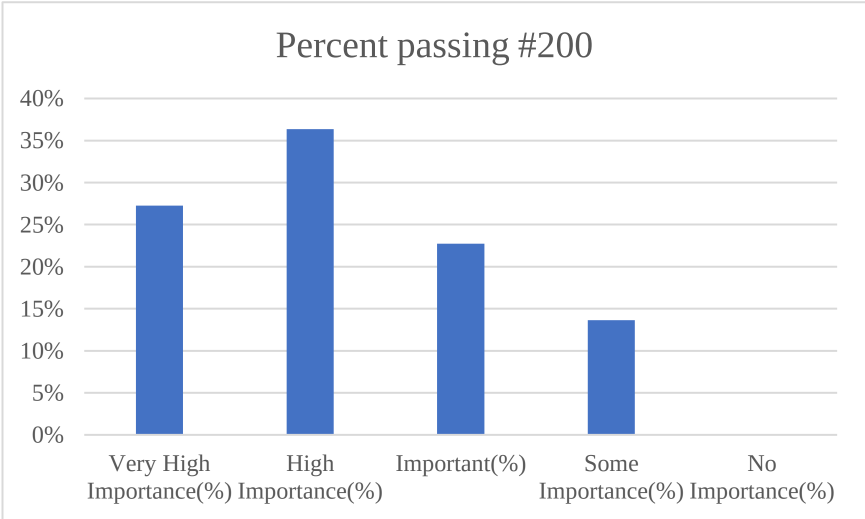
	1	2	3	4	5
Specific gravity	○	○	○	○	○
Absorption	○	○	○	○	○
Gradation	○	○	○	○	○
Percent passing #200	○	○	○	○	○
Soundness OR Unconfined Freeze-Thaw	○	○	○	○	○
Abrasion resistance (L.A., Micro-Deval or Other)	○	○	○	○	○

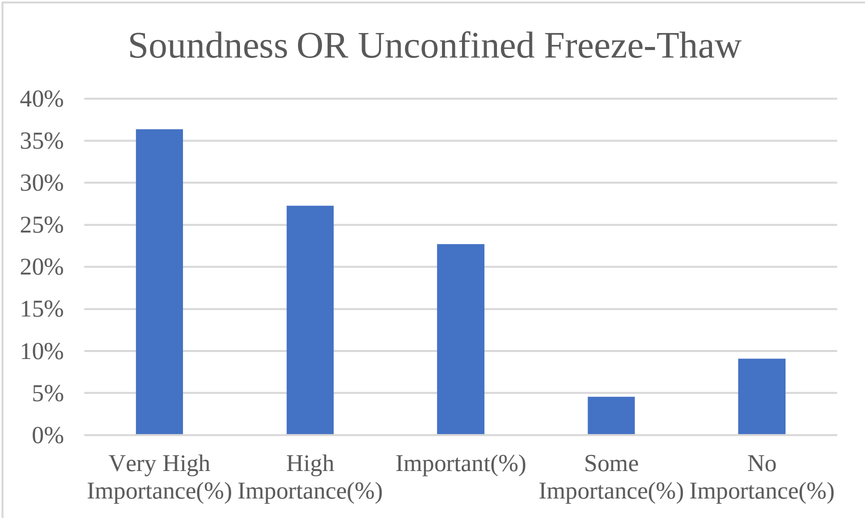
Other Tests (please describe):

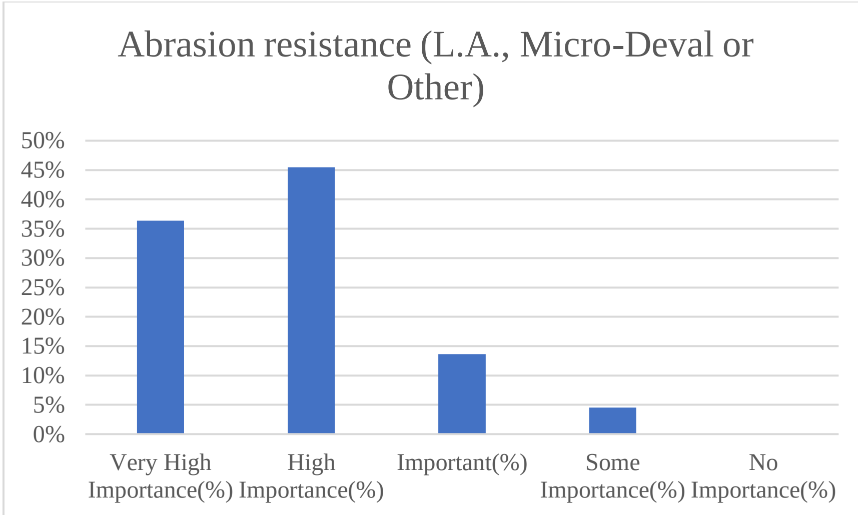





Gradation
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Percent passing #200
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Soundness OR Unconfined Freeze-Thaw
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

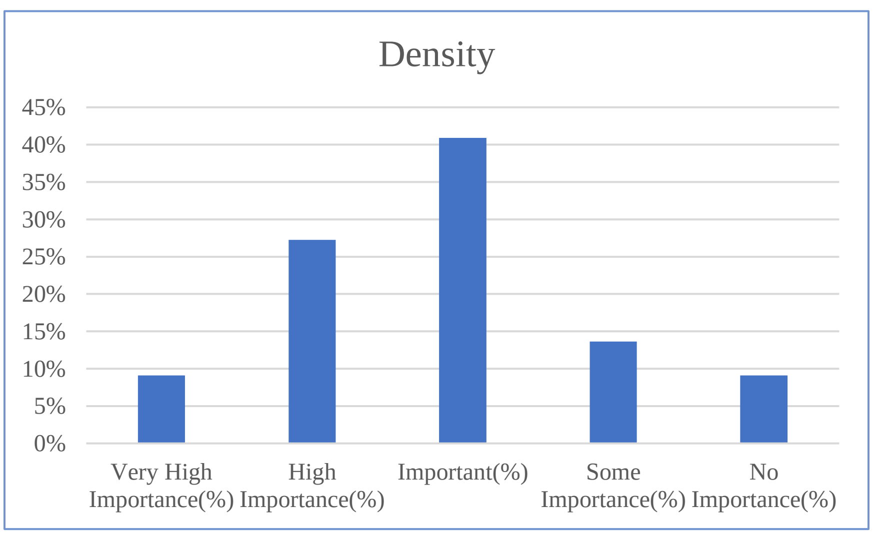


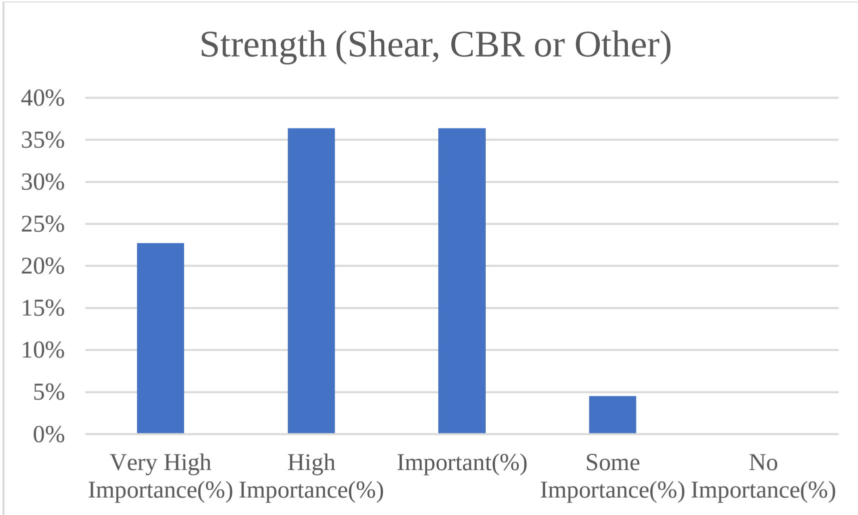
11) What characterization tests of unbound base material incorporating recycled or by-product aggregates would provide your agency confidence in their use as an aggregate or filler material in pavement foundations or new concrete?

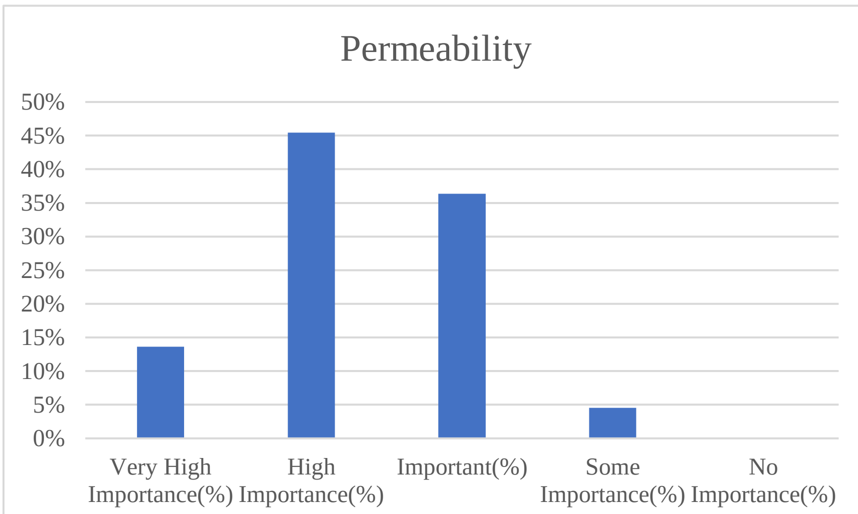
Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

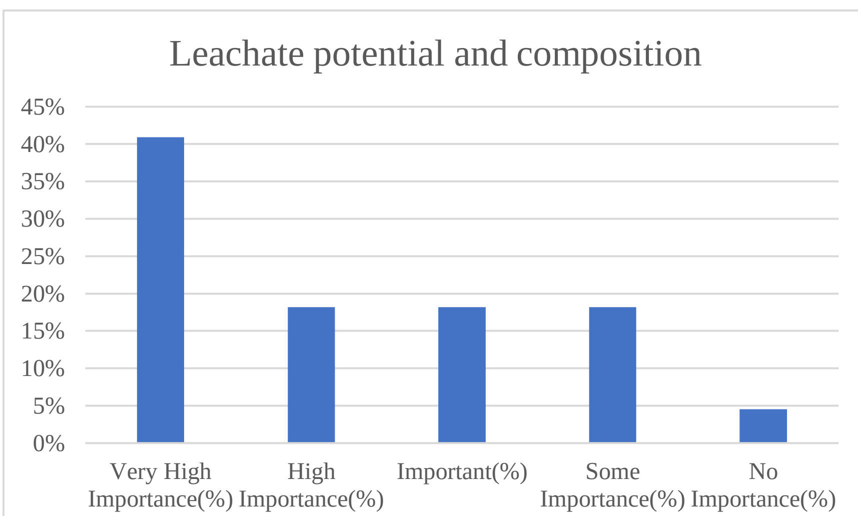
	1	2	3	4	5
Density	○	○	○	○	○
Strength (Shear, CBR or Other)	○	○	○	○	○
Permeability	○	○	○	○	○
Leachate potential and composition	○	○	○	○	○

Other Tests (please describe):




Strength (Shear, CBR or Other)
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Permeability
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

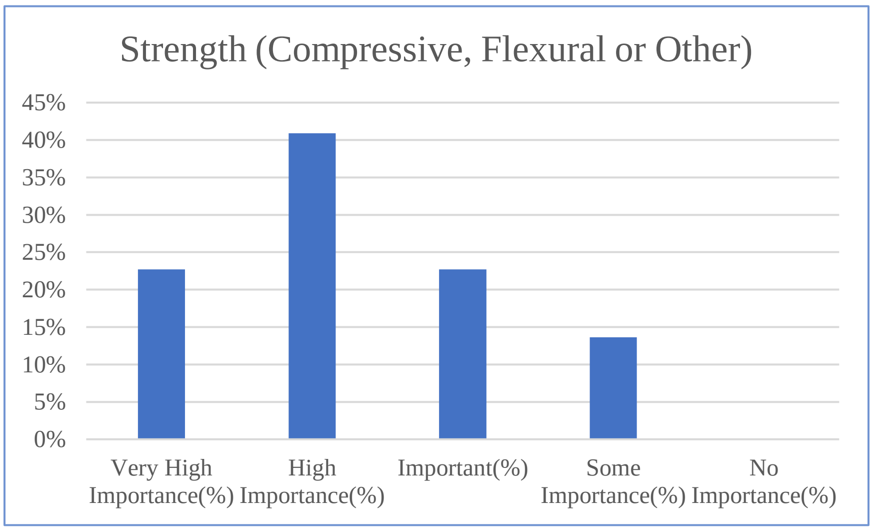

Leachate potential and composition
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

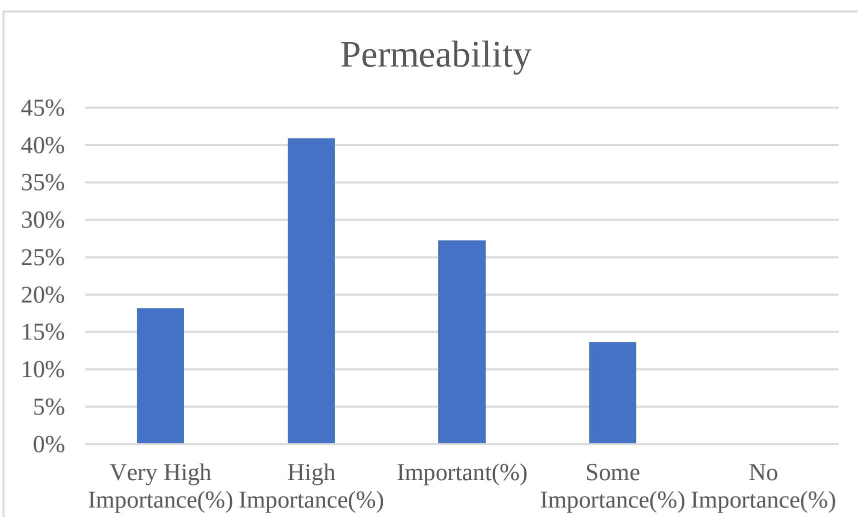
12) What characterization tests of stabilized base material incorporating recycled or by-product aggregate would provide your agency confidence in their use as an aggregate or filler material in pavement foundations or new concrete?

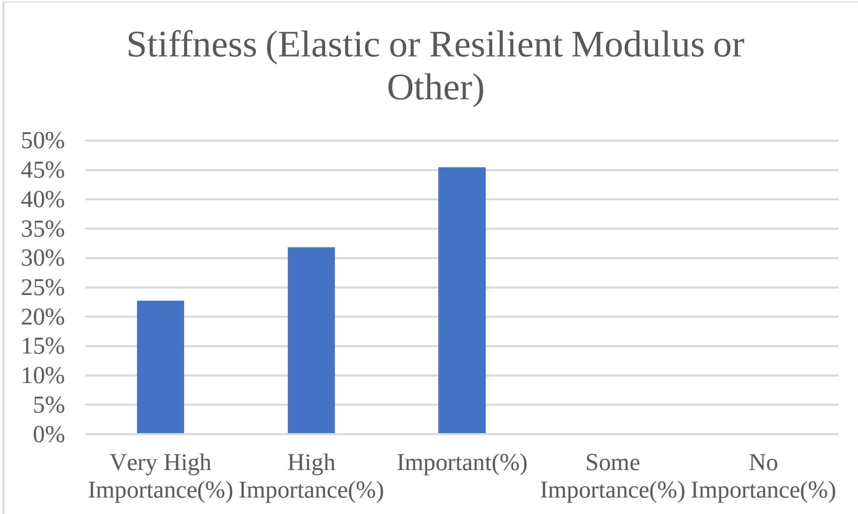
Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

	1	2	3	4	5
Strength (Compressive, Flexural or Other)	○	○	○	○	○
Stiffness (Elastic or Resilient Modulus or Other)	○	○	○	○	○
Permeability	○	○	○	○	○

Other Tests (please describe):





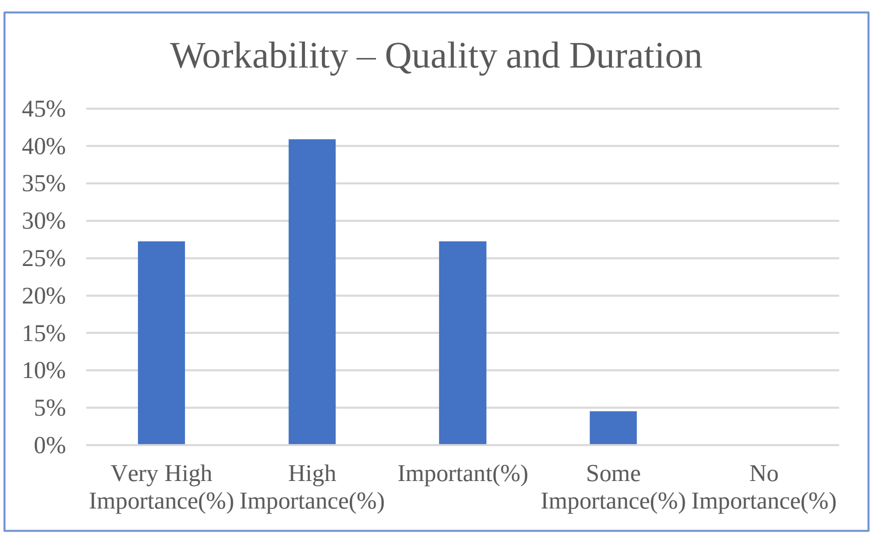


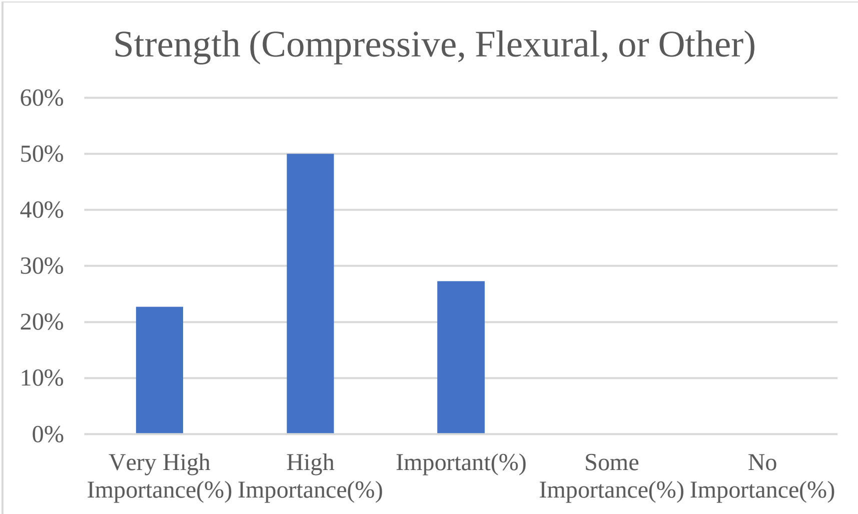
13) What characterization tests of concrete incorporating recycled or by-product aggregate would provide your agency confidence in their use as an aggregate or filler material in pavement foundations or new concrete?

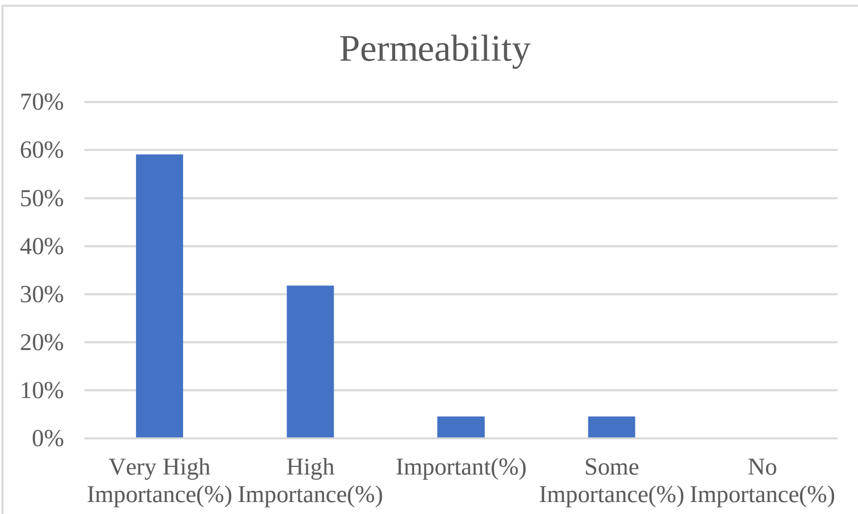
Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

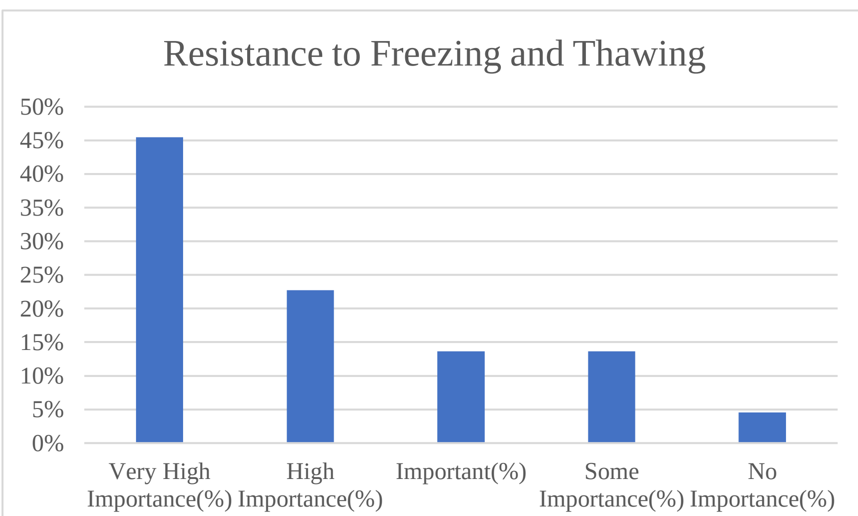
	1	2	3	4	5
Tests of Concrete Incorporating Recycled or By-Product Aggregate:	○	○	○	○	○
Workability – Quality and Duration	○	○	○	○	○
Strength (Compressive, Flexural, or Other)	○	○	○	○	○
Permeability	○	○	○	○	○
Resistance to Freezing and Thawing	○	○	○	○	○
Resistance to Deicing Salts (Salt Scaling, Formation Factor, or Other)	○	○	○	○	○
Susceptibility to ASR	○	○	○	○	○
Susceptibility to Sulfate Attack	○	○	○	○	○

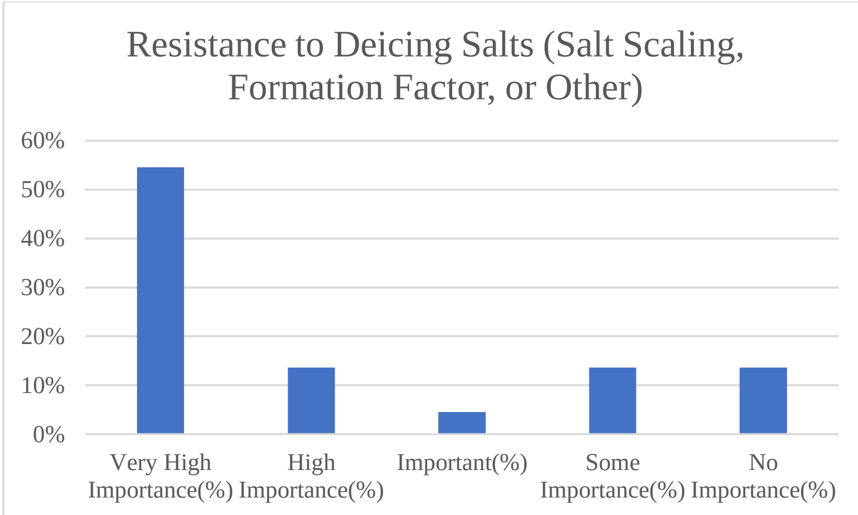
Other Tests (please describe):

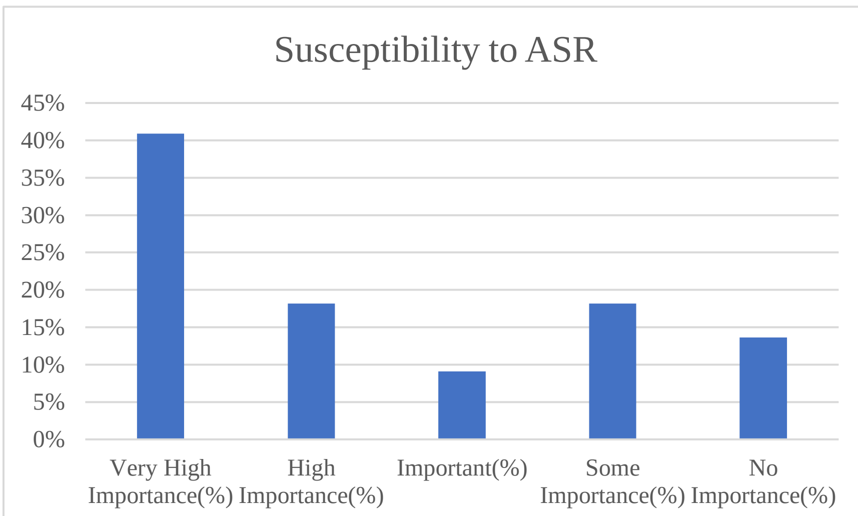


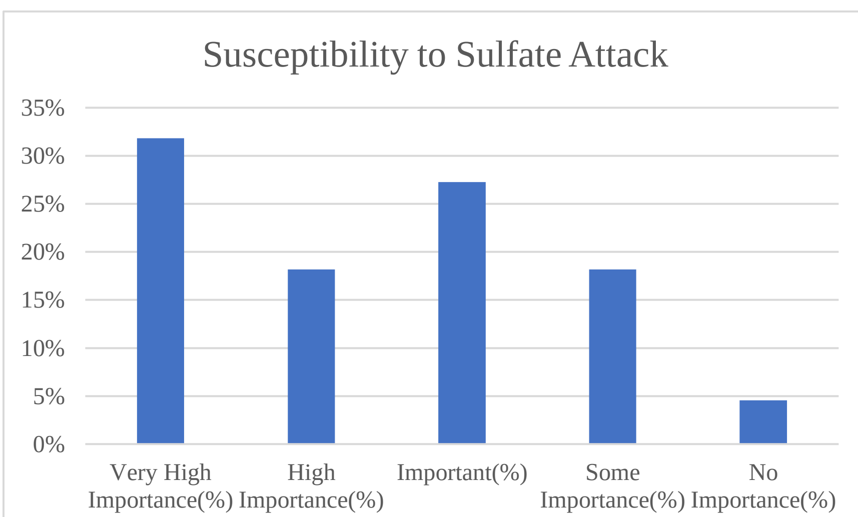

Strength (Compressive, Flexural, or Other)
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Permeability
70%
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Resistance to Freezing and Thawing
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Resistance to Deicing Salts (Salt Scaling, Formation Factor, or Other)
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Susceptibility to ASR
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

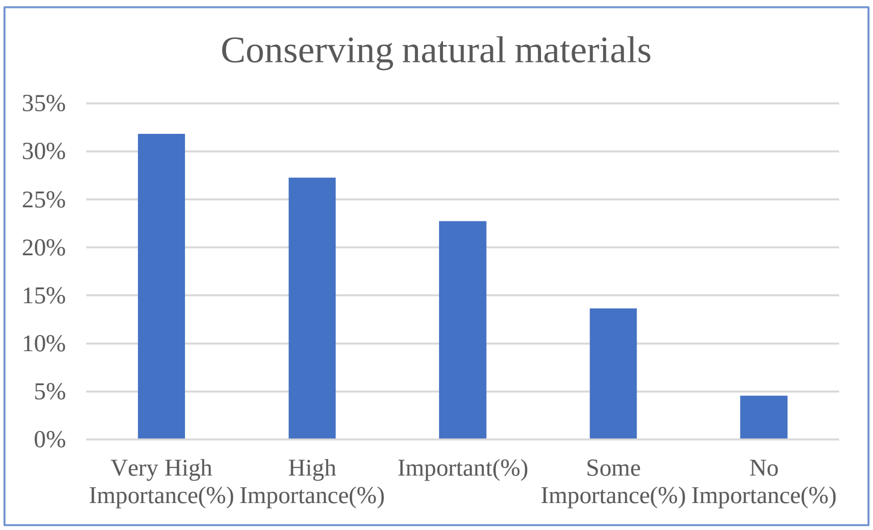

Susceptibility to Sulfate Attack
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

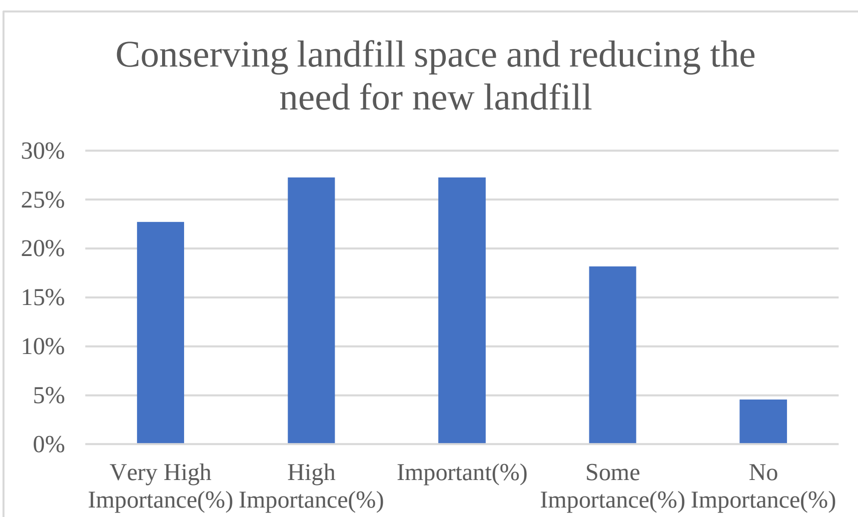
14) Please rate the importance of the following potential benefits associated with the use of construction and industrial by-products in your transportation infrastructure.

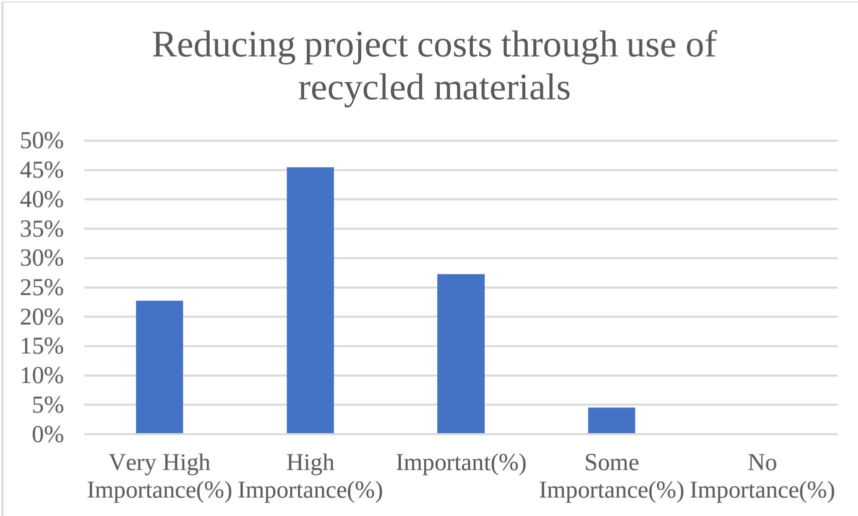
Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

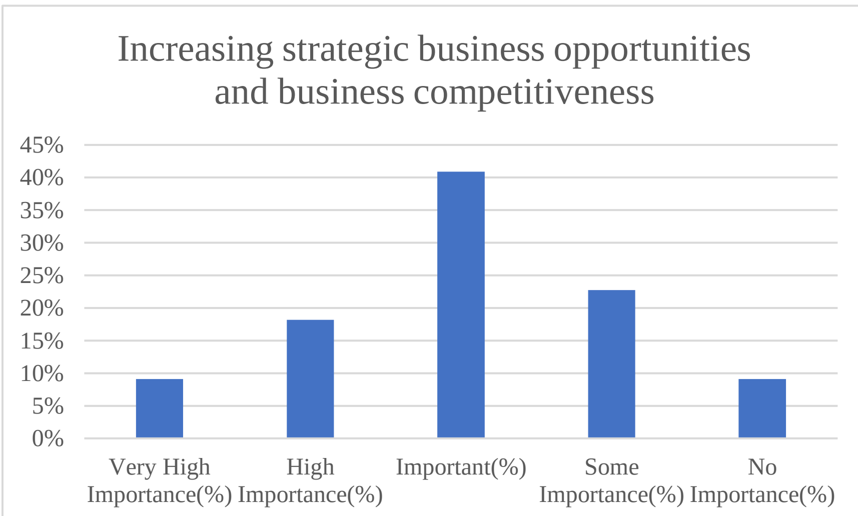
	1	2	3	4	5
Conserving natural materials	○	○	○	○	○
Conserving landfill space and reducing the need for new landfill	○	○	○	○	○
Reducing project costs through use of recycled materials	○	○	○	○	○
Increasing strategic business opportunities and business competitiveness	○	○	○	○	○
Reducing the environmental impacts of cement and aggregate production	○	○	○	○	○
Enhancing foundation material and/or concrete quality	○	○	○	○	○

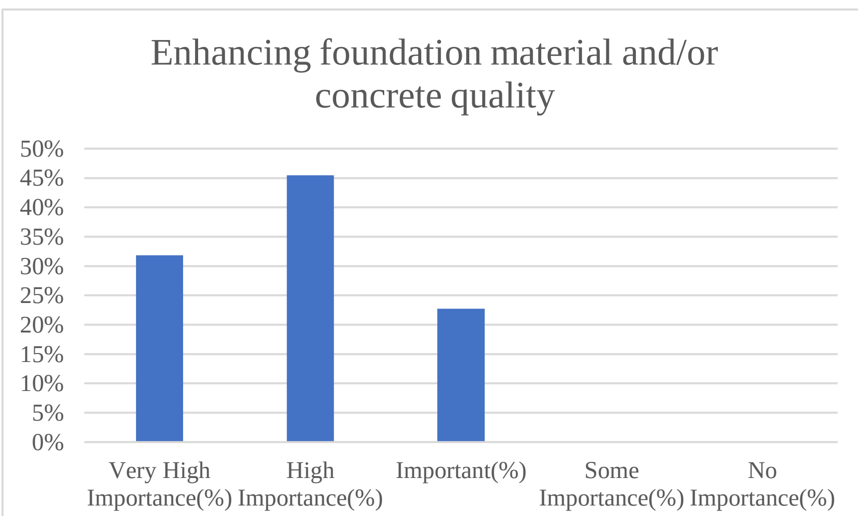
Other (please describe):

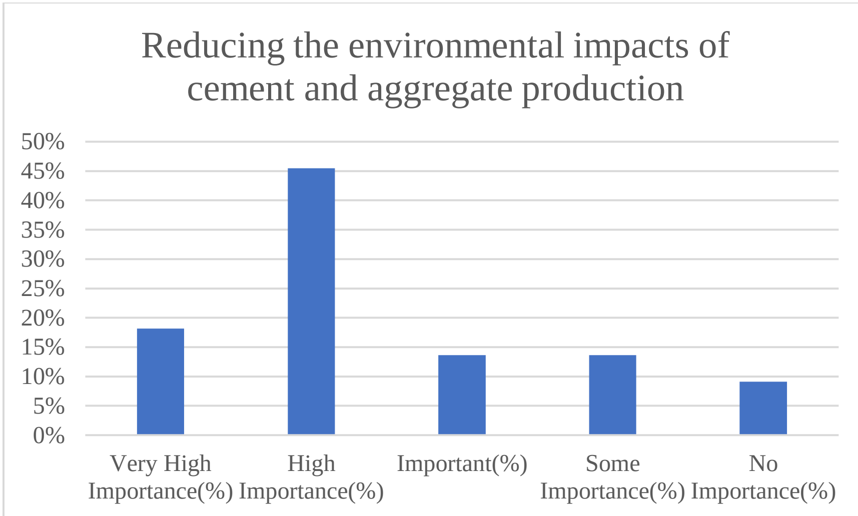





Reducing project costs through use of recycled materials
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Increasing strategic business opportunities and business competitiveness
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Enhancing foundation material and/or concrete quality
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)



15) Do you have any additional information that you could share regarding your agency's consideration of use of construction and industrial by-products in new transportation applications?

Comments:

1. "All depends on the properties of the final products and the regulations".
2. "One potentially big hurdle not addressed herein is any need for additional silos or bins to accommodate these by-products, especially if they are not a suitable like-for-like substitution for conventional materials. Not necessarily a huge issue in more developed/competitive markets, but definitely a concern in smaller markets".

APPENDIX B: FHWA RECYCLING AND REUSE OF WASTE PRODUCTS IN CONCRETE PAVEMENT APPLICATIONS: INDUSTRY INQUIRY

Inquiry objectives:

Information gathered through this inquiry will be used to identify the current and potential uses of construction and industry by-products in concrete pavement applications across the United States. Once compiled, this information will be available for sharing with agencies, consulting engineers, and contractors. Ultimately, this information will be utilized to develop tools to promote evaluation and effective use of these by-product materials in pavement construction. All inquiry responses will be held in the strictest confidence and remain anonymous in all report

1) Introductory questions:

Name of survey respondent:	
Name of firm:	
Address:	
City:	
State:	
Zip:	
Email:	

2) Which of the following construction and/or industrial byproducts are you using (or interested in using) in concrete pavement applications?

By-product	**Using in pavement foundations?**	**Using in new concrete?**
Bottom ash	Select one... ▼	Select one... ▼
Off-specification fly ash	Select one... ▼	Select one... ▼
Rice husk ash	Select one... ▼	Select one... ▼
Sugar cane ash	Select one... ▼	Select one... ▼
Water treatment residuals	Select one... ▼	Select one... ▼
Recycled concrete aggregate	Select one... ▼	Select one... ▼
Mixed rubble (recycled aggregates from mixed sources)	Select one... ▼	Select one... ▼
Recycled asphalt pavement	Select one... ▼	Select one... ▼
Concrete grinding residual material	Select one... ▼	Select one... ▼
Hydro demolition residual material	Select one... ▼	Select one... ▼
Brick waste	Select one... ▼	Select one... ▼
Crushed glass	Select one... ▼	Select one... ▼
Crumb rubber	Select one... ▼	Select one... ▼
Porcelain	Select one... ▼	Select one... ▼
Plastics	Select one... ▼	Select one... ▼

Other (please identify)

Comments:

1. “Sorry, I am not familiar with all the By- products to give you an honest answer. Recycled concrete aggregate we have used for subbase for a lot of our projects and when compacted correctly, it’s been very successful”.
2. “Slag Cement”.
3. “Currently using C ash and Slag”

3) For what reasons are you using (or interested in using) the construction and/or industrial by-products in concrete pavement applications? (select all that apply)

	Lack of availability of other products (supplementary cementitious materials and/or aggregates)	Cost savings over other products (supplementary cementitious materials and/or aggregates)	Economic benefits of recycling these materials from a project (or sourcing from a local industry or project)	Other (please describe in the box below)
Bottom ash				
Off-specification fly ash				
Rice husk ash				
Sugar cane ash				
Water treatment residuals				
Recycled concrete aggregate				
Mixed rubble (recycled aggregates from mixed sources)				
Recycled asphalt pavement				
Concrete grinding residual material				
Hydro demolition residual material				
Brick waste				
Crushed glass				
Crumb rubber				
Porcelain				
Plastics				

Other (please identify)

Comments:

1. "We have no interest in these products".
2. "The 3 noted are the only 3 we encounter in our market".
3. "Again, not familiar with all the products".
4. "Generally, it is the right thing to do to recycle. I believe we, as an industry, have a responsibility to use recycled material whenever possible".
5. "Many of these materials are by products or waste from other processes. Incorporating them into the highway pavement system as useful materials eliminates the need to otherwise dispose of them. It also helps to conserve virgin material sources - which are depleting in some areas - and generally seems more sustainable than producing new material. Finally, I expect it would bring cost

savings to the owner in the form of lower prices on materials from standard sources, due to the increased competition".

6. "Other responses are there is considerable potential waste, and it needs a place to go besides landfills Crumb rubber & Plastics - better used as a whole tire and fuel source for cement kilns".
7. "Slag and Fly Ash offer High Performance and heat hydration control. Bottom Ash not suitable cementitious material".
8. "Not using any of the above".

4) On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products in pavement foundations. Foundation applications include bound bases/subbases, unbound bases/subbases, and natural/stabilized soils.

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

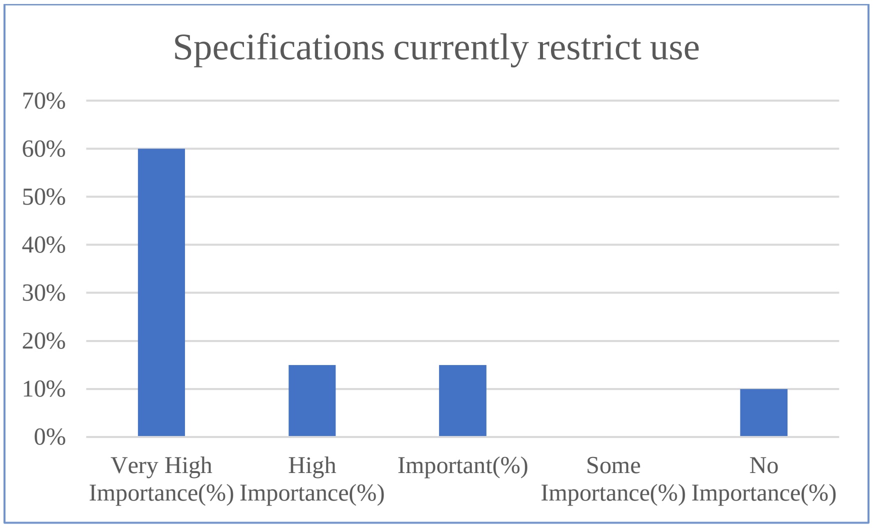
	1	2	3	4	5
Specifications currently restrict use					
Concerns regarding the material supply being consistently available					
Concerns regarding foundation strength and/or stability					
Concerns regarding durability of the by-product in service					
Concerns regarding variability in material properties					
Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials)					
Ready availability of conventional materials that are suitable and inexpensive					
Regulatory barriers (permitting, environmental regulations)					
Concerns regarding environmental impacts (e.g. runoff, leachate, etc.)					

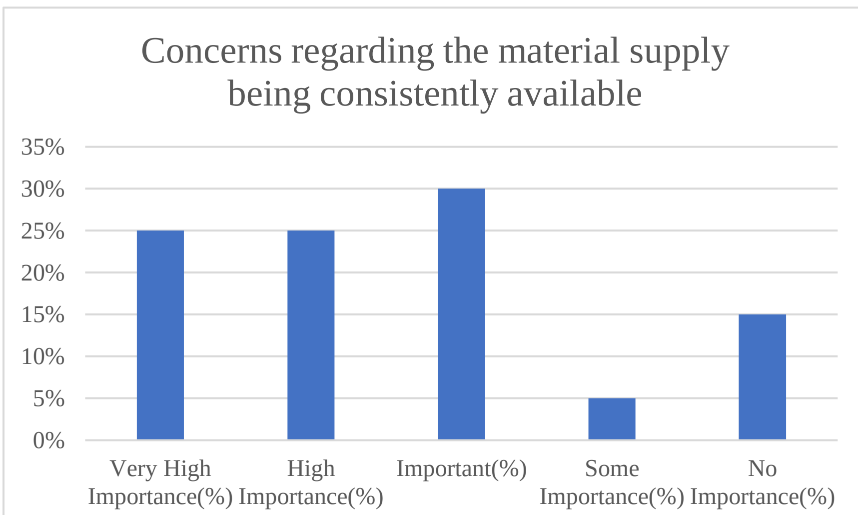
Other (please describe)

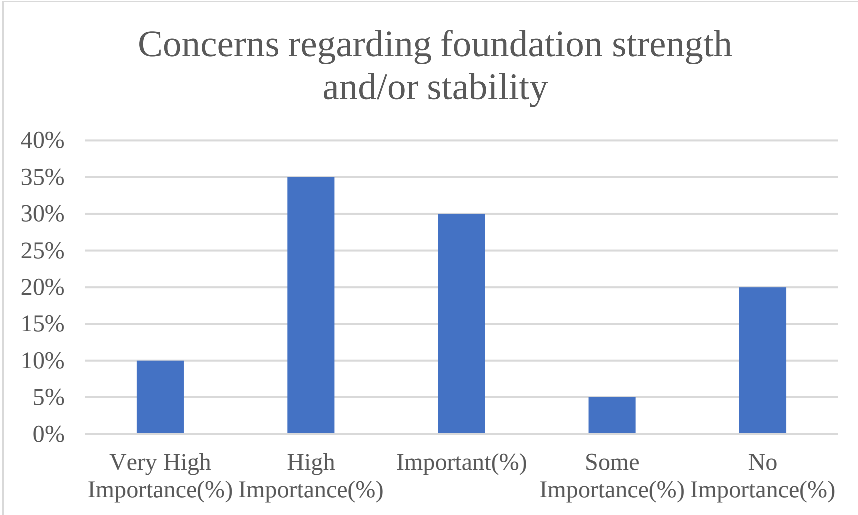
Comments:

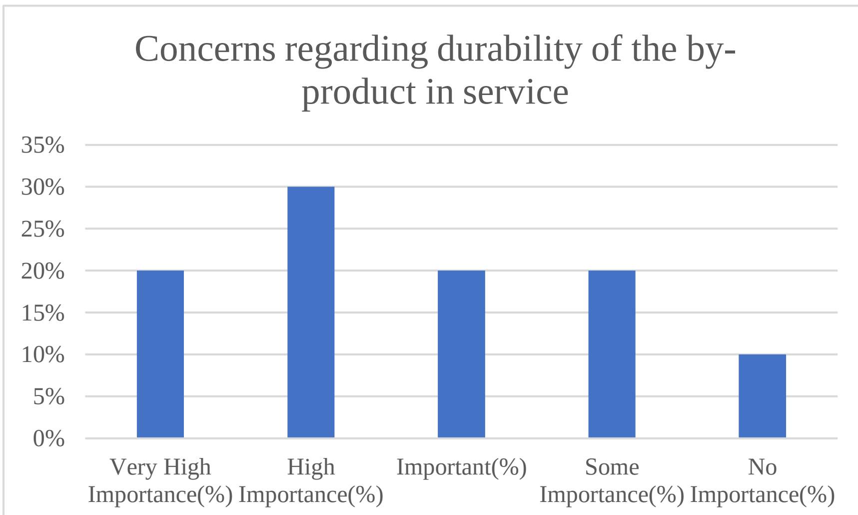
1. "People's perceptions. The NIMBY syndrome, or NIMP (Not in my pavement) and owners/DOT reluctance to change will be the biggest barrier".

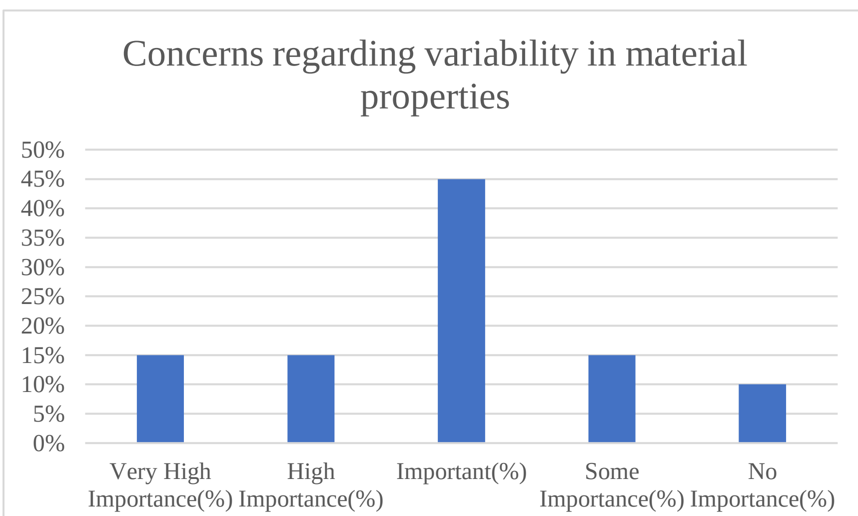
2. “NA, I have no background in the pavement foundations only to say I support cementitious stabilized soil and full depth reclamation with cement slurry mix. Survey requires answers so I wanted to qualify my answer with not much background or experience”.

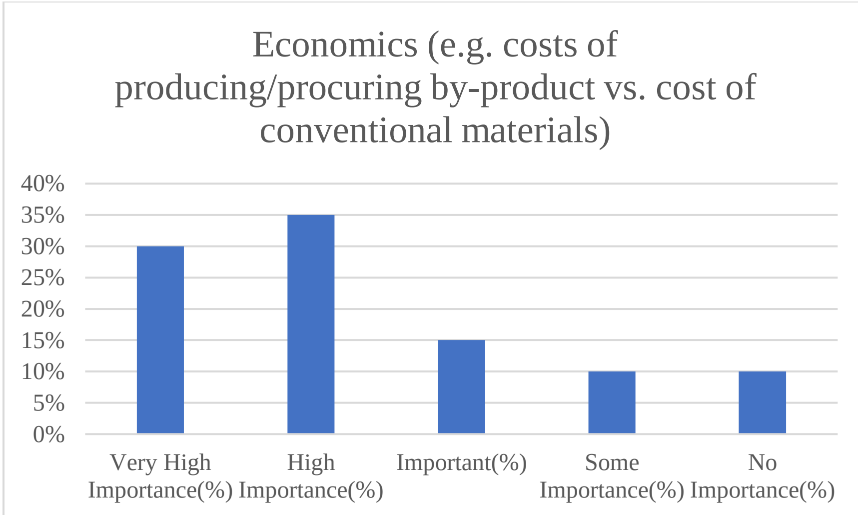


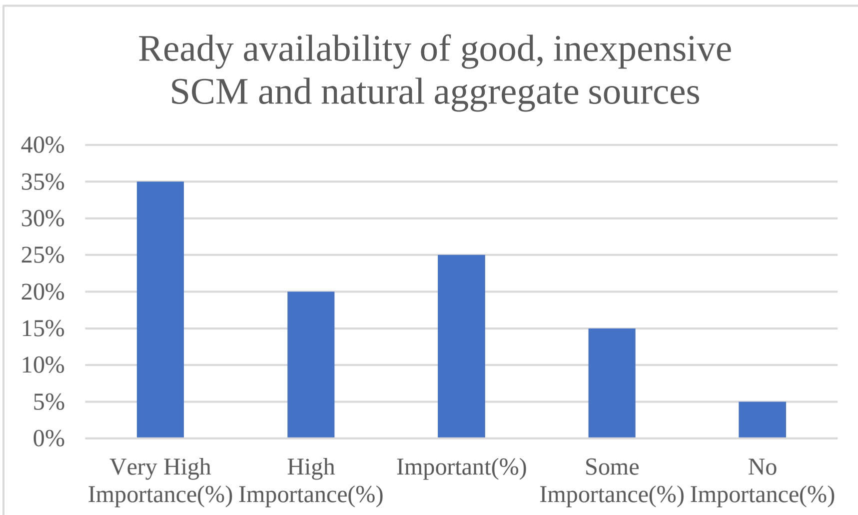


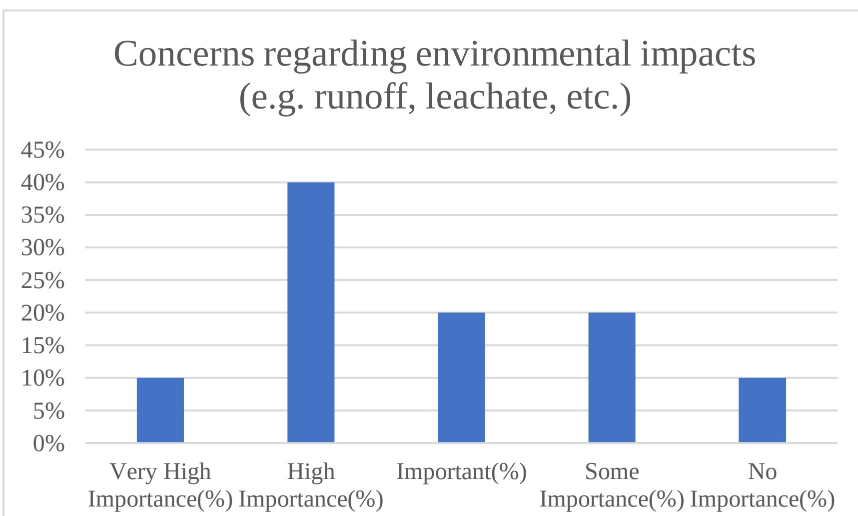

Concerns regarding foundation strength and/or stability
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

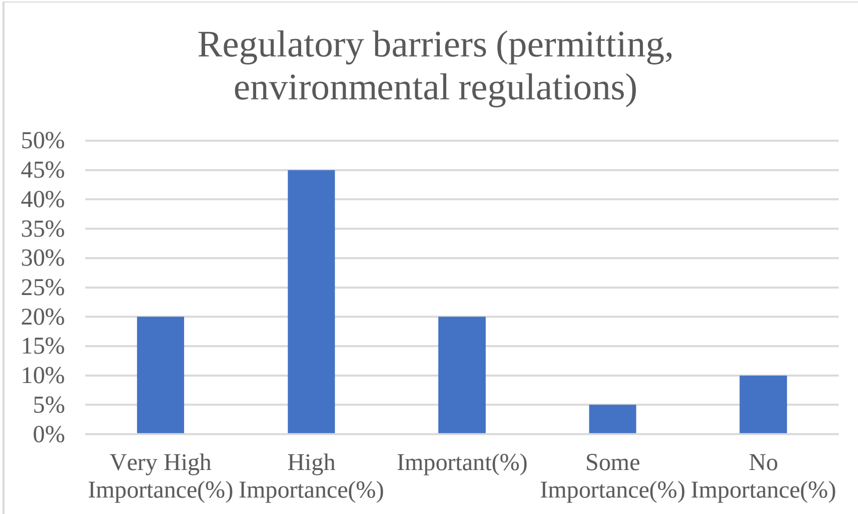

Concerns regarding durability of the by-product in service
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

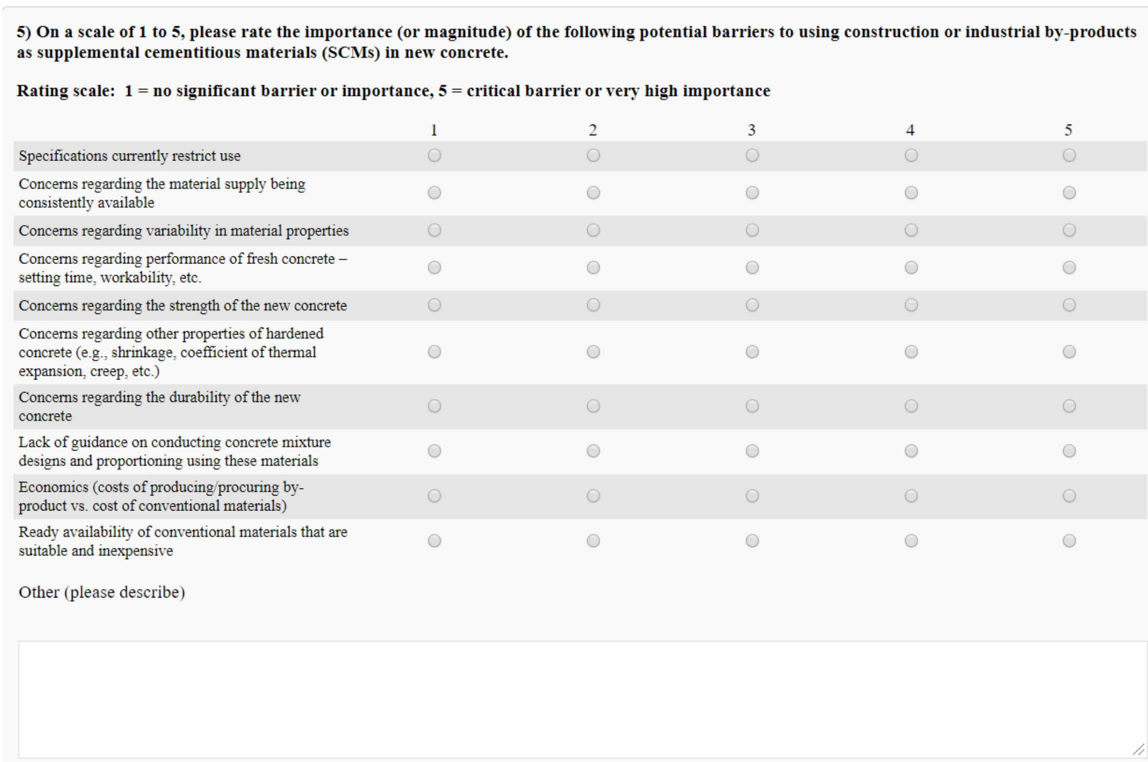

Concerns regarding variability in material properties
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials)
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Ready availability of good, inexpensive SCM and natural aggregate sources
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Concerns regarding environmental impacts (e.g. runoff, leachate, etc.)
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)





5) On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products as supplemental cementitious materials (SCMs) in new concrete.

Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

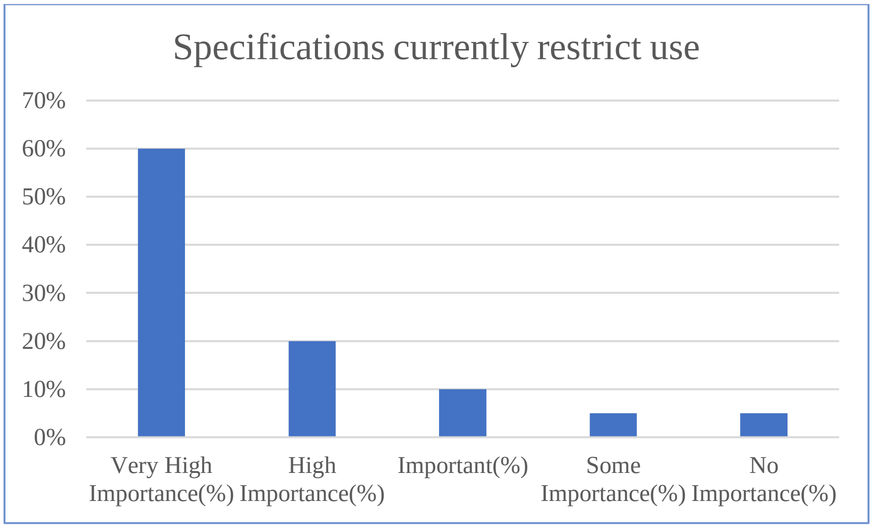
	1	2	3	4	5
Specifications currently restrict use					
Concerns regarding the material supply being consistently available					
Concerns regarding variability in material properties					
Concerns regarding performance of fresh concrete – setting time, workability, etc.					
Concerns regarding the strength of the new concrete					
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)					
Concerns regarding the durability of the new concrete					
Lack of guidance on conducting concrete mixture designs and proportioning using these materials					
Economics (costs of producing/procuring by-product vs. cost of conventional materials)					
Ready availability of conventional materials that are suitable and inexpensive					

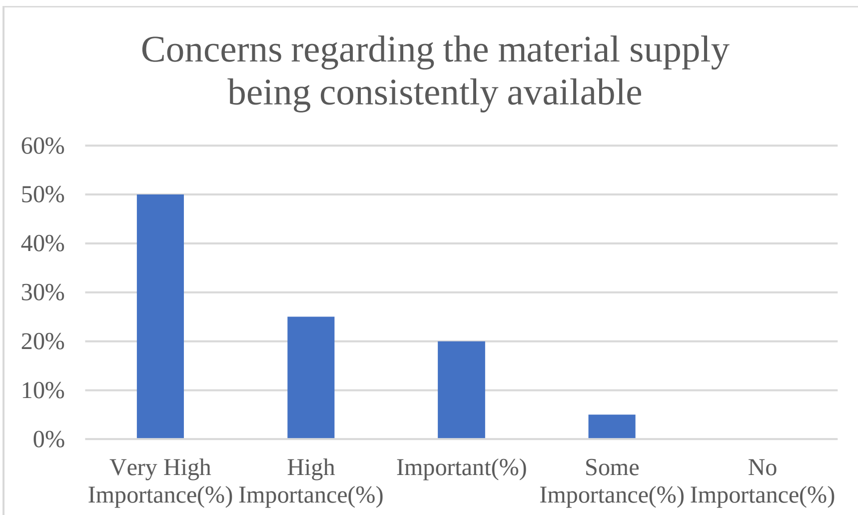
Other (please describe)

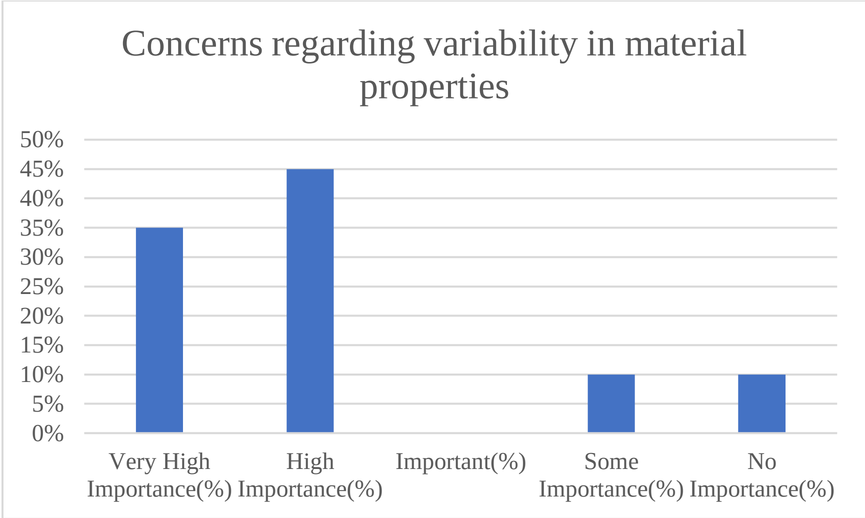
Comments:

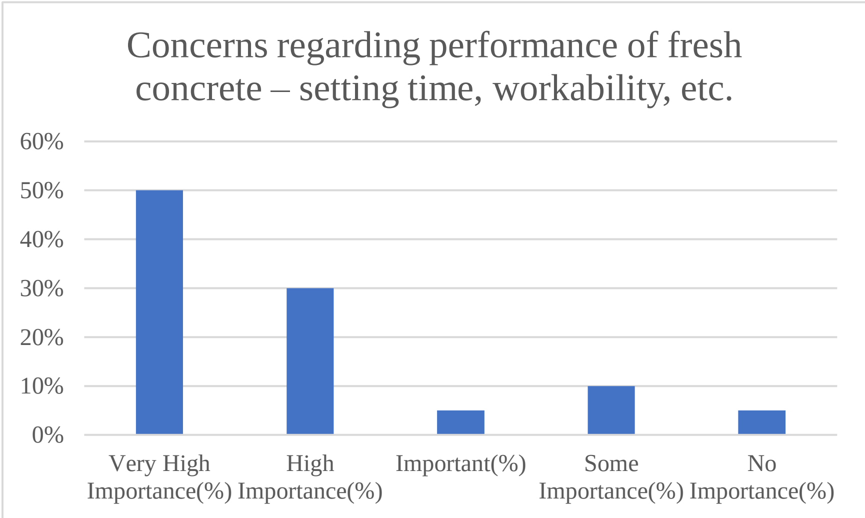
1. "All of our work is public low bid--if the specifying agency allows it we will use it with the economic confines of lost cost using spec material".
2. "An additional concern is the specification that may regulate the produced material. For example, I expect the air content would be much more unstable using bottom

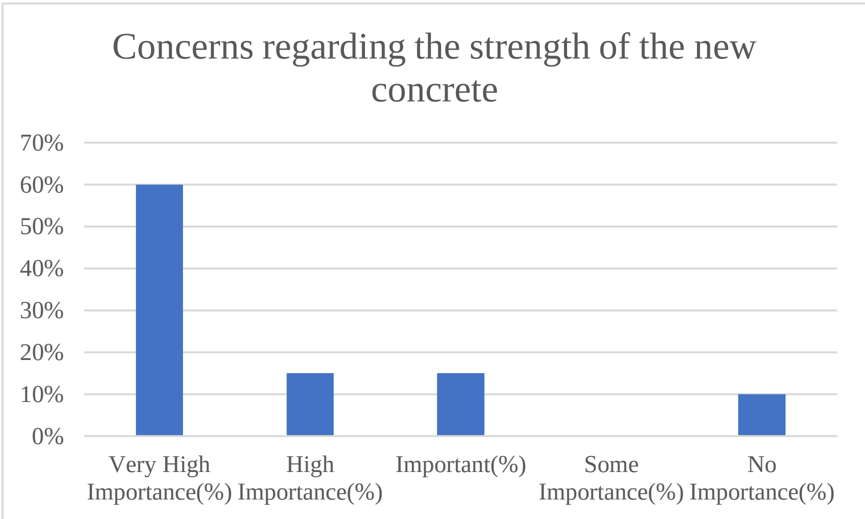
ash than a quality fly ash. If we were not able to meet the specification using the waste product, we would not be able to utilize it".

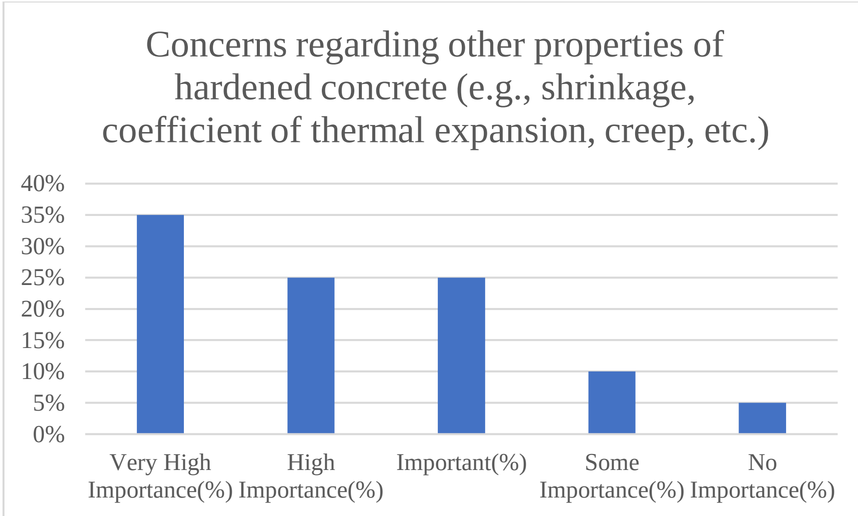


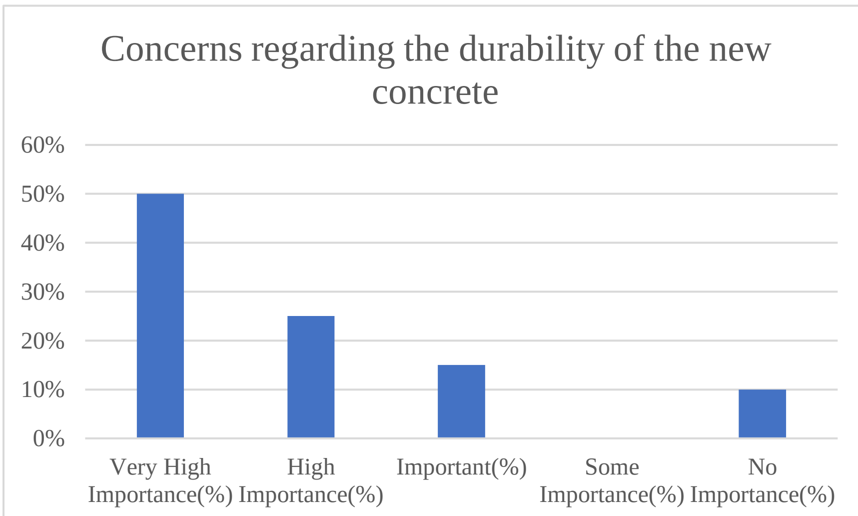


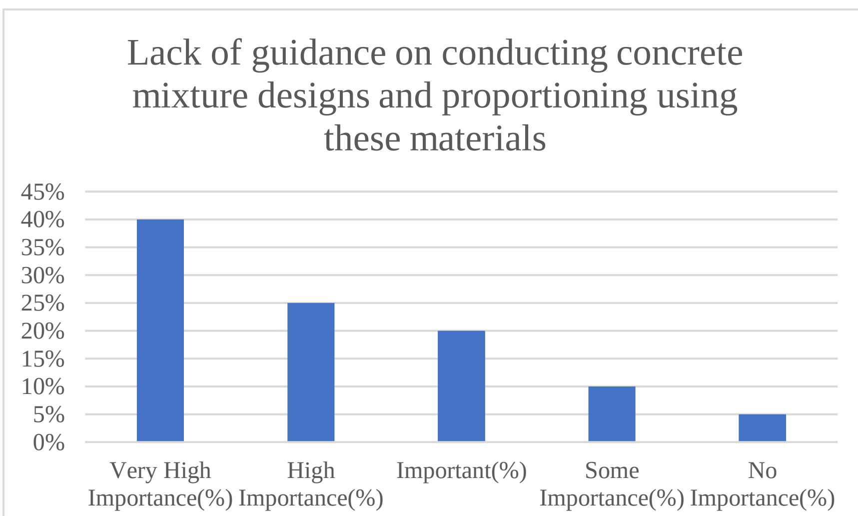

Concerns regarding variability in material properties
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

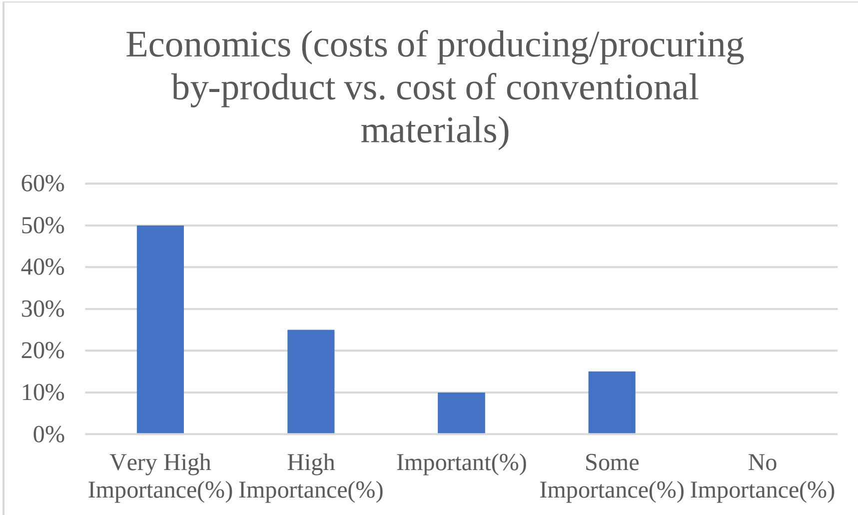

Concerns regarding performance of fresh concrete – setting time, workability, etc.
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

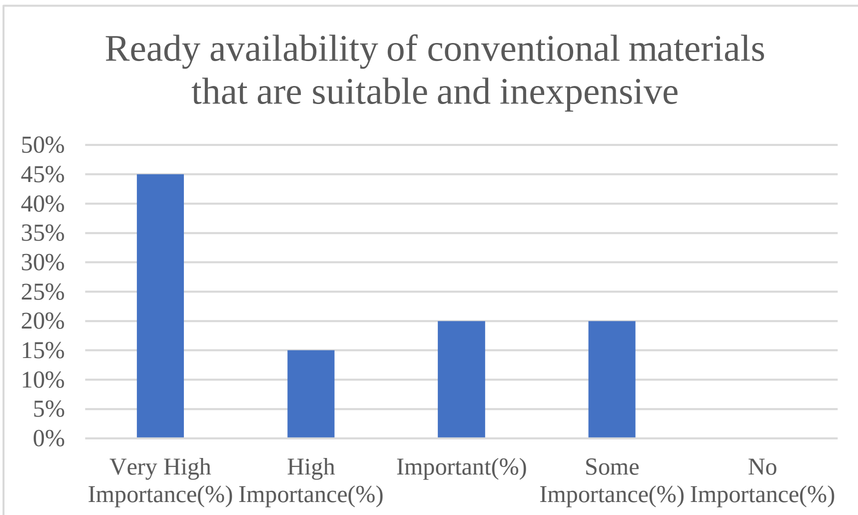

Concerns regarding the strength of the new concrete
70%
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Concerns regarding the durability of the new concrete
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Lack of guidance on conducting concrete mixture designs and proportioning using these materials
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Economics (costs of producing/procuring by-product vs. cost of conventional materials)
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

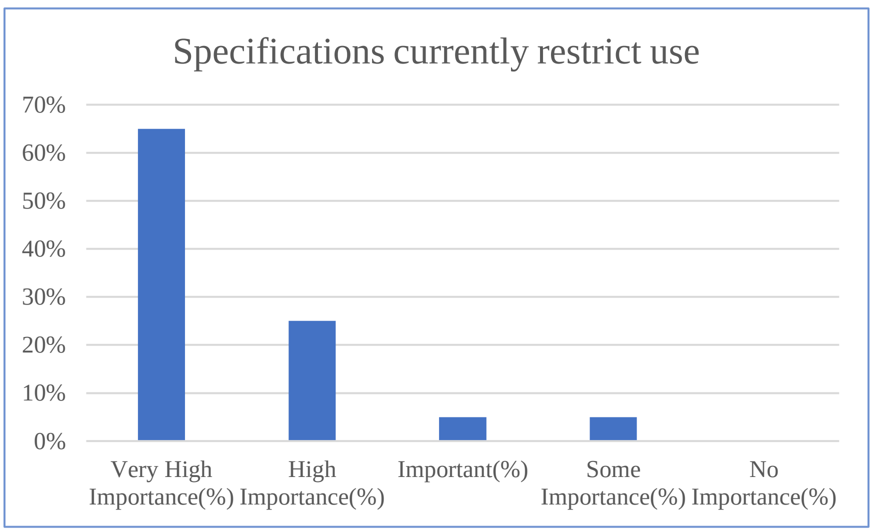

Ready availability of conventional materials that are suitable and inexpensive
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

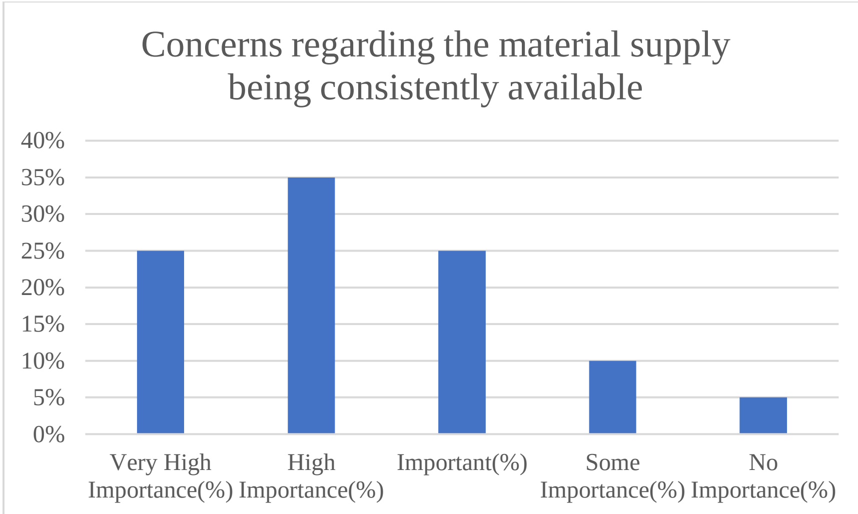
6) On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products as aggregates or inert fillers in new concrete.

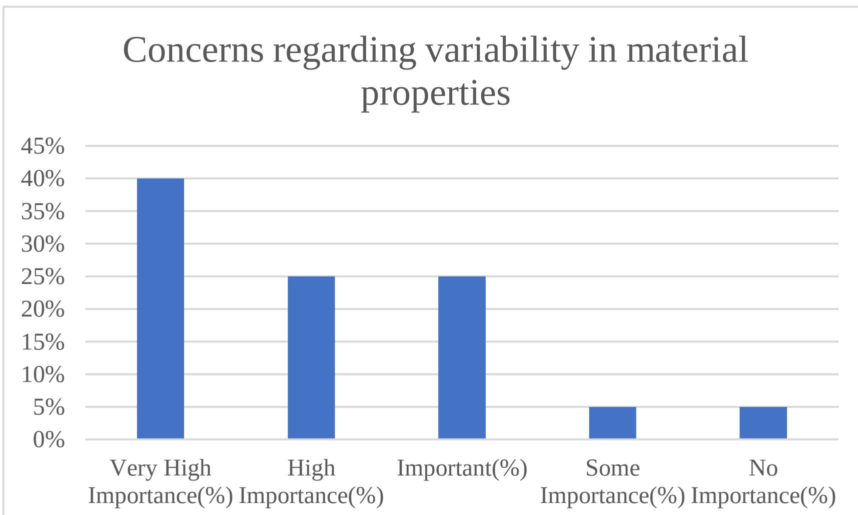
Rating scale: 1 = no significant barrier or importance, 5 = critical barrier or very high importance

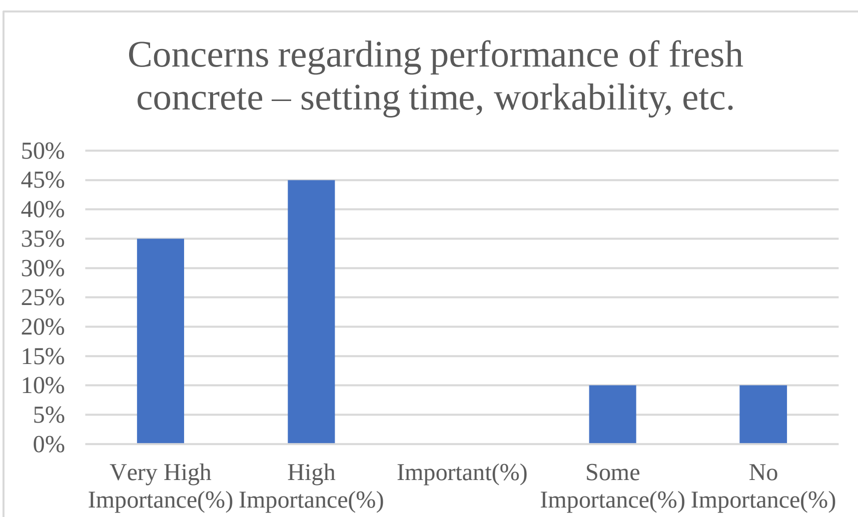
	1	2	3	4	5
Specifications currently restrict use	○	○	○	○	○
Concerns regarding the material supply being consistently available	○	○	○	○	○
Concerns regarding variability in material properties	○	○	○	○	○
Concerns regarding performance of fresh concrete – setting time, workability, etc.	○	○	○	○	○
Concerns regarding the strength of the new concrete	○	○	○	○	○
Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)	○	○	○	○	○
Concerns regarding the durability of the new concrete	○	○	○	○	○
Lack of guidance on conducting concrete mixture designs and proportioning using these materials	○	○	○	○	○
Economics (costs of producing/procuring by-product vs. cost of conventional materials)	○	○	○	○	○
Ready availability of conventional materials that are suitable and inexpensive	○	○	○	○	○

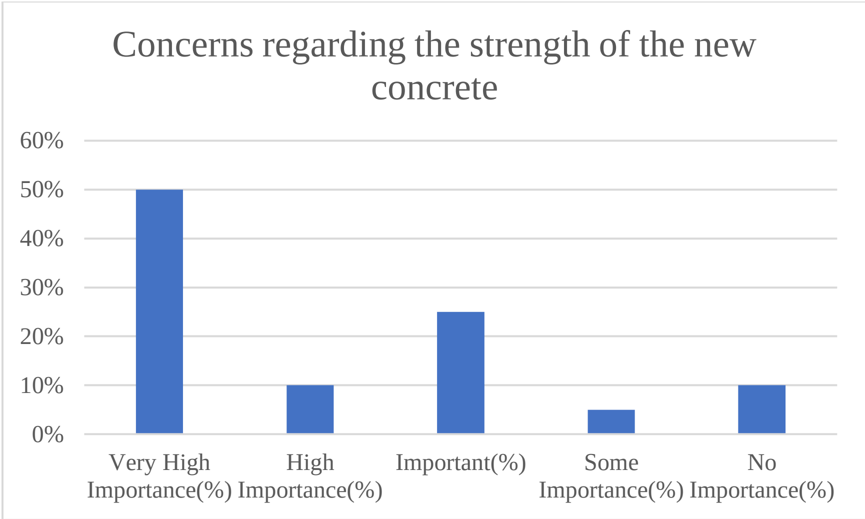
Other (please describe)

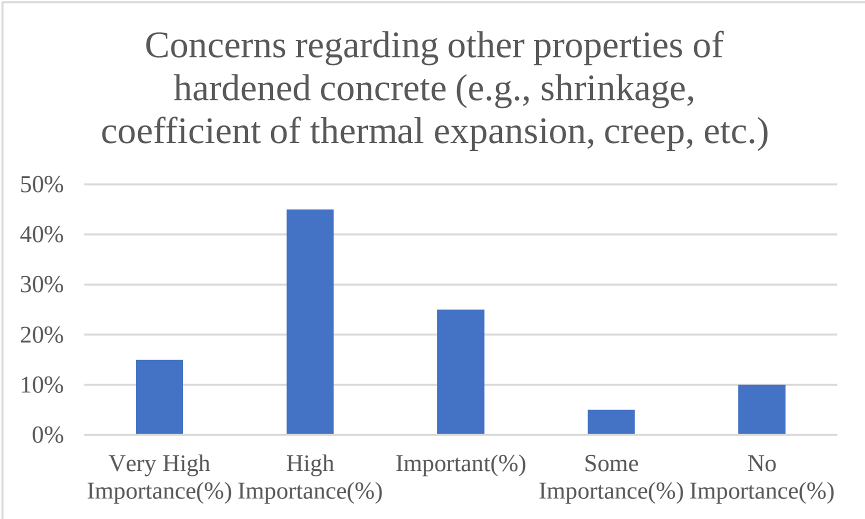


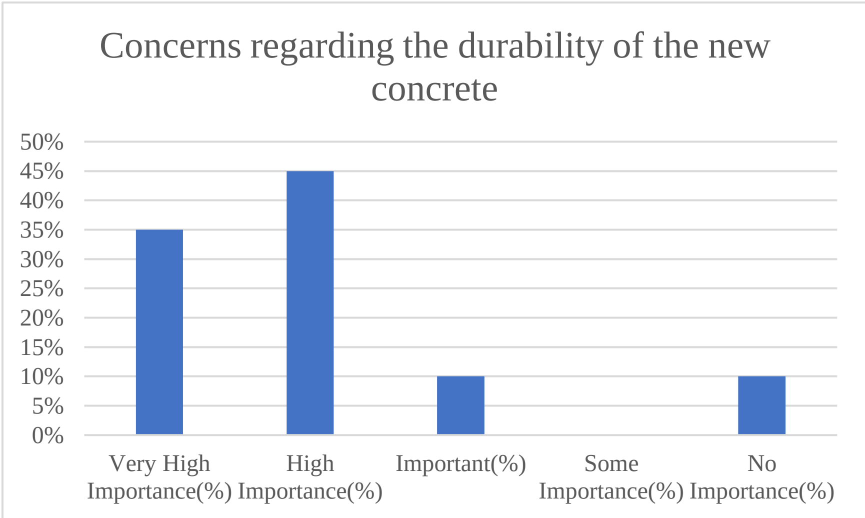

Concerns regarding the material supply being consistently available
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

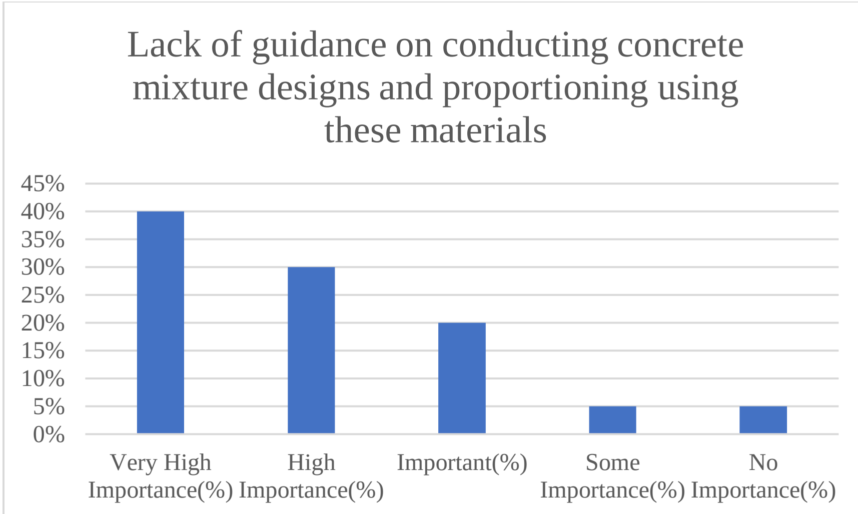

Concerns regarding variability in material properties
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

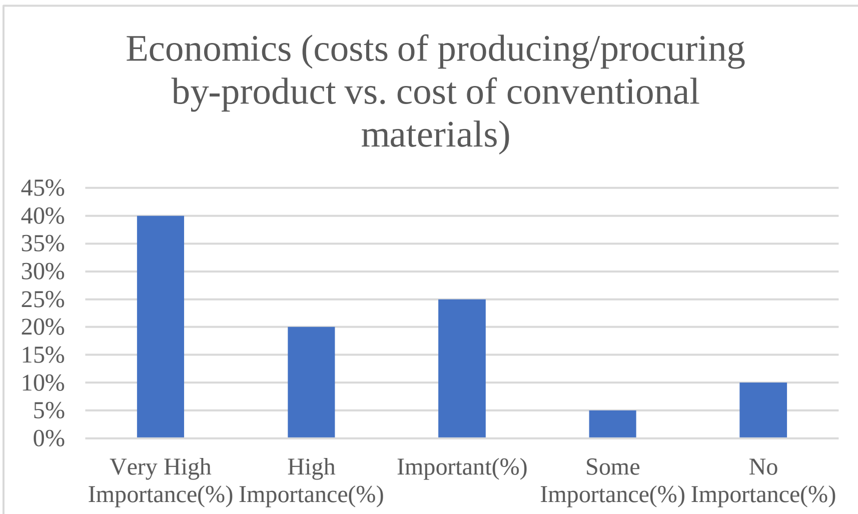

Concerns regarding performance of fresh concrete – setting time, workability, etc.
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

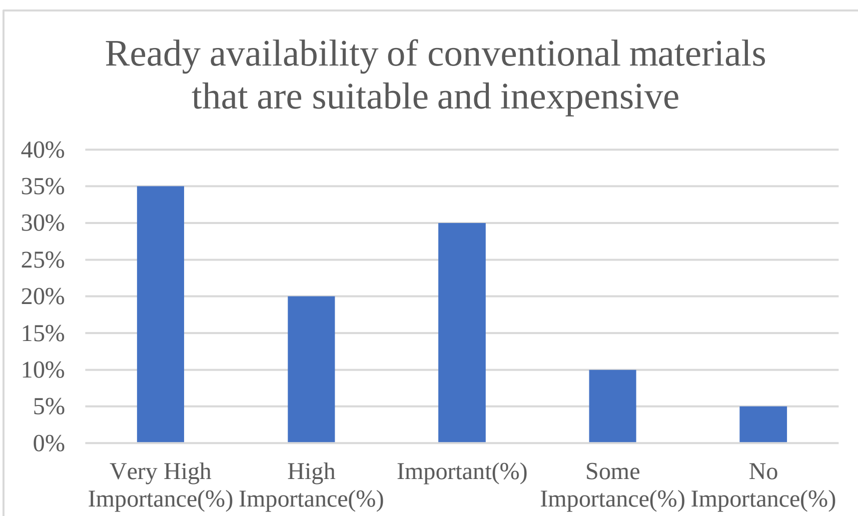

Concerns regarding the strength of the new concrete
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.)
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Concerns regarding the durability of the new concrete
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Lack of guidance on conducting concrete mixture designs and proportioning using these materials
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

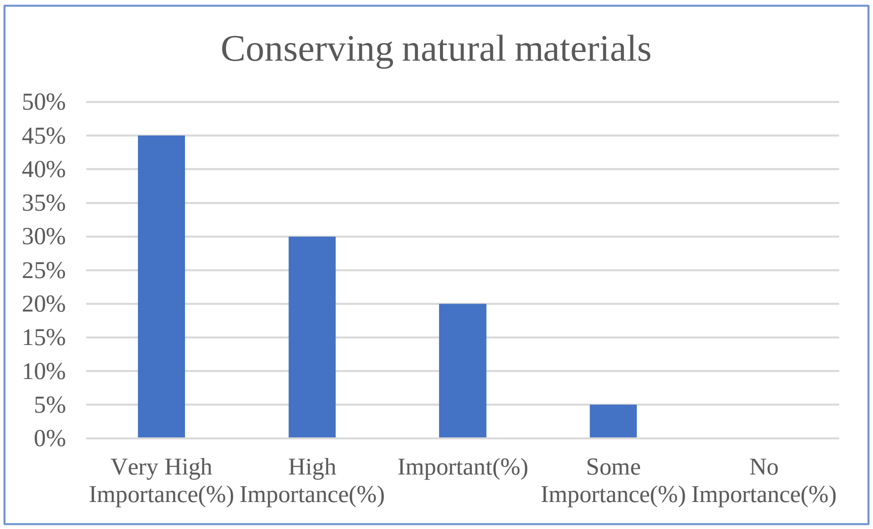

Economics (costs of producing/procuring by-product vs. cost of conventional materials)
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

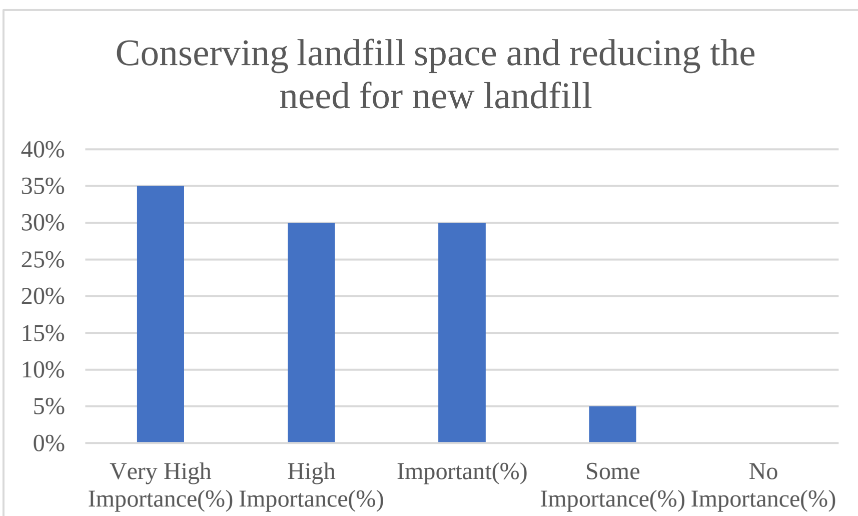

Ready availability of conventional materials that are suitable and inexpensive
40%
35%
30%
25%
20%
15%
10%
5%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)

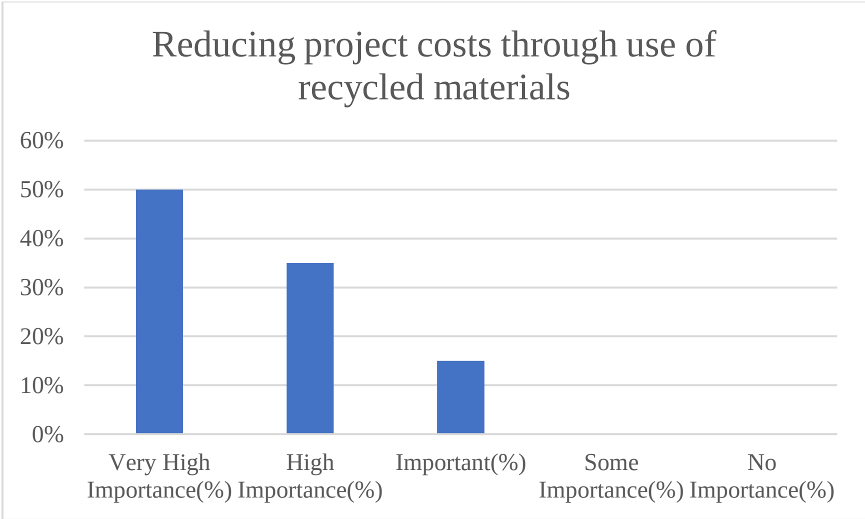
7) Rate the importance of the following potential benefits associated with the use of construction and industrial by-products in your transportation infrastructure.

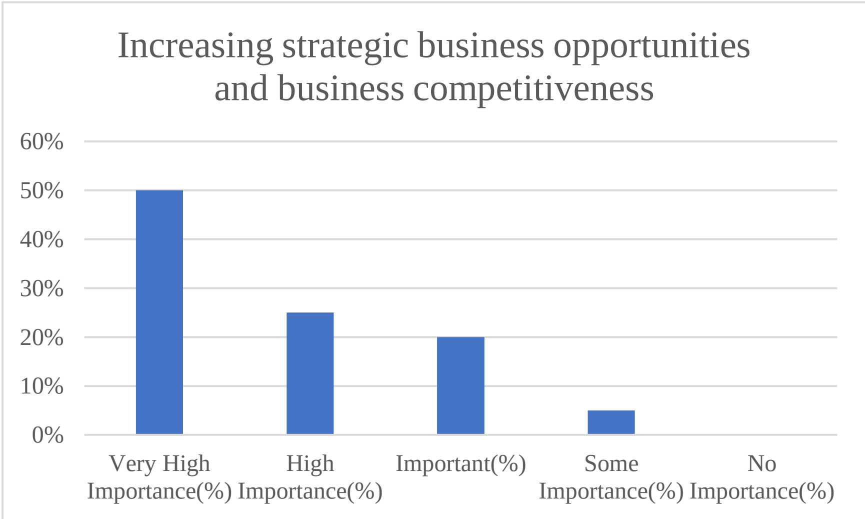
Rating Scale: 1 = not significantly important, 5 = of very high importance

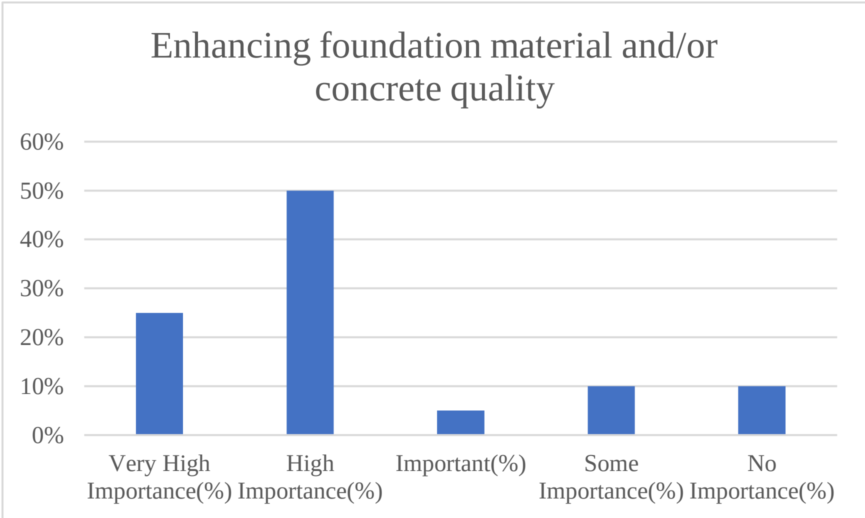
	1	2	3	4	5
Conserving natural materials					
Conserving landfill space and reducing the need for new landfill					
Reducing project costs through use of recycled materials					
Increasing strategic business opportunities and business competitiveness					
Reducing the environmental impacts of cement and aggregate production					
Enhancing foundation material and/or concrete quality					

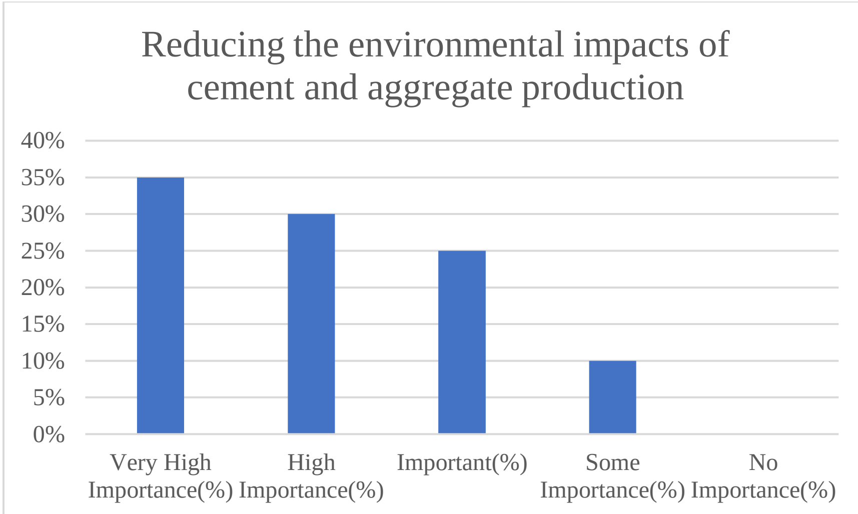





Reducing project costs through use of recycled materials
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Increasing strategic business opportunities and business competitiveness
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)


Enhancing foundation material and/or concrete quality
60%
50%
40%
30%
20%
10%
0%
Very High Importance(%)
High Importance(%)
Important(%)
Some Importance(%)
No Importance(%)



8) Do you have any additional information that you could share regarding your firm's consideration of use of construction and industrial byproducts in new transportation applications?

1. "Quality of concrete and base is first and foremost, but savings is a close 2nd. If any of these by-products can achieve similar qualities as we have now and save money with it then there should be no reason to implement by-product use".
2. "We have used recycled concrete on numerous commercial airfield projects for P-219 and in P-304 cement base. The product works well and is a cost savings. WE have not been allowed to do that on any military work as of yet. We also have not used any recycled materials in our PCCP. We do need a substitute for Class F Fly ash to help mitigate ASR. Class F fly ash has been a very hard commodity to come by".
3. "I was invited to share this survey with a select group of our ready-mix producer members. I related my answers first with my perspective as the Executive Director of

IRMCA, but I also owned and operated my own Ready-Mix business for 42 years. So, my experience and knowledge also enter into my survey answers”.

APPENDIX C: COMPARISON OF RESPONSES FROM AGENCY INQUIRY AND INDUSTRY INQUIRY

Q4. On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers within your agency to using construction or industrial by-product in pavement foundations. Foundation applications include bound bases/subbases, unbound bases/subbases, and natural/stabilized soils.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Specifications currently restrict use is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.010	Reject the null hypothesis.
2	The distribution of Concerns regarding the material supply being consistently available is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.685	Retain the null hypothesis.
3	The distribution of Concerns regarding foundation strength and/or stability is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.069	Retain the null hypothesis.
4	The distribution of Concerns regarding durability of the by-product in service is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.003	Reject the null hypothesis.
5	The distribution of Concerns regarding variability in material properties is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.001	Reject the null hypothesis.
6	The distribution of Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials) is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.008	Reject the null hypothesis.

Hypothesis Test Summary				
	Null Hypothesis	Test	Sig.	Decision
7	The distribution of Ready availability of good, inexpensive SCM and natural aggregate sources is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.979	Retain the null hypothesis.
8	The distribution of Regulatory barriers (permitting, environmental regulations) is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.014	Reject the null hypothesis.
9	The distribution of Concerns regarding environmental impacts (e.g. runoff, leachate, etc.) is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.602	Retain the null hypothesis.
Asymptotic significances are displayed. The significance level is .050.				

Q5. On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products as supplemental cementitious materials (SCMs) in new concrete.

Hypothesis Test Summary				
	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Specifications currently restrict use is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.002	Reject the null hypothesis.
2	The distribution of Concerns regarding the material supply being consistently available is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.018	Reject the null hypothesis.

Hypothesis Test Summary				
	Null Hypothesis	Test	Sig.	Decision
3	The distribution of Concerns regarding variability in material properties is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.504	Retain the null hypothesis.
4	The distribution of Concerns regarding performance of fresh concrete – setting time, workability, etc. is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.294	Retain the null hypothesis.
5	The distribution of Concerns regarding the strength of the new concrete is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.106	Retain the null hypothesis.
6	The distribution of Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.) is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.655	Retain the null hypothesis.
7	The distribution of Concerns regarding the durability of the new concrete is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.253	Retain the null hypothesis.
8	The distribution of Lack of guidance on conducting concrete mixture designs and proportioning using these materials is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.011	Reject the null hypothesis.
9	The distribution of Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials) is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.001	Reject the null hypothesis.

Hypothesis Test Summary				
	Null Hypothesis	Test	Sig.	Decision
10	The distribution of Ready availability of conventional materials that are suitable and inexpensive is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.116	Retain the null hypothesis.
Asymptotic significances are displayed. The significance level is .050.				

Q6. On a scale of 1 to 5, please rate the importance (or magnitude) of the following potential barriers to using construction or industrial by-products as aggregates or inert fillers in new concrete.

Hypothesis Test Summary				
	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Specifications currently restrict use is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.001	Reject the null hypothesis.
2	The distribution of Concerns regarding the material supply being consistently available is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.743	Retain the null hypothesis.
3	The distribution of Concerns regarding variability in material properties is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.730	Retain the null hypothesis.
4	The distribution of Concerns regarding performance of fresh concrete – setting time, workability, etc. is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.915	Retain the null hypothesis.

Hypothesis Test Summary				
	Null Hypothesis	Test	Sig.	Decision
5	The distribution of Concerns regarding the strength of the new concrete is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.570	Retain the null hypothesis.
6	The distribution of Concerns regarding other properties of hardened concrete (e.g., shrinkage, coefficient of thermal expansion, creep, etc.) is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.061	Retain the null hypothesis.
7	The distribution of Concerns regarding the durability of the new concrete is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.064	Retain the null hypothesis.
8	The distribution of Lack of guidance on conducting concrete mixture designs and proportioning using these materials is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.005	Reject the null hypothesis.
9	The distribution of Economics (e.g. costs of producing/procuring by-product vs. cost of conventional materials) is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.048	Reject the null hypothesis.
10	The distribution of Ready availability of conventional materials that are suitable and inexpensive is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.383	Retain the null hypothesis.
Asymptotic significances are displayed. The significance level is .050.				

Q7/14. Rate the importance of the following potential benefits associated with the use of construction and industrial by-products in your transportation infrastructure.

Hypothesis Test Summary				
	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Conserving natural materials is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.215	Retain the null hypothesis.
2	The distribution of Conserving landfill space and reducing the need for new landfill is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.178	Retain the null hypothesis.
3	The distribution of Reducing project costs through use of recycled materials is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.056	Retain the null hypothesis.
4	The distribution of Increasing strategic business opportunities and business competitiveness is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.001	Reject the null hypothesis.
5	The distribution of Reducing the environmental impacts of cement and aggregate production is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.324	Retain the null hypothesis.
6	The distribution of Enhancing foundation material and/or concrete quality is the same across categories of Group.	Independent-Samples Mann-Whitney U Test	.499	Retain the null hypothesis.
Asymptotic significances are displayed. The significance level is .050.				