

Survey of the Current Status of Sustainable Concrete Production in the U.S.

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Abstract: The wide use of concrete in construction has significantly impacted energy use and environmental quality. Fortunately, the emergence of sustainable concrete, made with alternative or recycled waste materials, offers great opportunities to improve concrete sustainability. This paper studies the current status of sustainable concrete production in the U.S. through a questionnaire survey. It revealed that the surveyed companies varied largely in their recognition and adoption of supplementary cementitious materials (SCMs) and alternative aggregates (AAs). Of the various alternative materials available, the most widely used by survey participants were limited to the three SCMs (fly ash, slag cement, and silica fume) and two types of aggregates (lightweight and recycled concrete aggregates). Multiple benefits and barriers to the adoption of SCMs and AAs, e.g., concrete properties, cost, and local availability, were also disclosed by survey participants. Statistical comparisons identified differences in sustainable concrete production between ready mixed concrete suppliers and concrete prefabricators, as well as in its applications in structural and non-structural concrete components. The findings provide a better understanding of the U.S. sustainable concrete production and offer insights into how researchers can help address industry concerns about the implementation of sustainable concrete.

Keywords: Sustainable concrete; Sustainable development; Supplementary cementitious material (SCM); Alternative aggregate (AA); Waste; Construction.

1. Introduction

The production and use of concrete, the most widely used building material worldwide, raises significant environmental concerns (Aïtcin, 2000; Henry and Kato, 2014; Meyer, 2005; Mobasher, 2008). Especially, the manufacturing of Portland cement (PC) is energy-intensive while releasing a large amount of greenhouse gases (Bentz, 2010; Bondar et al., 2011; Meyer, 2005). Also, extraction, processing and transportation of virgin aggregates cause various environmental issues such as loss of habitat, erosion and sedimentation, and greenhouse gas emissions (Langer and Arbogast, 2002; USGS, 2009). In recent years, the concept of sustainable concrete has emerged and been frequently referred to as concrete with lower environmental and economical impacts, which can be achieved by: 1) using supplementary cementitious materials (SCMs), recycled aggregates or other industrial wastes in concrete mixtures to reduce the use of cement and virgin materials, and/or 2) enhancing the performance, durability and service life of concrete to lower its life cycle impact/cost (Aïtcin, 2000; Lepech et al., 2008; Malhotra, 1999; Mehta, 2009; Sakai, 2009; Susilorini et al., 2014). In this study, aggregates from recycled waste or other non-conventional aggregate materials such as lightweight aggregates (LWA) are defined as alternative aggregates (AAs); both SCMs and AAs are referred to as sustainable raw materials. According to Mannan and Ganapathy (2004), using agricultural and industrial wastes as replacement materials in concrete has dual advantages of cost reduction and a better means of waste disposal. The material recovery from the conversion of these wastes into useful materials benefits the environment and conserves natural resources.

Although concrete sustainability can be improved by using waste materials, adding SCMs or AAs could impact concrete properties, including compressive strength, workability, permeability, etc. In addition, concrete made with waste materials is not necessarily considered sustainable unless its durability has been proven (Lepech et al., 2008). To address these potential issues, researchers have conducted extensive studies to identify waste

materials that can be used as SCMs and AAs in concrete production (Alsheyab and Khedaywi, 2013; Bondar et al., 2011; Limbachiya et al., 2012; Manso et al., 2006; Polanco et al., 2011; Sabai et al, 2013; Topçu and Boga, 2010; Trussoni et al., 2012). Despite all these efforts, a gap still exists between academic research and industry practice; i.e., materials studied in academia may have critical restrictions to limit their wide application in industry. For example, researchers have advocated producing new concrete using recycled concrete aggregate (RCA), a waste material recovered during demolition activities. However, this type of concrete has been recognized by its inferior quality and lower strength (Etxeberria et al., 2007; Limbachiya et al., 2012). To achieve higher strength, concrete made with RCA may require a higher amount of cement than conventional concrete (Etxeberria et al., 2007), or the source and mechanical properties of RCA have to be strictly controlled (Alam et al., 2013). So far there are still limited studies (Ling et al., 2013) of linking SCMs or AAs to their industrial practices in concrete products.

By adopting a questionnaire survey approach, this study aims to: 1) investigate the status of sustainable concrete production in the U.S. construction industry and the associated benefits and barriers from the perspectives of concrete suppliers/manufacturers, 2) identify available industry guidelines and applications related to the use of sustainable raw materials in concrete, and 3) provide insights into how academic research could better serve the industry's felt needs. The ultimate goal is to bridge the gap between academia and industry in their understanding of sustainable concrete production and types of waste/alternative materials that might have broad industry applications, and are therefore worthy of further investigation. The survey results from concrete suppliers/manufacturers are presented and analyzed in this paper.

2. Background

2.1 Sustainability of Concrete Production

Concrete has become the second most-consumed resource worldwide (only next to water) (Sakai, 2009). The annual concrete production was estimated by Meyer (2009) at 10 billion tons, and this amount was expected to grow to 18 billion tons by 2050 (Metha and Monteiro, 2006). The enormous environmental impacts of concrete production have already been widely recognized. According to Mehta (2002), 10 billion tons of sand and rock, 1 billion tons of water, 1.6 billion tons of cement, and 3 billion tons of related raw materials were consumed each year in the concrete industry. As estimated by Meyer (2005), the cement industry alone generates 7% of CO₂ emissions globally. At present, it is technically impossible to lower the energy consumption below 3.79 million British thermal units (Btu) per ton of concrete. In the U.S., concrete production had almost doubled from 170 million m³ per year in the early 1990s to more than 330 million m³ in 2004 (Mobasher, 2008). According to the U.S. Geological Survey (USGS, 2015), domestic production of cement reached its highest of 99 million tons in 2005 and decreased to around 87 million tons in 2014 due to the downturn of the construction industry; recent years' data showed that about 70% of cement was used for making ready-mix concrete while 11% was used to manufacture concrete products.

Using SCMs and other alternative/waste materials in concrete saves energy, protects the environment, and conserves natural resources, e.g., virgin aggregates. Malvar et al. (2002) estimated that replacing 25% of all cement used in concrete with SCMs could save the U.S. economy more than \$1 billion per year. A life cycle inventory analysis conducted by Nisbet et al. (2002) quantified the effects of SCMs on energy savings as: 1% replacement of cement with fly ash (the by-products of coal-fired furnaces at power generation facilities) resulted in 0.7% reduction in energy consumption of cement production. In addition, Portland limestone cement (PLC), which has been used in Europe for decades, recently became available in North America as a lower carbon footprint alternative to conventional Portland cement.

Previous research also confirmed that using LWA in concrete production would result in environmental benefits: Although extra energy is needed to expand shale, clay or slate in a rotary kiln to produce LWA, the energy expenditure could be easily recovered from associated materials savings in constructed facilities, where the use of lightweight concrete leads to lighter structures, reduced footing, column and beam sizes, and reduced amounts of reinforcement (Haque et al., 2002). LWA concrete can also achieve superior structural and thermal performance (Bremner, 1976; Haque et al., 2002).

2.2 Green Rating Systems Promoting the Use of Sustainable Concrete

The sustainability and green building movement has grown into the mainstream of the U.S. construction industry. Using selected green rating systems to evaluate the sustainability of built facilities also becomes common practice. To reduce the environmental impacts from material use, most green rating systems promote the reuse and recycling of waste materials in building and infrastructure projects. For example, the Leadership in Energy and Environmental Design (LEED®) green building rating system (version 3) developed by the U.S. Green Building Council (USGBC) contains a sustainable category titled “Materials and Resources (MR).” This category is dedicated to minimizing the environmental impact of building materials and reducing wastes sent to landfills and incinerators (USGBC, 2009). The LEED requirements that can be applied to concrete production are listed below:

- Construction Waste Management (MR Credit 2): Old concrete from demolition projects can be diverted from landfills by recycling. The amount of old concrete recycled will contribute to the total waste diversion rate calculation to earn this credit.
- Recycled Content (MR Credit 4): **This credit aims to reduce impacts from extraction and processing of virgin materials. The value of SCMs and other recycled raw materials (e.g., RCA) used in new concrete or concrete products for a project can be counted toward this credit. It is worth noting that RCA concrete will need strict**

quality control for structural applications or it can be used for non-structural applications, including foundation trenching, levelling surfaces, driveways, sidewalks, etc. RCA can also be widely applied as backfill/subbase materials for roadways, buildings, and airport structures to help achieve this LEED credit.

- Regional Materials (MR Credit 5): The use of regional materials reduces the environmental impacts from transportation. The LWA used in sustainable concrete would be a regional material for many projects (i.e., within 500 miles of the building site) due to the wide presence of LWA manufacturers in the U.S. (see Fig. 1). Locally available SCMs (e.g., fly ash) or AAs can also be counted toward this credit.

In addition, sustainable concrete such as LWA concrete with improved thermal performance could help lower a building's heating and/or cooling loads, contributing to the energy saving LEED points. Similarly, the Greenroads Rating System developed by the University of Washington and CH2M HILL, Inc. has MR requirements on using sustainable concrete in roadway projects (University of Washington, 2011). The increasing use of green rating systems in practice will promote the use of sustainable concrete to benefit the environment and potentially reduce construction costs. However, so far many existing rating systems have not adopted or fully adopted a life cycle assessment approach for material selection, if implemented, which would provide a complete, balanced, and quantitative evaluation on the life cycle impact of sustainable concrete and concrete products.

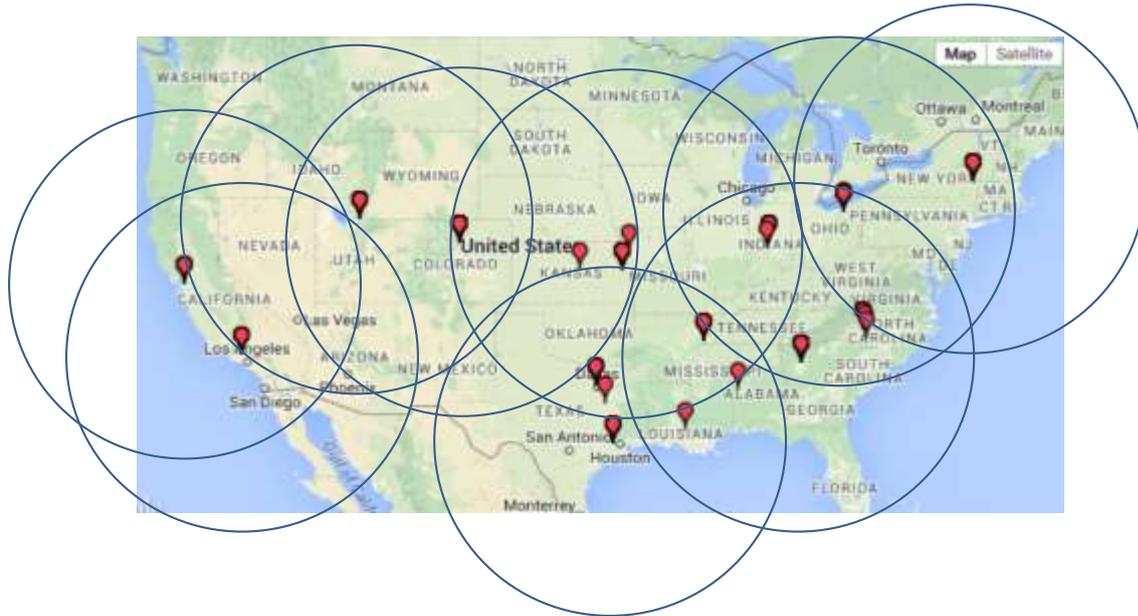


Fig. 1. Locations of LWA manufacturers in the U.S. and 500-mile regional material circles (Adapted from ESCSI, 2010).

2.3 The Emergency and Potential Use of Sustainable Raw Materials for Concrete

The use of emerging SCMs and AAs in concrete production has been widely investigated, particularly on how these materials impact concrete properties. The frequently studied SCMs are fly ash (Basri et al., 1999; Kevern et al., 2011), furnace slag (Kevern et al., 2011), silica fume (Limbachiya et al., 2012), etc. The investigated AAs include, but are not limited to, RCA (Alam et al., 2013; Etxeberria et al., 2007; Limbachiya et al., 2012; Sabai et al., 2013), building rubbles (Khalaf and Devenny, 2004), tire rubber (Nehdi and Khan, 2001), oil palm shells (Basri et al., 1999), and waste glass (Berry et al., 2011; Ling et al., 2013). Several researchers further investigated the structural applications of sustainable concrete in reinforced concrete beams or slabs (Akhtaruzzaman and Hasnat, 1986; Berry et al., 2011; Mannan and Ganapathy, 2004; Kumar et al., 2007). The research findings were mixed. While the use of an SCM or AA could improve certain concrete properties, it might simultaneously compromise some other properties (Batayneh et al., 2007; Berry et al., 2011; Sabai et al., 2013; Siddique et al., 2008; Yang et al., 2005). This is partially due to the presence of so many concrete properties, e.g., workability, compressive strength,

tensile/flexural strength, and durability. The replacement rate used for SCMs and AAs in concrete mix design is another factor that may even impact the same concrete property (e.g., workability) differently. Compared to conventional concrete, there are inadequate quantitative data in support of the use of sustainable concrete (Duxson et al., 2007).

In addition to these technical barriers, other factors also hinder the wide application of SCMs and AAs in concrete. For example, recycling and reusing wastes requires extra labor and energy input (e.g., for crushing old concrete), and may also incur additional transportation cost compared to the use of virgin materials such as gravel (Batayneh et al., 2007; Meyer, 2009). Also, the construction and building products industries are conservative due to fear of product failure. They tend to follow existing building codes and standards and are resistant to new technologies, including the utilization of waste materials. The industries also had some negative perceptions towards non-conventional practices in concrete production, which might not hold true; e.g., fly ash-contained cement perceived to have poor freeze-thaw resistance (Duxson et al., 2007). Therefore, it is extremely important to advance the understanding of sustainable concrete properties and to address these real-world barriers.

3. Research Methodology

This study aims to investigate the current status of sustainable concrete production in the U.S. construction industry. The researchers developed a structured 18-item questionnaire (see Appendix) and used it to 1) conduct face-to-face interviews with local concrete suppliers/manufacturers and related organizations and 2) survey their counterparts from other U.S. regions online. Architects and engineers were not included in the survey because they usually do not specify concrete mix design; instead, concrete suppliers design the mixture to ensure that the produced concrete meets the specification requirements (e.g., strength). The questions in the survey were in multiple-choice and open-ended formats. They were organized into three parts: background about survey participants and their involvement in

sustainable concrete production; the use of SCMs; and the use of AAs. Survey questions in the second and third parts were designed to learn: What types of sustainable raw materials are or could be potentially used in the concrete industry? What are the benefits and barriers to using them? What are the industry guidelines or standards for using these sustainable raw materials in concrete applications? And what are the applications of sustainable concrete in structural and non-structural concrete components?

The local area surveyed in this study represents Central Ohio, a metropolitan area with a population of around 1.9 million in the U.S. Midwest. Before the interviews and online surveys were conducted, the questionnaire was reviewed by a representative (Mark Pardi, Central/Southeast Director) from the Ohio Ready Mixed Concrete Association (ORMCA) to determine its relevance and accuracy to the industry. The questionnaire was then revised based on the feedback. Both the finalized questionnaire and survey procedures were reviewed and approved by the University Institutional Review Board.

Survey participants from Central Ohio were first identified by searching two publicly available directories: the ORMCA membership list containing mainly concrete producers and the membership directory book of the Builders Exchange of Central Ohio. Then, the list of selected companies was revised based on the feedback from the ORMCA representative (Mark Pardi, personal communication, April 16, 2012). The researchers then contacted these companies and explained the purpose of this study and the measures to ensure the confidentiality of participants' information. After obtaining their commitment, researchers interviewed one person (recommended by the company to have the best knowledge or expertise in concrete production) per company. Concrete companies selected for online survey were found through the websites of the National Ready Mixed Concrete Association and the Precast/Prestressed Concrete Institute in the field of concrete production/manufacturing. As of July 2012, 152 ready mixed concrete suppliers and 71

prefabricators were listed on these websites as registered members. Considering the low response rate often associated with online survey, all of these 223 companies were invited for the survey to ensure that a reasonable sample size could be achieved. To administer the online survey, researchers directly contacted these companies through their email addresses. In each email, an online survey recruitment script and a link to the web survey were included. The interviews and online surveys were performed between July and October, 2012. No identifiable information was collected from participants.

Besides summarizing the survey results, this study adopted a one-tailed Barnard's exact test (Barnard, 1945) to compare survey responses between selected subgroups, i.e., subgroups based on the services they provide, years in business, and the number of full-time employees. This study also compared the applications of sustainable concrete in structural and non-structural concrete components. These statistical tests were all based on the null hypothesis that there was no difference in percentage of responses to a specific answer between subgroups at a level of significance of 0.05. A p value lower than 0.05 would reject the null hypothesis and indicate a significant difference between the two sample groups.

Barnard's exact test used in this paper is a statistical significance test for analyzing contingency tables. The other two widely applied methods in 2×2 contingency tables, i.e., Pearson's chi-squared test (Pearson, 1900) and Fisher's exact test (Fisher, 1925), were not considered a good fit for this study. This is because the chi-squared test is not suitable for smaller samples and Fisher's exact test, though valid for small sample sizes, is conservative and not as powerful as Barnard's exact test (Mehta and Hilton, 1993; Mehta and Senchaudhuri, 2003; Lydersen et al., 2009). As a non-parametric alternative to Fisher's exact test (Galili, 2010), Barnard's exact test is more powerful because the loss of power due to the greater discreteness of the Fisher statistic is somewhat offset by the requirement that Barnard's exact test must maximize over all possible p -values by considering the nuisance

parameter(s) (Mehta and Senchaudhuri, 2003). Andrés and García (2009) compared various statistical methods including Barnard's method, Fisher's method, and others in 2×2 multinomial trials, and concluded that Barnard's method was most powerful and "the best." The reason to adopt a one-tailed test lies in that it can provide more power to detect an effect and is appropriate when consequences of missing an effect in the untested direction are negligible and irresponsible (UCLA: Statistical Consulting Group, 2015). For each question involved in this statistical analysis, the percentage of respondents from each comparing subgroup who chose each particular answer option was calculated and compared, which provided a hypothesis about which one of the comparing subgroups might have a significantly higher response rate to a particular answer option. Therefore, the one-tailed test is sufficient.

4. Results and Discussion

In this study, five local concrete suppliers, one trade organization (ORMCA), and one state agency (the Ohio Department of Transportation [ODOT]) were interviewed for their opinions on and experience with sustainable concrete production. Note that these five local suppliers were selected based on a review of their background, including the number of trucks, plants, and years of business in the region, as well as the recommendation from the ORMCA representative. They were considered the major players in the Central Ohio concrete industry and could represent the local practice. Of the 152 ready mixed concrete suppliers and 71 concrete prefabricators invited for the online survey, 23 and 11 of them had responded and completed the questionnaire, representing response rates of 15.1% and 15.5%, respectively. The overall response rate for this online survey was 15.2% (34 out of 223 companies). The background of these companies (e.g., company business, products, and number of plants) were then carefully reviewed and considered typical for ready-mixed concrete suppliers or prefabricators. More importantly, the size of these surveyed companies was reasonably

distributed to represent various practices from small, mid-size, and large businesses, reflecting the fragmented nature of the U.S. concrete industry. It is worth noting that although questionnaire response rates in construction-related research could reach 20-30%, e.g., Li et al. (2005) and Yuan et al. (2009), many studies received much lower response rates, such as 7.4% in Abdul-Rahman et al. (2006) and 7.5% in Jaapar and Torrance (2009). Gibson and Whittington (2010) reviewed survey research methods employed extensively to study construction industry related topics and indicated that responses rates for national questionnaire surveys could range as low as the single digit percentages and response rates at 15% were usually considered acceptable.

4.1 Background about Survey Participants and Their Involvement in Sustainable Concrete Production

The results obtained through interviews and online surveys were combined for the data analysis (N=39). The background information regarding the size of company, years the company has been in business, and years that the survey respondents have worked in the concrete industry is summarized in Figs. 2 and 3. As shown in Fig. 2, of the 39 companies surveyed, their maximum and minimum years in business were 130 and 6, respectively. The mean value was 50 years. For individual survey respondents, their maximum and minimum years of concrete industry experience were 44 and 3, respectively. The mean value was 23 years. The distribution of respondents' years of experience is close to a normal distribution while the distribution of companies' years in business is slightly skewed. Since 82% of surveyed individuals had at least 10 years of experience, the information provided by them should be able to reflect industry practice. The box-plot for the company size is not available since the survey only asked companies to choose a proper range for their employment numbers (e.g., 10-49). This made the survey easier for the participants. Fig. 3 shows that the survey participants represented different sizes of companies: approximately 70% for small

and mid-size businesses (<200 employees) and 30% for larger companies (≥ 200 employees).

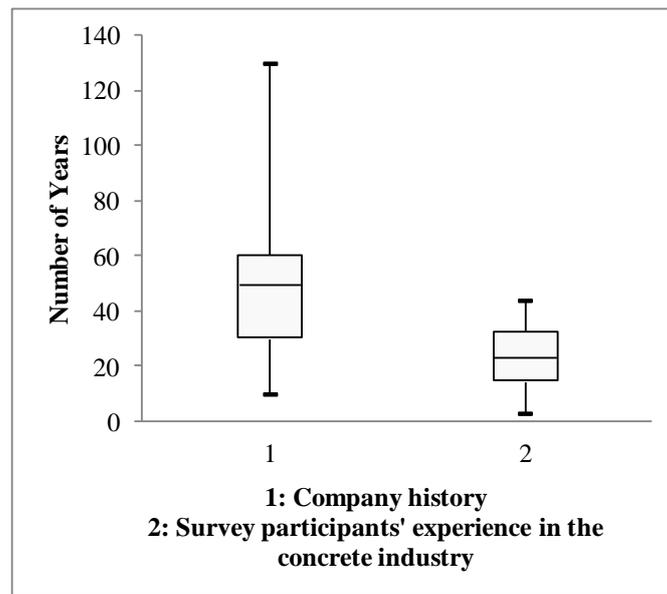


Fig. 2. Box-plot for company history and survey participants' experience (N=39).

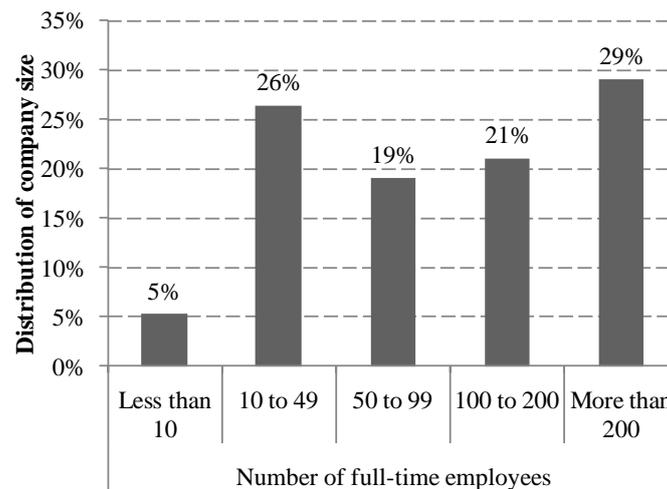


Fig. 3. Number of full time employees of surveyed companies (N=39).

The services provided by these companies include ready mixed concrete (64% of the total number of companies), prefabricated concrete components (44%), and others such as quarrying or manufacturing concrete/construction aggregates (22%). The total percentage (130%) is greater than 100% since some companies provide more than one service (e.g., both ready mixed concrete and aggregates). A similar scenario applies to the following two questions. When asked what industry sectors their companies' concrete served, their

responses were distributed as follows: the building sector (89%), roadways/bridges (84%), or other sectors such as industrial or agricultural (39%). When asked what method(s) they used for concrete mix design, 81% of them said that they used industry specifications or the standards of the American Concrete Institute (ACI), American Society for Testing and Materials (ASTM), the Department of Transportation (DOT) in their states, etc. About 68% of them stated that their mix design was based on their own companies' historical data, and 19% mentioned other methods such as trial batches.

The survey results also showed that 73% of companies surveyed had utilized sustainable raw materials and 74% had received inquiries from customers for sustainable concrete, showing a strong interest among their clients in using environmentally friendly building materials. According to a couple of companies, one driving force for using sustainable concrete was the LEED project requirements. To study subgroup differences in producing and receiving inquiries about sustainable concrete, the survey sample was divided into three pairs of subgroups by type of service provided, years in business, and number of full-time employees. Under "type of service provided," the sample selected in the analysis excluded companies whose service only fell under "others." There were also four companies supplying both ready mixed concrete and prefabricated products, so they were counted in both subgroups. Table 1 displays the one-tailed statistical analysis results. (Ling et al., 2013, Alsheyab and Khedaywi, 2013)

Table 1 Statistical analysis of subgroups using Barnard's exact test on producing and receiving inquiries about sustainable concrete.

| Question | Analysis items | Subgroup categorization | | | | | |
|--|---|------------------------------|----------------------------------|-------------------|------------|-------------------------------|-------|
| | | Type of service provided | | Years in business | | Number of full-time employees | |
| | | Serving ready mixed concrete | Prefabricating concrete products | < 50 years | ≥ 50 years | <100 | ≥100 |
| Whether they produced sustainable concrete | Total sample size (N) | 23 | 15 | 16 | 21 | 19 | 18 |
| | Number of companies that answered "yes" | 21 | 9 | 12 | 16 | 13 | 15 |
| | Percentage of "yes" | 91% | 60% | 75% | 76% | 68% | 83% |
| | <i>p</i> value | | 0.016 ^a | | 0.499 | | 0.501 |

| | | | | | | | |
|--|---|-----|--------------------|-----|-------|-----|-------|
| Whether they had received inquiries about sustainable concrete | Total sample size | 23 | 15 | 16 | 21 | 19 | 18 |
| | Number of companies that answered “yes” | 20 | 9 | 12 | 15 | 13 | 14 |
| | Percentage of “yes” | 87% | 60% | 75% | 71% | 68% | 78% |
| | <i>p</i> value | | 0.042 ^a | | 0.463 | | 0.300 |

^aDenotes a statistically significant difference between the two subgroups.

In these comparisons, two statistically significant differences (having a *p* value of less than 0.05) existed between ready mixed concrete suppliers and prefabricators (providing prefabricated concrete products including precast/prestressed concrete companies). Specifically, a higher percentage of ready mixed concrete suppliers (91%) were producing sustainable concrete than that of prefabricators (60%). Also, a higher percentage of ready mixed concrete companies (87%), compared to only 60% of concrete prefabricators, had received inquiries about sustainable concrete. These implied that, in practice, client interests in freshly mixed sustainable concrete might be higher than that in prefabricated sustainable concrete products. Factors, including years in business and company size, did not cause differences between subgroups.

4.2 The Use of SCMs

The second part of the survey asked specific questions related to the use of various SCMs. First, survey participants were asked to describe their use of five pre-specified SCMs, including fly ash Class C, fly ash Class F, ground-granulated blast-furnace slag (GGBFS) or slag cement, silica fume, and calcined shale. They were also allowed to name any other SCM(s) they used. Fig. 4 illustrates the percentage of companies using each pre-specified SCM. It can be seen that currently fly ash (including Class C and Class F), GGBFS, and silica fume are the three major SCMs used in the U.S. concrete industry. In addition, Portland limestone cement (PLC) was used by 19% of respondents. Other SCMs include metakaolin (mentioned by two participants) and rice hull ash (mentioned once). Survey participants were also asked to list three most commonly used SCMs based on their industry experience. As shown in Fig. 5, the top three most commonly used SCMs are GGBFS, fly ash and silica

fume, consistent with the earlier findings. Since some participants only mentioned fly ash but did not specify Class C or F, “fly ash” was counted separately.

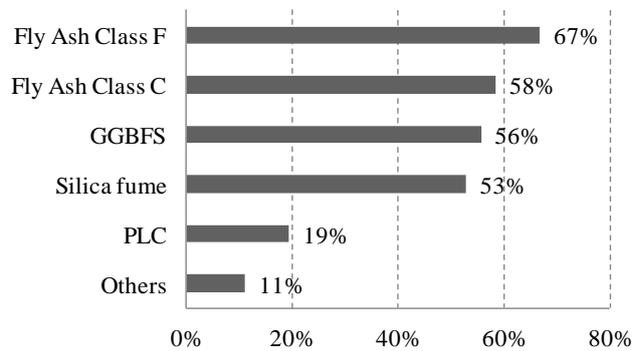


Fig. 4. Percentage of companies using each pre-specified SCM (N=36).

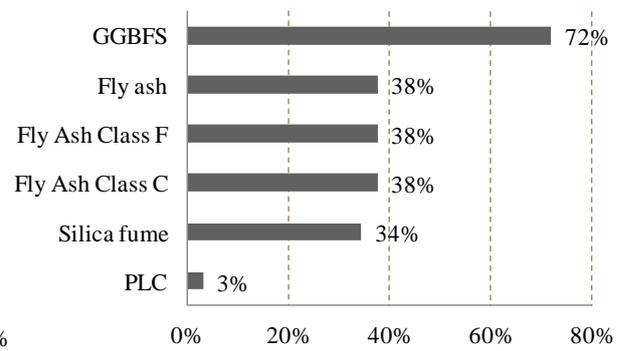


Fig. 5. Percentage of companies that named each material as one of the three most commonly used SCMs in the industry (N=32).

When asked what SCMs could be potentially used in the concrete industry, fewer responses (N=17) were received. Those additional SCMs include rice husk ash (mentioned by 2 participants), grounded limestone, leachates from petroleum waste, natural pozzolans, ultrafine fly ash, metakaolin, and bottom ash (all mentioned once). This shows different levels of knowledge on possible SCMs among industry practitioners. While some materials such as metakaolin and rice husk ash had already been used by a few companies, they were only considered potential SCMs or not recognized at all by others. This implies that there may not be enough information to prove the applicability of those not widely used SCMs, or such information exists (e.g., data generated by researchers or historical data from individual industry practitioners), but is not made widely available to the industry. The SCM usage was compared between ready mixed concrete suppliers and prefabricators and the results are shown in Table 2. Statistically, the percentage of ready mixed concrete suppliers using fly ash Class F and GGBFS is higher than that of prefabricators. Percentage-wise, the major SCMs have been more commonly used by ready mixed concrete suppliers than prefabricators.

Table 2 Comparison of SCM usage between ready mixed concrete suppliers and prefabricators.

| Subgroups and analysis items | Pre-specified SCM | | | | |
|---|-------------------|--------------------|--------------------|-------------|-------|
| | Fly ash Class C | Fly ash Class F | GGBFS | Silica fume | PLC |
| % of ready mixed concrete suppliers selecting an SCM (N=23) | 61% | 65% | 65% | 48% | 17% |
| % of concrete prefabricators selecting an SCM (N=19) | 37% | 37% | 26% | 42% | 11% |
| <i>p</i> value | 0.074 | 0.043 ^a | 0.007 ^a | 0.399 | 0.385 |

^aDenotes a statistically significant difference between the two compared subgroups.

Participants were then asked to select or name benefits and barriers to using each of the three most commonly used SCMs they mentioned. The frequency of each benefit or barrier mentioned by participants is summed up in Figs. 6 and 7.

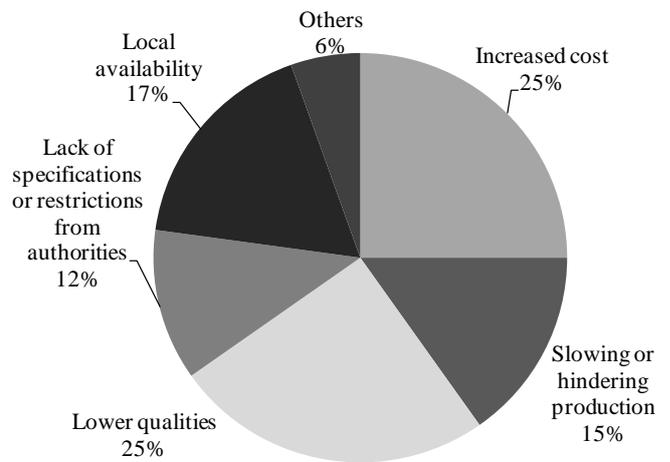
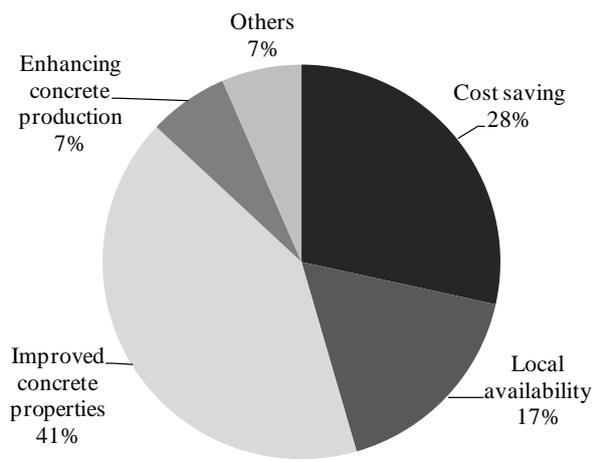


Fig. 6. Benefits for the use of SCMs (N=123).

Fig. 7. Barriers to the use of SCMs (N=92).

This research found that the three most frequently mentioned benefits and barriers were the same: impact on concrete properties (either improved or lowered quality), cost, and local availability. Among them, concrete properties were the most important factor in adopting an SCM. The advantage (e.g., local availability) an SCM could provide for one company might be a disadvantage for another company. Also, due to the existence of various concrete properties, one SCM could have both advantages and disadvantages as existing studies have noted. Noticeably, suppliers/manufacturers were not widely aware that using sustainable raw materials in concrete production was environmentally beneficial. This benefit was mentioned by only 2% of those surveyed. Besides the top three, two other frequently mentioned barriers were slowing/hindering production and the lack of specifications or restrictions from authorities such as engineers.

The perceptions of ready mixed concrete suppliers and prefabricators regarding the benefits and barriers to using SCMs were compared. As shown in Table 3, the two subgroups shared consistent views regarding the top three benefits. Inconsistency existed in the top three barriers. Whereas increased cost and slowing down/hindering production were two of the top three concerns for both subgroups, local availability, deemed as the third biggest barrier by ready mixed concrete suppliers, was not mentioned by any prefabricator. A statistical difference was found in that prefabricators had more concerns about quality than ready mixed concrete suppliers. This is understandable since prestressed concrete manufacturers are always more concerned with concrete chemistry because of prestressed steel corrosion, rate of strength gain for casting bed turnover, bond, creep, and other concrete properties. Thus, alternative raw materials such as SCMs are only considered when they have been proven by extensive research and industry practice. However, for the three most commonly used SCMs, especially GGBFS, there is still room for continuously promoting their usage among concrete prefabricators based on the survey results. In this analysis, some responses were counted under both subgroups if they came from a company providing both ready mixed concrete and prefabrication services. On the other hand, responses from companies that provide neither of these two services were excluded.

Table 3 Comparison of perceptions between ready mixed concrete suppliers and prefabricators regarding SCM usage.

| Item | Ready mixed suppliers | | Prefabricators | | <i>p</i> value | |
|----------|--|----------------------|--------------------|----------------------|----------------|--------------------|
| | Number of comments | % in total responses | Number of comments | % in total responses | | |
| Benefits | Improved concrete properties | 39 | 40% | 12 | 43% | 0.396 |
| | Cost saving | 22 | 22% | 8 | 29% | 0.325 |
| | Local availability | 19 | 19% | 4 | 14% | 0.407 |
| | Ease concrete production (e.g., improving pumpability) | 9 | 9% | 1 | 4% | 0.233 |
| | Being sustainable | 4 | 4% | 2 | 7% | 0.458 |
| | Aesthetic | 3 | 3% | 0 | 0% | 0.344 |
| | Specifications available | 2 | 2% | 1 | 4% | 0.659 |
| | Subtotal | 98 | 100% | 28 | 100% | - |
| Barriers | Increased cost | 18 | 26% | 4 | 22% | 0.468 |
| | Slowing/barricading production | 15 | 22% | 4 | 22% | 0.535 |
| | Local availability | 12 | 18% | 0 | 0% | 0.062 |
| | Lower qualities | 11 | 16% | 8 | 44% | 0.020 ^a |

| | | | | | |
|---|----|------|----|------|-------|
| Lack of specifications or restrictions from authorities | 7 | 10% | 0 | 0% | 0.118 |
| lack of acceptance or understanding | 2 | 3% | 1 | 6% | 0.579 |
| Safety | 2 | 3% | 0 | 0% | 0.483 |
| Aesthetic | 1 | 1% | 1 | 6% | 0.303 |
| Subtotal | 68 | 100% | 18 | 100% | - |

^aDenotes a statistically significant difference between the two compared subgroups.

Survey participants were asked whether there were industry guidelines or standards governing the use of SCMs and if so what their companies followed. Of the 29 participants answering this question, 28 of them (97%) indicated specific specifications, standards or guidelines used by their companies. These include project specifications, construction specifications/codes from related cities, and guidelines from ACI or DOT in the states in which they operated.

To understand to what extent SCM-based concrete is applied in the industry, participants were asked in separate questions whether their companies used SCMs in non-structural or structural concrete components. Up to 93% of companies surveyed had applied SCMs in structural components, such as footing, columns, grade beams, walls, slabs, bridge piers and decks, and drilled shafts/caissons. This implied that such concrete could achieve good strength. On the other hand, 89% of companies had applied SCMs in non-structural components, including sidewalks, curbs, driveways, etc. Companies not using SCMs in non-structural components provided the following reasons: the color variation of architectural concrete caused by SCMs, increased cost, or the company simply did not use any SCM.

The responses regarding SCM applications were also compared between ready mixed concrete suppliers and prefabricators. As shown in Table 4, no significant difference was found in the use of SCMs in structural components. In contrast, the statistical test found a significant difference in SCM usage in non-structural components. Prefabricators seemed to have more limitations in applying SCMs due to the aesthetic or cost reasons mentioned above.

Table 4 Comparison of SCM applications between ready mixed concrete suppliers and prefabricators.

| Subgroups and analysis items | Non-structural components | | | Structural components | | |
|--------------------------------|---------------------------|--------------------------------|-----------------------------|---------------------------|--------------------------------|-----------------------------|
| | Number of total responses | Number of companies using SCMs | % of respondents using SCMs | Number of total responses | Number of companies using SCMs | % of respondents using SCMs |
| Ready mixed concrete suppliers | 21 | 20 | 95% | 18 | 17 | 94% |
| Prefabricators | 6 | 3 | 50% | 10 | 9 | 90% |
| <i>p</i> value | - | - | 0.010 ^a | - | - | 0.588 |

^aDenotes a statistically significant difference between the two compared subgroups.

4.3 The Use of AAs

Similar questions were asked in the third part of the questionnaire regarding the use of AAs in the industry. Fig. 8 shows the AAs currently used by surveyed companies, of which lightweight aggregate (LWA) and RCA are the most widely used. These two materials were also more frequently perceived by survey participants as the most commonly used aggregates in the industry (shown in Fig. 9). However, the open-ended feedback from concrete suppliers showed their concerns about using RCA in concrete production. The uncertainty in the sources of old concrete made it hard to determine the original concrete properties (e.g., strength). Difficulties also existed in controlling the size of crushed concrete. Other concerns included the inferior engineering properties of RCA due to its higher water absorption and affinity, the lack of specifications, and the risk of quality control. All of these made RCA, seemingly promising in utilizing recycled waste streams to produce new concrete, limited in its real-world applicability. Other AAs such as crushed glass, tire rubber, and brick rubble, although studied by researchers, had limited use in practice. When asked about other potential AAs, fewer participants provided feedback. Only cullet pumicite and natural zeolite sludge were mentioned.

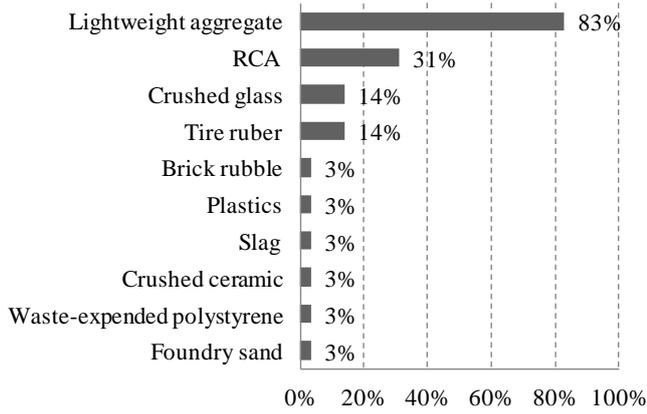


Fig. 8. Percentage of companies that had used each specified AA (N=29).

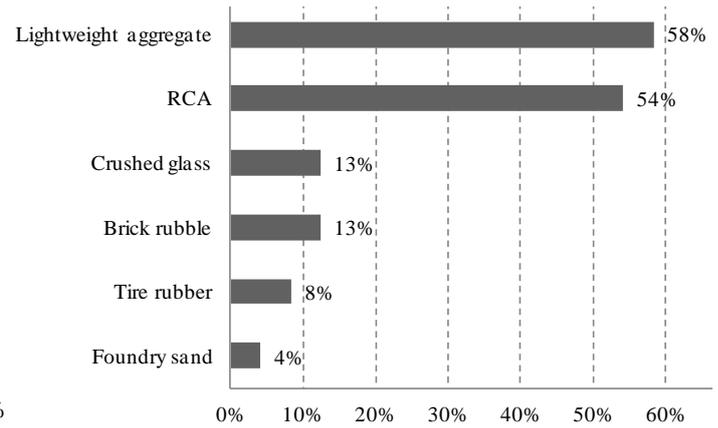


Fig. 9. Percentage of companies that had named each AA as one of the three most commonly used aggregates (N=24).

Similar to the comparison of SCM usage between ready mixed concrete suppliers and prefabricators, a comparison of AA usage between these two subgroups was also conducted. The results are displayed in Table 5. The only inconsistency was found in the usage of LWA. Compared to prefabricators, a higher percentage of ready mixed concrete suppliers have applied LWA in concrete production.

Table 5 Comparison of AA usage between ready mixed concrete suppliers and prefabricators.

| Subgroups and analysis items | Pre-specified AA | | | | |
|--|--------------------|-------|---------------|-------------|--------------|
| | LWA | RCA | Crushed glass | Tire rubber | Brick rubble |
| % of ready mixed concrete suppliers selecting an AA (N=23) | 70% | 30% | 17% | 13% | 0% |
| % of prefabricators selecting an AA (N=19) | 42% | 5% | 5% | 11% | 5% |
| <i>p</i> value | 0.041 ^a | 0.085 | 0.147 | 0.660 | 0.319 |

^aDenotes a statistically significant difference between the two compared subgroups.

Compared to the number of times that benefits and barriers of using SCMs were mentioned by survey participants (123 and 92, respectively), fewer responses were received on the benefits (37) and barriers (47) to using AAs. This was likely due to less knowledge and experience practitioners had in AAs. As shown in Figs. 10 and 11, the top three benefits and barriers to using AAs were not consistent. While the structural advantage and cost saving were the two most frequently mentioned benefits by survey participants, being “green” was ranked the third highest. As further explained by survey respondents, using AAs could

recycle waste materials and save natural resources. In terms of barriers, the top three frequently mentioned items were cost increase (34%), local availability (23%), and technical barriers (17%). Technical barriers were clarified as the difficulty in controlling aggregate gradation and the complexity in mix design. The findings on the major barriers to using SCMs and AAs are consistent with what have been identified in the literature (e.g., Batayneh et al., 2007; Duxson et al., 2007; Meyer, 2009).

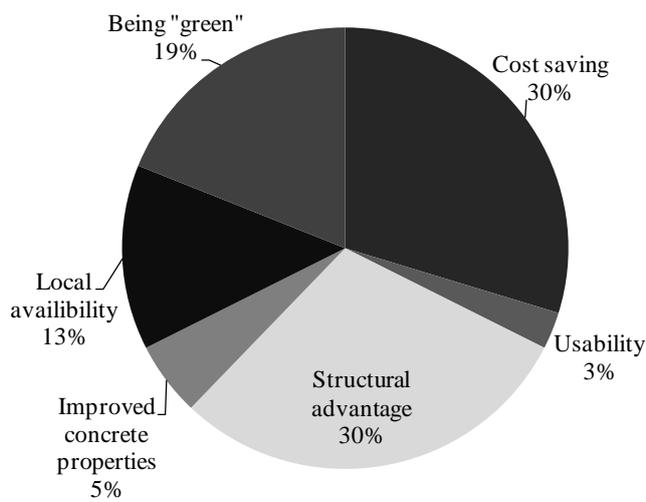


Fig. 10. Benefits for the use of AAs (N=37).

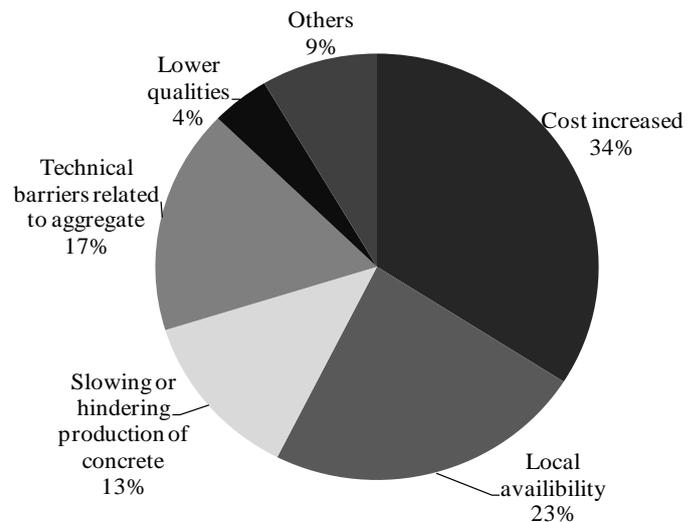


Fig. 11. Barriers to the use of AAs (N=47).

Similarly, a comparison study of the benefits and barriers to using AAs was performed between ready mixed concrete suppliers and prefabricators. The statistical analysis results shown in Table 6 indicate no significant difference between the two subgroups. Noticeably, all positive perceptions of using AAs regarding being “green” and using local materials came from ready mixed concrete suppliers. It seems that prefabricators surveyed in this study were less environmentally conscious or they just focused on cost saving, structural advantage (e.g., light weight), and improved concrete properties when considering the adoption of an AA.

Table 6 Comparison of perceptions between ready mixed concrete suppliers and prefabricators regarding AA Usage.

| Benefits and barriers | Ready mixed concrete suppliers | | Prefabricators | | p value |
|-----------------------|--------------------------------|-----------|--------------------|-----------|---------|
| | Number of comments | Frequency | Number of comments | Frequency | |
| | | | | | |

| | | | | | | |
|----------|---|----|------|----|------|-------|
| Benefits | Cost saving | 8 | 35% | 4 | 40% | 0.398 |
| | Structural advantage | 4 | 17% | 4 | 40% | 0.116 |
| | Being “green” | 4 | 17% | 0 | 0% | 0.114 |
| | Local availability | 4 | 17% | 0 | 0% | 0.114 |
| | Improved concrete properties | 2 | 9% | 2 | 20% | 0.244 |
| | Usability | 1 | 4% | 0 | 0% | 0.535 |
| | Subtotal | 23 | 100% | 10 | 100% | - |
| Barriers | Cost increase | 11 | 35% | 6 | 46% | 0.341 |
| | Slowing/hindering production | 4 | 13% | 3 | 23% | 0.275 |
| | Local availability | 6 | 19% | 3 | 23% | 0.528 |
| | Technical barriers related to aggregate | 5 | 16% | 0 | 0% | 0.106 |
| | Lower qualities | 3 | 10% | 0 | 0% | 0.201 |
| | Lack of data on concrete properties | 1 | 3% | 1 | 8% | 0.487 |
| | Aesthetic | 1 | 3% | 0 | 0% | 0.558 |
| | Subtotal | 31 | 100% | 13 | 100% | - |

When asked whether there were industry guidelines to follow in applying AAs, only 29% of participants answered “yes,” which is quite low compared to 97% of respondents answering “yes” to a similar question for the use of SCMs. It seemed that fewer or limited specifications or standards were available for the use of AAs. Most of specifications or standards mentioned by respondents were for the use of LWA from ACI and ASTM. This may help explain why LWA is currently the most widely used AA. Through the interview, the researchers learned that ODOT had already published a standard for using RCA in Ohio transportation projects (ODOT, 2011). However, the survey results did not show that the Central Ohio survey participants were aware of the standard, suggesting a potential problem of information dissemination.

Participants were asked in separate questions whether their companies had used AAs in non-structural or structural concrete components. It was found that up to 69% of respondents had applied AAs in non-structural components, including sidewalks, concrete barriers, signs/fences, and residential applications. Approximately 63% of respondents had applied AAs in structural components such as decks, footing, and slabs. One respondent mentioned that the replacement of virgin aggregate was specified in Europe (i.e., up to 20% replacement of virgin aggregate in non-structural components and up to 10% in structural components), but similar specifications were unavailable in the U.S. Due to the small number of responses

(12 and 13, respectively) for these two questions, no subgroup comparison was conducted.

The one-tailed Barnard’s exact test was used to compare the actual usage of SCMs and AAs in structural and non-structural concrete components among the surveyed companies. The results shown in Fig. 12 indicate that SCMs were statistically more frequently used in structural concrete components than AAs ($p=0.016$). Although survey participants did not specify the lack of industry standards/guidelines as a barrier that lowered the usage of AAs in structural applications, improvements on standard/guideline development and information dissemination, especially related to the use of RCA, can certainly alleviate concerns about structural performance of RCA concrete and help practitioners with concrete recycling and mix design.

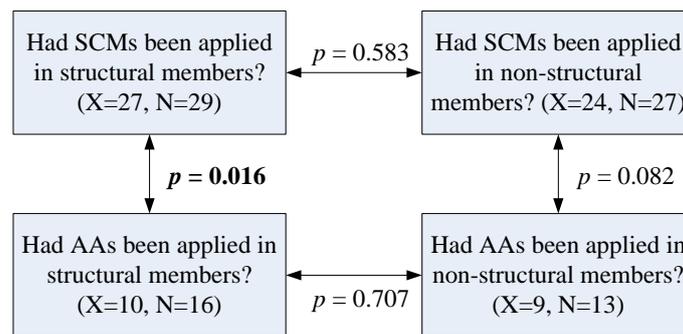


Fig. 12. Statistical analysis results for the use of SCMs and AAs (X: the number of positive responses; N: the total responses received for the question).

4.4 Difference between Local Companies and National Counterparts

Further analysis revealed some differences in AA adoption between the five major concrete suppliers interviewed in Central Ohio and the other 34 companies surveyed online. Regardless of many AAs available, only one of the five local companies used LWA; the rest used only traditional limestone or gravel. It seemed that they were aware of some options as all of them suggested RCA and two of them suggested LWA as potential AAs. In contrast, 96% of companies surveyed online had used LWA, followed by 33% that used RCA and 17% that used tire rubber and crushed glass. There are many factors that could lead to the low use of AAs by Central Ohio concrete suppliers and prefabricators such as the relatively low tipping

fee for construction and demolition debris. The researchers also found that the aforementioned ODOT standard is stringent in that the RCA used for ODOT projects must also come from an ODOT project, and non-ODOT sources are not allowed. In addition, a survey needs to be conducted based on sublots at the roadway to determine the material quality and special requirements are placed on concrete mix design. This could present additional challenges to Central Ohio concrete suppliers and prefabricators. (Ling et al., 2013)

5. Conclusions

This paper presented a questionnaire survey on the current status of using sustainable raw materials in the U.S. concrete industry. **In this study, the background and distribution of survey companies were carefully analyzed to ensure that they can represent the studied populations. Barnard's exact test was adopted in subgroup comparison to minimize the loss of statistical power due to the small sample size.** It was found that despite a large number of academic studies on various types of SCMs and AAs, their current use in practice was still limited to the top three SCMs (fly ash, GGBFS, and silica fume) and two most common AAs (LWA and RCA). Also, the surveyed companies were at different levels of recognition and utilization of SCMs and AAs. One sustainable raw material used by some companies might still be new to their peers. This research found that the three most commonly perceived benefits and barriers to using SCMs in concrete production were all related to concrete properties, cost, and local availability of such materials. Benefits of using SCMs were more frequently mentioned than barriers. Comparatively, benefits and barriers regarding the use of AAs were mentioned fewer times by survey participants. Besides structural advantage and cost saving, some surveyed companies were aware of the environmental benefits from using AAs, e.g., the reuse of waste and conservation of natural resources. Cost increase, local availability and technical barriers were the three most commonly perceived barriers.

Subgroup comparison and the one-tailed Barnard's exact test performed in this study

yielded the following results:

- Statistically, higher percentages of ready mixed concrete suppliers than prefabricators had produced sustainable concrete ($p=0.016$) and received related inquiries ($p=0.042$). No correlation existed between companies' size or years in business and whether they had made sustainable concrete or received inquiries from customers.
- Statistically, greater percentages of ready mixed concrete suppliers than prefabricators had utilized GGBFS ($p=0.007$), fly ash Class F ($p=0.074$), and LWA ($p=0.041$) in concrete production.
- Prefabricators were statistically more concerned about the potential quality issues caused by using SCMs in their products with a p value of 0.020.
- No significant difference was found between ready mixed concrete suppliers and prefabricators regarding the perceived benefits and barriers to using AAs. However, only ready mixed concrete suppliers had identified being "green" as one of the benefits of using AAs.
- No significant difference existed between the application of SCMs or AAs in structural and non-structural concrete components. However, a statistically higher percentage of ready mixed concrete suppliers than prefabricator had applied SCMs in non-structural components ($p=0.010$).
- Statistically, a higher percentage of companies in the survey had used SCMs than AAs in structural concrete components ($p=0.016$). No significant difference existed in the use of SCMs and AAs in non-structural components. Practitioners perceived that there were more readily available guidelines or specifications for the application of SCMs than AAs.
- The overall perception gained from this subgroup comparison was that ready mixed concrete suppliers were ahead of prefabricators in the utilization of sustainable raw

materials to produce concrete.

This paper provides some insight into how researchers could help the industry solve its real problems in sustainable concrete production and application. For example, based on the identified benefits and barriers, researchers will need to focus their studies on the impact of SCMs or AAs on concrete properties (e.g., the long-term durability of concrete made of RCA and quality control for RCA concrete), cost effectiveness, local availability of sustainable materials, etc. It is also important to develop specifications and industry standards corresponding to any recommended new alternative materials. Furthermore, more assistance needs to be provided to help prefabricators address potential concerns they have in applying sustainable raw materials to particular products. These will increase the acceptance and implementation of sustainable raw materials in various concrete applications.

It is worth noting that this study will serve as a starting point for future research in this area. Although the results obtained from this study allowed valuable conclusions and insights to be drawn on the current status of sustainable concrete production in the U.S., further research based on an enlarged sample size is necessary to improve the accuracy of findings and obtain more profound insights. Also, tailored questionnaires can be developed to collect more specific, in-depth information from certain subgroups (e.g., prefabricators) to help advance their practice in sustainable concrete production.

Appendix: Questionnaire for the Survey of Sustainable Concrete Production in the U.S.

Background and Your Involvement in Sustainable Construction Production

1. Does your company produce sustainable concrete by using waste material(s)? a. Yes; b. No.
2. What field does your company work in? Select all that apply. a. Providing ready-mixed concrete; b. Providing pre-fabricated concrete products; c. Others (Please specify).
3. For how many years has your company been involved in the concrete industry?
4. For how many years have you been working in the concrete industry?
5. How many full-time employees work for your company? a. Less than 10; b. 10 to 50; c. 50-100; d. 100-200; e. More than 200.
6. In which industry sector is your company's concrete used? a. Building; b. Roadway/bridge; c. Other sector(s) (Please specify).
7. How does your company design concrete mix given a required concrete property? a. Using company historical data; b. Using industry specification(s) or standard(s) (Please specify, e.g., ACI or ASTM standard); c. Other ways (Please specify).
8. Has your company received inquiries regarding the use of recycled materials in any of your mix designs? a. Yes; b. No.

Supplementary Cementitious Materials (SCMs)

9. Does your company use any of the following wastes or supplementary sources to replace portion of cement in your concrete? If so, please also specify the *substitution percentage range* of this SCM in the cementitious material weight and the related concrete *28-day compressive strength* (e.g., 4ksi). Select all that apply: a. Fly ash Class C; b. Fly ash Class F; c. Ground-granulated blast-furnace slag; d. Silica fume; e. Calcined shale; f. Others (Please specify).
10. Are there other potential SCMs that could be used in mix designs? Please specify.
11. Please identify the top three most suitable SCMs and evaluate them based on the following items. For rating questions, please rate the SCMs on selected items on a scale of 1-5: (1) Worst, (2) Poor, (3) Neutral, (4) Good, (5) Very good. Select N/A when you have no idea. i. Indicate where the material comes from; ii. Rate local availability; iii. Rate cost effectiveness (i.e., price, labor, etc.); iv. Rate the following concrete properties: a. Strength; b. Workability; c. Durability; d. Other properties (Please specify); v. Other factors (Please specify); vi. Indicate benefits and barriers to applying this material in concrete production. .
12. Are there any industry guidelines or standards for the use of SCMs in concrete production (e.g., the percentage of fly ash, slag cement, etc.)? If yes, does your company follow any of them? Please specify the guideline(s) or standard(s) you used.
13. Has concrete made with SCMs been applied to non-structural and/or structural members? Select all that apply and provide examples. a. Non-structural members (e.g., sidewalks, concrete curbs, etc.); b. Structural members (e.g., building footing, columns, bridge decks, etc.).

Alternative/Recycled Aggregates

14. Does your company use any of the following wastes or supplementary sources to replace portion of aggregates in your concrete? If so, please also specify the *substitution percentage range* of this alternative aggregate in the total aggregate material weight and the related concrete *28-day compressive strength* (e.g., 4ksi). Select all that apply. a. Recycled concrete aggregate; b. brick rubble; c. Plastics; d. Tire rubber; e. Electric arc furnace (EAF) slag; f. Crushed ceramic; g. Crushed glass; h. Waste-expanded polystyrene; i. Others (Please specify).
15. Are there other potential alternative aggregates that could be used in concrete mix design? Please specify.
16. Please identify the top three most suitable alternative/recycled aggregates and evaluate them based on the following items. i. Indicate where the material comes from; ii. Rate local availability; iii. Rate cost effectiveness (i.e., price, labor, etc.); iv. Rate the following concrete properties: a. Strength; b. Workability; c. Durability; d. Other properties (Please specify); v. Other factors (Specify); vi. Indicate benefits and barriers to applying this material in concrete production.
17. Are there any industry guidelines or standards for the use of recycled concrete aggregates in concrete production (e.g., its percentage in the total aggregate weight)? If yes, does your company follow any of them? Please specify the guideline(s) or standard(s) you used.
18. Has concrete made with alternative/recycled aggregates been applied to non-structural and/or structural members? Please select all that apply and provide examples. a. Non-structural members; b. Structural members.

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