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An Overview of Concrete Recycling Legislation and Practice in the United States

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Abstract: Recycling concrete waste helps reduce the negative environmental impacts of construction activities. Worldwide, concrete recycling rates and available applications of recycled concrete vary largely. A deep understanding of the current status of concrete recycling in individual countries or regions would allow for the development of applicable and effective strategies for improvement. This empirical research on concrete recycling in the United States (U.S.) consists of two parts: a qualitative study of the legislation, regulation and practice of solid waste management (SWM) and concrete recycling in 46 states/district as well as a questionnaire survey of practitioners' views of concrete recycling in Ohio and California. Based on the qualitative analysis, this research grouped the studied states/district into three categories, representing advanced, average, and below average SWM practices, with the majority of states having average to below average practice and in greater need of improvement. The survey results showed that practitioners inthe two selected stateshad positive, consistent perceptions on practice, benefits, and recommended methods for concrete recycling and identified no major difficulties except for the lack of government awareness and support. This research not only provides an updated understanding of concrete recycling legislation and practice, but

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alsooffersusefulstrategies for government and industry to work together for expediting the concrete recycling progress.

Keywords: Construction industry; Solid waste management (SWM); Concrete recycling; Sustainability; Questionnaire survey; United States (U.S.).

Introduction

The wide use of concrete in construction has raised multiple environmental concerns due to its high usage of raw materials, energy-intensive cement manufacturing, energy use and air emissions associated with transportation, and the creation of large volumes of concrete waste from demolition (Oikonomou, 2005). According to previous studies (Ahmad and Aimin, 2003; Kim and Kim, 2007; Tam, 2008), concrete waste accounts for 50-70% (by weight) of the total construction and demolition (C&D) waste. Since on average 30-40% of total solid waste comes from C&D activities (C&D Waste Management Guide, 2016; European Commission, 2011; Rodríguez et al., 2015; Wang et al., 2008; World Business Council for Sustainable Development [WBCSD], 2009), concrete waste could range from 15-28% of total solid waste.

Environmental consciousness, protection of natural resources, and sustainable development have become significant concerns in modern construction industries (Oikonomou, 2005). Recycling old concrete is one of the main approaches to addressing these concerns.As a result, recent years have seen increasing attention paid to the management of concrete waste. However, recycling of old concrete faces difficulties such as the inferior quality of recycled aggregates and increased labor cost (Gull, 2011; Oikonomou, 2005). Its actual progress may also differ across countries or regions due to the lack of technology, insufficient governmental regulations, and the lack of coordination in waste transport (Lockrey et al., 2016). A deeper understanding of the current state of concrete recycling and related barriers faced by individual countries or regions will enable the development of more applicable and effective coping strategies.

In the literature, Lauritzen (2004) provided an overview over the development of and challenges to concrete recycling worldwide. Tam (2009) compared concrete recycling practices and perspectives of field practitioners between Australia and Japan. Consequently, strategies and recommendations, including technical specifications and advancements, policy support, education and training, etc., were proposed forimprovement. However, so far, limited studies have been performed to understand the current status of and challenges to concrete recycling in the U.S.; especially,as noted by U.S. Environmental Protection Agency (USEPA, 2018), solid waste management (SWM) differs across states. An inadequate understanding of SWM regulations and implementations in individual states, along with statewide guidelines and practices related to the management of C&D waste (including waste concrete), would hinder the development of effective strategies to improve concrete recycling in this country.

The primary goal of this empirical research is two-fold: 1) to provide a qualitative study of the current U.S. legislation, regulation, and practice on SWM and concrete recycling across states, and 2) to furtherexplore industry practitioners' perceptions on the current status of concrete recycling through a questionnairesurvey. In addition to providing an updated understanding of U.S. concrete recycling, this study offers valuable insights and improvement recommendations based on industry feedback and research findings.

Literature Review

Progress in Concrete Recycling

Wilburn and Goonan (1998) estimate that up to 1998, more than half of cement concrete debris generated in the U.S. ended up in landfills. Of all recycled cement concrete debris, 85%

was used as road base. Further,recycled concrete aggregate (RCA) was being increasingly used to replace natural aggregate in various other road construction applications. U.S. Geological Survey (USGS, 2000) estimates that at least 83% of concrete recycled in 1997 was used as aggregate; specifically, 68%, 9%, and 6% used in road base, asphalt hot mixes, and new concrete mixes, respectively. The lower transportation cost of RCA (when it is produced on-site for reuse or has a shorter hauling distance than virgin aggregate)might have been the incentive that promoted its use in the U.S. construction industry (Gilpin et al., 2004). As the U.S. consumes more than 2 billion tons of aggregate each year and only 5% comes from recycled sources (USGS, 2000), this leaves a huge room for growth ofconcrete recycling, especiallyrecycling concrete waste into aggregate. The literature search did not find any newer study that provides up-to-date concrete recycling rates and applications nationally.

A review of concrete recycling progress worldwide suggests that the U.S.is lagging behind other leading countries or regions in concrete recycling,denoting great potential for advancement. For example, Japan reached the concrete recycling rate of 96% in 2000 and 100% more recently (Kawano, 2003; Tam, 2009).In Europe, countries that are active in C&D recycling and reuse such as the U.K. and Germany had achieved recycling rates at or close to 90% (European Commission, 2011). Some other European countries have also achieved very high recovery rates of concrete waste.Specifically, recycled aggregate accounted forover 20% and 15% of aggregateuse in Netherlands and Belgium, respectively (WBCSD, 2009).

Difficulties Encountered in Concrete Recycling

Recycling strategies, cost, energy consumption, available techniques,and environmental impact are key considerations in adopting concrete recycling. Tam (2008)'s case study showed that compared to landfilling, converting concrete waste into RCA could be more cost effective while also protecting the environment and achieving construction sustainability. Gull (2011), in contrast, was concerned about the incurred labor cost when extracting waste aggregates from demolished buildings and the cost of using admixture to increase the strength of RCA concrete. Akbarnezhad and Nadoushani (2014) found that the economic and environmental benefits of concrete recycling would depend on multiple parameters, including travel distance, prices of natural aggregate, and the desired quality of the recycled products. Also, the techniques selected for concrete recycling matter. For example, the heating and rubbing method can produce high-quality recycled aggregate with reduced CO_2 emission (Shima et al., 2005) while acid treatment is less eco-friendly and economical than mechanical treatment (Pandurangan et al., 2016).

Another concern about concrete recycling lies in the quality of products made with RCA. Oikonomou (2005) indicated that the source of old concrete was usually unknown. Therefore, the use of RCA should be restricted due to the different properties of RCA compared with virgin aggregates. Limbachiya et al. (2012) found that RCA concrete requires a lower water to cement ratio and higher cement content to obtain strength comparable to conventional concrete. Meyer (2009) noted RCA's negative effects on concrete production and properties, such as the variety of contaminants in RCA concrete. Further, various environmental concerns associated with concrete recycling (e.g., waste containing hazardous materials and the effect of RCA on water quality such as pH) were noted(Federal Highway Administration [FHWA], 2004). If these concerns are not properly addressed, concrete recycling in practice could face various barriers.

Policies for SWM

SWM legislation and regulation, which govern or influence C&D waste management, vary across countries or regions. In general, developing countries focus more on economic growth and lack national policies, regulations, and/or enforcement measureson waste management (Lockrey et al., 2016; Mian et al., 2017). In contrast, more developed countries tend to have established laws, regulations, and programs that aim to reduce waste generation, increase recycling, and better manage solidwaste (e.g., Australian Government Department of the Environment and Energy, 2016). Especially, developed countries or regions with denserpopulation and limited land resources such as Japan and Europe have more advanced laws and regulations to enforce waste diversion (EU-Japan Center for Industrial Cooperation, 2015; European Commission, 2016).

In the U.S., the Congress enacted the comprehensive Resource Conservation and Recovery Act (RCRA) in 1976. This primary law sets national goals for waste reduction and environmentally-sound SWM. Accordingly, USEPA, the health and environmental regulation writing and enforcing agency, established a goal to achieve 25% recycling and source reduction ratenationally by 1992 (USEPA, 2002). USEPA encourages states to implement their own waste management programs and develop statutes and regulations that are equivalent to or more stringent than the federal acts and regulations (USEPA, 2018). This leaves room for individual states to set waste management laws, regulations, and goals based on their own conditions, causing big variation among states. Especially, C&D debris(excluding waste materials that meet the federal definition of hazardous waste) is not federally regulated exceptthatC&D landfills must follow a few basic standards outlined in RCRA. This allows states to play a primary role in defining and regulating C&D waste management. Particularly, clean, uncontaminated concrete waste is not considered hazardous waste and is recyclable (USEPA, 2004).

Research Methodology

This empirical study consists of two parts. The first part adopted a qualitative analysis on the most current U.S. SWM policies at the state level. In total, SWM legislations and policies of 45

U.S. states and one federal district were thoroughly reviewed based on the information published on the website oftheir main environmental protection department or agency. The search of each websiteincludedexploringall the webpages of the division or office related to waste management, checking the statutes/policies pages, and performing the embedded search function using keywords,including waste management, C&D waste, construction waste, recycling, regulation, etc. The concrete recycling practice in individual states/district, if any information was publicly available through online search, was also investigated. A few states (e.g.,Georgia, Colorado, and Nebraska) either had very limited SWM information publishedon their websites or hadinformation (such as cleanup programs, hazardous waste management, and recycling of tires)not relevant to the purpose of this study, and therefore were not included in the qualitative analysis.In the second part of this study, aquestionnaire was developedfor face-to-face interviews and online surveys of industry practitioners. Local concrete contractors anddemolition/recycling companies in Central Ohio (a U.S. Midwestern metropolitan area with a population of two million) were identified for face-to-face interviews through the Membership Directory of Builders Exchange (BX) of Central Ohio.The face-to-face interview method would allow more insights to be communicated during the process.Online survey participants were found from the Membership Directory of Ohio Concrete and the C&D facility list from the California Department of Resources Recycling and Recovery (also called CalRecycle).

Ohio and California practitioners in concrete recycling were included in this empirical study due to two reasons. First, both states had resource available for identifying survey participants; the list of concrete recycling practitioners was hard to obtain in many other states. Second, according to this study, samples from Ohio and California represented average and advanced SWM practice in this country. Practitioners in these states were likely more active in concrete recycling than their counterparts from states with below average SWM practice, and were able to offer more insights based on their experience. Although the collected data may not reflect the perceptions of concrete recycling professionals all over the country, the survey findings that represent more prevailing concrete recycling practices in the U.S. are more useful to the majority of the states. Especially, California generates 17% of all waste nationally (CalRecycle, 2016), and is worth further study.

Companies that did not specify concrete recycling as part of their services/products were contacted by phone to clarify whether they were already involved in concrete recycling or wereconsidering entering this business within three to five years. Companies that answered “no” to both questions were not included in the survey list.Theidentified survey participants, including contractors, demolition/recycling companies,consultants, etc., were major players or foreseeable future players of concrete recycling in these two states.The sampling procedure was consistent with that in Cao et al. (2016) and Jin et al. (2017a), by focusing on those who have been actively practicing or are about to start practicing in the studied field. While the researchers attempted to involve more practitioners in the survey, those who had not practiced concrete recycling or were not considering doing so usually indicated no interest in taking the survey.

The questionnaire (see Appendix) contains two parts. Part One collects the background information of survey participants using multiple-choice and open-ended questions. Part Two was adapted from Tam (2009)’s study that investigated and compared the concrete recycling practices between Australia and Japan. The questions were divided into foursections: Practice, Benefits,Difficulties, and Recommended Methods. The “Practice” section adopted multiple-choice questions while the other three sections used Likert scale questions: Five options from “1” to “5” were available for each given statement, with “1” denoting “least important” or “strongly disagree," "3" denoting "neutral," and "5" denoting "most important" or "strongly agree." The questionnaire was reviewed by representatives from the BX of Central Ohio and Ohio Concrete and adjusted accordingly to ensure its relevance to the U.S. concrete industry. The survey was conducted between July and October, 2012. Companies were asked to have their most knowledgeable or experienced people to take the survey.

It was estimated that 10-15 minutes would be needed for respondents to read the instruction and complete the questionnaire. Each completed survey was manually inspected to verifyits validity (e.g., a survey might be deemed invalid if the answers to all the Likert scale questions were the same).This study adopted the two-sample t-test to assess the consistency of the collected data between the two states and decide how the data would be analyzed (i.e., separately or jointly). For each of the three Likert scale question sections related to individuals' perceptions on benefits, difficulties, and recommended methods, Relative Importance Index (RII) ($0 \leq RII \leq 1$)of each questionwas calculated to determine the relative ranking of questions within the sectionbased on a widely-used equation (e.g., Jin et al., 2017b; Kometa et al., 1994; Tam, 2009):

$$RII = \frac{\sum w}{A \times N}$$

where *w*denotes the numerical Likert score selected by each respondentranging from *1* to *5*,*A* is the maximum score (i.e., *5* in this study), and*N* denotes the number of responses. A question with a higher RII value would be more important than those having lower RII values.All these analyses were performed using Minitab. The complete results from the qualitative analysis and questionnaire survey are presented in the following section. Note that a comparison of survey results fromthe U.S. practitioners with that from their counterparts in Australia and Japan (Tam, 2009) was presented in Jin and Chen (2015).

Results and Discussions

Analysis of SWM Legislation, Regulation, and Practice among States

Solid waste in the U.S. includes municipal solid waste (MSW) (e.g., glass, metal, container, etc.), C&D waste, and other waste (e.g., industrial waste), but excludes hazardous waste. In this country, the generation, recycling, and disposal of MSW have been tracked much more closely than that of C&D waste at both the federal and state levels. Although these two types of waste are different, how MSW is managedby a state could somehowreflect the attitude and approach a state has toward C&D waste. According to USEPA (2016), while a more significant growth in the recycling/composting rate of MSW was seen in the past (from 16% in 1990 to 34% in 2010, nationally), the growth rate has leveled off in recent years: By 2014, only34.6% of MSW in this country was recycled/composted. There might have been various reasons, e.g., economics (the Great Recession,slow recovery of national economy, etc.).

The review results from this study show that the statewide waste diversion goals and recycling rates vary largely, which could also have partially contributed to the slow growth of the national recycling rate. For example, Idaho, as a predominately rural state with low landfill fees, does not have a mandated waste diversion goal in current statutes. Thus, recycling is only supported and encouraged by the state authority through public education and outreach activities (Idaho Department of Environmental Quality, 2016). In Alabama, the recycling goal set by the state was only 25%. A number of local jurisdictions have not fully developed and implemented recycling programs (Alabama Department of Environmental Management, 2008). In contrast, states such as Arizona and California have well-developed recycling programs. Specifically, California has established the 75% recycling goal through legislation with defined strategies and focus areas (CalRecycle, 2016). A recycling goal of 80% was also found in the District of Columbia (D.C.) (DC Department of Energy & Environment, 2016). Vermont has gone further to define C&D waste including concrete waste as recyclable materials and require the recycling of certain C&D waste streams (e.g., drywall, plywood, and scrap metal) in the state law (Vermont Department of Environmental Conservation, 2016).

Driven by the intended waste diversion goals and the gaps that need to be filled, the state and local governments' practice in SWM can be very different. For instance, Tennessee's diversion rate in 2011 was defined at 31%. Tennessee Department of Environment and Conservation (TDEC) may issue specific types of directives stipulated in the Solid Waste Management Act of 1991 to regions that do not improve their waste diversion practices (TDEC, 2015). The Maryland Recycling Act has required jurisdictions to develop and implement recycling programs since 1994 and the state government to reduce waste disposal by at least 20% or by a feasible rate. Each county depending on population has also been required to recycle between 20-35% of waste streams. By 2013, Maryland's waste recycle rate was close to 45% (Maryland Department of the Environment, 2015). Nevertheless, for states where the recycling and reuse of solid waste remains optional (e.g., Delaware, Idaho, and Wisconsin), government actions and interventions merely exist and recycling is mainly driven by economics and market.

While SWM regulations and guidelines are widely available in most of the studied states, the level and type of support provided by state authorities differ. These supports include the development of local SWM plans, technical standards, financial incentives for recycling, grants for recycling market study and enhancement, technical and educational assistance, etc. The availability and breadth of government supports in SWM could be one of the important influential factors that determine whether a state can meet or even exceed its recycling rate goal.

Based on the review and analysis results of individual states' SWM regulations and practices, this study divided the 45 states and D.C. into three categories (see Table 1), representing advanced (Category One), average (Category Two), and below average SWM practices (Category Three). This categorization does not intend to discriminate against states that seem to lag behind in SWM, but to increase the awareness about the existing gaps and encourage making improvementby learning from states with advanced practices.

INSERT TABLE 1 HERE!

It can be noted that most states in Category One are located in the Northeast region, East Coast, or West Coast. The less recycling-active states such as Nevada and Wyoming are mostly located in Midwestern regions with low population densities and more land resources for waste disposal (see Fig. 1). Usually in these states, the low disposal fees, the geographic isolation from processing facilities and markets, and collection and transportation over long distances for recycled products outweighed the values of recyclable materials (Idaho Department of Environmental Quality, 2016). However,other factors such as the establishment of recycling standards, the growth of the recycling market, and goals set in increasing recycling rates could drive the movement of waste diversion or recycling (Nevada Division of Environmental Protection, 2016). The above-mentioned factors may also affect the practice of C&D waste management and concrete recycling in individual states, causing variations across the country.

INSERT FIG. 1 HERE!

C&D Waste and Concrete Recycling Practice among States

In the U.S., C&D debris is defined at the state level (Napier, 2012). The disposal of C&D waste is also overseen by states (USEPA, 2018). Historically, C&D waste has not received the same level of attention as MSW. For example, the Minnesota Waste Management Act defines waste as mixed MSW. Consequently, state funding for SWM programs, composition studies, and research and market development efforts have all been centered on mixed MSW, leading to a high recycling rate of nearly 42%. In contrast, state efforts to properly categorize and recycle C&D waste, develop the recycling markets, and collect and report data lag behind (Minnesota Pollution Control Agency, 2008). Also, only a limited number of states, includingFlorida, Illinois, New York, etc., publish information on the amount of C&D waste recycled within the state with various limitations on the scope of materials included, the approaches used to estimate the amount of C&D waste recycled, etc. (USEPA, 2012). Hence, the statewide concrete recycling rates are often unknown and may not be directly comparable. An updated estimation of national concrete recycling rate is hard to obtain, not to mention timely measurement of progress.

A review of C&D waste management guidelines andrelevant informationobtained through the online search disclosed that only 20 of the states/district had practiced or regulated the diversion of C&D wastes from landfill. For example, Massachusetts developed consensus-based guidance to increase its C&D materials reuse and recycling and had achieved a 30% recycling rate by 2016 with a projected 50% recycling rate by 2020 (Commonwealth of Massachusetts, 2018). The remaining 26 states either did not specifically mention C&D wastes in their solid waste guideline such as North Dakota (North Dakota Legislative Branch, 2018) or indicated that the main practice of handling C&D wastes was land-filling such as Wyoming (Wyoming Department of Environmental Quality, 2018). Based on this review, it can be inferred that concrete recycling has less likely been properly addressed by many state environmental agencies.Further analysis showsthat the states/district defined as Category One (i.e., advanced in SWM) in Table 1 all belong to the 20 states/districthaving specific regulations or practices in C&D waste diversion. Also, all states included in Category Three (i.e., below average in SWM) fall into the remaining 26 states that did not specifically mention C&D waste diversion.

Fortunately, some government agencies that regulate building and building materials (e.g., FHWA and many State Transportation Agencies [STA]) have endorsed the use of recycled concrete, which helped promote the concrete recycling practice. An early study by FHWA (2004) surveyed 50STAs and found that 41(82%) of them allowed recycling concrete as aggregate, of which 38 states (76%) used RCA as aggregate base and 11 (22%) used it as aggregate for new Portland cement concrete (PCC). By performing an on-site review in five leading states, the study captured the most advanced uses of RCA in transportation projects,existing barriers to these RCA applications,and best practices to overcome these barriers.The main findings are summarized in Table 2. It can be seen that individual states usually had their own focuses, and developed and applied the coping strategies accordingly. In addition to the measures to address technical challenges, STAs had beenactively working with their state environmental protection agencies to lower regulatory burdens on concrete recycling.

INSERT TABLE 2 HERE!

Caltrans Division of Research and Innovation (2012) conducted another surveyamong STAs eight yearslater.The results showed that among 30 respondents, 87% of the states allowed using RCA in transportation projects. Specifically, 80% ofthe respondents had applied RCA in fill, embankments, or noise barriers, 33% of them had used RCA in non-structural pavement including sidewalks, curbs and gutters, and median barriers, and less than 10% of respondents applied RCA in bridge structures, revealing slow progress in expanding the use of RCA among states (i.e., 5% increase) as well as beyond the typical fill/base materialand non-structural concrete applications.

For properly characterizing old concrete and applying RCA in new concrete production, some state agencies have developed their own technical guidelines (New Jersey Department of Environmental Protection, 2010; ODOT, 2011). Additionally,standards setting bodies and trade associations have been continuously publishing and updating standards and making recommendations on the application of concrete waste, which can be readily adopted by state or local authorities. For example, American Concrete Institute's Committee 555 (2002) produced ACI 555R-01 to provide information on removal and reuse of hardened concrete, including the evaluation and process of waste concrete for producing RCA suitable for concrete construction.Portland Cement Association (2015) recommended no more than 30% of coarse RCA or up to 10-20% of fine RCA to be used in new concrete production to avoid any significant changes on concrete properties.American Society for Testing and Materials [ASTM] newly released a standard on recycling returned fresh concrete (i.e., ASTM C1798/C1798M) that incorporates the process, verification, and record-keeping procedures for recycling concrete. It was anticipated to help manufacturers better recycle returned fresh concrete and support sustainable concrete practices (CDR staff, 2017).

This review study noted that many state authorities had not created a one-stop resource center or clearinghouse to provide field practitioners with all the necessary information and resources available for C&D waste recycling in general and concrete recycling in particular. California, as a leading state in waste recycling, presents a good example of having a dedicated state agency—CalRecycle—to oversee the state's waste management and recycling programs, landfills, disposal operations and recycling facilities, and grants and loans. Its website serves as a clearinghouse for information and resources. On the specific webpage for recycled aggregate, educational materials, equipment information, a list of recyclers, RCA markets, specifications, etc. are made widely available to the public (CalRecycle, 2014). CalRecycle also makes a strong push toward sustainable design and green building, which also has the emphasis on waste diversion and use of recycled content products.

Questionnaire Survey Results

Six local, central Ohio companies involved in concrete recycling were interviewed face-by-face. The online survey link was sent to 56 and 99 concrete recycling practitioners in Ohio and California, respectively. Of them, seven Ohio companies and 10 California companies completed the questionnaire. Overall, the survey response rate was 14.3% (i.e., 23 respondents out of 161 invited participants). It is not uncommon to see low response rates in surveys involving the construction industry, e.g., 7.4% in Abdul-Rahman et al. (2006). On many occasions, a response rate of 15% was acceptable (Gibson and Whittington, 2010). This study combined all the collected questionnaires for data analysis because the two-tailed statistical tests showed that both states' responses to Part Two of the questionnaire were highly consistent, except for two difficulty items. It was noted that these two states, though geographically distant and categorized differently, shared some common ground in the landfill tipping fee, recycling market, guides from local government or public agencies, and availabilities of relevant specifications (CalRecycle, 2014; Ohio EPA, 2006, 2015). This suggests that the practitioners from different states may have similar viewsif facing similar external environments. Therefore, the sample could be representative of the concrete recycling practitioners in Ohio, California, and states with similar environments.

Background of Survey Participants

Fig. 2 shows the distribution of survey respondents' roles,industry sectors they served, and their involvement and practice in concrete recycling. Respondents were allowed to select all options that applied.

INSERT FIG.2 HERE!

The diverse roles played by survey participants can be seen from Fig. 2a.Whilemore than half (approximately 57%) of the surveyed companies served as a recycler/hauler,around 26%, 22%, and 17% of companies identified themselves as demolition companies, general contractors, and subcontractors, respectively. Additionally, around 26% of survey respondents playedother roles as building materials, construction waste management consultants, etc. The survey results also show that the same percentage (50%) of survey participants served in the building and roadway/bridge sectors. Some other sectors mentioned include recycling, demolishing, sorting procedure in landfills, and aggregates only.

Fig. 2b shows various sources of recyclable concrete the surveyed companies had handled. These include demolition of old structures (selected by 86% of survey participants), waste from site tests or leftover from pumping, over-order and design changes (32%), and others from infrastructure work, e.g., concrete roadways, bridges, barriers, parking lots, and dams (40%). When asked how their companies handled waste concrete, 91% of respondents selected "recycled" while only 14% selected "disposed to landfill." Those who picked "others" specified that they used waste concrete as aggregate in roadbase or for resale. This should also be considered one form of concrete recycling. Noticeably, some respondents chose both recycling and disposal as their ways to handle waste concrete, suggesting that they only recycled portions of concrete wastefrom their projects due to some reasons.

In terms of the usage of recycled concrete, the majority of respondents (77%) selected "backfill/road base," 23% selected "aggregate for new concrete," and 32% selected applications such as aggregate filling, sub-base, roadway and building pads, base/drain rock, etc. Survey participants were asked to estimate the percentage of each application. The backfill/roadbase usage ranged from 20-100% with an average value of 70%. The percentage applied to new concrete varied from 5-95%, with an average value of 30%. When asked to pick a typical range for concrete waste that was recycled in their previous projects, two and four respondents picked 0-25% and 25-50%, respectively, andthe majority (15 respondents) selected "above 75%." Although the findings show that the surveyed practitioners in these two states had relatively high involvement in concrete recycling(i.e., over 90% of respondents) and the percentage of recycled concrete used as aggregate for new concrete seemed to be increasing (ranging from 20-30%), the progress is still slow compared to two decades ago, not to mention when comparing with other leading countries or regions.

The background of surveyed individuals and companies is summarized in Fig. 3. It can be seen from Fig. 3a that the companies' experience in the concrete industry ranged from 3 to 83 years, with an average of 22 years. More than half of the companies (57%) had been involved in the concrete recycling business for over 20 years. Individuals completing the survey had relevant industry experience of 2-30 years, with a mean value of 16. The distribution of companies' years in business is slightly skewed and the distribution of individuals' industry experience is close to a normal distribution. Since around 80% of individuals had more than 10 years of experience, their perceptions should well reflect industry practice. The box plot for the size of surveyed companies is not available since this questionnaire only asked them to select a proper range for the number of full-time employees (e.g., 50-99) to ease the survey process. According to Fig. 3b, the participants represented different sizes of companies: approximately 80% were small and mid-size businesses (<200 employees) and 20% were larger companies (≥200 employees), compatible with the fragmented nature of the U.S. construction industry.

INSERT FIG. 3 HERE!

Practice in Concrete Recycling

This section consists of six questions. Table 3 displays the survey results. Of 23 U.S. companies surveyed, 85-95% of them had positive answers to three practice items, including P1) having concrete recycling policies, goals, and procedures, P2) having implemented one or more concrete recycling methods, and P6) having handled waste concrete as recyclable materials. However, only 33% of survey participants had employees participating in training or programs regarding concrete recycling, and only half of the surveyed companies had a specific concrete recycling division or department, showing some room for improvement. Since a higher percentage of companies (i.e., 74%) were planning to invest more resources in concrete recycling, advancements in recycling technology, equipment, and training may be anticipated.

INSERT TABLE 3 HERE!

Benefits Gained in Concrete Recycling

Eight Likert scale questions were designed to learn survey participants' perception of the benefits of concrete recycling. The survey results are shown in Table 4. The high mean values of these questions (from 3.71 to 4.32) indicate that the respondents had very positive and widely agreed upon views of the benefits gained by recycling concrete. Among eight items, B1) conserving landfill space, B2) saving natural materials, and B3) reducing project costs were deemed most positively.Respondents also agreed that concrete recycling can increase their overall business competitiveness and strategic business opportunities. With the elevatedenvironmental consciousnessamong practitioners and pro-environment market conditions, it is now a good time to advance the concrete recycling practice.

INSERT TABLE 4 HERE!

Difficulties in Concrete Recycling

In total, 19 Likert scale questions were asked regarding the difficulties in concrete recycling.

They were divided into four subcategories: high-cost investment, management skills, issues related to recycled concrete products, and lack of support. Table 5 displays the survey results.

INSERT TABLE 5 HERE!

Ten out of the 19 difficulty items had mean values falling between scales 2 "disagree" and 3 "neutral." This means that in generalsurvey participants did not deem these items barriers. They were confident about their management skills for recycling concrete. They also did not consider D10) and D11) related to thepoor quality of recycled products and their limited applications difficulties. This might be due to that in the U.S. waste concrete is mostly recycled into aggregates for road base, backfill, and non-structural concrete applications that do not have high quality requirements.The remaining nine items received the mean Likert-scale value between 3 "neutral" and 4 "agree." Except for D18) a lack of governmental awareness and support with an average score of 3.82,survey participants did not identify any other significant, widely perceived difficulty in concrete recycling. However, they had some minor concerns,includingD3) placingrecycling machine onsite,D1)the costlywaste sorting procedure, D12)an imbalance of supply and demand on recycled products, etc. Overall, the low awareness of these difficulty itemssuggests that there do not exist major barriers preventing field practitioners from recycling concrete waste in practice.

Recommended Methods in Concrete Recycling

The section of recommended methods forimplementing concrete recycling includes nine items. Table 6 displays the survey results. Survey participants gave high scores to R2) identifying and classifying various uses of recycled waste (4.15), R4) considering concrete recycling in design (4.10), and R3) developing techniques and the best management practices for recycling concrete (3.90). Actually, only two items in this section, R5) improving concrete recycling management in your organization and R6) providing in-housing training on concrete recycling, were not recommended. It seems that companies preferred external measures/support over their internal actions (i.e., organization management and employee training). They would like to receive more technical guidance on how recycled waste can be used specifically and design documents that have incorporated concrete recycling to facilitate implementation and lower their project risks.

INSERT TABLE 6 HERE!

The survey findings comply with previous field practices. For example, the Japanese concrete industry has established guidelines for applying both fine and coarse RCA in multiple civil and building applications, including the lower structure of bridges, reinforced concrete buildings, foundations, cast-in-place piles, etc. (Tomosawa and Noguchi, 2000). Japanese Industrial Standards (2005, 2006) further specify the classes of recycled aggregate to be applied in different types of concrete structures. All these measures contribute to Japan's 100% concrete recycling rate. In the U.S., although some guidelines and standards related to RCA applications have beengradually developed by state agencies (e.g.,ODOT Supplement 1117) and trade associations (e.g., ACI 555R-01), they may not be widely known by practitioners. Further, they are neither comprehensive to include various potential applications nor simple enough to implement. As indicated by National Concrete Pavement Technology Center (2018), contractors'unfamiliarity with the technical requirements or uncertainty of how the use of RCA will affect a specific application prevents recycled pavements to be used to their full potential. This explains why contractors would like to receive more technical assistance or prefer the use of RCA being incorporated into the design documents.

Besides the statistical results reported above, some feedback was garnered during the face-to-face interviews with Central Ohio contractors/companies.These practitionerswere either unsure of the application of recycled concrete waste, or their experience was limited to applying it to roadway or pavement as a backfill material. They also expressed concern about the quality of recycled concrete products. The feedback of interviewees wasconsistent with the statistical analysis results in that practitionersemphasized the need for external support to enhance concrete recycling (e.g., technical assistance and better managerial practice).

It should be noted that this study has some limitations. First, the perspectives from practitioners in Ohio and California may not be representative of the entire U.S. Therefore, survey targeting individual states especially those with below average SWM practice would be needed to provide more accurate and specific information for improving concrete recycling in these states. Second, whilethe review of waste management and concrete recycling policies and practices are current, the survey data was a couple of years old. However, considering that U.S. progress in waste management and concrete recycling has been slow over the past few years due to various reasons (e.g.,the Great Recession and laggingrecovery of the construction industry), the researchers expect that the practitioners' current views would be similar to that captured by this survey. Slightly more positive perceptions on the benefits of concrete recycling may be anticipated due to the active growth of the green building sector that outpaced overall construction growth in recent years (USGBC, 2016).

Recommendations

The survey results suggest that it is now a good time to advance concrete recycling in the U.S. due to the increased environmental awareness and more favorable market conditions, and there are no major barriers perceived by surveyed practitioners that prevent them from recyclingconcrete waste, except for a lack of governmental awareness and support as well as some other minor concerns. Based on the findings from this empirical study, the authors would like to make the following recommendations to help promote and expedite concrete recycling practice in the U.S. Since it is unlikely to make laws or create regulations purely for concrete waste management, many of these recommendations made to the federal and state authorities target C&D waste as a whole. Nevertheless, these recommendations could be readily applied to address the concrete recycling issues if desired.

First and foremost, the federal government will need to elevate its data reporting requirements on the C&D waste. A national database of C&D waste recycling and disposal information should be created. A data reporting system or mechanism will need to be developed to allow individual states to report their data on an annual basis based on separate waste streams (i.e., wood, drywall, concrete, etc.). It is noted that USEPA has been developing the Sustainable Materials Management tool. By aggregating recycling and disposal information across all 50 states, this effort aims to create a national data clearinghouse to allow for comparisons among states and regions (Calrecycle, 2016). Such an effort would enable the timely measurement of concrete recycling progress nationally, based on which the gap between the U.S. and other leading countries or regions can also be properly assessed.

At the state level, legislation and regulation need to be improved to better define, characterize, and categorize C&D waste and recyclable materials. For states that do not track C&D waste recycling data, they will need to develop a data reporting system and start collecting data from C&D processing facilities, recyclers, and haulers. It would be helpful if USEPA can provide a standardized C&D waste classification and quantification model for states to adopt, so that the scope of included recycled waste materials and the approaches to estimating the weight of generated C&D waste and recycled materials are more consistent across states to allow for a fair comparison. Also, it is necessary for state environmental agenciesto strengthen their role in C&D waste management.A statewide resource center or clearinghouse (including a web portal) should be created to provide comprehensive one-stop assistance. Besides offering both technical and financial assistance on C&D waste recycling to local governments, developers and builders, C&D processing facilities, and recyclers, state governments should also help develop the recycling markets for C&D waste. This will facilitate recycling and improve economics while offering other benefits such as creating jobs and contributing to a state's economy.

For states that have an urgent need to improve their C&D waste recycling rates, adynamic model can be developed to determine the proper level of landfill tipping fee given the targeted recycling rates, costs of recycling, and other factors or constraints that would need to be included in the consideration (e.g., additional financial incentives). In the literature, a simulation model has been developed for determining optimal levels of recycling and landfilling MSW in Finland, taking account of the physical costs of recycling, benefits associated with recycling, the environmental and social costs of landfilling, and consumers' environmental preferences. Thus, the recycling rate goals can be both economically and environmentally justified (Huhtala, 1997). A similar approach can be taken to determine an optimal recycling rate of C&D waste or concrete waste in particular for each state or municipality. This will ensure that the recycling rate goals set by state/local authorities are not too conservative or too aggressive.

Besides recommendations made to the governments, it is necessary for the industry to take a more proactive approach in concrete recycling as joint efforts by government and industry would speed up the progress. While the governments and public agencies create more effective policies and guidelines to enforce or encourage concrete recycling, the industry needs to improve its knowledge (e.g., taking more training, advancing technical standards to expand RCA applications, etc.), processes (e.g., increasing efficiency in waste recycling), and technologies (e.g., better equipment for waste sorting and onsite placement) and further lower the physical costs of recycling concrete. With the assistance of governments, trade associations, research institutes, and/or other organizations, the industry can investigate the feasibility and economics of constructing more concrete recycling facilities to reduce the transportation costs and alleviate the needs for placing recycling machines on confined job sites. The government agencies, trade associations, and educational institutions can also work with companies to develop and establish concrete recycling and training programs and to promote best management practices for improving efficiency, lowering costs, and addressing difficulties faced by practitioners.

While many federal agencies, state governments, and municipalities are adopting new approaches to procuring building materials and services, the construction industry is obligated or actively utilizes these opportunities to improve waste management practices. For example, due to the mandatory adoption of the Leadership in Energy and Environmental Design (LEED) Green Building Rating Systems by many public agencies and state/local governments, contractors involved in LEED projects may be required to divert C&D waste and employ recycled content products for achieving LEED points. Hence, the potential for recycling concrete waste or using products made of recycled concrete is increasing. In addition, the selection of subcontractors with design-build or in-house fabrication capabilities is often preferred in the procurement of green building to help minimize waste and increase waste recycling rates.Bossink and Brouwers (1996) identified the lack of contractor influence and construction knowledge in design as a major cause of waste generation. This suggests that contractors also need to be actively involved in the design process to provide insights into waste minimization and recycling.Thus, the increasing use of advanced project delivery methods including Construction Management at Risk, Design-Build, Integrated Project Delivery, and Design-Assist(America Institute of Architects, 2007; Andre, 2012), which allow early contractor involvement in the project design process, may help incorporate concrete recycling into the design documents. This research recommends jointly promoting green building and advanced project delivery methods by government and industry to improve concrete recycling.

Conclusion

This empirical study provided an updated understanding of concrete recyclingin the U.S. in terms of legislation, regulation, and practice. Specifically, the SWM regulations and practices in 46 states/district were investigated and grouped into three categories with most states having average to below average practice and with greaterneed for improvement. Compared with the leading countries or regions in waste management, overall the U.S. has a comparatively higher landfilling rate, and more C&D waste ends up in landfills. This study found inadequate state legislation and regulation on C&D waste (e.g., classification of C&D waste) and a lack of a data reporting system to measure the progress of C&D waste recycling in general and concrete recycling in particular.

This study chose Ohio and California (two states representing average and advanced SWM practice in the U.S., respectively) for the questionnaire survey of field practitioners in concrete recycling. The survey results revealed that the respondents had positive and consistent perceptions on items regardingcompany policies on concrete recycling,benefits, and recommended methods. However, most surveyed companies had neither offered in-house training for their employees nor formed specific recycling departments/divisions in their organizations. With respect to the recommended methods for concrete recycling, companies weighted more on the external influence/support from the government, effective communication among parties, and technologies to improve concrete recycling. They did not identify any significant difficulties or barriers to concrete recycling except for a lack of governmental awareness and support that was deemed the major obstacle.

As disclosed in this paper, concrete recycling legislation, regulation and practice in the U.S. vary largely by states. Nationwide, there is a huge room for improvement in various areas including data reporting, concrete recycling rates,applications of RCA, etc. Due to the increased environmental awareness, a stronger economy with improving market conditions, and less difficulties faced byindustry practitioners, it is now the right time to advance concrete recycling in this country.While governments should strengthen their legislation, function, and support, the industry also needs to be more proactive in advancing knowledge, improving technologies and processes, and implementing training and development programs.

The primary contribution of this research is to providean updated understanding of U.S. concrete recycling legislation and practice, based on whichvarious coping strategies are proposed forgovernment and industry to make joint efforts to accelerate the progress. Although this study focused on the U.S., the issues identified may be seen in other countries or regions. The recommended strategies may also be applicable beyond the U.S.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request.

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Appendix: Questionnaire for Concrete Recycling

Background and Experience in Concrete Recycling

1. Has your company received inquiries regarding recycling of concrete?
2. What generates the potentially recyclable concrete? a. Demolition of old structures; b. Road and bridge projects; c. Waste from site tests or leftover from pumping, over-order, design change; d. Others (please specify).
3. How do you deal with the potentially recyclable concrete as mentioned above? a. Disposed to landfill; b. Recycled; c. Others (Please specify).
4. Please provide the typical range of concrete waste that is recycled in your previous projects. a. 0-25%; b.25-50%; c.50-75%; d. Above 75%; e. Other range to be specified.
5. What is the recycled concrete used for (please also estimate the percentage)? a. Road base __%; b. As aggregate for producing new concrete__%; c. Others (please specify the use and its percentage)_________.

Perceptions in Concrete Recycling

Please answer the multi-choice questions related to practice, benefits, difficulties, and recommended methods for implementing concrete recycling.

Options will be Yes, No, or N/A (i.e., have no idea) for questions below.

1. Practice in Concrete Recycling:

- Does your company have policies, goals, and procedures for concrete recycling?
- Has your company implemented any concrete recycling methods to achieve the stated policy or other requirements (e.g., LEED)?
- Does your company have a specific division/department for concrete recycling?
- Has any employee in your company participated in training or program(s) regarding concrete recycling?
- Is your company planning to invest more resources in concrete recycling?
- Has the waste concrete in past projects been handled as recyclable materials?

Options for the questions below will be 1-5 scale (1: strongly disagree, 2: disagree, 3: neutral, 4: agree, 5: strongly agree, N/A: have no idea).

2. Benefits Gained in Concrete Recycling:

- Conserving landfill space and reducing the need for new landfills
- Saving natural materials
- Reducing project costs by using recycled materials
- Saving the cost of transportation between sites and landfills and tipping fee compared with recycling
- Increasing overall business competitiveness and strategic business opportunities

3. Difficulties in Concrete Recycling:

- The industrial waste sorting procedure is costly.
- Transportation is costly from sites to recycling plants.
- Placing recycling machines (e.g., crushers) on-site is difficult.
- The charge of hauling away recyclable concrete is higher than that of normal concrete removal.
- Recycling concrete increases labor and management costs.
- It is difficult to create a plan of actions for recycling concrete on a specific project.
- Recycling of concrete increases workload, such as documentation, supervision, etc.
- Recycling of concrete changes the existing practice of company structure and policy.
- There lacks staff participation and training in concrete recycling.
- Recycled products are in poor qualities (e.g., reduced compressive strength).
- There are limited applications in using recycled concrete products.
- There is an unbalance of supply and demand on recycled products.
- There is insufficient research investment on concrete recycling products.
- There is a lack of support in technologies, resources, training, and competent staff for recycling concrete.
- Our clients do not ask for the use of recycled concrete.
- There are not enough concrete recycling companies.
- There is a lack of industry's awareness and support toward concrete recycling.
- There is a lack of government's awareness and support toward concrete recycling.
- There is a lack of certain regulatory standards regarding concrete recycling.

Options for the questions below will be 1-5 scale with 1 being least important and 5 being most important, N/A: have no idea.

4. Recommended Methods for Implementing Concrete Recycling:

- Comprehensive and accurate evaluation of concrete recycling
- Identifying and classifying various uses of recycled wastes
- Developing techniques and best management practices for recycling concrete
- Considering concrete recycling in design
- Improving concrete recycling management in your organization
- Providing in-house training on concrete recycling
- Effective communication on concrete recycling among all parties
- Government restrictions on concrete waste volume generated on site
- High landfill charge for disposing of concrete waste