Feasibility Analysis for Reclaim Device During Shotcrete Application

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Shotcrete application has proven advantages over cast-in-place concrete under many different situations. Ease of access, minimal formwork, and higher productivity are prime examples. Its uses have exponentially increased through technical innovations to improve the ready-mix, nozzlemen technique, application surfaces, and to ensure higher dependability of the equipment. Unfortunately, concrete waste is still one of the highest percentages of overall waste in the construction industry. Shotcrete rebound, the material that falls from the wall due to lack of cohesion during installation, has slowly been reduced due to ready-mix alterations over the years, but effective recycling processes have yet to be implemented. Concrete recycling plants have helped to re-route concrete waste from landfills, but they still increase time and money spent cleaning and transporting the material. In some cases, such as gunite solutions, the material cannot be recycled, and becomes waste once it comes in contact with the ground. Instituting reclaim devices underneath shotcrete nozzles will not only catch the rebounded material, but feed it through the main hose for re-application. Since this has never been implemented, initial feedback from industry professionals will set the tone for the marketing and feasibility of this potential product.

Key Words: shotcrete, sustainability, rebound, waste, ready-mix, recycled concrete, reclaim, material waste

Introduction

Over the past 100 years, shotcrete application has revolutionized the way the construction industry installs structural and non-structural concrete. The creation of the dry-mix "gunite" cement mix which blends with water at the end of the nozzle marked the first breakthrough in use of this method. As time progressed, more experimentation geared towards higher efficiency and potential cost savings lead to the rise of wet-mix solutions, which utilize direct concrete plant mixtures and allow for lower waste and ease on the nozzlemen. Generally shotcrete mixtures prove to meet the structural standards of cast-in-place concrete in both strength requirements and overall finish aesthetics, so in situations of limited overhead access and minimal site laydown shotcrete provides an advantage (Zhang 2010). Concrete placement on elevated decks where pump access is difficult, thickening of existing walls underground, and vertical walls with limited layout space are the most common circumstances where shotcrete application provides the most logical solution. Overall, this process saves on equipment costs of cranes, pumps and forms, and can often be easier to apply and finish to the owner's desired standards (Knowles Industrial Services 2014).

Even though pneumatic concrete placement has lead to increased efficiency for subcontractors and schedule and cost reductions for general contractors, it does not address the problem of dwindling material resources. Concrete and shotcrete are consumed at a rate of 11 billion tons per year, making it the most consumed material on Earth (Sawoszczuk 2013). We cannot sustainably continue this rate of extraction of mineral ore from the Earth, given its adverse impact to both the surrounding ecosystems as well as the underlying groundwater resources. Much of this material mined from the Earth ends up in a landfill, despite promising increases in the percentage of material that ends up recycled and reused (See Figure 1).

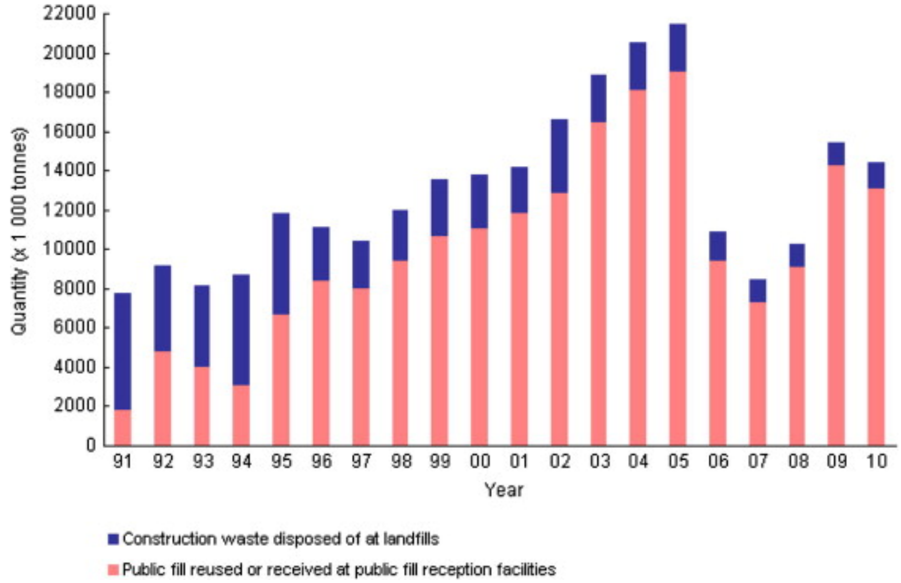

Figure 1 – Quantities of Construction Waste in 1991 – 2010
Source – Waste Management

We have three natural filters on Earth – the land, the ocean, and the atmosphere. The construction industry contributes to the degradation of these three big safety nets. Cement production is considered to be one of the most energy intensive processes in the manufacturing industry, and is responsible for 5% of total global carbon dioxide emissions (Rieder 2016). When LEED organizations analyze building practices for the owner and builder's accreditations, many of the points awarded stem from reductions in material waste streams and carbon footprint. Sustainable regulation organizations like LEED and Envision are still relatively new to the construction industry, and still have not yet influenced the wasteful practices in construction that have been ongoing for generations. There has been research geared towards reducing the overall usage of concrete in construction projects, yet waste as a percentage of overall material ordered is still relatively high. Further speculation into different methods of onsite concrete recycling will prove beneficial to the entire industry; specifically reclaim devices working in conjunction with the nozzlemen.

Innovations in Ready-Mix

Since its inception over a century ago, the shotcrete industry exhibited dramatic change in its early years with the shift from dry-mix to wet-mix methods, yet shotcrete application has since stagnated. Over the last 50 years much of the effort towards increasing efficiency of shotcrete applications has been towards experimenting with various mix designs. This is either done through adjusting the percentages of traditional materials in the mix, or adding new composites into the final product. There are many factors that play a role in how much rebound falls from the substrate surface, including: the position of the application, angle of the nozzle, skill and expertise of the nozzlemen, air flow, impact velocity, thickness of layer, amount of reinforcement, and mixture design (Rieder 2016). Many of these factors are due to specific jobsite conditions and nozzlemen techniques, so only the mixture design can be controlled for the purpose of universal applications.

Concrete mix designs have changed over the years to address needs for higher compressive strength, faster or slower curing process, resistance to cyclical freezing and thawing, lower weight per volume, overall reduction in cracking, and higher percentage of recycled materials. Many of the admixtures recently introduced to address these problems also assist with improving the quality, efficiency, and sustainability of shotcrete application. When adjusting traditional mixes, varying levels of cement content, fly ash and aggregate size result in differences for both rate of rebound and pumpability. From a study performed in

Vancouver, researchers performed a gradation analysis of the in-situ and rebound material and found that the rate of rebound of all individual aggregate sizes is reduced with the greater cement content (Armelin 1997). Aggregate predominantly ends up as the highest percentage of rebound material that falls from the shooting surface, thereby confirming why a higher cement ratio leads to less overall rebound. This is due to the difficulty of forcing aggregate through areas of dense wire mesh or reinforcing steel, which is common in high load bearing structural members. Using low density or lightweight aggregate with a proper gradation creates a mix with higher cohesiveness and penetration ability.

Introducing new elements into dry and wet shotcrete mix has proved effective in both maintaining the cohesiveness of the placed shotcrete, as well as reducing the need for cement, aggregate and sand. Adding metakaolin, an element found in clay and used to manufacture porcelain objects, has increased the cement efficiency as a binder. In a study performed to analyze potential greener concrete batches, the most benefit was observed in the mixtures containing 8% metakaolin and 100% Portland cement, improving the mix 43% for similar strength performance (Rieder 2016). This dehydroxylated form of clay not only increases the cohesiveness of fresh shotcrete, but also adds to the later-age strength development. The same study additionally looked into a pozzolanic based phenology control agent as an additive to the cement portion of their mix design, and found positive results for both strength performance and rebound rate. With the addition of TYTRO RC 430, the control agent, the cement content was reduced and the rebound rate was decreased from 20 to 5% due to increased cohesiveness (Rieder 2016). Higher compressive strength at early state of 6-8 hours differs from metakaolin, but allows for shorter cycle time during the application process. When looking into improving overall cohesiveness, silica flume acts as a glue-like substance to improve the stickiness of the ready-mix. It is typically added at 8-10% by mass of cement, and utilized most strategically in overhead installations. From the same study undertaken to determine aggregate gradation effects on compressive strength, silica fume was tested for any reducing effects on rebound. Figure 2 below shows the results from the controlled laboratory tests.

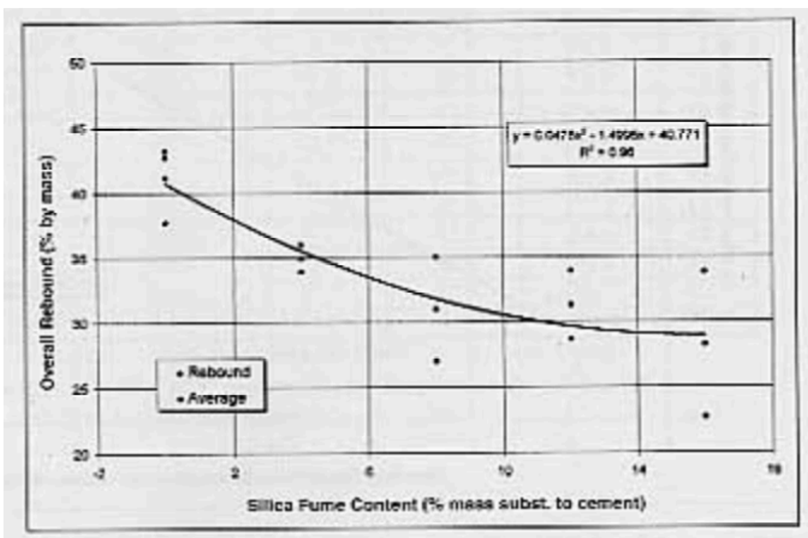

Figure 2 – Variation of Rebound with Silica Fume Content
Source – Rebound in Dry Mix Shotcrete

The tangent to the best fit trend line showed that the decrease in rebound was around 8% less for every 10% of silica fume substitution for cement (Armelin 1997). While these additives for ready-mix look to improve the efficiency of the shotcrete process by lowering rebound rates, concrete recycling plants minimize the amount wasted sent to landfills

Recycling Procedures

Almost all shotcrete waste, with the exception to gunite mixes, is transported to a concrete recycling plant, so that the material may be washed, separated, and re-tumbled into new batches ready to be reused. Thin membranes or substrates will line the ground surface for rebound catchment, and as the nozzlemen shoot throughout the day, the wasted material is collected and sent to an onsite dumpster that will be transported to the plant. This method allows for LEED credits on overall recycled material content, which is becoming more challenging to meet every year. Although this process may seem practical, improvements still need to be made. Transportation of waste materials to and from the recycling plant increases the carbon footprint, and the various processes taking place during the recycling process utilize vast amounts of energy, further adding to the carbon footprint. Cement, due to its hydrating reaction when in contact with water, cannot be recycled, so this portion of the mix ultimately goes to the landfills. There has been little to no research performed for different methods of shotcrete recycling.

The author has created a conceptual rebound catchment device attached to the underside of the shotcrete nozzle, equipped with a secondary hose for suctioning material that falls from the application surface. It proposes a pioneer solution to not only improve the recycling process, but also saves the owner both time and costs. Figure 3 shows the physical attachment to the underside of an existing shotcrete nozzle, as well as the estimated size and reach of the catchment device or "net".

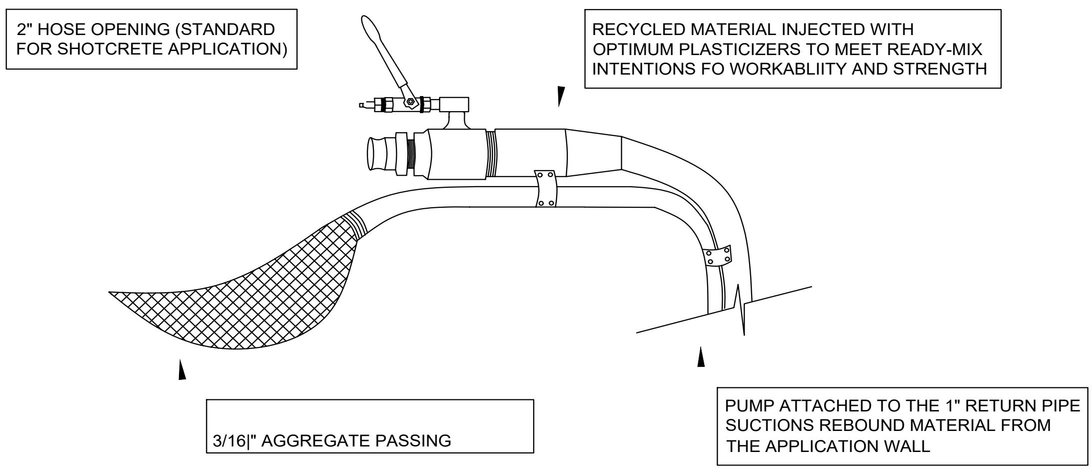

Figure 3 – Conceptual Design for Reclaim Attachment to Shotcrete Nozzle

Having the ability to ensure all concrete ordered would be fully utilized can reduce labor costs of cleanup, allow for more accurate estimates for material purchasing, and shorten the duration of applying shotcrete. Since the industry is relatively slow to adopt change, initial feedback on this design is necessary to determine what challenges it might present for both nozzlemen and jobsite managers.

Methodology

The methodology the author chose for this paper mainly involves analyzing the qualitative data received through numerous interviews of three concrete superintendents and three shotcrete nozzlemen. In addition, observations from ongoing projects managed by Nibbi Concrete and Paul's Concrete Company provide insight and context for best-case situations for maximizing onsite-recycling techniques. Stemming from the formal and informal interviews, the author compiled both the similarities and differences in feedback regarding the value of an onsite form of recycling shotcrete. The varying perspectives offered by all those interviewed will help depict how the industry feels as a whole towards this novel product, and any constructive feedback will determine whether a reclaim device is feasible in the field. With any new market idea, skepticism is always present. Both positive and negative criticism will provide useful insights to address any design or implementation issues.

The main objective of the interviews was to gain an initial understanding of the need the shotcrete or concrete industry might have for a new way to reduce waste during application processes. Since the proposed product is purely theoretical and conceptually designed, a feasibility analysis was not needed. Only firsthand reactions backed by years of field experience were analyzed to determine whether future experimental research towards designing this device would be of value. While monetary savings elicit the biggest interest from owners and builders, the potential for safeguarding the environment is what the author hopes to achieve. Even if a majority of the industry exhibits skepticism, initiating this idea provides a platform for other researchers or forward-thinking designers to focus their energy towards something universally beneficial.

Interviews

Qualitative data received from interviews with both concrete superintendents from Bradley Concrete and Nibbi Concrete and shotcrete nozzlemen from Nationwide Shotcrete and Cabrillo Shotcrete provided a comprehensive picture of initial industry sentiment. Everyone interviewed had an extensive history either performing shotcrete installation or managing the process on the jobsite. They all know the current state of the industry with regards to adopting new techniques, ultimately expressing that only large sustainable impacts have created reform in recent years. The interview method was semi-formal, with a mix of conversational topics and straightforward questions. Questions focused on the feasibility of actually equipping the recycling device to the shotcrete hose, installation methods where it would be most beneficial, possible struggles nozzlemen would have learning new technique, and whether or not they believed the benefits to outweigh the initial capital cost and training impact. Superintendents will be analyzed separately from the nozzlemen, showing different dispositions. Their varying views will provide diverse of insight towards specific areas that could benefit from more intensive research.

Shotcrete Nozzlemen

Interviewees ranged in experience from working on large commercial projects in the Bay Area to smaller and more diverse projects in San Luis Obispo County. Their diverse of backgrounds provided a similar eclectic spectrum of responses. Regarding the feasibility of attaching the recycling device to the shotcrete nozzle and using it effectively, both the employees from Nationwide and Cabrillo concurred that introducing another device to their equipment would not only increase the weight of the entire structure, but increase difficulty of shooting at certain angles and reduce overall mobility. Optimum airflow of approximately 300 cfm is found for the 2-inch internal diameter hose, which is industry standard for most shotcrete installations (Armelin 1997). They unanimously stated that this high pressure of 300 cfm shotcrete mix leaving the hose is extremely difficult to aim, and requires intense physical strength. Continuous shooting for an eight-hour workday puts intense physical strain on the nozzlemen, such that adding more weight would likely reduce productivity and accuracy. In areas of dense rebar, where structural columns will be poured or where the load-bearing capacity is imperative, nozzlemen must shoot very close to the rebar cage in order for the aggregate to penetrate (Ballou 2009). This will be an issue if the catchment device restricts the ability to get in viable range.

Regarding specific jobs where the reclaim device would prove most efficient, nozzlemen working for Cabrillo Shotcrete believed there were very few instances where benefits would be substantive, but the Nationwide Shotcrete nozzlemen believed there was a market for such a product in downtown San Francisco. Contractors in this area strive for the most innovative techniques regarding green building and lean practices. In addition, large commercial projects order significant amounts of concrete for their foundation and exterior walls, so implementing a rebound reduction device could result in substantial cost and material savings. The nozzlemen that were skeptical of the entire system had only shot concrete on small retaining walls, residential renovations and pools. They were correct to assume that this recycling system would not have much economic benefit with regards to offsetting increased labor costs, but failed to recognize the impacts in other sectors of the industry. Regardless of their position as to the feasibility of using the recycling device, both nozzlemen agreed that in order to successfully implement this product onto construction projects, the economic benefits must be substantial. As Chris Halley, nozzlemen with Cabrillo Shotcrete stated, "implementing this practice would be like installing solar panels in your building – you only make this decision with the belief that a real payback is evident in your future." Many people in the shotcrete business have been implementing the same techniques for the past 30 years, and need strong proof of benefits to change something they know works.

Concrete Superintendents

This group of individuals works at Nibbi Concrete and Bradley Concrete, two prominent concrete subcontractors in the Bay Area. Their projects range from both structural and non-structural concrete installations for mixed use and commercial real estate buildings. Project costs range from $5 million to $20 million, which allow for extensive experience in large-scale building practices. Similar questions were asked of these superintendents to include a focus on management and business aspects. Overall, the superintendents were much more optimistic, seemingly due to their ability to visualize the "bigger picture." Superintendents work much more closely with the owners of the project and with management within their contracting company, so they are able to sympathize with factors other than just productivity or ease of application. They understood that it is owners and upper management within companies that would be enticed with a method of reducing waste and promoting material sustainability.

Even though every superintendent questioned had never performed shotcrete installation on any of their construction projects, they all have an extensive knowledge of the subject. They understood how labor intensive it is to hold and control the flow of shotcrete onto a surface, and that adding a secondary device to the hose would alter the balance of the entire hose structure, as well as increase its overall weight. In addition, the ability to continuously move the hose in circles (common application technique) would be hindered, as well as the ability to shoot at certain angles. Almost all agreed that productivity would decrease in every aspect, and labor wages would need to be increased for the additional training and more intensive work, but they also understood the benefits that would potentially offset these costs.

At the Nibbi Concrete project at the San Francisco International Airport, they are building a utility tunnel beneath the new terminal that is still in design. The walls of the tunnel are one foot thick, about 25 feet all, and will be entirely shotcrete. Nationwide is the shotcrete subcontractor, and implements a 10% waste factor when ordering shotcrete material. For maximum productivity, they strive to install around 100 cubic yards of shotcrete in a single workday, with about 13 to 15 workers shooting, working the pump, or troweling for the rough finish. With the cost of concrete estimated at around $150 per cubic yard in the Bay Area, there would be around $1500 in material savings if the recycling devices caught 100% of the rebound falling from the utility tunnel walls. These savings are shown in Figure 5 below.

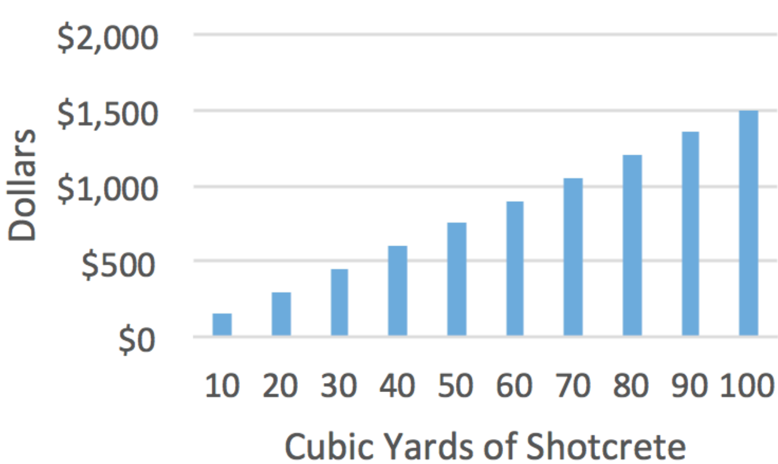

Figure 5 – Dollar Savings Per Cubic Yard of Shotcrete

This is the best-case scenario. The author believes the percentage caught would be anywhere from 60-80%. Throughout this process, there were 3 or 4 laborers continuously scraping fallen material into plastic sheets, which would then be carried off to a dumpster for transport to the closest recycling plant. These laborers would not be needed or could be performing other work on the jobsite if rebound material was completely recycled onsite. Eliminated costs of renting dumpsters or trucks to carry material offsite are secondary benefits. These cost savings would help offset the increased labor costs for nozzlemen and the potential for decreased productivity. There are many other factors that go into discerning the feasibility of this device, yet these are likely the biggest factors in determining its acceptance in the construction industry.

Disregarding the nozzlemen's feasibility towards this new method of installation, another difficulty mentioned by a few of the superintendents was the ability for inspectors to determine the exact measurements of material in the recycled rebound mix. The ready-mix supplied by the concrete plant is engineered to meet structural standards for certain aspects of the building, yet any rebound that falls from the surface of the wall is not the responsibility of the concrete plant. Historically, rebound is mainly composed of aggregate particles, which leads to significantly higher in situ cement content (Banthia 2016). If this is the case, much of the recycled material will increase the original ready-mix's aggregate percentage, ultimately contributing to layers of the shotcrete wall having high and low levels of aggregate. Possible filtering of the recycled material for equal distribution of aggregate into the original ready-mix would need to be implemented in order for inspector satisfaction, yet this design might be difficult to test in jobsite conditions.

It is easy to see that there are numerous initial design and implementation challenges, but that is always the case when new ideas are presented and tested. All of the superintendents interviewed knew that extensive research and experimentation would be needed before nozzlemen would accept learning a new method. Workers are generally inclined to obtain higher accreditation if compensated with higher wages. Likewise, if a practical design could be created, they would be very willing to adopt such a recycling device. The reduced costs for material and labor alone would have major impacts in owner satisfaction. The environmental benefits from reduced dependence on mineral extraction and a smaller carbon footprint support the future of green building. Superintendents are more inclined to see the bigger picture, so they can see the potential long-term paybacks.

Qualitative Analysis

It was important for the author to question and observe both sides of the industry – workers and managers – that would be affected by this product. As expected, the shotcrete nozzlemen were less inclined than the superintendents to adopt such a new technique. They are looking at this product from a feasibility and productivity standpoint, both of which would be hindered by this process. Many workers have been performing the same techniques for over thirty years, so in order for them to embrace change willingly, there would need to be substantial benefits for all parties involved. It will take some time for engineers to design the catchment device so that workers are minimally impacted, and can produce the finished product equal to or better than historical quality. Positive change must come from every facet of an organization, so potential users of this product must be willing and satisfied with its overall workability and functionality.

Superintendents (and management as a whole) held skeptic views at first, but eventually they began to see potential positive outcomes. Similar to the nozzlemen, they saw the difficulties with trying to maintain the same level of productivity with added weight and restricted movement, but believed that these negatives could be offset by a decreased need for cleanup labor and overall reduction in estimated waste material. In order for these offsets to prove fruitful, the design and engineering behind the product would need to be proven successful, as well as in the situations where they are utilized.

After the thorough interview process, it is best believed that implementing such a reclamation device would only deem worthy during the installation of certain shotcrete structures. Large commercial or heavy civil projects that require sizable amounts of shotcrete (minimum of 200 cubic yards) would have the greatest return in material savings. Within those types of jobs, large uniform vertical walls with minimal areas of dense rebar prove the most efficient application surface. These projects would likely have the ground beneath the application surface not allow rebound material to comingle. Lastly, even though gunite dry-mix is not as popular today as it was 50 years ago, its rebound waste factor of 20-30% suggests that project using this material can implement the reclaim device in numerous situations. Figure 5 below provides an example of ideal conditions.

Figure 5 – Shotcrete Application on Commercial Foundation

Conclusion

Since 1909 when Carl Akeley first introduced shotcrete applications as a new form of building structural systems, the road toward innovation has been both fast and slow. Methods for improving the strength and finish qualities of the mix have been a continuous process, yet research geared towards eliminating its material waste is still needed. The author's suggested onsite recycling device aims to create huge strides towards reducing material waste and saving both time and costs for the client. Initial feedback from concrete superintendents and shotcrete nozzlemen showed that comprehensive research towards improving the design and engineering of the device is needed to mitigate reductions in equipment weight, allow for close proximity to rebar, and maintain full mobility of the hose for any angle required. If this can be done, the industry will be quick to adopt this product, starting with more progressive contractors and owners, and then filtering through to the mainstream contractors. LEED credits will not play a huge role in promoting this type of onsite recycling, for owners already receive these credits from sending their building waste to recycling plants. However, they will promote the newfound principles of lean construction and green building, which has many marketable advantages. The past decade has seen tremendous strives towards building with a sustainable mindset. The industry is well positioned to support more research to further this conceptual idea. Once it is recognized in the industry as a viable and efficient option during shotcrete installation, standards for rebound waste and overall application methods will likely rise and face more stringent guidelines.

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