# An Approach for Improving the Sustainability of Shotcrete

By Ezgi Yurdakul, Klaus-Alexander Rieder, and Diego Granell Nebot

According to the World Commission on Environment and Development,[1] sustainability is defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." Based on this definition, it is clear that the construction industry is showing weakness on sustainability because cement production is one of the most energy intensive of all manufacturing industries[2] and it contributes 5% of total global carbon dioxide ($CO_2$) emissions,[3] as shown in Fig. 1. These numbers are more drastic in the United States as a result of being the third largest cement producer in the world.[4]

With the increased rate of industrialization and urban development globally, construction business is significantly growing, which further increases the demand on cement production followed by higher energy consumption and $CO_2$ emissions. In the last decades, the cement industry has already significantly reduced the amount of $CO_2$ per ton of cement produced by reducing the amount of clinker while maintaining 28-day strength. Considering shotcrete applications, where a typically high amount of cementitious materials are used and often 20 to 30% of batched concrete is lost during the spraying process as a result of rebound, there is certainly a need to improve the sustainability of shotcrete. Therefore, the aim of this paper is to propose a few methods for greener shotcrete with the aid of the latest advancements in chemical admixture technology.

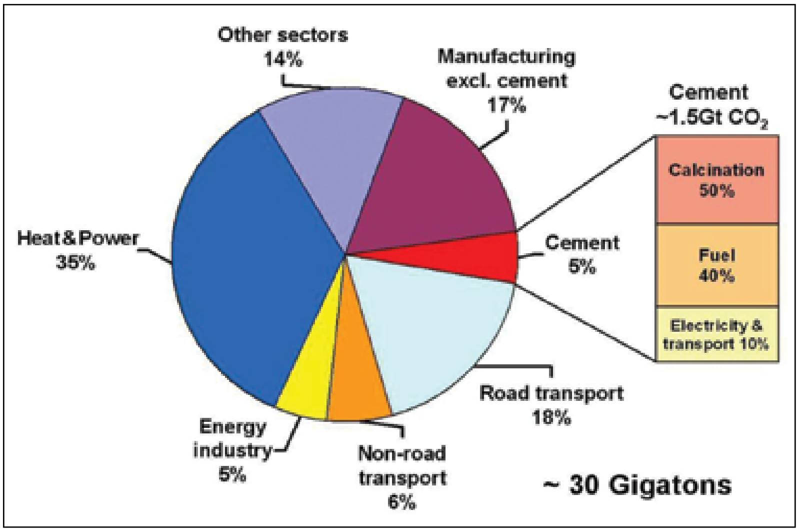


*Fig. 1: Global $CO_2$ production*[5,6]

## Proposal 1—Reduction of Cementitious Materials Content

The production of each ton of portland cement clinker emits approximately 1 ton (900 kg) of carbon dioxide. Therefore, in an era of global warming and climate change, either a reduction in the production or a more efficient use of carbon-intensive materials is desirable to meet the future needs of society. Although the production of structures that are highly sustainable is still challenging to accomplish, the industry has shown progress by motivating alternative solutions such as using recycled aggregates, binary and ternary mixtures with high levels of supplementary cementitious materials, and alternative binders with different chemistries with lower carbon footprints than portland cement.[7-10] Among all these available options, a simple approach for improving sustainability of shotcrete would be to use cementitious materials more efficiently without sacrificing the shotcrete performance. Furthermore, considering that cementitious materials such as ordinary portland cement and silica fume are the most expensive mixture components in shotcrete, minimizing the cementitious content will not only lead to a more sustainable method of shotcreting but also reduce the project cost.

Researchers[11] have studied the minimum paste content requirement for optimum pumpability in shotcrete, and found out that a minimum of 34.2% of real paste content is needed to achieve the desired pumpability (10.2% of paste is required to form a lubricating layer and 24% is required to fill the voids between aggregates). However, once the paste content of a mixture reaches an optimum value (which should be determined based on the desired pumpability, sprayability, durability, and strength requirements), the use of more cementitious material does not further increase the performance.[12,13] In fact, in some cases, excessive amounts of cementitious materials may adversely affect durability and shrinkage due to the increased risk of cracking.

## Outcome 1—Improved Shotcrete Performance

With the advancements in chemical admixture technology, it is now possible to replace a portion of cementitious materials with a pozzolanic-based rheology control agent (TYTRO® RC 430) to reduce the total cementitious materials content without compromising the performance. A recent study was conducted on a few shotcrete mixtures under laboratory conditions to assess the performance of mixtures containing 6 lb/yd³ (3.6 kg/m³) of TYTRO RC 430 to replace 56 lb/yd³ (33 kg/m³) of ordinary Type I portland cement in mixtures incorporating various supplementary cementitious materials, as shown in Table 1.

Early- and later-age strength results indicate that regardless of the binder type presence in a given mixture, the addition of 0.8% TYTRO RC 430 by weight of binder content was able to reduce the cementitious materials content by 7% and still achieve equivalent cylinder compressive strength at 28 days (Fig. 2). Furthermore, mixtures containing the reduced paste content supplemented with a small addition of TYTRO RC 430 pozzolanic-based rheology control agent provided higher strength at very early ages of 6 and 8 hours, which

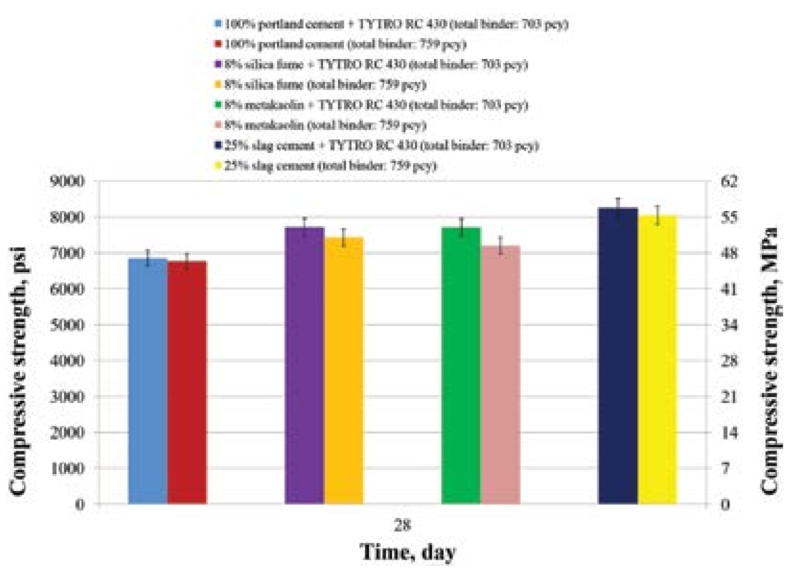


*Fig. 2: Comparison of 28-day cylinder compressive strength*

**Table 1: Mixture Design**

| Mixture components | Mix 1 | Mix 2 | Mix 3 | Mix 4 | Mix 5 | Mix 6 | Mix 7 | Mix 8 |
|---|---|---|---|---|---|---|---|---|
| ASTM C150 Type I ordinary portland cement, lb/yd³ (kg/m³) | 642 (381) | 698 (414) | 642 (381) | 698 (414) | 513 (304) | 569 (337) | 703 (417) | 759 (450) |
| Silica fume, lb/yd³ (kg/m³) | 61 (36) | 61 (36) | 0 | 0 | 0 | 0 | 0 | 0 |
| Metakaolin, lb/yd³ (kg/m³) | 0 | 0 | 61 (36) | 61 (36) | 0 | 0 | 0 | 0 |
| Slag cement, lb/yd³ (kg/m³) | 0 | 0 | 0 | 0 | 190 (113) | 190 (113) | 0 | 0 |
| Total binder content, lb/yd³ (kg/m³) | 703 (417) | 759 (450) | 703 (417) | 759 (450) | 703 (417) | 759 (450) | 703 (417) | 759 (450) |
| Water-cementitious materials content | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 |
| Sand-to-total aggregate, % | 68.4 | 68.4 | 68.4 | 68.4 | 68.4 | 68.4 | 68.4 | 68.4 |
| High-range water-reducing admixture: TYTRO® WR 157, % of total binder | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| Set-accelerator: TYTRO® SA 530, % of total binder | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Pozzolanic-based rheology control agent: TYTRO® RC 430, % of total binder | 0.8 | 0 | 0.8 | 0 | 0.8 | 0 | 0.8 | 0 |

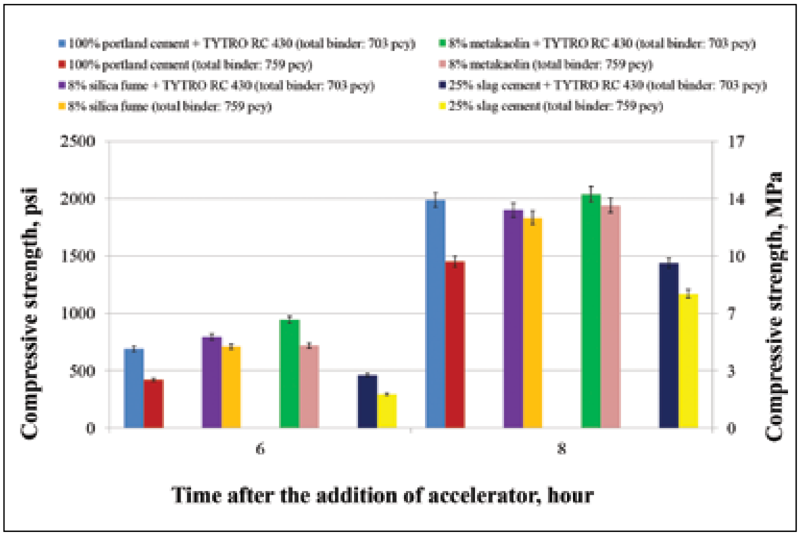


*Fig. 3: Comparison of compressive strength at early ages*

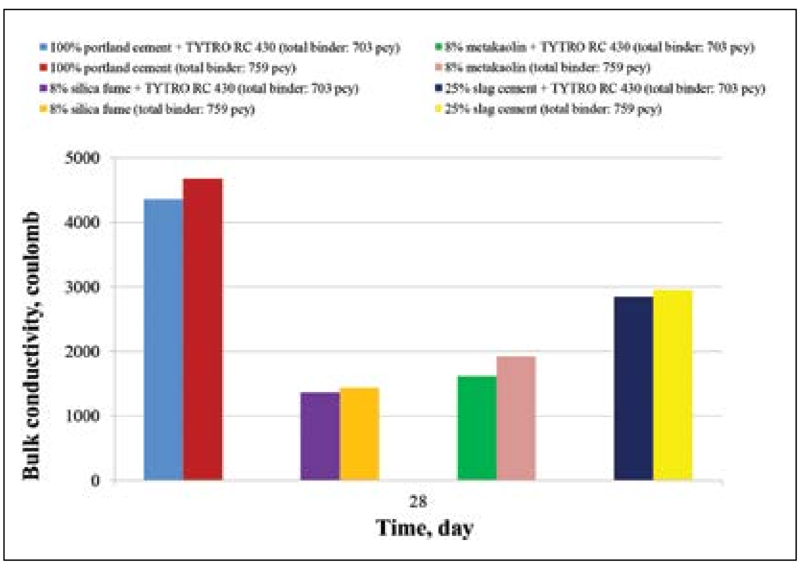


*Fig. 4: Comparison of bulk conductivity at 28 days*

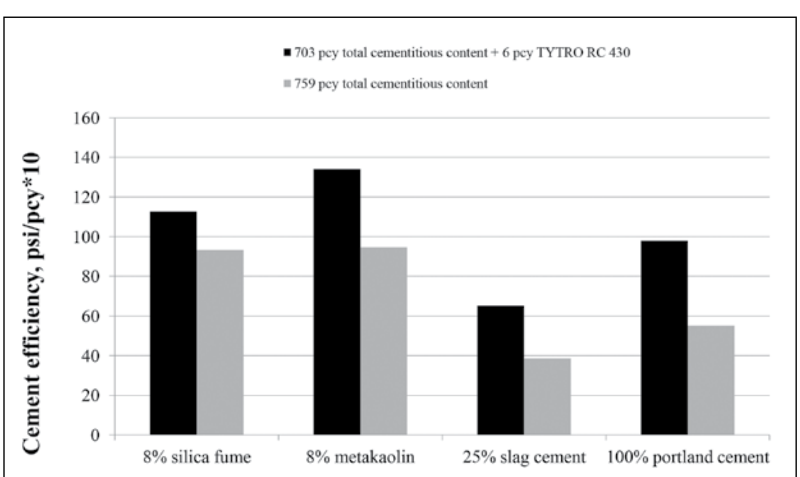


*Fig. 5: Cement efficiency*

is an additional benefit, as it would allow shorter cycle time for shotcrete applications (Fig. 3).

Longevity is an important parameter for sustainability, as it determines the service life of structures; therefore, durability aspects of the shotcrete mixtures were also evaluated. As shown in Fig. 4, mixtures with lower paste content (reduced by 56 lb/yd$^3$ [33 kg/m$^3$] of cementitious materials content that was supplemented with the addition of 6 lb/yd$^3$ [3.6 kg/m$^3$] of TYTRO RC 430) had slightly higher (or equal at minimum) durability compared to the mixtures having higher paste content. The improved durability of the mixtures with lower paste content is likely due to the impact of TYTRO RC 430 pozzolanic-based rheology control agent on improving the interfacial transition zone (ITZ) and reduced porosity. Furthermore, the impact of using supplementary cementitious materials such as metakaolin, slag cement, and fly ash is also significant on the reduction of the conductivity, which is consistent with what has been reported in the literature.

## Outcome 2—Increased Cement Efficiency

Based on the obtained test results, cement efficiency was calculated by dividing the strength at 6 hours per unit mass of total cementitious material content in a mixture. Figure 5 supports the findings discussed previously (that the addition of 6 lb/yd$^3$ [3.6 kg/m$^3$] of TYTRO RC 430 provided 32% more efficiency for the portland cement available in these mixtures than adding 56 lb/yd$^3$ [33 kg/m$^3$] of ordinary portland cement to achieve equivalent strength at 6 hours). The most benefit was observed in the mixtures containing 8% metakaolin and 100% portland cement, as the cement efficiency was improved as much as 43% for similar strength performance.

## Outcome 3—Reduced Carbon Dioxide Emissions

Because the production of each ton of portland cement clinker emits approximately 1 ton (900 kg) of carbon dioxide, reducing 56 lb/yd$^3$ (33 kg/m$^3$) of ordinary portland cement would result in a reduction of 0.033 metric ton $CO_2$. If this approach is applied on a middle-size project with a shotcrete production volume of 6500 yd$^3$ (5000 m$^3$), the carbon dioxide emissions of the project would be reduced by 182 tons (165 metric tons) $CO_2$ as a result of reducing the cement content by 7% with the addition of 0.8% of TYTRO RC 430 by total cementitious materials content.

**Table 2: Cost Comparison**

| Mixture component | Reference mixture | | Proposed mixture | |
|---|---|---|---|---|
| | Dosage, lb/yd³ (kg/m³) | Cost, %$/yd³ (%$/m³) | Dosage, lb/yd³ (kg/m³) | Cost, %$/yd³ (%$/m³) |
| Portland cement | 703 (417) | 45 (45) | 703 (417) | 45 (45) |
| Silica fume | 56 (33) | 22 (22) | 0 | — |
| Aggregates | 2865 (1700) | 33 (33) | 2983 (1770) | 34 (34) |
| TYTRO® RC 430 | 0 | — | 6 (3.6) | 10 (10) |
| Total | — | 100 (100) | — | 89 (89) |

### Outcome 4—Cost Savings

Considering that an equivalent performance is obtained with the reduced binder content, the proposed approach would not only be a sustainable but also a cost-efficient solution. A simple cost analysis was done to compare a mixture containing 56 lb/yd³ (33 kg/m³) of silica fume that was replaced with the addition of 6 lb/yd³ (3.6 kg/m³) of TYTRO RC 430. Table 2 shows the cost comparison between the reference mixture containing silica fume and the mixture with the reduced binder content. Because the cost of the materials varies based on the geographical regions, a relative comparison was done based on the percentage of US$ cost per a given material to produce 1 yd³ (0.8 m³) of shotcrete. Based on the comparison, at least 10% less expensive shotcrete production is expected in the mixture with reduced cementitious materials content accompanied with TYTRO RC 430.

## Proposal 2—Reduction of Rebound

Shotcrete has material loss due to rebound of aggregates because the concrete is pneumatically applied.[14] Although a certain percentage of rebound is inevitable and even necessary because a higher paste content is needed to create a sticky surface for subsequent shotcrete material to become compacted into the surface, it is desirable to keep the rebound to a minimum.[15] The rebound loss is affected by many factors, such as the position of the application, angle of the nozzle, skill and expertise of the nozzleman, air flow, impact velocity, thickness of layer, amount of reinforcement, and mixture design (for example, cementitious materials content, water content, size and gradation of aggregates, and type and dosage of admixtures). In many field applications, it is common to have a rebound rate of 20 to 30%. While high rebound rates are considered to be a waste of material, time, labor, material and removal cost, and a burden on environment, it should be noted that they also adversely affect shotcrete performance by increasing the tendency toward shrinkage cracking because the paste content of the in-place shotcrete is higher due to rebound, resulting in loss of aggregates.[16]

### Outcome 1—Rebound Reduction

To reduce rebound, a “sticky” and cohesive shotcrete is desirable, as it will exhibit a lower tendency to bounce off the wall on impact, thus providing a mixture with a better coating of the reinforcing bar surface and fewer voids than shotcrete displaying poorer cohesive characteristics. Considering a high volume of rebound material consists of mainly aggregate particles, paste stickiness and aggregate gradation play a more important role on rebound reduction than the amount of cementitious materials content as long as a sufficient amount of paste is used that would fill the voids between the aggregate. In other words, the “quality of paste” is more important than the “quantity of paste” for evaluating rebound characteristics.

According to the previous experiments conducted in the field, plain portland cement mixtures with a high cement content of 760 lb/yd³ (450 kg/m³) exhibited a rebound rate of 20% on average. However, when the cement content was reduced by the addition of TYTRO RC 430, the rebound rate was decreased from 20 to 5% due to the increased cohesiveness promoted by the pozzolanic-based rheology control agent.

### Outcome 2—Reduction of Carbon Dioxide Emissions

Carbon dioxide emission factors of various mixture components and construction activities are listed in Table 3.

**Table 3: $CO_2$ Emission Factor[17]**

| Activity | Emission factor | Unit |
|---|---|---|
| Portland cement | 0.8200 | t $CO_2$/1000 kg |
| Coarse aggregates | 0.0357 | t $CO_2$/1000 kg |
| Fine aggregates | 0.0139 | t $CO_2$/1000 kg |
| Concrete batching | 0.0033 | t $CO_2$-e/m$^3$ |
| Concrete transport | 0.0094 | t $CO_2$-e/m$^3$ |
| On-site placement activities | 0.0090 | t $CO_2$-e/m$^3$ |

**Table 4: Estimated $CO_2$ of Shotcrete Production**

| Activity | Dosage, lb/yd$^3$ (kg/m$^3$) | $CO_2$ emission, t/m$^3$ |
|---|---|---|
| Portland cement | 759 (450) | 0.3690 |
| Coarse aggregates | 905 (537) | 0.0192 |
| Fine aggregates | 1960 (1161) | 0.0161 |
| Concrete batching | — | 0.0033 |
| Concrete transport | — | 0.0094 |
| On-site placement activities | — | 0.0090 |
| Total | — | 0.4260 |

When the listed factors are applied to calculate the carbon footprint of shotcrete production, for a mixture containing 759 lb/yd$^3$ (450 kg/m$^3$) of portland cement, a total of 0.47 tons (0.43 metric tons) $CO_2$ emission is expected to batch, transport, and place 1.3 yd$^3$ (1 m$^3$) of concrete, as shown in Table 4. Therefore, for a project with a shotcrete production volume of 6500 yd$^3$ (5000 m$^3$), reducing rebound by 15% (from 20 to 5%) would result in reducing $CO_2$ emissions by 350 tons (320 metric tons).

### Outcome 3—Cost Savings

The reduction of rebound by 15% would result in providing more than 15% cost savings, as it would not only prevent 15% of the ordered concrete from being waste material but also save from efficiency of the operation and reduced labor time. Considering many shotcrete applications are composed of fibers, high-range water-reducing admixtures, and set accelerators, 15% cost savings due to rebound reduction would be significant.

## Conclusions and Recommendations

Based on the obtained test results, the following conclusions can be drawn:

- Performance—When the cementitious materials content was reduced by 7% with the aid of a pozzolanic-based rheology control agent, an equivalent 28-day strength was achieved compared to the mixture containing higher cementitious materials content. Furthermore, mixtures with lower paste content supplemented with the addition of TYTRO RC 430 had slightly higher durability and 15% lower rebound compared to the mixtures having a higher paste content. The cement efficiency was improved as much as 43% for early strength performance.
- Carbon dioxide emission—When cement content was reduced by 56 lb/yd$^3$ (33 kg/m$^3$), a reduction of 0.034 tons (0.031 metric tons) $CO_2$ is expected; and when the rebound rate is reduced by 15%, a further reduction of 0.071 tons (0.064 metric tons) $CO_2$ is expected for 1.3 yd$^3$ (1 m$^3$) of shotcrete production.
- Cost savings—When 7% silica fume is replaced with the addition of 0.8% of TYTRO RC 430 by total cementitious materials content, at least 10% less expensive shotcrete is produced. Furthermore, more than 15% cost savings would be obtained with the reduction of rebound.

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