Cement & Concrete: Where are we going?

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ABSTRACT

In 2014, the world used 4.2 billion tons of cement to produce approximately 12 billion cubic meters of concrete. As a byproduct, a similar amount of carbon dioxide (CO_2), 4 billion tons, was released into the atmosphere. This accounts for 5% of the total carbon emissions around the globe. The Paris Climate Change Accord has put renewed pressure on countries to reduce such emissions.

New approaches in the manufacture of cement and concrete could potentially help meet the goal of reducing CO_2 emissions. In this paper we explore alternatives to reduce emissions, some of which could be economically viable by saving energy, accelerating the speed of construction cycle, and making concrete structures more reliable. We believe that these concepts offer new, feasible and attractive avenues for the development of novel environmentally acceptable technologies in the area of cement–based materials.

Keywords: cement, concrete, carbon dioxide, trends, directions

INTRODUCTION AND BACKGROUND

It is not an exaggeration to say that our civilization is built on concrete. Just look out the window: Our buildings, bridges, tunnels, dams, and roads are built out of concrete. Its presence is ubiquitous because concrete is readily available, affordable, malleable and durable. Its extensive use and long history inspires the confidence of engineers and architects and makes it the construction material of choice.

The key raw material for making concrete is cement. Cement is made from limestone and clay, materials that are readily available and relatively inexpensive. A crushed mixture of limestone and clay is burned in a kiln at about 1500ºC releasing carbon dioxide and water; forming clinker that is ground to a fine powder we call cement, or more precisely, Ordinary Portland Cement (OPC).

It is estimated (Fig. 1) that by 2020 the global annual production of cement will exceed 5 billion tonnes. It is predicted to grow at a steady rate of about 3% per year, with the largest increases concentrated in the developing economies [1].

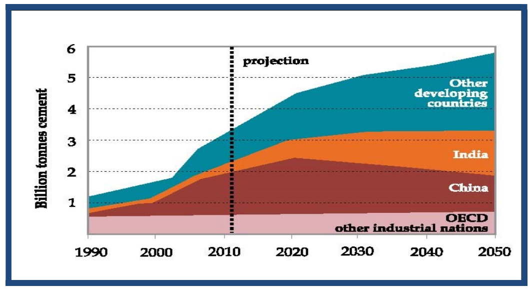

Fig 1: Forecast increases in cement production until 2050 (adapted from CEMBUREAU).

The challenge is that to produce one ton of cement, we release about the same amount of carbon dioxide. With about 5% of total man–made carbon dioxide coming from the manufacture of cement, this is a problem that needs to be addressed.

There are two principal strategies to address the problem of CO_2 emission from cement. The first is to develop innovative techniques to manufacture cement. The second is to find efficiencies in the use of cement during the production of concrete.

1. WHAT CAN WE DO ABOUT CEMENT?

1.1 Alternative Cements

An alternative to Ordinary Portland Cement must satisfy the following requirements:

- Is readily available and affordable
- Be environmentally benign
- Meets existing building practices and codes
- Has proven long term durablity

Two possible candidates that have been considered are calcium aluminate and calcium sulfoaluminate cements [2]. They are made with different ratios of calcium, aluminum, and sulfur. Both use less limestone and lower kiln temperature releasing much less CO_2 than OPC. Currently, these cements are used at a ratio of about 0.1% to all other cements. The primary issue is that they are 3-5 times more expensive than Ordinary Portland Cement (OPC).

Geopolymers (also called “soil cements”) made from clays, fly ash, slag and concentrated sodium silicate have also been considered as an alternative. Their use has been limited as they are prohibitively expensive, very sensitive to small variations in composition, and have unknown durability.

It is unlikely that in the next two decades any of the alternative cements will have a significant impact on the total use of OPC.

1.2 Improve process for making cement

Approximately 40% of the CO_2 released during the production of OPC comes from burning fuels, with the remaining 60% coming from the decomposition of limestone ($CaCO_3$) in the kiln. Over the years, the cement industry has learned to utilize energy at 70% of theoretical efficiency, very high for an industrial process of this type [3]. Since the industry is also using large amounts of waste fuels (up to 80%), there appears to be little potential to achieve meaningful progress in this arena.

Improving the process to make an improved product is another approach to consider. Grinding the cement finer exposes more surface area, making it more effective. Less cement would be required to achieve the same strength when making concrete. The problem is that the increased energy during grinding likely offsets any possible gains.

The third approach under evaluation is to change the process conditions. Lowering the kiln temperature by using chemical additives (fluxing agents) during the production of OPC leads to lower amounts of fuel utilization [2]. This approach negatively affects the properties of OPC and so far has been not been widely used.

All these avenues are being pursued currently and are likely to make some inroads, however we do not expect any of them to make a step-change progress in the reduction of CO_2 emission from the production of OPC.

1.3 Use extenders with cement

A number of materials have been successfully utilized as supplementary cementitious material (SCM). The most prominent example is fly ash: A residue from burning coal that is widely used to extend OPC. However, we are already using all fly ash suitable for this purpose. Decreases in coal utilization will further limit this approach.

Other supplementary materials include slag and volcanic ashes. Slag, a waste residue from steel manufacturing, works well as an extender. However, slag is only available at 5% of clinker, and we are using almost all that is available today already. Volcanic ashes are also limited in availability and have variable qualities limiting their use as extenders.

There is more promise in the recent work [4] coming primarily from Karen Scrivner's laboratories at EPFL in Switzerland. This work experiments with using calcined clays in combination with limestone to produce cement. The approach could allow for 50% replacement of OPC. The advantage is that the clay utilized is readily available in large quantities. More importantly, the calcination temperature of 700°C to produce the clay is significantly lower than the 1500°C needed to produce OPC. This reduces carbon emission and energy costs by burning less fuel than would have been used to decompose limestone. An additional advantage is that the approach utilizes the same equipment and processes that are used in cement production. There is more work needed to demonstrate the durability of such cements, but this is an area that calls for more involvement from the wider research community.

1.4 Capture CO_2 during cement production

A final option to reduce CO_2 emissions is to capture and store it. One option that should be technically feasible is to adapt technology from the LPG industry for transport. Also storage of CO_2 is already practiced by the Enhanced Oil Recovery processes. But, the costs for transport and storage will likely make it practically prohibitive for the cement industry. In absence of specific regulatory requirements this is unlikely to become dominant technology.

Capturing of CO_2 followed by bio-conversion to fuels seems like an attractive and elegant route. This approach calls for integrating algae-based bio-conversion plants that capture CO_2 released from the kiln and converting it into oil, essentially making the entire process carbon neutral. This concept warrants more attention from the cement and biotechnology scientists and engineers. However, the significant capital investment needed in this case could make this approach economically unacceptable.

2. WHAT CAN WE DO ABOUT CONCRETE?

Since the only use of cement is to make concrete, we can look to use cement more efficiently in the production of concrete to reduce the CO_2 emissions. To limit the use of cement, we need to find ways to make concrete stronger, use cement more efficiently, and make concrete more ductile, tougher, and bendable.

2.1 Make concrete stronger

Making concrete stronger increases its load bearing capacity. This allows for thinner supporting sections and results in the use of less cement without compromising the concrete's compressive strength.

Calcium-Silicate-Hydrate (C-S-H), the main product of OPC hydration, is the principal bonding agent in concrete. It is primarily responsible for concrete's compressive strength. Using nano-size particles of C-S-H as nucleation agents (seeds) can speed up the formation of C-S-H network and more effectively utilize the cement [5]. This increases the early compressive strength of concrete. Fig. 2 and Fig. 3 depict a schematic representation of this process. BASF has recently introduced new products (Master X-Seed) based on this concept. More research is needed to make such products economically viable, but it appears to be a fruitful direction.

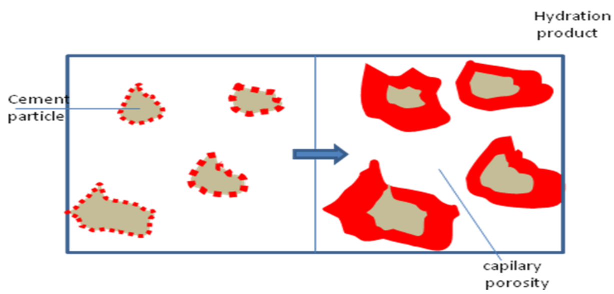

Figure 2: Hydration in a conventional system

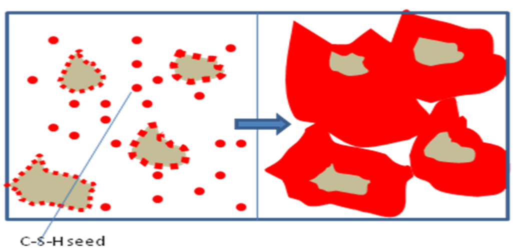

Figure 3: Hydration in the presence of nano-particles

2.2 Use cement more efficiently

At its simplest, concrete is formed by hydrating cement. But when you examine old concrete you quickly discover that about 20% of the cement has not been hydrated and is just serving as expensive filler. This is because when the cement is first hydrated, the surface of the cement exposed to the water turns into a water tight barrier. This prevents the remaining cement from being penetrated by the water and blocks the hydration chemistry from proceeding. Modern concretes use dispersing agents to mitigate this problem. While there have been significant and steady advances in this area, there is still plenty of room to improve on the efficiency of dispersing agents.

2.3 Make concrete bendable

Since Romans first made concrete about 2000 years ago, the brittleness of concrete has been its main shortcoming. Concrete's low ductility is primarily responsible for its propensity for cracking and compromised durability. Victor Li's research group at the University of Michigan [6] has pioneered tougher, more ductile concrete that has been coined as Engineered Cementitious Composites (ECC). Using the principles of micromechanics and fracture mechanics, Li's group has developed bendable concrete. See Fig. 4. It is a mixture of OPC, limestone, fumed silica, and small fibers without large aggregates. ECC has already been used in road expansion joints and in Japan for energy absorbing beams to reduce damage and to stabilize buildings during earthquakes. The EEC system is much more durable than conventional concrete, allows for less concrete cover, and it significantly reduces the possibility for catastrophic failure. ECC's higher initial cost is offset by lower lifetime expenditures.

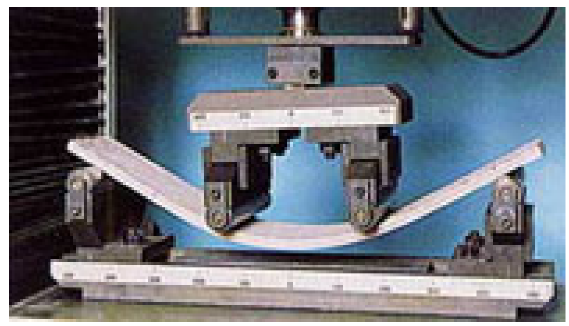
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Figure 4: Strain capacity for ECC: 2-5%.
Strain capacity for conventional concrete: 0.1%.

3. CONCLUSIONS & RECOMMENDATIONS

We have outlined a few approaches to reduce the carbon footprint of cement. Some promising ways to make the production of cement more efficient include the use of calcined clays and capturing and converting CO_2 into bio-fuels. Another way to attack the problem is to focus on efficiencies in the end product of cement – concrete. Here, the promising approaches are to improve concrete properties by making it stronger (nano-particles), develop more powerful dispersants, and elevate its ductility.

It is difficult to persuade the construction industry to adopt new technologies. To overcome the barriers and accelerate the adoption of novel technologies, attention to the following factors might help:

- Reduce the time to occupancy: Construction projects are invariably very expensive and any technology that shortens a construction cycle is an attractive candidate for adoption.
- Reduce labor cost: Since the construction process is very labor intensive, with labor representing typically over 50% of the overall cost, a technology addressing this issue is a welcome candidate for adoption.
- Increase reliability and ease of use: The inherently complex and intricate construction process will always

value reliable, fail-proof technologies that are easy and simple to use.

- Minimize the lifetime cost: Technologies contributing to a structure's durability, thereby requiring less maintenance, are valued by the owners, engineers and contractors.
- Reduce environmental load: The importance of this area is growing, and environmental concerns (i.e., LEED points) are starting to have a significant impact on the construction industry around the globe.
- Regulatory (building codes) compliance: This is of absolute importance for an adoption of new technology in the field of construction.

Our suggestions on the directions of efforts to limit the carbon footprint of cement are guided by methods that appear technically feasible. The success of these approaches would not only result in a significant reduction of CO_2, but would also improve the end products, enable new design possibilities, and create more durable and efficient structures.

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