After several important technical improvements, concrete made with Portland cement is probably the world’s most used man-made material. Global cement production in 1997 was 1.57 billion tonnes (Humphreys and M, 2002). That much cement, mixed with water, gravel and other substances, equals some 1.05 trillion tonnes of building materials to produce houses, office buildings, sewage pipes, dams, concrete roads, etc.

Cement production is widespread: plants are found in 150 countries (Marland et al., 2002), with China being responsible for roughly one-third of the total. Global cement production is increasing as consumption in developing countries rises between 1990 and 2000, production grew 55% in developing countries and 3% in the developed ones. Cement demand in 2020 is expected to be 120-180% higher than in 1990, with most of the growth in developing countries (Humphreys and M, 2002). The basic way to make Portland cement is to heat a mixture of limestone and clay – two largely available, natural, non-renewable materials – in a kiln at about 1500°C to produce cement “clinker”. After cooling, the clinker is finely ground and mixed with gypsum and, frequently, other finely ground materials such as fly ash and blast furnace slag to produce various commercial varieties of cement.

Cement production and the environment
The major global impact of cement production is global warming. Humphreys and M (2002) estimate that the cement industry is responsible for 3% of global anthropogenic greenhouse gas emissions and 5% of global anthropogenic CO2 emissions. About half the CO2 is released by limestone decomposition in the kiln – “cement process CO2” (Humphreys and M, 2002; Gale and Freund, 2000) – and the other half is due mainly to fuel burning (Figure 1).

CO2 release rates differ among countries, depending on a) production process, b) clinker content, c) energy efficiency in the calcination phase, which is responsible for 90% of energy consumption (Gale and Freund, 2000), and d) differences in fossil fuels’ carbon content. Old cement plants are less energy efficient and sometimes still use the wet process, which consumes 20-40% more energy (Gale and Freund, 2000).

Cement production also generates emissions of NOx, SOx, dust, dioxins, etc.

Blending materials
Mixing clinker with other materials, a process called “blending”, reduces CO2 emissions and increases energy efficiency during cement production.

Table 1 presents the most common blending materials. Fly ash (including from cement-making itself) and blast furnace slag are the types of waste most used in blending. Their use could be greatly increased except where local shortages exist.

Clinker content can range from about 95% (when only gypsum is added) to 5%. In the mid-1990s average clinker content was 88% in the US, 80% in Japan and 70% in Europe. The overall trend has been towards decreasing clinker content.

Recent research into new sources of blending materials has concentrated on waste from agriculture, industry and mining, including ash from burning lignocellulosic material (e.g., rice husk), fly ash slag from municipal solid waste incineration, paper mill sludge ash, colliemantite waste and ceramic waste.

Concrete and the environment
Concrete typically contains 8-15% cement, 2-5% water, about 80% aggregates (e.g., gravel, sand, limestone filler) and less than 0.1% chemical admixtures.

Despite its size, the 80% share of natural or recycled aggregates causes less than 3% of total emissions and energy use in concrete production (Vares and Hakkinen, 1998). Hence cement content and composition, as determined by engineers and architects, determine the concrete’s environmental load.

For a constant set of materials, the cement content is a function of the desired mechanical strength, production variability, service life requirement and concrete workability, along with the nature of the admixtures used.

Chemical admixtures can reduce the cement consumed for a given strength, or increase concrete workability, without increasing cement consumption. A modern concrete mix design, combining several aggregate grades with admixtures, produces a more eco-efficient concrete. M minimiz-

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**Table 1**

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
<th>Nature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blast furnace slag</td>
<td>Pig iron by-product</td>
<td>Waste</td>
</tr>
<tr>
<td>Fly ash</td>
<td>Coal combustion by-product</td>
<td>Waste</td>
</tr>
<tr>
<td>Silica fume</td>
<td>Silicon metal/ferrisilicon alloy by-product</td>
<td>Waste</td>
</tr>
<tr>
<td>Natural pozzolan</td>
<td>Volcanic ash</td>
<td>Natural</td>
</tr>
<tr>
<td>Burnt clay</td>
<td>Pozzolan calcinated at ~700°C</td>
<td>Industrial</td>
</tr>
<tr>
<td>Limestone filler</td>
<td>Ground limestone</td>
<td>Natural</td>
</tr>
<tr>
<td>Metakaolin</td>
<td>Kaolin (a special clay) calcinated at ~700°C</td>
<td>Industrial</td>
</tr>
</tbody>
</table>

Source: author
ing concrete production variability by using adequately trained personnel, carefully selected raw materials and more sophisticated proportioning and mixing equipment, as most ready-mix companies today can do, is also an effective way to reduce concrete's environmental impact.

When concrete is made on site by do-it-yourself home builders or small contractors, the above approaches are not viable. In Brazil, for instance, 68% of the cement sold is bought by building material dealers and used with little or no controls.

A large share of concrete used worldwide is reinforced with steel. In Brazil most steel rebars are made by recycling steel scrap in electric mini-mills. In countries where the steel for concrete reinforcement is often made from virgin pig iron, the environmental impact is higher. Steel's contribution to the environmental load of reinforced concrete is greater than that of the aggregates but much less than that of the cement.

Service life

Increasing the service life of concrete structures is a very efficient way to improve the eco-efficiency of the global economy. Service life can be dramatically extended with little or no increase in – or even a reduction of – the environmental load. Doubling the thickness of the concrete over the steel rebar from 10 mm to 20 mm, for instance, quadruples the service life of reinforced concrete, defined at the time it takes carbonation reach the rebar, but increases concrete consumption by only 5-10% (Helene, 1993). In marine environments, a high blast furnace slag or fly ash content can increase service life and decrease the environmental load.

At the end of its service life, most concrete can be recycled as aggregate or even in cement production. But because natural aggregate is usually cheaper, concrete is not extensively recycled except in a few European countries (e.g. the Netherlands). In Brazil, as in most developing countries, only local authorities run recycling plants processing concrete and other construction and demolition waste, and the resulting aggregate is generally used as road base. Additional recycling opportunities for such waste need to be investigated.

Making concrete a more sustainable material

Aside from some specialized applications such as the use of chalk or glue as mortar, there are currently no viable alternatives to clinker-based cement and concrete, and despite intensive research it will probably take decades to develop any. And while the technical options mentioned above, along with other technologies, can increase the sustainability of concrete and are available on markets worldwide, they are not always explored.

The first reason seems to be lack of knowledge or awareness on the part of professionals and authorities. With few exceptions, there is almost no technical reason to use cement with high clinker content, but many engineers and architects still prefer it. Designing reinforced concrete structures for an extended service life is a relatively new, often unfamiliar concept that needs to be refined and has not yet been incorporated into concrete design codes and standards, which sometimes set a minimum of cement consumption in structural concrete. Much effort is needed in the technical and environmental education of civil engineers and architects, and to change design codes and create incentives to use blended cement.

Other barriers are market based. Old, inefficient cement plants may still be competitive. Advanced admixtures can be expensive. Ready-mix concrete sometimes costs more than concrete produced at the building site, so DIY builders and small contractors often prefer the latter option. Here the need is to balance social sustainability with environmental sustainability.

Finally, concrete's sustainability must be judged in real situations. A generic life-cycle assessment approach that may work for more standardized materials, like plastics and metals, will seldom be adequate to evaluate concrete. There is a great need for more accurate and independent data about life-cycle loads of cement – and other building materials – especially in developing countries.

References


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