Carbon Reduction in Tunnelling

In this article, Benoit Jones investigates ideas to reduce carbon dioxide emissions in the tunnelling industry.

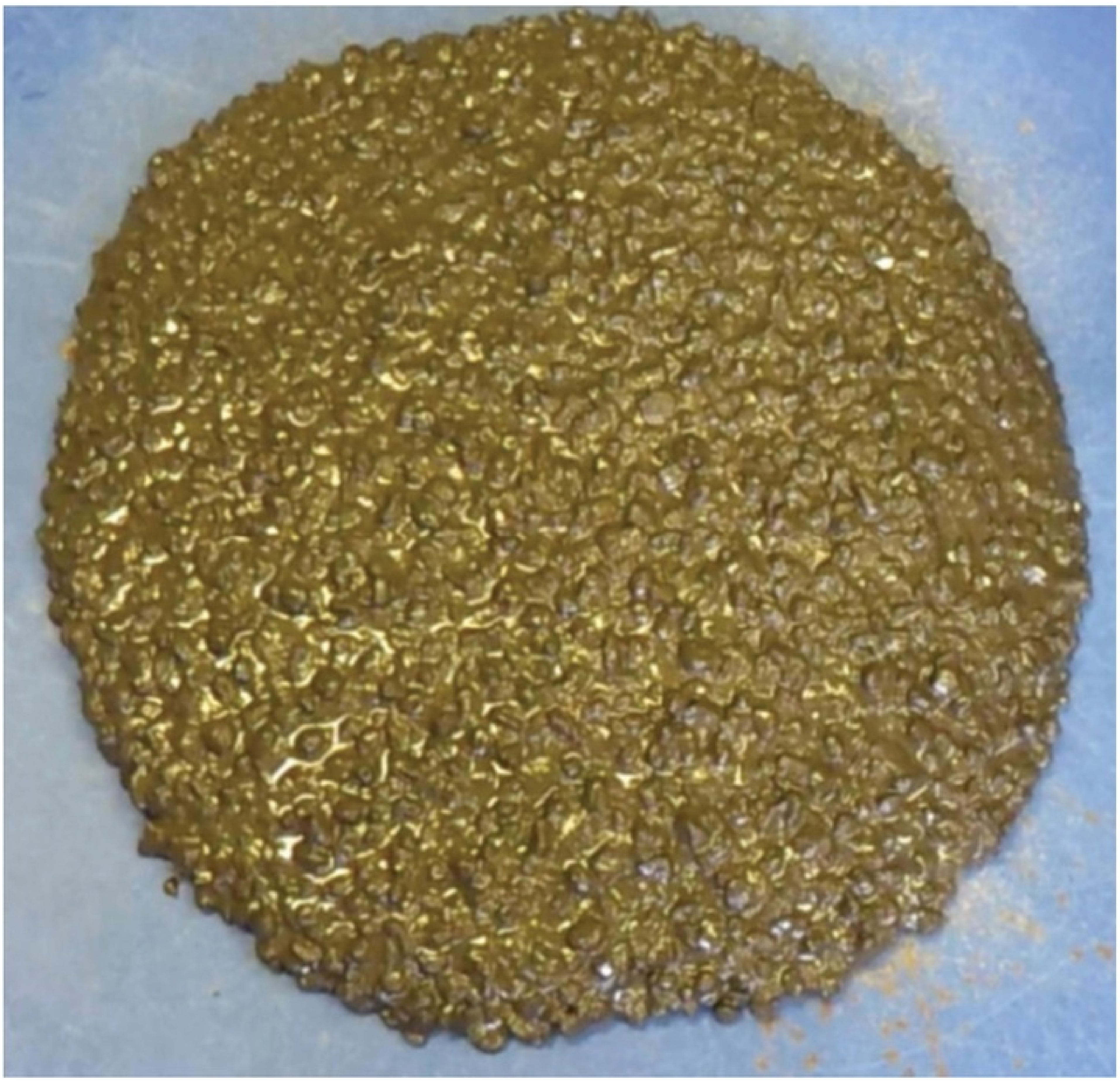
WE NEED TO INVEST in sustainable, durable and resilient infrastructure to maintain and improve quality of life, protect the environment and stimulate economic growth. At the same time, we need to drastically reduce greenhouse gas emissions to prevent catastrophic climate change. So what can we do in the tunnelling industry to reduce carbon dioxide emissions? Some innovative ideas will be presented in this article including reduction of Portland cement consumption, spoil reuse and automation.

Portland cement

The world used 3.6 billion tonnes of Ordinary Portland Cement (OPC) in 2012. Production of 1 tonne of OPC causes the emission of approximately 1 tonne of CO2, and OPC production is responsible for 5-7% of global CO2 emissions (IPCC, 2005; McLellan et al., 2011). Therefore, any measures to reduce OPC consumption will have a substantial impact on anthropogenic CO2.

There are several ways to reduce OPC consumption in a tunnel, which can be broadly summarised as follows:

- Use less concrete by efficient design or reduction of waste
- Use less OPC by reduction of cement content per cubic metre of concrete
- Use alternative materials instead of OPC-based concrete



Right: Flow test on a fly ash geopolymer concrete (Yeung, 2013)

In precast concrete, designs are usually highly optimised and often a large proportion of one or more cement replacement materials are used, such as pulverised fuel ash (PFA, also known as 'fly ash', a by-product of burning coal in power stations), silica fume (also known as microsilica, a by-product of silicon and ferrosilicon alloy production), ground granulated blastfurnace slag (GGBS, a by-product of steel production) or limestone powder. However, there may be scope to change the design of the tunnel lining if, for instance, the depth of overburden varies significantly along the length of the tunnel. Due to how the TBM (tunnel boring machine) is set up, it would be easier to achieve this by changing the mix design or quantity of reinforcement than by changing the lining thickness. If cement content is driven by factory production cycles and the need to demould at early age, or durability of the tunnel lining in situ, then perhaps void formers could be introduced to reduce concrete volume without reducing the thickness or the concrete mix specification.

For sprayed concrete, the need for early strength gain to meet the requirements of the design specification usually require a high cement content of 350 – 400kg/m^3. There may be ways to reduce this – for instance, strength is dependent on water/cement ratio, not cement content. So if the volume of water and cement in the mix are both reduced then the strength will still be approximately the same. However, this provides challenges for pumping, spraying and ensuring good compaction of the concrete, which in turn may affect strength and durability. To some extent these problems can be overcome by the use of superplasticisers to improve workability and a careful grading of the particles in the mix. Cement replacement in sprayed concrete mixes is also possible, and tests show that early age strength up to 6 hours is relatively unaffected by up to 25% cement replacement with PFA (Hallam, 2014). Another possibility is to use a different sprayed concrete mix where early strength requirements are less stringent, for instance in the invert of the tunnel or for portal slope protection.

There is usually a fair amount of waste when using sprayed concrete, of typically 1.8 to 2 times the theoretical volume on the design drawings. The most common causes of wasted concrete are overexcavation and then needing to fill that overexcavation with sprayed concrete, breakdowns of equipment resulting in the need to dispose of the concrete before it sets, and batching more than is needed. It is possible that automation of the excavation process may lead to better control of overexcavation in the future. Breakdowns can only be avoided to some extent through planned preventative maintenance, but concrete wastage can be mitigated by having backup pumps and spray robots on hand and by having a long pot life for the concrete using hydration control admixtures.

A more radical solution is to not use OPC at all. OPC causes a lot of problems after all: early age thermal cracking, shrinkage cracking and poor fire resistance. An alternative that is readily available, at least for precast concrete, is geopolymer. Geopolymer is a concrete-like material made, in its most common form, from an amorphous silica such as PFA mixed with some strong alkalis such as sodium silicate and sodium hydroxide. Unlike OPC concrete, water is not one of the active ingredients but is added to enable mixing. After mixing the amorphous silica in the PFA is dissolved by the alkalis and then the geopolymer gradually solidifies as polymeric mineral chains are formed. Its composition is similar to the geologic material feldspar, hence the name 'geopolymer' (Davidovits, 2002). The production cost of geopolymer is similar to OPC concrete, but its carbon footprint is 6 times lower.

Above: Photo-optical system for in-line characterisation of spoil - laboratory prototype for the DRAGON project (Galler, 2015)

It may not be possible to produce a sprayed geopolymer concrete, but certainly it is feasible for precast concrete. It has some challenges, such as the gradual loss of workability with time beginning almost immediately after mixing (which can be avoided through careful choice of admixtures), and the need to cure it at warm temperatures. In China, 80% of their energy comes from coal-fired power stations and so there are huge surpluses of fly ash and bottom ash that have to be disposed of in landfill. At the same time, China produces nearly 60% of global OPC production, mostly for China's internal market (CEMBUREAU, 2013). So geopolymer could both produce a more durable, less permeable, fire resistant concrete tunnel lining and find a use for massive amounts of ash that would otherwise be going to landfill. The cost of geopolymer has been estimated to be similar to that of OPC concrete (McLellan et al., 2011), so it is a sustainability win-win-win.

Spoil reuse

If spoil can be reused for concrete aggregate, industrial processes or as fill, instead of elsewhere quarrying or mining the materials, then this should save energy, and also obviate the need to dump the spoil somewhere. If the spoil can be reused on or near to the construction site, then even more energy may be saved in transportation.

As part of the EU's 'Europe 2020 strategy', one target is to reduce greenhouse gas emissions by 20% compared to 1990 levels. Since this target has pretty much been achieved by 2015 (European Environment Agency, 2015), they might try for 30%. There is also a plan to reduce emissions to 40% by 2030 and to 80% by 2050, which are both quite ambitious on current trends. One aspect of this strategy is 'resource efficiency', which will also, as is the case for most carbon reduction strategies, drive down costs, improve productivity and encourage growth. One of the projects funded by the EU under this scheme is the DRAGON project, which seeks to reuse tunnel spoil in the most streamlined and efficient way possible (Galler, 2015).The innovative idea is to analyse the spoil in-line, i.e. in the TBM itself as it passes by on the conveyor, in an automated way, without slowing or stopping the tunnel construction logistics. This also allows spoil characteristics to be compared to the geological model in real time and allows it to be sent to where it can be used best. It may also be separated using screens or crushed in the TBM's backup to achieve a target grading for reuse.

Automation

Rio Tinto's 'Mine of the future' programme should create the world's first fully automated mine in the next couple of years. Competitors such as BHP Billiton are soon following suit. How long before we have fully automated tunnels? We are already part way there, with semi-automated shotcrete spraying (can manage constant thickness but not constant profile yet), automated drilling, and surveying systems that can set themselves up and create a 3D point cloud of an underground space. TBMs can be remotely controlled, as microtunnelling machines have been for years.

There are potentially large gains in productivity and accuracy to be gained from automation, as well as cost savings, but the biggest gain would be health and safety. Automation removes soft human beings from 'interactions' with heavy hard plant. Concerns about noise, dust and emissions inside a tunnel would go away if no-one had to enter during construction. Similarly, robots wouldn't mind going straight in after blasting.

So how can automation produce resource and energy efficiency savings? One way is through big data. Either by humans analysing the data or by using machine learning algorithms, the operations can be finessed. If a few percent improvement can be achieved in multiple areas, this will result in a significant increase in productivity.

Conclusions

Some ideas for carbon reduction in the areas of cement consumption, spoil reuse and automation have been discussed and it seems there are existing and emerging technologies that will enable huge reductions in CO2 emissions if we adopt them. Perhaps clients should consider rewarding contractors based on CO2 emissions targets rather than target cost, because it seems that most carbon reduction strategies will also reduce cost and it may help collaboration to have a target everyone can work towards that isn't money.

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