Steve Huckle, Student No. 1050565 **11/07/2011**

How Best to Increase the Sustainability of Modern Binders?

Module CEM 152 focused on environmentally responsive materials. Stafford Holmes gave a lecture in which he introduced cementitious binding agents. This paper looks at the sustainability of such binders. Knowledge of the difference between mortars, renders and plasters is assumed as these terms are used without explanation.

This paper does not investigate the reasons for Portland Cement production being much greater than that of lime. Neither does it suggest the means by which this situation could be reversed. What it does do is suggest that it would be in our interests to reverse the situation because in many circumstance, lime provides a far superior solution to that of cement. Particularly when lime has such good environmental credentials (when compared against cement) and the world is facing uncontrollable climate change.

A History of Cementitious Binders

Cementitious materials were widely used in the ancient world; the Assyrians and Babylonians used clay as a cement (Bellis 2011) and the Egyptians used calcined gypsum. The Greeks and Romans heated limestone to produce lime, which they added to sand and coarser stones to make mortar and concrete. The Romans also added crushed volcanic ash from the village of Pozzuoli, near Vesuvius, to make "pozzolanic" cement (Winter 2011) and the term “pozzolan” is still used today to refer to materials added to cements to enhance its properties.

The History of Portland Cement

In 1824, an English bricklayer called Joseph Aspdin patented a process of manufacturing hydraulic cement, a powder like substance that is mixed with water and that dries to produce a strong, stiff material useful for structural purposes. This involved carefully prepared proportions of pulverized limestone and clay that were then burnt and ground into a powder. Aspdin thought that that the colour of the finished product resembled that of the stone quarried on the Isle of Portland, and so he gave it the name “Portland Cement”. However, it was not until 20 years later that the Portland Cement industry began to take-off, when J. D. White and Sons set up a cement factory in Kent. By the early part of the 20^{th} Century worldwide annual production was 40 million tonnes (Quillin 2001). By 1970 this had reached 594 million tonnes and in 2005 it was up to 2284 million tonnes, when 98% of the cement produced in the United States was Portland Cement (Buckley 2001). Annual cement production is forecast to continue rising, reaching 4.5 billion tonnes by 2050 (Quillin 2008).

Manufacturing Portland Cement

Portland Cement is still manufactured using the same basic principles as in Aspdin's day but four key manufacturing processes have been developed; wet, semi-wet, semi-dry and dry. The dry process is the most efficient of these; it typically involves blending 80% calcium carbonate ($CaCO_3$), in the form of limestone or chalk, 17% shale and 3% sand. This mix is preheated to 750^{o}C and 900^{o}C before it reaches the main rotating kiln that is heated to 1450^{o}C (Lyons 2007). This produces cement clinker (hard lumps of cement that are 3-25 mm diameter) which is then mixed with additional materials such as Gypsum ($CaSO_4 \cdot 2H_2O$) before being ground to produce the consumer product – Portland Cement.

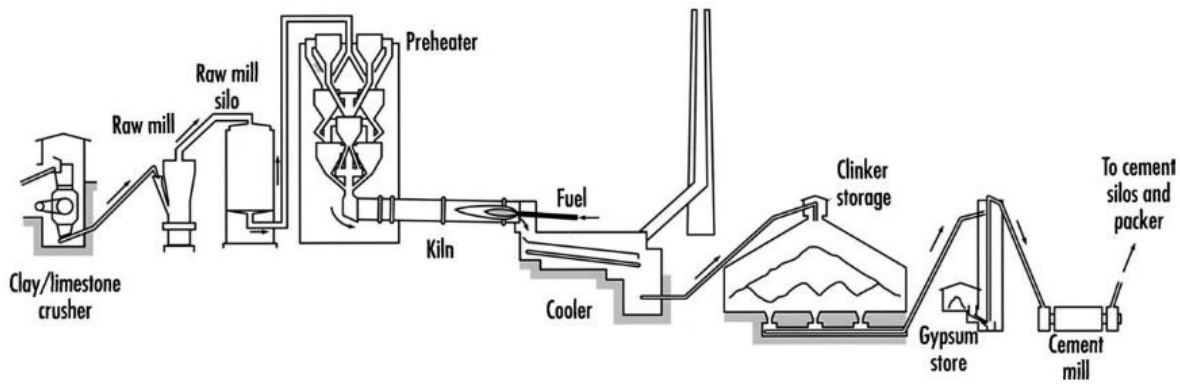

Figure 1 – The dry process for manufacturing Portland Cement (Lyons 2007)

Portland Cement Production and its Environmental Impact

The manufacture of Portland Cement is energy intensive due to the extreme heat needed to produce the clinker; it requires about 3 GJ of energy to produce a tonne of clinker for modern dry process kilns, upwards to 6 GJ per tonne for inefficient wet process kilns (Quillin 2008). Embodied energy refers to the total primary energy consumed and normally includes the extraction, manufacturing and transportation (GreenSpec 2010); for UK standard Portland Cement with a composition of 94% clinker and 5% gypsum, the energy used at the kilns contributes to an estimated embodied energy of 5.5 MJ per Kg. In addition, cement also releases large amounts of CO_2 into the atmosphere; this type emits approximately 0.95 Kg CO_2 per Kg (Jones & Hammond 2011). This is mostly due to the calcination of limestone at high temperatures, whereby Calcium Oxide (quicklime) and CO_2 are produced.

$CaCO_3 \rightarrow CaO + CO_2$.

Figure 2 – The calcination of limestone.

Since approximately 1.2 tonnes of $CaCO_3$ are required to produce a tonne of typical Portland Cement, theoretically 0.2 tonnes of CO_2 are released during calcination. However, this is just a part of the whole process; recent data concerning cement manufacture gives an overall average of 0.88 tonnes global CO_2 emissions per tonne of cement produced. Furthermore, because Portland Cement is a hydraulic material that sets by absorbing moisture it will not sequester this released CO_2 during its operational lifetime. So given global production, this implies that approximately 2 billion tonnes of CO_2 are emitted annually by cement manufacture. This accounts for a massive 7.5% of total global anthropogenic CO_2 emissions (Quillin 2008).

Improving the Sustainability of Cement

Parrot defines sustainable development as:

"...*meeting present needs without compromising the ability of future generations to meet their needs.*" (Parrot 2002)

Is it possible for cement production to meet such criteria? The World Business Council for Sustainable Development (WBCSD) believe so. They are an association of some 200 leading international companies and their Cement Sustainability Initiative lists key steps that would aid cement's role in sustainable development (WBCSD 2010):

- Monitoring and thereby reducing the CO_2 emissions of the manufacturing process through plant modernisation, using biomass fuels to heat the kilns and substituting more environmentally sympathetic raw materials into the cement mix.
- Smarter, more responsible use of fuels and raw materials through reuse and recycling and using domestic, industrial, or agricultural waste. The WBCSD have produced a nice visual representation of the cement industries waste stream, showing that waste is "a potential recovery opportunity, rather than simply a disposal problem".

Figure 3 – The WBCSD's Waste Hierarchy

- Environmental and social impact assessments in order to understand and mitigate the effects of issues such as dust, noise and habitat loss through limestone quarrying.
- Recycling schemes for cement based structures, such as concrete, with an aim to achieve "zero landfill" and thereby reduce natural resource exploitation.

One could question WBCSD's environmental credentials and ask whether the organisation exists merely to provide 'greenwash' for developed Western Global Corporations whose primary concern is shareholder profit. Might the WBCSD exist merely to promote the cement industry in the developing world, where there is the most growth potential?

However, such concern *may* be unfounded; at the 2002 Earth Summit, the WBCSD and Greenpeace delivered a united message demanding greater action by governments on climate change (Greenpeace & WBCSD 2002), and many of the reports produced by the WBCSD are written in consultation with environmentally responsible groups like the World Wildlife Fund. Furthermore, a 2007 list of the 100 most influential people in business ethics ranked WBCSD President Bjoern Stigson as the 2nd most influential NGO leader

(Ethisphere 2007), so one has to hope that the WBCSD's motives are pure.

Furthermore, Parrot agrees with many of the WBCSD's initiatives and promotes maintaining a UK database of the industry's resource and energy use in order to benchmark performance and highlight areas where sustainability can be improved. He also concurs with the idea that the industry should minimise the environmental impact of cement based structures by conducting life-cycle analysis and looking at the end-of-life of buildings with regard to material recycling (Parrot 2002).

Quillin promotes sustainability improvements in cement production through many of the measures listed by the WBCSD, including the substitution of materials like ground granulated blastfurnace slags (ggbs), pulverized fly ash (pfa) and pozzolans to produce blended cements. Cement with 66-80% ggbs has an estimated embodied energy of 2.96 to 2.4 MJ per Kg and emits 0.38 to 0.26 Kg CO_2 per Kg (Jones & Hammond 2011), figures that compare very favourably against those detailed earlier for standard UK Portland Cement that has 5.5 MJ per Kg embodied energy and emissions of approximately 0.95 Kg CO_2 per Kg.

As an aside, both the WBCSD and Quillin cite carbon capture and sequestration (CCS) as a means of reducing cement plant CO_2 emissions (Quillin 2008). However, experiments involving CCS are still very much at the formative stage and in fact, there are many skeptics who believe that the technology remains infeasible due to issues such as increased energy demands of CCS plants and concerns over CO_2 leakage (World Resources Institute 2011).

An Alternative to Portland Cement

Despite organisations such as the WBCSD promoting cement's sustainability, it's very nature as a hydraulic material make its environmental credentials somewhat problematic, chiefly because it cannot sequester any CO_2. This is especially so when there is a superior and viable alternative material. That material is lime.

A History of Lime

Lime has been used successfully as a construction material for millennia; it was used extensively throughout the ancient world, particularly by the Romans who used it on bridges, viaducts and many buildings that are still stood today. One fine example of a building built using lime is the 124 AD Pantheon in Rome whose magnificent dome spans 43.3 metres (Holmes 2011). Another is the Great Wall of China. Both of these are historic and lasting testaments to lime's durability.

Manufacturing Lime

Like cement, lime is produced from calcium carbonate ($CaCO_3$) and the most common raw material for this is one of the worlds most abundant minerals; limestone. The production process begins by evenly heating the raw material in a kiln at a relatively low temperature when compared against cement (about 900^oC). This drives off CO_2 to produce Calcium Oxide (CaO), also known as quicklime. This is then slaked in cold water, a process which creates heat and breaks up the quicklime to produce the finished product – calcium hydroxide ($Ca(OH)_2$). In its purest form this is known as non-hydraulic lime, or lime putty. This putty should be left to mature; for general mortar this can take one month and for plaster three months. However, the longer the putty is left the more likely any risk of failure will be removed and qualities such as water retention and plasticity will be improved. With this in mind, Danish authorities have stipulated that for repair work on historic churches, lime putty must be at least 5 years old (Holmes & Wingate 2002).

Lime's Environmental Credentials

Lime putty sets through carbonation, whereby it recombines with the CO_2 emitted during production to recreate calcium carbonate ($CaCO_3$). This completes a process known as the lime cycle (shown below). The significance of this is that it means that lime sequesters the carbon it emits during its manufacture and so emissions are significantly less than those of cement.

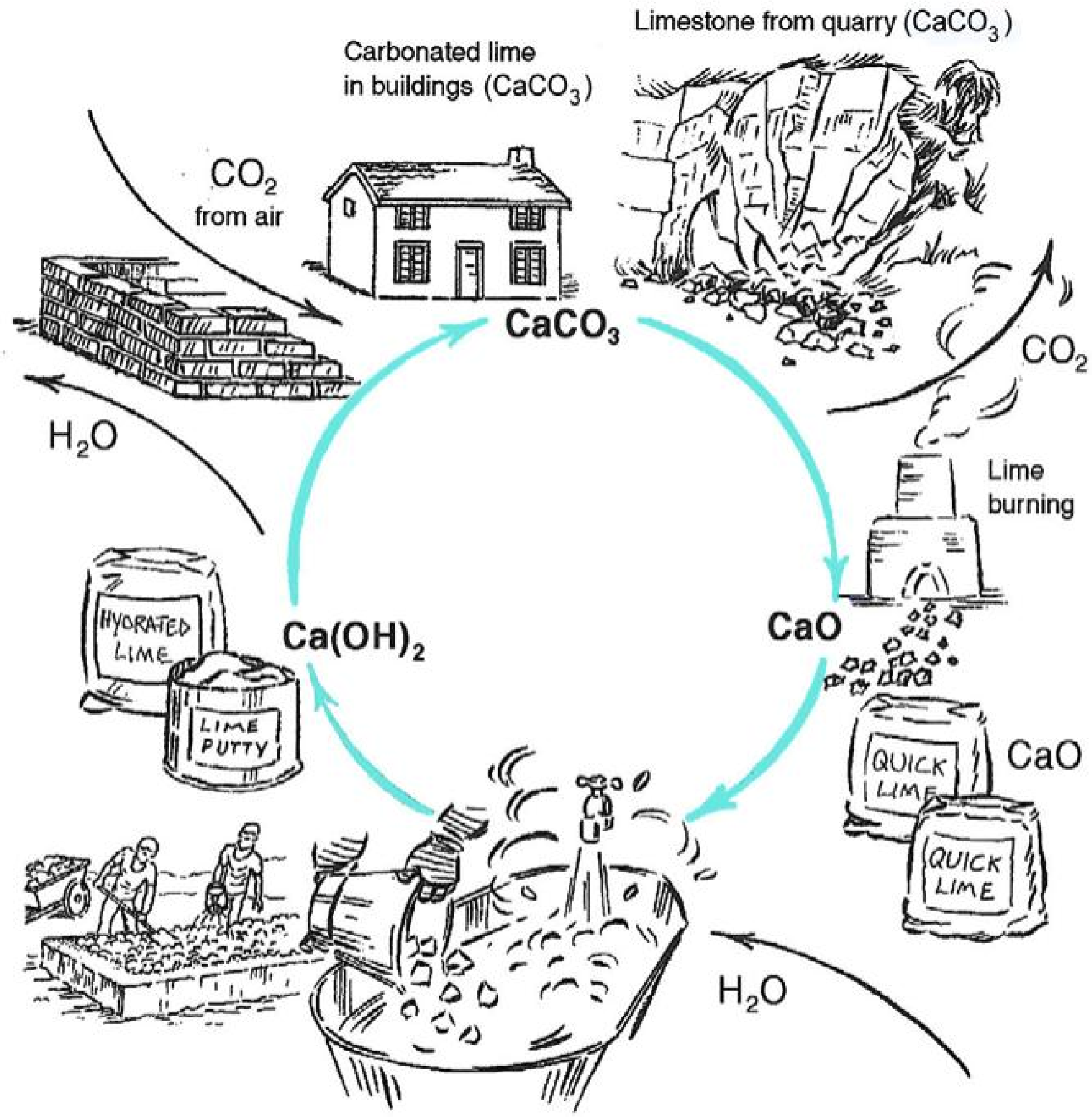

Figure 4 – The Lime Cycle (Holmes & Wingate 2002).

Further emission reductions are possible because of the abundance of limestone throughout the world, which means that lime can be produced locally, reducing its transportation requirements and therefore its embodied energy.

Cement versus Lime

The special characteristic of Portland Cement is its great strength, which make it ideal for very large structures. Unlike non-hydraulic lime, Portland Cement also sets under water, making it ideal for structures such as bridges and dams and for work in damps soils below ground. However, hydraulic limes might also be suitable in such cases because they are often stronger than lime putty (Holmes & Wingate 2002). These are produced from non-pure calcium carbonate or through the addition of pozzolans. Cement also sets quickly, which make it ideal for professionals who need to complete work fast in order to maximise profit. It is also easier to work with than lime because although it has a degree of causticity, lime is highly caustic and so care must be taken to protect the eyes and skin.

But lime is a far superior material than Portland Cement in many aspects. Lime is porous, so vapour can pass through it and this 'breathing' property helps regulate humidity. This also makes it weatherproof rather than waterproof, which helps protect a building without sealing it. Cement is impermeable, so it creates humidity, rather than regulates it, and it seals, rather than breathes. This can cause problems with condensation (amazonails 2011). Lime is soft and flexible so it aids good workmanship because it can penetrate voids and gives a good key. Furthermore, stones laid in it can move without causing structural defects. Lime's softness also mean that it binds gently, so mortars can be made that are less strong than adjacent materials. This is good because these will fail first and mortar is easily replaced. This makes it a brilliant material for restorative work (Holmes & Wingate 2002). Cement is just the opposite because it is hard and inflexible. This strength also means that it has a high life cycle cost because it is difficult to recycle materials from it. Because lime is non-hydraulic and sets by absorbing air, not water, it is not susceptible to frost damage, whereas highly hydraulic cement is. Lime also 'self-heals' so it does not crack easily because water penetration into fine cracks can dissolve 'free' lime and bring it to the surface (Holmes & Wingate 2002). Because of the lime cycle, lime also sequesters carbon whilst setting, whereas cement does not. And whilst lime's carbonation process and longer setting time mean that more care must be taken than one might expect with cement, one might equally argue that this greater craftsmanship often leads to work of a much higher quality. Quite simply, lime has many qualities that make it a superior material to cement.

Conclusion

Cement has its place as a strong material that sets hard under water. This makes it ideal as a binder for large structural constructions such as bridges, dams and tall buildings. Therefore, efforts by organisations such as the WBCSD to increase its sustainability and reduce its estimated 7.5% of global CO_2 emissions are to be lauded.

However, lime's environmental credentials alone give it a significant advantage over cement. So although laudable, one could ask whether the WBCSD and similar organisations would be better focusing their efforts on promoting lime as a binding material rather than trying to lessen cement's environmental impact. Especially when properties such as lime's permeability and flexibility often make it a much more suitable and superior choice anyway. Lime requires a knowledge of its properties in order to use it successfully. But this leads to great craftsmanship and beautiful results; just the sort of care required if the globe's construction industry is to head toward sustainable development and not career headlong into further contributions to anthropogenic contributions to climate change.

This paper was limited to comparing the properties of Portland Cement and lime and in particular focuses on the environmental credentials of each of these binders. It may have touched on the reasons that cement production vastly outweighs that of lime today, but that requires further research. Did lime fall out of favour because it requires great craftsmanship, or was it Portland Cement becoming ever more popular because it is so strong? Another interesting area of research might be a social study that investigates the skill levels amongst today's construction professionals, with a particular focus on the properties of lime that make it such a fantastic binder. For instance, how many realise that it is best to use inexpensive and easily repaired mortars that are not as strong as adjacent materials? How many are aware of the importance of 'breathability' in comfort provisioning and building welfare? How many realise the life-cycle costs of cement and how lime might mitigate these?

Lime is a great binder. Our elders knew it. It's such a shame we seem to have forgotten it. But with climate change a reality, it's time we remembered.

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