BREEAM and Sustainable Concrete Construction

by

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"I hereby declare that, except where specifically indicated, the work submitted herein is my own original work"

Summary

Sustainable use of concrete has been identified as a key issue in the construction industry for years. Concrete and cement use is accelerating across the world, most notably in China and India. There are several well-established methods of achieving more environmentally friendly concrete but how can their effects be quantified? Which ones have the largest potential for improvement? What measures should be taken to incentivise their use?

This report summarises the key methods currently employed to reduce the carbon dioxide (CO_2) emissions, water demand, mineral resource extraction and waste disposal impacts associated with the use of concrete. The report sets out a methodology for assessing the total environmental impact of several mixes with differing constituents. The aim of this investigation is to show which mix constituents result in the largest improvements for concrete sustainability.

Considering the four environmental impacts described above, the sustainability of a typical concrete mix can be improved by as much as 35%. Improvements of just under 50% are possible if extreme measures are employed. Water-reducing admixtures, Ground Granulated Blast Furnace Slag (GGBS) and Pulverised Fuel Ash (PFA) cement replacements prove to have the largest effect. This is mainly due to the fact that they partially replace the Portland cement content, which is associated with particularly high CO_2 emissions.

It should be noted that the use of recycled aggregate has a negligible effect on the environmental impact of any particular mix. In fact, it will often lead to a less sustainable use of concrete. This has implications for the Building Research Establishment Environmental Assessment Method (BREEAM) in the UK, which are addressed in the concluding sections of the report.

1 Technical Abstract

The use of concrete has numerous impacts upon the environment. The main source of environmental damage is from the release of CO_2 during the manufacture of Portland cement, which is a key constituent. Water extraction, mineral resource extraction and waste disposal are other key issues associated with concrete production.

Concrete is widely used throughout the world. Manufacture is accelerating particularly rapidly in emerging economies such as China and India. Coupling this with the energy-intensive manufacturing process, cement is estimated to contribute over 5% of CO_2 emissions worldwide.

The environmental damage associated with concrete is a well-established issue and many measures to reduce this have been developed. However, methods are often used without much consideration for the complete lifecycle and all the contributing factors. For example: use of recycled aggregate reduces the amount of virgin material extracted but if it is sourced outside a 14km radius its use gives rise to more CO_2 emissions than virgin aggregate.

This report focuses on issues currently experienced in the UK relating to structural concrete. Data and statistics are sourced from the UK and concrete of strengths RC30/37 and above are considered.

In order to evaluate the options and present their effects this report sets out a unique assessment methodology. Concrete is made up of several different components: cement, water, air and aggregate. Admixtures are also often used as well and these alter the properties of a mix as required. The quantities of these constituents for any particular mix vary substantially depending on specific conditions. Each constituent will have its own impacts. As a result of concrete's variability, impacts are measured relative to a standard rather than using raw values.

The report is structured such that the options for each constituent are summarised and discussed before the environmental assessment takes place. Different types of aggregate, cement replacements and admixtures are highlighted.

For the assessment, the effects of the various constituents are broken down (for example: the embodied CO_2 of Ground Granulated Blast Furnace Slag (GGBS) cement replacement is 67 $kgCO_2$/tonne GGBS). A spreadsheet-based analysis calculates the total embodied CO_2, water extraction, mineral resource extraction and waste disposal associated with each constituent of different mixes. These raw values are then normalised to a standard mix and weighted to give an overall total rating. If a mix gets a rating of less than 1 some level of improvement has been achieved compared with the standard.

Figure 1.1 shows an example output of the assessment and how it quantifies the effect that different components have on the environmental impact of a concrete mix.

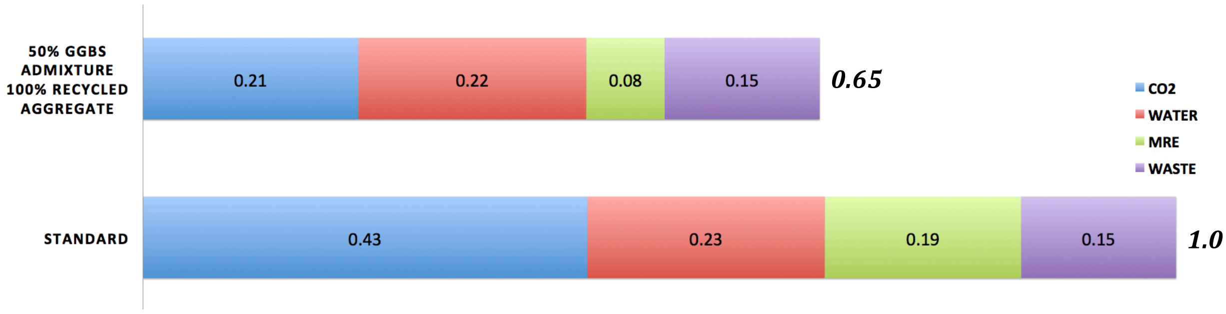

Figure 1.1: Performance of the best typical RC40/50 concrete mix compared to the standard.

It is found that cement replacements and water-reducing admixtures have the largest effect on improving the environmental impact of concrete. A typical combination of these can yield an improvement of 35%. The maximum improvement found using extreme values is 49%. The use of recycled aggregate results in a small improvement (1-5%), which can often be outweighed by transportation costs and quality issues.

Finally, it is concluded that the future of sustainable structural concrete should be focused on the use of cement replacements and admixtures. Recycled aggregate should only be used if available close to the site and if it is of good quality. This has implications for the Building Research Establishment Environmental Assessment Method (BREEAM), which rewards the use of recycled aggregate regardless of these factors. To improve this an environmental calculator is proposed based on the assessment methodology used here. This could help to specify more sustainable use of concrete for more applications although further analysis would need to be done to verify its suitability.

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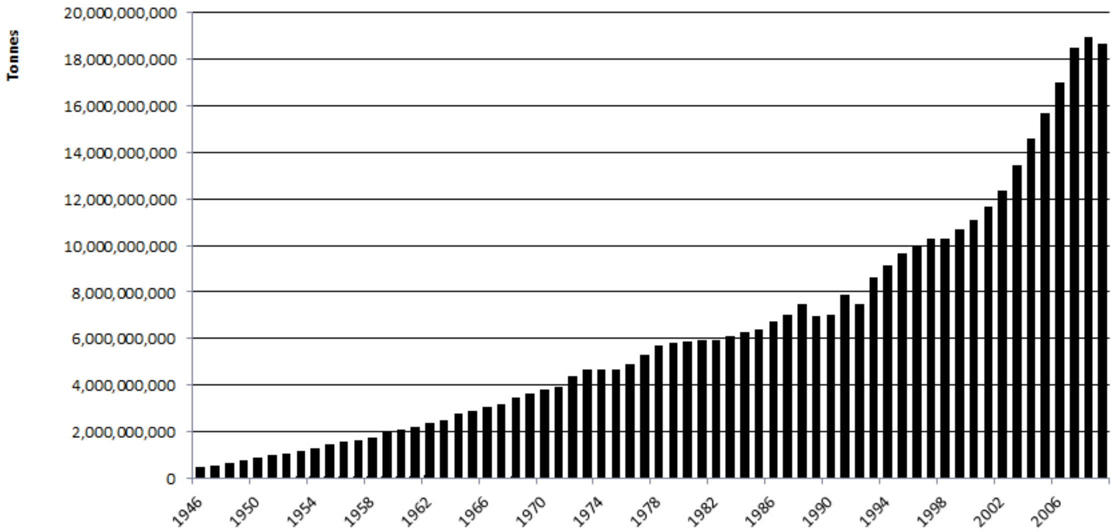
2 Introduction

Concrete is a very well established construction material. It has been in use for over two thousand years in various forms. Its accelerated use in recent times has been driven by the invention of Portland cement (so called as its colour is similar to that of Portland stone), patented in 1824 by Joseph Aspdin (Clarke, 2009). Portland cement mixed with water, air and fine sand forms mortar. This is used to join larger rocks or 'aggregate' to create concrete.

Concrete is an incredibly versatile material and is used in almost all large-scale civil engineering projects including the construction of bridges, buildings, roads and tunnels. Figure 2.1 shows the recent trend in world production of concrete since 1946.



Source: Cement data: USGS Minerals Yearbooks
Assume concrete includes 15% cement.

Figure 2.1: World production of concrete since 1946.

As can be seen, worldwide production is increasing very quickly. Emerging economies such as China and India are driving production now such that this trend will be set to continue.

As with any man-made material, increases in production on this scale pose a threat to the environment. Figure 2.2 compares the CO_2 emissions associated with various activities and concrete compares badly here. CO_2 causes temperature changes across the globe and is often considered the most important of the environmental issues.

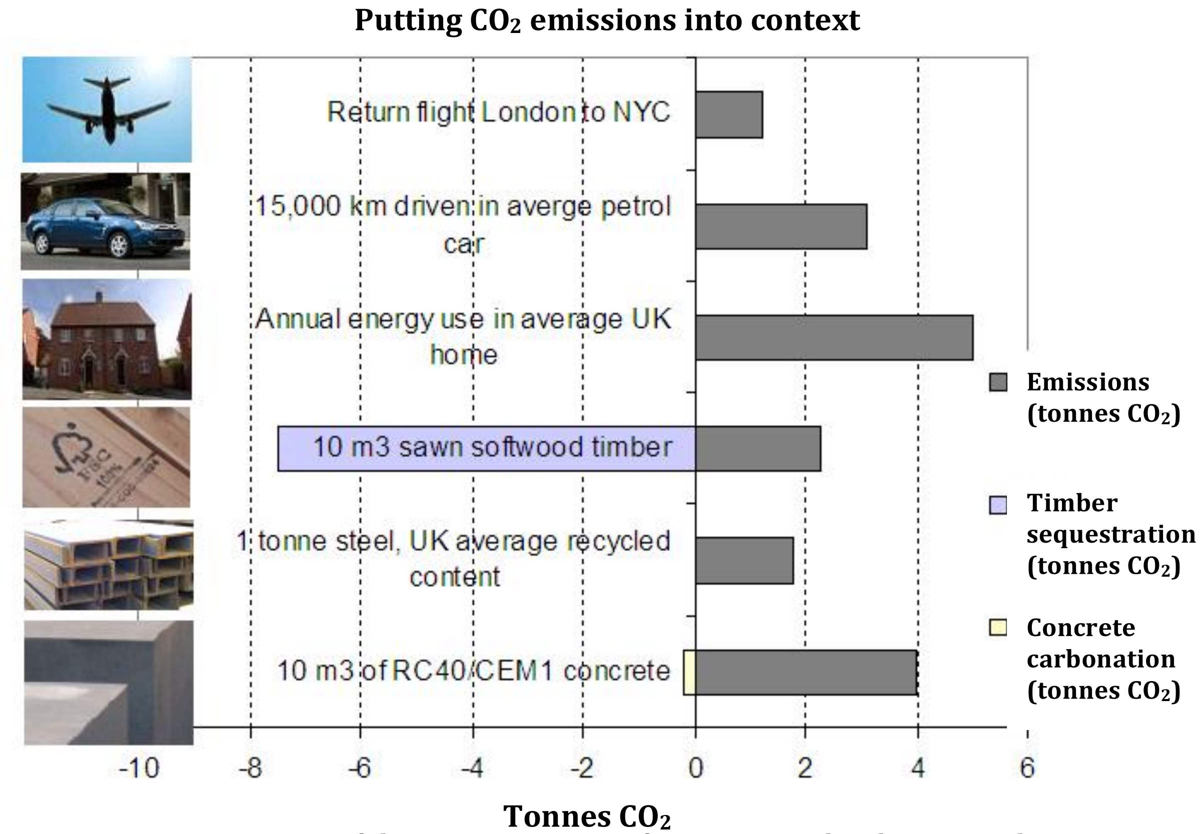


Figure 2.2: Comparison of the CO_2 emissions of concrete with other everyday activities.

Source: (Borchers, 2013)

Portland cement is the key constituent driving these figures. It is very energy-intensive to manufacture and when it reacts, it releases CO_2. Coupled with the increased rate of use shown in Figure 2.1 it is estimated that cement production contributes to at least 5% of global CO_2 emissions (Crow, 2008). Figure 2.3 illustrates this in the context of other emission sources.

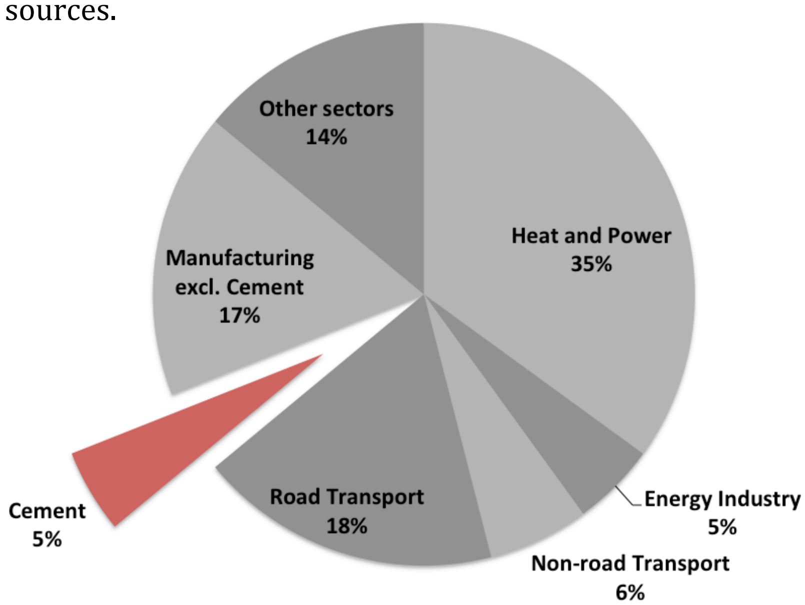


Figure 2.3: Contribution of cement to global CO_2 emissions.

Source: Cement sustainability initiative progress report, June 2005

As a result, minimising the impact of concrete is a key aim in order to hit CO_2 emissions targets. Use of cement replacements, recycled aggregates and admixtures alongside other methods help achieve this and are already employed to some degree. These are well researched but there is much work to be done to ensure their use is incentivised and specified in the right way.

2.1 Why use concrete?

When examining the CO_2 emissions associated with buildings it is important to consider them over their full life cycle. Figure 2.4 shows an empirical approximation of the operational (heating, cooling, lighting etc. CO_2 after construction) and embodied (construction CO_2) elements of a structure.

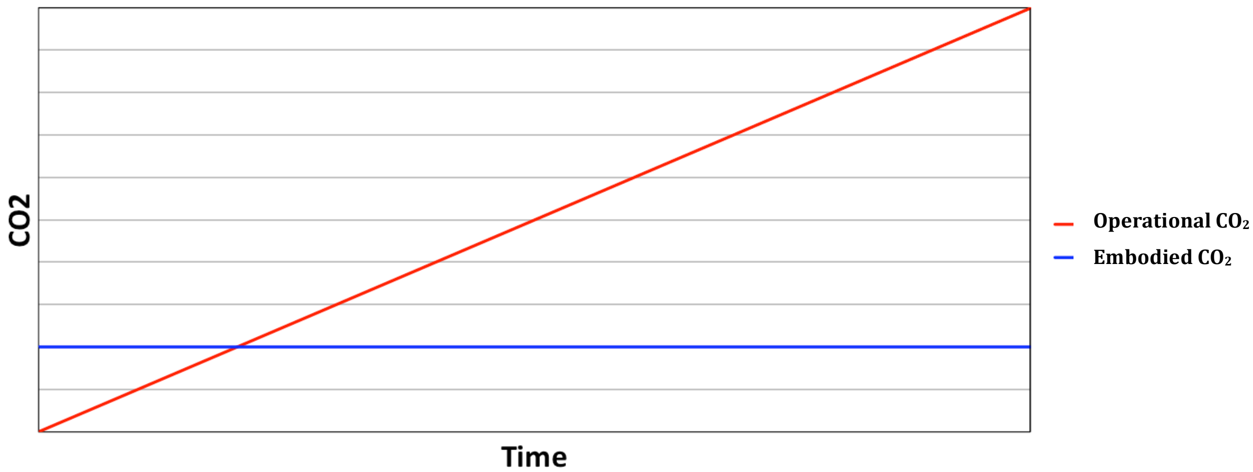


Figure 2.4: Operational and embodied CO_2 over a structure's life cycle.
Source: (Trippick & Aikenhead, 2013)

In some instances, concrete can reduce the gradient of the operational line thus reducing the cumulative CO_2 emissions over time. This is because it can provide thermal mass, which means that a building's heating and cooling demands can be greatly reduced (de Saulles, 2012). Typically, the energy used for heating in cooling represents 20-50% of a building's total energy consumption (IAG, 2008) thus this is hugely advantageous.

Architects and engineers encourage its use due to its incredible versatility as well as its high compressive strength. Mixes can be tailored to specific applications as desired by the designer. Often there is no better alternative. As a result, the industry must do what it can to limit the impact of its use. This report first provides background for the various techniques used to reduce the environmental impacts of concrete. Following this, the techniques are evaluated using a unique assessment methodology. This allows the effects of the improvement methods to be quantified. This report is focussed on identifying ways to reduce the magnitude of the 'embodied' line in Figure 2.4. Specifically, it considers concrete for structural applications with strengths above C30/37 but does not include calculations for steel reinforcement.

2.2 Concrete and BREEAM

The Building Research Establishment Environmental Assessment Method (BREEAM) is widely used in the UK to assess buildings for their sustainability. Credits are given for meeting different criteria and these are summed to give the building an overall rating. This ranges from 'Unclassified' to 'Outstanding'.

Of these criteria two are awarded in relation to concrete and thus are the most interesting for this report:

MAT 01 encourages use of materials with low environmental impact and linked heavily with the BRE Green Guide (Anderson, Shiers, & Steele, 2009)

WST 02 incentivises the use of 25% recycled aggregate in concrete as long as the aggregate is sourced within 30km of the site (BRE, 2011).

A key aim of this report is to investigate these credits. Can use of recycled aggregate lead to a less environmentally friendly mix? Concrete will always come out badly in comparison to other materials; should there be an element of comparison within individual material types?

The Green Guide grades material sustainability using its 'ecopoint' system. This gives materials a rating from A (good) to E (poor). The impacts are normalised to the average impact of a European citizen over 1 year to give all the impacts a common unit. Weightings are then applied to these values and the total is summed to give a material an overall 'ecopoint' which allows materials to be compared. These weightings are derived by a panel of ten European experts and are based on the relative importance of each of the thirteen key environmental concerns shown in Table 2.1.

Alongside CO_2 emissions and climate change, water extraction, mineral resource extraction and waste disposal are key issues relating to concrete.

#	Criteria		Weight	Report Weight*
1	Climate Change	MEASURED in kg CO_2	21.6%	**43%**
2	Water Extraction	MEASURED in m^3 WATER EXTRACTED	11.7%	**23%**
3	Mineral Resource Extraction	MEASURED in TONNES of MATERIAL	9.8%	**19%**
4	Stratospheric Ozone Depletion	MEASURED in kg CFC – equiv.	9.1%	
5	Human Toxicity	MEASURED in kg 1.4-DB	8.6%	
6	Ecotoxicity to Freshwater	MEASURED in kg 1.4-DB	8.6%	
7	Nuclear Waste	MEASURED in mm^3 RADIOACTIVITY	8.2%	
8	Ecotoxicity to Land	MEASURED in kg 1.4-DB	8.0%	
9	Waste Disposal	MEASURED in tonnes SOLID WASTE	7.7%	**15%**
10	Fossil Fuel Depletion	MEASURED in MJ	3.3%	
11	Eutrophication	MEASURED in phosphate	3.0%	
12	Photochemical Ozone Creation	MEASURED in kg ETHENE	0.2%	
13	Acidification	MEASURED in kg SO_2	0.05%	

***New weightings based on only including the four key criteria with respect to concrete production (shaded in Grey).**

Table 2.1: Thirteen key environmental impacts and their weightings

Source: (Anderson, Shiers, & Steele, 2009)

To assist with the assessment methodology in this report a similar system will be set up. However, it will be normalised to a 'standard' concrete mix rather than the impact of a European citizen. All measurements will be made relative to this. Also, only four of the thirteen criteria will be considered in this report. These are shaded in grey in Table 2.1.

2.3 Aims and objectives

1. Discuss the implications of findings on BREEAM. How should BREEAM be modified to ensure it always incentivises more sustainable use of concrete?
2. Discuss methods that reduce the environmental impact of concrete including the use of: recycled aggregate, cement replacements and admixtures. What are the barriers to their use and what effects do they have on concrete properties?
3. Compare the use of offsite and onsite concrete construction. What are the implications of each and can offsite construction result in considerable improvements for the environmental impact of concrete?
4. Perform an environmental assessment of numerous different mixes incorporating different methods of reducing the environmental impact of concrete. Which are the most effective?
5. Discuss the future for more sustainable use of concrete. How much has been achieved thus far? What steps must be taken now?

3 Concrete constituents

Concrete mixes are tailored to their specific application. There are numerous criteria that define how to specify a mix such as: workability, strength, exposure class and maximum aggregate size.

In order to produce a meaningful assessment this report considers each stage of concrete manufacture and the different decisions that can be made. Figure 3.1 shows the sequence of decisions that are made throughout the entire lifecycle of concrete. Often a decision made at an early stage can have a significant impact on properties and performance later on.

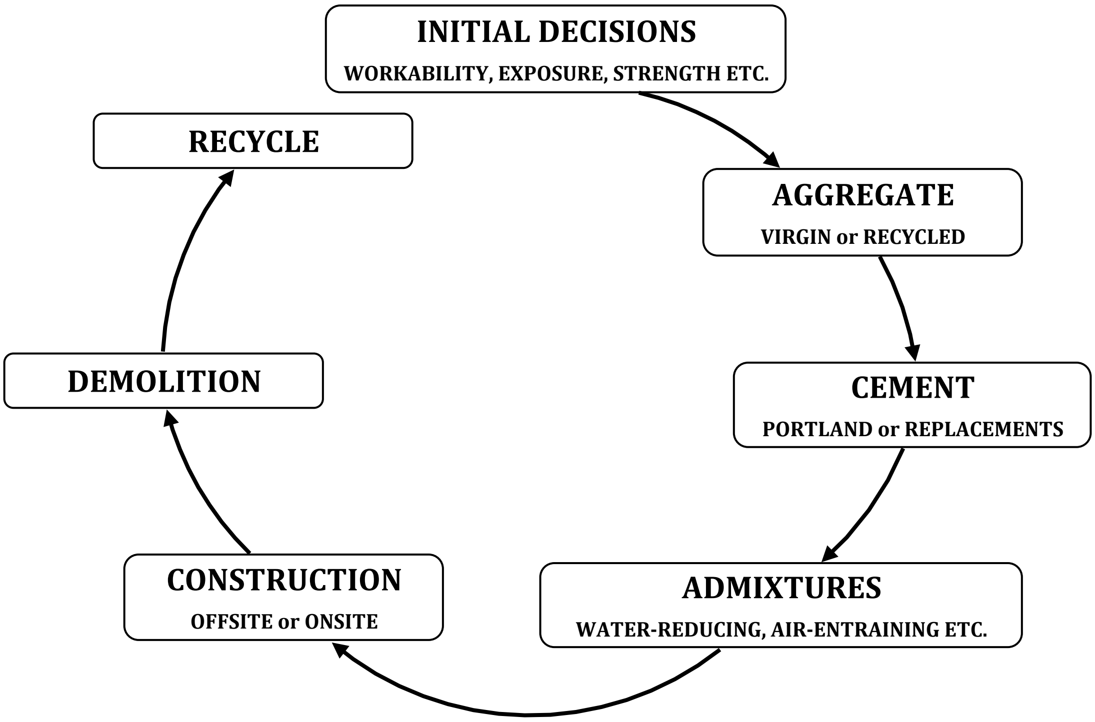


Figure 3.1. Concrete manufacture decision sequence.

The aim of this investigation is to compare the environmental effects of different decisions. In the subsections that follow the options will be presented with relevant background for their use. The focus will be on their properties and on specific implications of their use for the overall environmental impact of a mix.

3.1 Initial decisions

There are several initial considerations for concrete design that affect how the mix is specified. For the purposes of this investigation these are not considered in much detail, as they will not have a large effect on the environmental impact of a mix. However it should be noted that in some cases they could restrict the constituents of a mix and limit the capacity for environmental improvement.

There are several methods of specifying concrete as laid out in the British Standards. These are: designed, prescribed, standard and designated (BSi, 2002). This guidance ensures that the constituents are chosen correctly to achieve the desired properties.

The British Standards provide a number of discrete options for the properties of a mix. Some of these are shown in Tables 3.1, 3.2 and 3.3.

Exposure Class	Exposure to…
XA	Chemicals
XC	Carbonation
XS	Sea
XD	Chlorides
XF	Freeze/Thaw
X0	Mild conditions

Table 3.1: Exposure classes
Source: (BSi, 2006b)

Slump Class	Slump Range (mm)
S1	10-40
S2	50-90
S3	100-150
S4	160-210

NB Several other measures of consistency also available

Table 3.2: Slump classes
Source: (BSi, 2006b)

Strength Classes					
C8/10	C12/15	C16/20	C20/25	C25/30	C30/37
C35/45	C40/50	C45/55	C50/60	C55/67	C60/75
C70/85	C80/95	C90/105	C100/115		

Format: Max Characteristic Cylinder Strength/Max Characteristic Cube Strength in N/mm^2

Table 3.3: Strength classes
Source: (BSi, 2006b)

The classes highlighted in grey are those that will be considered for this investigation. These are aimed to be typical and will not change throughout the investigation to simplify analysis. It is assumed that while changes may put restrictions on the constituents of a mix, they will not affect the total impact. Several strength classifications are chosen as it is expected that differences here will be of interest for this investigation.

In addition to these factors the architect or engineer can also influence the appearance of concrete. If the concrete is required to look a certain colour or be finished to a certain quality for aesthetic purposes this can further alter the mix design requirements. Differences here will not be investigated but it is another area of concern and can affect decisions made later on.

3.2 Aggregate

Coarse aggregate and sand make up the largest proportion of concrete by weight. The ratio of solid constituents is typically around 1:2:3 (Cement: Sand: Coarse Aggregate) (Simpson, 2004). Figure 3.2 shows this graphically.

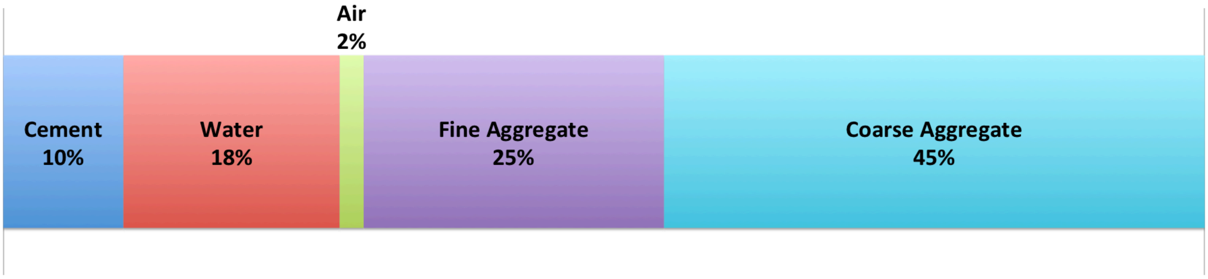


Figure 3.2: A graphical representation of the typical constituents of concrete.
Source: (Toogood, personal communication, 2013)

Aggregate sourced for the first time is referred to as virgin aggregate. This is an abundant resource that requires little processing. However, use of recycled forms of aggregate has become increasingly prevalent, especially in the UK (The Concrete Centre, 2011a). There is very little evidence that any hard demolition waste goes to landfill sites. This is a real success story. However, the majority of its use is in non-structural applications. Its quality is often debateable; does it make sense for structural concrete?

To answer this, background for the use of recycled aggregate must first be considered. Recycled aggregate is available in a number of forms (Chan, 2010):

- Recycled concrete aggregate (RCA): aggregate principally comprised of crushed concrete.
- Recycled aggregate (RA): aggregate sourced from reprocessing of inorganic material previously used in construction.
- Secondary aggregate (SA): by-products of industrial processes that have previously not been used in construction.

RCA is of particular interest as it derives from demolition waste and continues the lifecycle of structural concrete. Its quality is very important and it is processed in the following way (Kasai, 2004):

1. Inspected to confirm it is free from harmful contaminants.
2. First crushing
3. Vibrated and deleterious material removed by hand (wood chips etc.)
4. Second crushing } Repeat for third crushing
5. Vibrated and magnetically separated }
6. Machine removes mortar from the surface of the aggregate (often 4 cycles necessary to achieve desired quality.

While recycled forms of aggregate supply a significant proportion of the UK aggregate market only a small proportion of this is used for concrete (Lay, 2009). This is due to economic barriers, issues with supply and the onerous testing procedure as laid out in BS 8500 (BSi, 2003). However, work is being done to incentivise its use. As already mentioned there is a BREEAM credit dedicated to 25% recycled aggregate use in construction (BRE, 2011). Other documentation such as the Leadership in Energy and Environmental Design (LEED) issued by the US Green Building Council also specify that '*a minimum of 25% of building materials that contain an aggregate*' will contain *'a minimum weighted average of 20% post-consumer recycled content material, OR, a minimum weighted average of 40% post-industrial recycled content material'* (Portland Cement Association, 2013).

However, while the advantages of using recycled aggregate in concrete include a reduction in waste from demolition, a reduction of material sent to landfill sites (thus avoiding landfill tax) and credits in BREEAM and LEED, the disadvantages are also considerable. The main one of these and a key area of investigation in this report is whether the use of recycled aggregate in concrete can actually lead to a less environmentally friendly mix. There are several reasons for this and these are summarised in the sections that follow. The effects of the use of recycled aggregate on the properties of concrete are examined and the implications on the four key environmental criteria are also discussed.

3.2.1 Effect of the use of recycled aggregate on concrete properties

Property	Effect in comparison to virgin aggregate.
Density	5-15% lower[1].
Water absorption	4-6 times higher[1].
Workability	Reduced[1].
Surface absorption	Up to 30% RCA content has no influence. Above this it is increased due to an increased proportion of cement paste surrounding aggregate[1].
Carbonation resistance	Higher cement contents can lead to better resistance to carbonation but very little change is exhibited with contents of up to 30% RCA[1].
Chloride ingress	No negative influence from use of RCA[2].
Alkali-silica reaction	Minimal effect on this when using RCA[3].
Sulfate resistance	Little or no effect when using RCA but preferable that the source of the aggregate be sulfate resisting[1].
Freeze/thaw resistance	As for all concretes resistance is good as long as there is sufficient air entrainment[4].
Abrasion	No difference[1].

[1] (Dhir, Limbachiya, & Leelawat, Suitability of recycled concrete aggregate for use in BS 5328: Designated mixes, 1999)
[2] (Dhir & Paine, Suitability and practicality of using coarse RCA in normal and high-strength concrete, 2004)
[3] (Concrete Technology Unit, University of Dundee, 2005)
[4] (Salem, Burdette, & Jackson, 2003)

Table 3.4: Effect on concrete properties of use of recycled aggregate.

The key properties here are density, water absorptions and workability as well as strength concerns when using RCA of lower quality. They all represent barriers to the use of RCA and issues for the mix designs.

3.2.2 Climate change

The first major issue is transport and availability. Table 3.5 shows the implications of transporting recycled aggregates.

Material	Cradle to gate kg CO_2 / tonne	Delivery (to & from site by road)		Total kg CO_2 / tonne	+/- % CO_2
		Distance (km)	kg CO_2 / tonne		
Virgin Aggregate	6.6	58.5	2.7	9.3	**0%**
RA used onsite	7.9	0	0	7.9	**-15%**
RA used at 5km	7.9	10	0.5	8.4	**-10%**
RA used at 10km	7.9	20	0.9	8.8	**-5%**
RA used at 14km	7.9	28	1.4	9.3	**0%**
RA used at 20km	7.9	40	1.8	9.7	**+4%**
RA used at 50km	7.9	100	4.5	12.4	**+33%**
RA used at 50mls	7.9	322 (100 mls)	14.6	22.5	**+142%**

Table 3.5: Implications of transporting recycled aggregates.
Source: (Turner, 2009)

The extra processing necessary to use recycled aggregate in concrete equates to 1.3 kg CO_2/tonne of aggregate. Compare the use of virgin aggregate (which is typically transported 58.5km to and from site) with recycled aggregate. If recycled aggregate is transported 28km to and from site there is no net gain (in terms of kg CO_2/tonne) from its use.

Thus, recycled aggregate must be sourced within a 14km radius of a site. As already highlighted, BREEAM quotes a condition of 30km. Presumably this aims to reduce the barriers to the use of recycled aggregate. However, this should be amended to ensure that use of recycled aggregate is not more environmentally damaging.

Recycled aggregate is still not widely used for concrete manufacture. While suppliers are increasing in number, they do not cover the whole of the UK. Figure 3.3 shows a map of all current recycled aggregate suppliers in the UK. An approximate 14km radius is shown around them (note that this does not consider the distance that the aggregate will have had to travel from its source at a demolition site to the supplier's stockpile). Concrete used on any land outside the blue circles on this map should be sourced from a nearby demolition site or use virgin aggregate as these have lower CO_2 impacts that sourcing from a supplier.

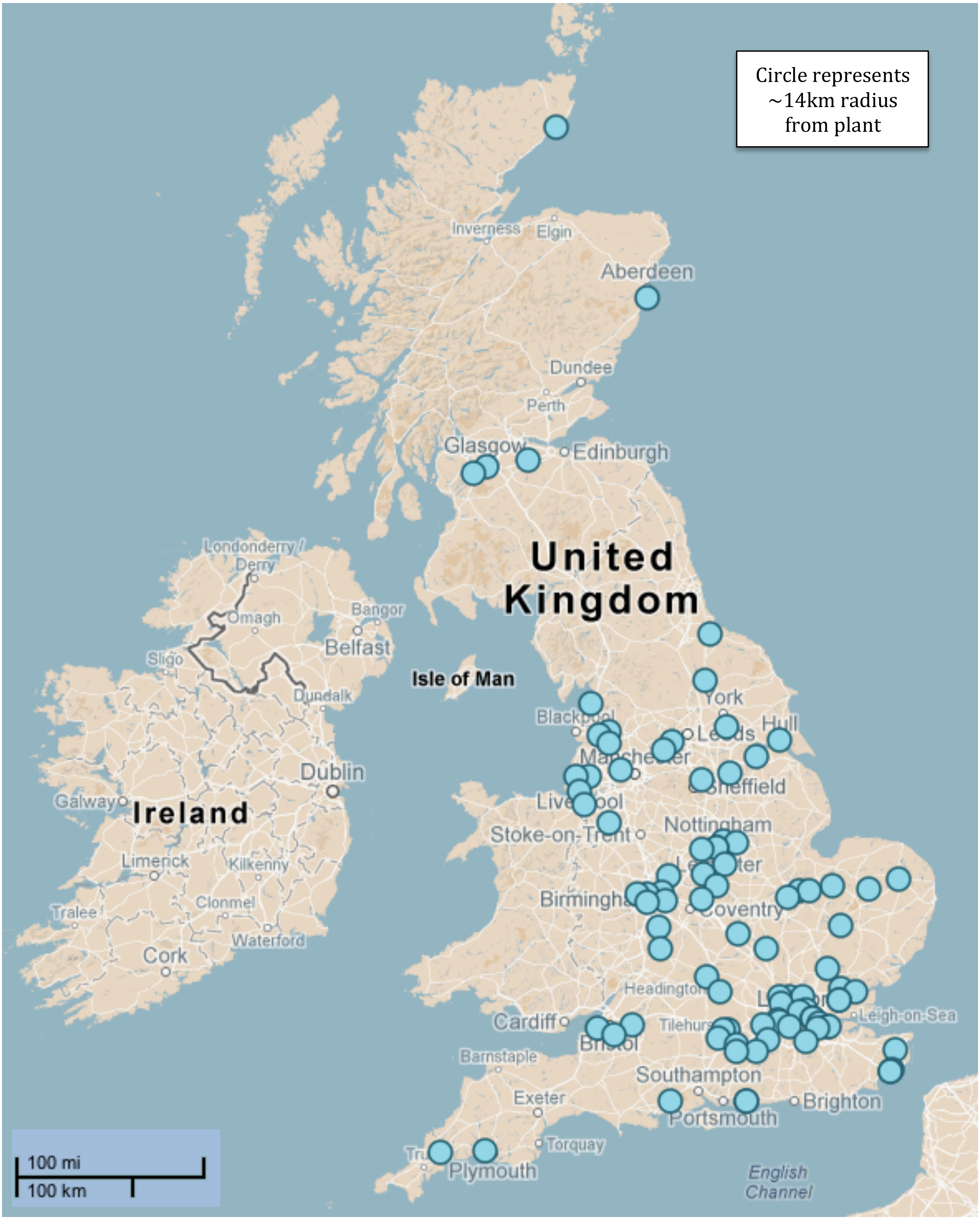


Figure 3.3: Map showing the locations of recycled concrete aggregate suppliers in the UK

Created in 2013 by the author using data on recycled aggregate suppliers for concrete from Aggregain website http://www.aggregain.wrap.org.uk

3.2.3 Mineral resource extraction

Recycling is the key activity that mitigates impacts under this heading. Use of recycled aggregate is favourable to avoid depletion of natural resources for future generations.

However, virgin aggregate is hugely abundant. There is enough in the UK to last for hundreds of thousands of years at current rates of usage (Mclaren, Bullock, & Yousef, 1999) so should there be the same concern for its depletion as for a less abundant resource? Especially as, for a large number of applications for structural concrete, use of recycled aggregate can actually have adverse environmental effects in other areas.

3.2.4 Waste disposal

Waste arising from aggregate is difficult to quantify. Due to the nature of the material before mixing any additional aggregate can be simply recycled back into the process. Thus the waste associated with this can be considered to be very low.

3.2.5 Implications of the use of recycled aggregate on mix design

The use of recycled aggregate can have a number of effects on the mix constituents of concrete when compared to use of virgin aggregate. There is some concern that the use of recycled aggregate may increase the amount of cement required for a mix to achieve the desired strength (The Concrete Centre, 2011b). Alongside the transportation issues already discussed this would further the adverse impact of recycled aggregate on the environment.

As well as implications on cement content the attached mortar in RCA results in significantly higher water absorption than for virgin aggregate. Therefore more water is needed in the mix to achieve the same workability (Hansen, Taylor, & Francis, 1992).

An experiment on 99 concrete specimens was carried out at the University of Belgrade, Serbia in 2010. The aim was to test the effect of using recycled aggregate on the strength and other parameters; the results are summarised in Tables 3.6 and 3.7 (Malesev, Radonjanin, & Marinkovic, 2010). All concrete mixes were designed to have a compressive strength of 40MPa at 28 days.

Concrete Mixture	Cement (kg/m³)	Virgin Aggregate Fine Agg (kg/m³)	Virgin Aggregate Coarse Agg (kg/m³)	Recycled Coarse Agg (kg/m³)	TOTAL Aggregate (kg/m³)	Water (kg/m³)
R0	352	612	1254	0	1866	181
R50	352	600	613	613	1826	200
R100	348	586	0	1179	1765	216

R0 – 100% Virgin Aggregate R50 – 50% Recycled Aggregate R100 – 100% RA

Table 3.6: Summary of mix proportions for testing of recycled aggregate performance

These mixes achieved approximately the same workability and air content. The bulk density varied slightly with the highest being 100% virgin aggregate and the lowest being 100% recycled aggregate. Also note that the cement contents are roughly the same and that the total aggregate decreases and water demand increases with more recycled content. In addition, the water needed increases by approximately 10% for 50% recycled aggregate content.

	Concrete Age (days)		
Concrete Mixture	**2**	**7**	**28**
R0 (MPa)	27.55	35.23	43.44
R50 (MPa)	25.74	37.14	45.22
R100 (MPa)	25.48	37.05	45.66
R50/R0 (%)	93	105	104
R100/R50 (%)	92	105	105

Table 3.7: Results for compressive strengths of the mixes at different ages

Although marginal, this research shows that while use of recycled aggregate might delay initial strength gain it can actually result in higher strength later on. The cement contents used were almost identical, as shown in Table 3.6. It must be stressed that the recycled aggregate used for these experiments was of good quality.

For this report, mix proportions will be calculated using trends shown in the Serbian research. Similar proportions of coarse aggregate by weight can be replaced with recycled aggregate and cement contents will be considered unchanged by the use of recycled aggregate (although this will not always be the case).

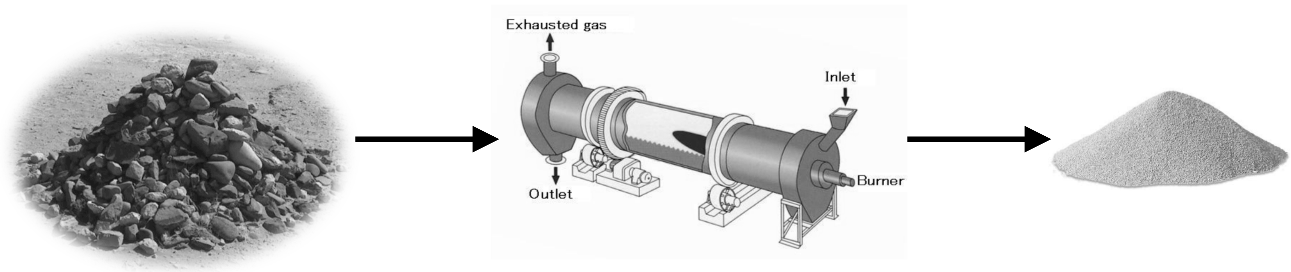
3.3 Cement

Cement is the largest contributor to the environmental impact of concrete. There are many different types of cement but the most commonly used is Portland cement. Other cement types are known as cement replacements and these reduce the Portland cement content thus improving the environmental credentials.

There are many different possible replacements, the most common being Ground Granulated Blast Furnace Slag (GGBS), Pulverised Fuel Ash (PFA), Limestone Fines, Silica Fume and Metakaolin (Clear & Sear, 2006). GGBS and PFA are the most established of these and will be the only replacements considered in this investigation.

3.3.1 Portland cement

Some proportion of Portland cement is present in every concrete mix as specified by British standards. A mix using 100% Portland cement is known as CEM I. Its manufacture is illustrated in Figure 3.4:



Quarried rock – 75% Limestone 25% Clay | Heated in a rotary kiln at 1400-1500^{0}C | Ground finely and gypsum added.

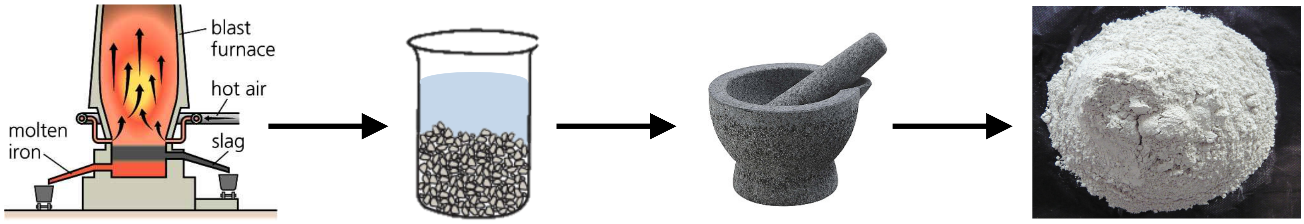
Figure 3.4: Manufacture of Portland cement

Source: (Burgoyne & Middleton, 2013)
Images sourced from Google image search (see list of tables and figures for URLs)

The bulk of the CO_2 released in this process is via two mechanisms: the heating of fossil fuels in the rotary kiln, and in calcination (when calcium carbonate is broken down to calcium oxide by heating, releasing CO_2) (NRMCA, 2008).

3.3.2 Ground Granulated Blast Furnace Slag (GGBS)

GGBS is a by-product of the steel manufacturing process and is tapped off from the blast furnace. Crucially, the slag must be quenched once it is extracted otherwise it is only useful as a secondary aggregate. The manufacturing process for GGBS is shown in Figure 3.5.



Slag tapped off from blast furnace | Quenched | Ground down finely | GGBS

Figure 3.5: GGBS manufacturing process

Source: (ACI, 2000)
Images sourced from Google image search (see list of tables and figures for URLs)

As a result of the fact that the slag is a waste product, its CO_2 credentials relative to Portland cement are very low. GGBS is a latent hydraulic binder and must be activated with some Portland cement in order to be useful. Replacement content can be as high as 95% if carefully controlled. One of the main issues with its use is its slower initial strength gain. Cement combinations with GGBS are known as CEM III (BSi, 2006a).

GGBS is widely available and is already used in half of all ready-mixed concrete deliveries. As well as a cement replacement it is also used for in-situ soil stabilisation (Madhabushi, Personal Communication, 2012). GGBS is rarely used for small-scale application and in 2008 two million tonnes of GGBS was sold in the UK (Higgins, Sear, King, Price, Barnes, & Clear, 2011).

3.3.3 Pulverised Fuel Ash (PFA)

Like GGBS, PFA is a waste product. It derives from the burning of coal in power station furnaces. The ash requires no further processing in order for it to be used as a cement replacement. However, it is often ground more finely, enhancing its properties (e.g. reducing the water demand of the mix) (Sear & Owens, 2006). Cement combinations with PFA are known as CEM II.

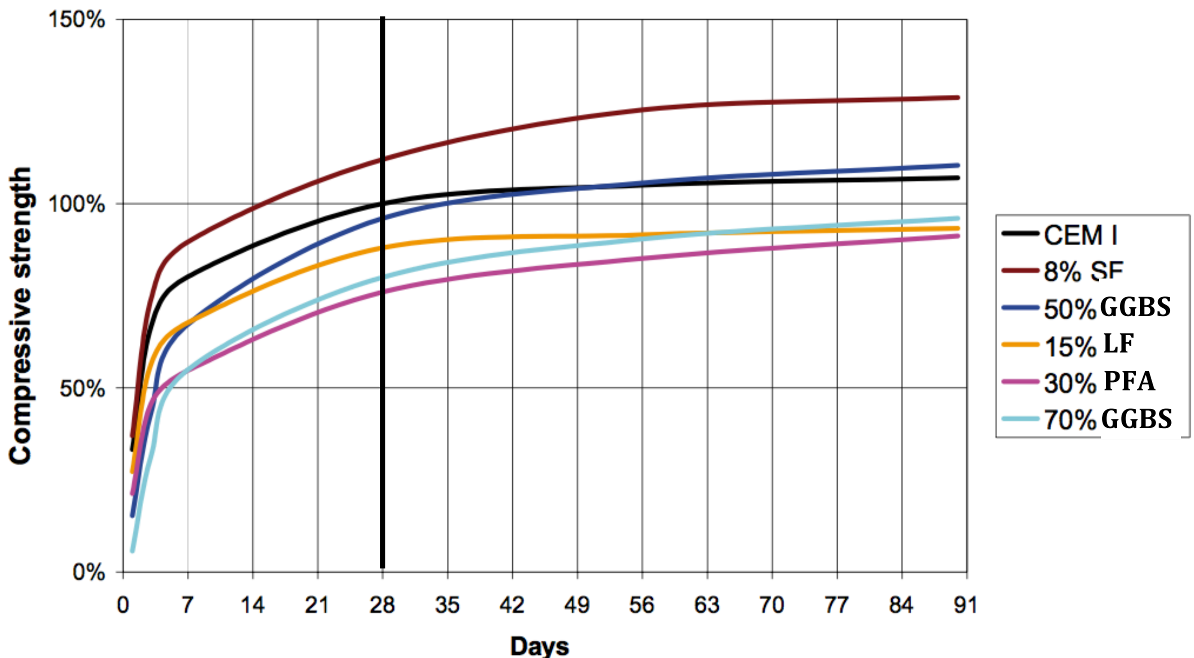
As with GGBS its use results in much slower initial strength gain. It is virtually inert at low ages (Hobbs, 1980). This is because it does not react with water alone but with the Carbon Hydroxide produced by the hydration of Portland cement. Thus, PFA is typically used in proportions of 30-50% with Portland cement (Higgins, Sear, King, Price, Barnes, & Clear, 2011).

Around 0.5 million tonnes of PFA were sold in the UK in 2008. According to some research undertaken by Ed Sauven at Buro Happold there is considerable potential to increase its use. Some 55Mt of PFA is currently stockpiled across the UK (Sauven & Addis, Personal Communication, 2012). The properties of PFA and GGBS are compared in Table 3.8. This highlights the potential barriers to its use.

3.3.4 Properties of cement replacements

The use of GGBS and PFA as cement replacements has a number of effects on the properties of concrete when compared to the use of 100% Portland cement. This often means that they cannot be used in some situations. These properties are summarised in Table 3.8.

One of the key issues is with strength development. Figure 3.6 compares the strength development of various cement replacements. The total cementitious content was kept constant for this analysis. The use of PFA performs particularly badly. GGBS causes less of an issue but will still require some increase in cementitious content to reach specified 28-day strengths. However, it is key to note that for these cements more strength develops later on. If a design team could justify specifying concrete strengths beyond 28 days (at 56 days, for example) the total cementitious content when using replacements could be reduced significantly. Thus environmental benefits could be increased.



CEM I = 100% Portland cement, SF = Silica fume, LF =Limestone fines, FA - PFA

Figure 3.6: Effect on strength development of cement replacements relative to 28-day strength
Source: (Higgins, Sear, King, Price, Barnes, & Clear, 2011)

Property	GGBS	PFA
Water demand	Smoother than PC so less water needed to cover particles. However, the reduced specific gravity of GGBS means a greater volume of particles is needed. Overall, this results in a small reduction in water demand[2].	Particles are small and spherical and as a result of the delayed reaction with PC water demand is reduced considerably [4].
Workability	Better dispersion of cementitious particles results in improved workability and ensures it retains its workability for longer[5].	Optimised packing due to spherical particle shape means that less water needed for given workability[1].
Setting time	Increased by 30 minutes (for 50% GGBS proportion) [1].	Increased by minimum of 2 hours (30% PFA), and can be as much as 4 hours if low temperatures[1].
Bleeding	Increased setting time (at high GGBS content) and as a result there is more time for bleeding to occur[1].	Lower permeability, increased cohesiveness and lower water content lead to reduced bleeding[1].
Temperature rise	Reduced peak and time to reach this peak [1] (also see the Shard case study in section 3.3.5)	Significant temperature reduction for 30% PFA[1].
Sensitivity to curing	Large issues with early drying reducing reaction time and affecting long term durability. Limiting GGBS content to 55% can help as well as curing in water[1].	Up to 20% content properties here are the same as PC. Above this the concrete can be more sensitive to poor curing[1].
Strength development	Up to 50% GGBS the same 28-day strength can be achieved with the same total cementitious content. At high GGBS contents and low temperatures the strength development will be much slower[1]. See Figure 3.6.	Increased strength in the long term but typically reduced strength at 28 days[1]. See Figure 3.6.
Striking times	Up to 50% GGBS striking times will not increase significantly to affect the programme[1].	For 30% PFA often does not significantly affect programme but times will increase[1].
Tensile strength	As a proportion of compressive strength it tends to be higher[3].	Tends to be identical to that of pure PC[6].
Permeability	Depends on the degree of hydration but typically permeability is reduced[1].	Pore sizes typically reduced and thus PFA concretes will have lower permeability[1].
Protection from corrosion (carbonation)	Typically very little change from pure PC mixes but tends to be marginally worse[1].	PFA content can reduce PH but alongside reduced permeability the carbonation time is similar to PC[1].
Protection from chlorides	Finer pore structure results in increased resistance to chlorides.	Typically increased[1].
Sulfate resistance	Lower permeability to sulphate ions results in significant improvement[1].	Increased[1].
Acid resistance	Enhanced[1]	Similar to PC, marginal improvement[1].
Freeze-thaw resistance	Essentially the same as for PC concretes. Marginally worse at high GGBS content[1].	Very similar to PC but often marginally worse[1].
Fire resistance	Similar to PC[1].	Similar to PC[1].
Colour	Lighter than PC[1].	Darker than PC[1].
Elastic modulus	Similar to PC[1].	Similar to PC[1].
Creep	Lower than for PC[1].	Lower than with PC[1].
NOTE: PC = Portland Cement		

[1] (Higgins, Sear, King, Price, Barnes, & Clear, 2011) [2] (Wood, 1981) [3] (Fulton, 1974)
[4] (Nustone Environmental Trust, 2000) [5] (Wainwright & Rey, 2000) [6] (Dhir & Munday, 1986)

Table 3.8: Comparison of properties of cement replacements.

3.3.5 Case Study: The Shard – An example of cement replacement use

Built in the centre of London the Shard stands as the tallest building in Europe. Engineer WSP's design for the basement raft slab is over 3m thick and the total volume of the concrete pour was 5,500m^3. The environmental footprint for a pour of this size using 100% Portland cement would have been extremely large. On top of this it would have lead to excessive temperature gain, which could have a considerable effect on durability. To combat this, much analysis was done and the outcome was that 70% GGBS cement replacement was used in the mix.

Concrete expert Christer Isgren of OTB concrete modelled the hydration and heat gain of the slab carefully to ensure temperatures were kept within tolerances. In the end temperatures only rose to a maximum of 50^{o}C some 50 hours after pouring (Isgren & Parker, Personal Communication, 2013). By performing this analysis and employing the use of cement replacements the total slab thickness was minimised and cracking was well controlled.

For upper floors of the Shard, cement replacements were widely used with PFA being the most common. This is a great example of a high profile building utilising effective methods of improving the sustainability of the construction.

3.3.6 Other cements

There is much research being done to come up with new types of cement that have improved properties and improved environmental credentials.

Eco Cement is a combination of Magnesia and PFA and it is mixed with Portland cement. This actually absorbs CO_2 as it cures (Meisel, 2010). Novacem is another innovation which utilises magnesium silicate. It requires less energy to manufacture and absorbs CO_2 throughout its lifetime (Borchers, personal communication, 2012). However, these two options have limited scope in the UK as reserves of Magnesium Oxide are low. Other research is ongoing such as that undertaken by the David Ball Group in Cambridge. Specific details of the product have not been released but it is belived that the cement contains 95% GGBS with the last 5% made of other recycled materials. Thus, it will be a 100% recycled form of cement with no Portland cement content at all.

3.4 Admixtures

Admixtures are added to a concrete mix to enhance its properties. They are typically added in dosages of less than 5% by mass of cement. There are several types which each fulfil a different role as summarised in Table 3.9.

Type	Use
Set-retarding	Delays the initial chemical reactions that take place and reduces the effect of high temperatures that develop. This helps reduce the chance of cracking during the set. These can also work to reduce the water content of the mix and cause some air entrainment
Air entraining	Increased freeze-thaw resistance. Also results in increased workability, reduced bleeding and reduced segregation of fresh concrete. However, compressive strength of the mix is reduced.
Water reducing	Designed to obtain specific concrete strength using less cement. Can give required slump at lower water/cement ratios.
Accelerating	Increased rate of strength development, reducing setting time. Useful for modifying properties for cold weather but can promote steel corrosion.
Shrinkage reducing	Reduced early and long-term drying shrinkage but can reduce strength development.
Super plasticisers	Increased workability especially useful for areas of heavy reinforcement. Good for high strength concrete and can increase freeze thaw resistance.
Corrosion-inhibiting	Slows the corrosion of steel in the concrete reducing maintenance costs may also accelerate early strength development.

Table 3.9: Types and uses of commonly used admixtures.
Source: (Rodriguez, 2012)

From an environmental point of view the most relevant of these is the water-reducing admixture. Water and cement reduction as a result of its use will have considerable implications on a mix's sustainability credentials.

The main barrier to the use of admixtures is that they are often expensive. However, as their use is increased these costs are likely to decrease.

3.4.1 Water-reducing admixture

High-range water reducing admixtures are available as well as normal water reducing types. Use of these can result in reductions in cement content of around 20% (Burridge, Personal Communication, 2013). The implications of this are considerable for the environmental credentials of a mix as will be investigated later in this report.

3.5 Onsite and offsite construction

Traditionally, concrete is poured onsite. The mix is ordered from a suitable batching plant nearby and delivered in trucks. In recent times there has been an increased move to completing construction work offsite. This has considerable implications for the economics of a project and the safety of workers. Offsite facilities can be controlled better and several elements of risk are removed. These benefits are clear but can there be considerable advantages for sustainability by using this method?

Traditional onsite methods often result in waste due to the need to slightly overestimate quantities. In addition to this, quality is often compromised due to a number of variable factors such as the weather or human error. This can result in concrete needing to be broken out and replaced incurring extra cost, environmental damage and time delays. However, batching plants are widely spread and trucks will only have to travel a relatively short distance to site.

Laing O'Rourke are leaders in the field of offsite concrete construction in the UK. Their newly developed plant in Steetley takes inspiration from car manufacturing lines to produce precast concrete elements for buildings. The benefits here from a sustainability point of view include: concrete mixes can easily implement some percentage of cement replacement; any concrete waste can be reprocessed and reused onsite (see Table 3.10), final concrete quality can be improved (especially air tightness) which can result in significant improvement for a building's long term operational costs (Ferguson, 2012) and water use can be reduced as curing conditions are also much simpler to control.

Waste reduction is a key benefit of offsite concrete construction and Table 3.10 compares waste figures for onsite and offsite construction projects since 2006.

Traditional onsite pours		**Predominantly offsite construction**	
Waste (t/100m²)	**Notes**	**Waste (t/100m²)**	**Notes**
17.1	2006 – Poor implementation of SWMP (pre-legislation).	**3.58**	2009 – Tight control over SWMP and processes.
12.6	2008 – Improved control over SWMP and processes.	**2.98**	2011 – Tight control over SWMP and processes.
8	2008 – Tight control over SWMP and processes.	**1.8**	Late 2011 – Tight control over SWMP and processes.

SWMP – Site Waste Management Plans

Table 3.10: Comparison of waste produced using onsite/offsite concrete construction
Source: (Rose, personal communication, 2013a)

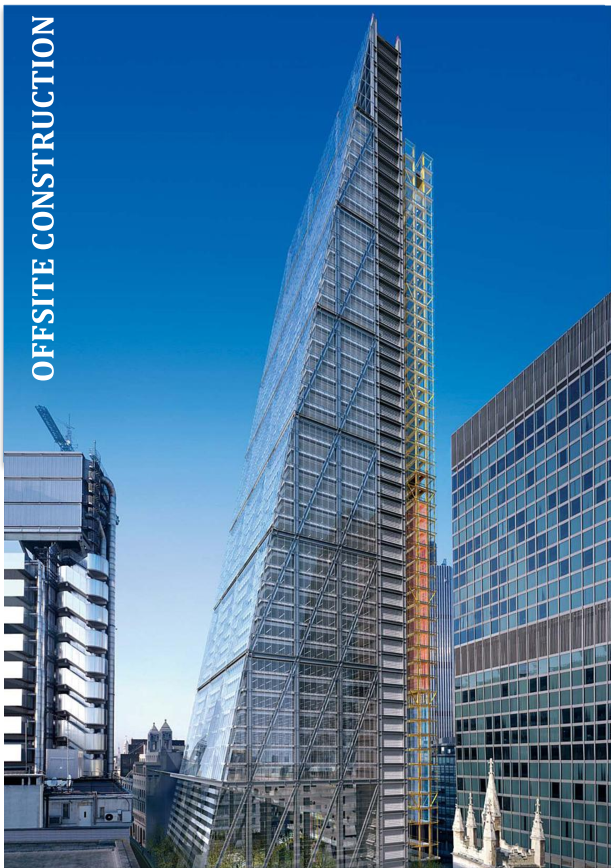
This shows that waste can be reduced by as much as 78% by offsite concrete construction even if tight controls are implemented for onsite concrete construction.

However, Steetley is the only plant of its kind located near Sheffield (Laing O'Rourke, 2013). As with the recycled aggregate, benefits are soon outweighed by transport costs with increasing distance to site. The distance to sites in London is over 250km. Before any considerable environmental gains can be achieved by using offsite concrete construction, more plants must be built nearer to key locations. However, it must first be determined whether or not this method will actually result in considerable gain from other points of view.

To demonstrate the benefits of using offsite concrete construction two case studies have been prepared. Leadenhall Street is currently under construction by Laing O’Rourke. The Shard was designed by WSP in London and was completed in 2012. The Shard used traditional onsite concrete pouring methods while the floors at Leadenhall Street are largely fabricated using offsite construction methods.

The key advantages and disadvantages are clear using these case studies. Use of offsite concrete construction represents some reduction in waste produced (although less marked than as shown in Table 3.10). However, transport distances and cement replacement use can negate this. Offsite concrete construction plants are reluctant to use a high proportion of cement replacements as the delayed setting times will result in bottlenecks for production. Transport distances are a larger issue as offsite construction plants will never be as widespread as concrete batching plants for insitu pouring. While this will vary between applications, this is a key issue with offsite manufacture that should be addressed.

Overall, offsite concrete construction does not represent any improvement environmentally and can often lead to being less so, especially if waste protocol for onsite construction methods continues to improve.



The Shard WSP + Byrne Brothers			Leadenhall Street Arup + Laing O'Rourke	
309m high-rise development at London Bridge using traditional onsite concrete construction. 97.7% average recycling rate.		**SUMMARY**	Targets: 85% offsite fabrication. 60% reduction of offsite labour. 30% reduced programme time.	
Insitu basement and concrete core to 260m. Concrete on metal deck to level 40. Post-tensioned to level 72.		**SCHEME**	Below 5th floor poured onsite, all other concrete delivered from offsite construction plant.	
tonnes/100m² concrete	5.53	**WASTE**	3.5	tonnes/100m² concrete
-		**WATER**	2.4	m³/100kg concrete
All materials sourced locally from manufacturing plants.		**TRAFFIC**	35%	Reduced traffic load onsite.
Distance by road from concrete plant to site.	4km	**TRANSPORT**	250km	Distance by road from concrete plant to site.
GGBS in slipform mix (dependant on height).	10-30%	**OTHER**	20%	GGBS in offsite concrete mixes.

Source: (Houston, personal communication, 2013)

Source: (Rose, personal communication, 2013b)

3.6 Demolition and recycling

As has already been mentioned, upon demolition, crushed concrete can be reused as an aggregate in construction. Its quality can sometimes be debateable and its use in structural concrete may not be suitable (as this report investigates). However, its use for low strength grades and other scenarios often makes sense to avoid expensive landfill taxes and achieve improved sustainability credentials.

Recycling aggregate in this manner is at such a position in the UK that only a tiny amount makes its way to landfill. In other countries such as the Netherlands, demolition concrete is banned from landfill sites (CSI, 2009). Thus the waste disposal credentials of concrete are good.

However, emphasis must be put on sourcing recycling waste from a demolition site located nearby to the proposed construction location. Otherwise the CO_2 emissions associated with its transport will outweigh any gains.

3.6.1 Recycling concrete waste onsite – Re-con Zero

Developed by Mapei, Re-con Zero allows for any waste concrete produced on site to be processed quickly so that it may be reused. Currently, aggregate is reclaimed by separating the cementitious component or adding a chemical stabiliser. This is both expensive and difficult to maintain. Re-con Zero works in the following way (for 1m^3 of concrete waste):

1. Add 0.5kg of Re-con Zero mix to the waste concrete.
2. Mix for 4 minutes
3. Add 6 more 1kg bags of Re-con Zero
4. Mix for 3 minutes
5. Aggregate is now fully reusable.

Mapei claim this has zero net impact. This is an innovative solution that could eliminate waste for concrete pours (NCE, 2013).

4 Assessment methodology

The various stages of concrete manufacture have already been discussed in some detail. The aim of this investigation is to compare and contrast the effect that different decisions have on the overall sustainability of a concrete mix. To achieve this several decisions will be considered. These are shown below in Figure 4.1.

STRENGTH	C30/37	C40/50	C50/60
AGGREGATE	100% VIRGIN AGGREGATE	25% RECYCLED AGGREGATE	100% RECYCLED AGGREGATE
CEMENT	100% PORTLAND CEMENT	50% GGBS	30% PFA
ADMIXTURE	NO ADMIXTURE	WATER REDUCING ADMIXTURE	

Figure 4.1: Concrete decisions matrix.

The objective of the assessment is to compare the effect of each decision made. For example: what effect does use of recycled aggregate have? How much difference does use of a water-reducing admixture have on the environmental impact of a mix? The relative impact of each set of decisions is most important to assess.

In order to find the relative impact a baseline must first be set. For the purposes of this investigation a 'Standard mix' will be set up. This is shown in by means of grey shading in Figure 4.1 for C40/50 strength. The standard mixes for the other strength grades are similar. The remaining mixes will be normalised to this so that the relative effect of any decision can be measured.

4.1 Mix designs

To start with, raw values for the constituents of mixes are needed. As already discussed, concrete is a very versatile material and the mix is often tailored to a specific situation. Sometimes cement contents might change by as much as ±20kg/m^3 from one day to the next. This can be due to the weather or any feedback relating to conditions of other recent pours (Birkinshaw, personal communication, 2013). For the purposes of this investigation typical mixes are taken as specified in a study undertaken by Arup. Table 4.1 breaks down the typical constituents of 3 different concrete mix designs.

Strength →	RC30/37			RC40/50			RC50/60		
Constituent ↓	**PC**	**PFA**	**GGBS**	**PC**	**PFA**	**GGBS**	**PC**	**PFA**	**GGBS**
Cement	290	231	148	350	287	183	420	329	223
PFA	-	99	-	-	123	-	-	141	-
GGBS	-	-	147	-	-	182	-	-	223
Sand	826	773	822	773	690	760	630	560	590
Coarse Aggregate	1053	1076	1045	1066	1091	1068	1180	1180	1180
Water	176	164	175	174	165	174	175	165	175

All values kg/m^3

PC: 100% Portland Cement PFA: 30% PFA GGBS: 50% GGBS

Table 4.1: Typical concrete mix designs.

Source: (Arup, 2006)

These values will form the basis of any calculations and once again the standard mix is shown in grey. Other mixes that use recycled aggregate and water-reducing admixtures will be defined relative to these mixes using the rules highlighted below.

From here calculations will be broken down into the four key environmental impacts: climate change, water extraction, mineral resource extraction and waste disposal.

4.2 Climate change (CO_2)

This will be measured in kg CO_2/m^3 concrete for this investigation. It can be broken down into each of the constituents and what they each contribute to the overall impact.

4.2.1 Cement

The raw values for the embodied CO_2 of Portland cement, PFA and GGBS are shown in Table 4.2. These values are from cradle to factory gate and do not include transport to the concrete plant or transport to site.

Cement type	Embodied CO_2	Units
Portland cement	0.913	kg CO_2/kg Portland cement
GGBS	0.067	kg CO_2/kg GGBS
PFA	0.004	kg CO_2/kg PFA

Table 4.2: Embodied CO_2 of Portland cement and cement replacements

Source: (MPA, 2010)

Transport costs here are difficult to estimate but the industry average is quoted as 0.011 kg CO_2/kg for transport to the concrete plant (MPA, 2010). So, for a mix with 30% PFA and 70% Portland cement:

$$TOTAL\ CO_2 = \left((0.913 + 0.011) \times kgPC/m^3\right) + \left((0.004 + 0.011) \times kgPFA/m^3\right)$$

For RC40/50 with 30% PFA (as shown in Table 4.1):

$$TOTAL\ CO_2 = (0.924 \times 287) + (0.015 \times 123) = \mathbf{267\ kg\ CO_2/m^3}$$

4.2.2 Aggregate

In section 3.2.5 it was shown that recycled aggregate could replace virgin aggregate by weight for these mixes. In order to determine the embodied CO_2 for recycled aggregate see Section 3.2.2 and Table 3.5. This is shown below in Table 4.3 for clarity.

Aggregate type	Embodied CO_2	Units
Virgin	0.066	kg CO_2/kg virgin aggregate
Recycled	0.079	kg CO_2/kg recycled aggregate

Table 4.3: Embodied CO_2 of virgin and recycled aggregate

Source: (Turner, 2009)

The distance travelled to the construction site will not be considered here. This will vary a lot between applications. Calculations will not go beyond the concrete plant.

4.2.3 Admixtures

High range water-reducing admixtures are used in relatively small quantities, typically at around 1.5% by weight of cement; this is the value that will be used for this assessment (CAA, 2006). The embodied CO_2 is calculated as 0.72 kg CO_2/kg admixture (EFCA, 2006).

4.2.4 Water

The embodied CO_2 associated with the use of water is estimated at 0.3 kg/m^3 water (The Concrete Centre, 2008).

4.3 Water extraction (WE)

This is only affected by the amount of water used in a mix. This is defined in Table 4.1 for typical mixes. However, the use of recycled aggregate increases the water used. For 25% recycled aggregate water demand is increased by 5%. For 100% recycled aggregate water demand is increased by 20% (Malesev, Radonjanin, & Marinkovic, 2010).

The use of water-reducing admixtures can also reduce water quantity by 20% (or more) (CAA, 2006).

Typically, all water used to wash out trucks is recycled (Burridge, personal communication, 2013) and so will not be considered in this investigation.

4.4 Mineral resource extraction (MRE)

Any material consumption that reduces the amount available for future generations will count towards this. So only the use of recycled aggregate, PFA and GGBS will not be included here. All other constituents will.

For the example shown in Section 3.2.5 the use of recycled aggregate demands less total aggregate by around 5% for a mix using 100% recycled aggregate. This will be taken into account but the effects will be small. The recycled aggregate is assumed to be of good quality and as a result it will not alter the cement content of the mix.

Water-reducing admixtures will be taken to reduce the cement content of the mix by 20% (Burridge, personal communication, 2013).

4.5 Waste disposal (WD)

As already mentioned, almost all concrete can be recycled upon demolition and this will not vary much between mixes. A uniform value will be used across the board here. Using this measure is important to evaluate the overall performance of a mix.

Use of offsite construction versus onsite construction may be considered as an aside in the discussion section following these results. Use of Re-con Zero will not be considered but it is noted that this can also result in considerable improvements for waste disposal.

5 Results

The results for the assessments are shown in Tables 5.1, 5.2 and 5.3. The numbers are found using the rules discussed in Section 4. The lifecycle is only considered up to the concrete factory gate. After this, values will be more variable from project to project.

The raw numbers output for each environmental impact under each mix do not mean much on their own. In order to make sense of these numbers to allow for meaningful comparison they must be normalised and given a weighting.

To normalise the data, values are related to the standard mix within each strength category. For example, in Table 5.2 the normalised value for climate change (CO_2) for mix number 5 is found as follows:

CO_2 *(Standard Mix)* = 336 $kgCO_2/m^3$ CO_2 *(Mix 5)* = 279 $kgCO_2/m^3$

CO_2 *(Normalised for Mix 5)* = 279/336 = **0.83**

This is repeated for all the values in the table. They are all related to the standard mix for that strength class.

In order to find the total environmental impact of a mix, importance weightings are applied to each of these normalised values. These weightings are based on those given in the BRE Green Guide (see Section 2.2). The weighting is applied in the following way (staying with the example above):

CO_2 *(Normalised for Mix 5)* = 0.83 *Importance weighting for* CO_2 = 0.43

CO_2 *(Weighted for Mix 5)* = 0.83 × 0.43 = **0.36**

The different weightings are applied to each environmental impact for each mix and summed to give each mix a rating. The standard mix will get a rating of 1. If a mix's rating falls below 1 it is more environmentally friendly, if above 1 it is less. By looking at these results the effect of each of the decisions can be quantified and compared.

The discussion following will focus on what can be learned from these tables and how the lessons learned can be applied to future mix designs.

Mix	Strength	**RC30/37 70mm**																	
	Aggregate	100% Virgin Aggregate						25% Recycled Aggregate						100% Recycled Aggregate					
	Cement	100% PC		50% GGBS		30% PFA		100% PC		50% GGBS		30% PFA		100% PC		50% GGBS		30% PFA	
	Admixture?	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
	Name	**STANDARD**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Climate Change CO2 (kgCO2/m3)	Cement	268	214	137	109	213	171	268	214	137	109	213	171	268	214	137	109	213	171
	GGBS			11	9					11	9					11	9		
	PFA					1	1					1	1					1	1
	Virgin Coarse Aggregate	7	7	7	7	7	7	5	5	5	5	5	5						
	Sand	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	Recycled Aggregate							2	2	2	2	2	2	8	8	8	8	8	8
	Admixture		3		3		2		3		3		3		3		3		3
	Water	0.05	0.04	0.05	0.04	0.05	0.04	0.06	0.04	0.05	0.04	0.05	0.04	0.06	0.05	0.06	0.05	0.06	0.05
	TOTAL	280	229	161	133	227	186	281	230	161	134	227	187	281	230	161	134	228	188
Water Extraction (m3/m3)	Water in mix	0.176	0.141	0.174	0.139	0.165	0.132	0.185	0.148	0.183	0.146	0.173	0.139	0.211	0.169	0.209	0.167	0.198	0.158
	TOTAL	0.176	0.141	0.174	0.139	0.165	0.132	0.185	0.148	0.183	0.146	0.173	0.139	0.211	0.169	0.209	0.167	0.198	0.158
Mineral Resource Extraction (kg/m3)	Cement	290	232	148	118.4	231	184.8	290	232	148	118.4	231	184.8	290	232	148	118.4	231	184.8
	GGBS			147	117.6					147	117.6					147	117.6		
	PFA					99	79.2					99	79.2					99	79.2
	Coarse Aggregate	1053	1053	1045	1045	1076	1076	780	780	774	774	797	797						
	Sand	826	826	822	822	773	773	816	816	812	812	763	763	785	785	781	781	734	734
	Recycled Aggregate							260	260	258	258	266	266	1000	1000	993	993	1022	1022
	Admixture		3.5		3.5		2.8		3.5		3.5		4.0		3.5		3.5		4.0
	Not included in TOTAL																		
	TOTAL	2169	2114	2015	1989	2080	2037	1886	1831	1734	1708	1791	1749	1075	1020	929	903	965	923
Waste Disposal (kg/m3)	Average Waste	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	TOTAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Normalised	**CO2**	1.00	0.82	0.57	0.48	0.81	0.66	1.00	0.82	0.57	0.48	0.81	0.67	1.00	0.82	0.58	0.48	0.81	0.67
	WE	1.00	0.80	0.99	0.79	0.94	0.75	1.05	0.84	1.04	0.83	0.98	0.79	1.20	0.96	1.19	0.95	1.13	0.90
	MRE	1.00	0.97	0.93	0.92	0.96	0.94	0.87	0.84	0.80	0.79	0.83	0.81	0.50	0.47	0.43	0.42	0.45	0.43
	WD	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	TOTAL	4.00	3.59	3.49	3.18	3.71	3.35	3.92	3.50	3.41	3.09	3.62	3.26	3.70	3.25	3.19	2.84	3.38	3.00
Weighted																			
0.43	**CO2**	0.43	0.35	0.25	0.20	0.35	0.29	0.43	0.35	0.25	0.20	0.35	0.29	0.43	0.35	0.25	0.21	0.35	0.29
0.23	**WE**	0.23	0.18	0.23	0.18	0.22	0.17	0.24	0.19	0.24	0.19	0.23	0.18	0.28	0.22	0.27	0.22	0.26	0.21
0.19	**MRE**	0.19	0.19	0.18	0.17	0.18	0.18	0.17	0.16	0.15	0.15	0.16	0.15	0.09	0.09	0.08	0.08	0.08	0.08
0.15	**WD**	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	TOTAL	1.00	0.87	0.80	0.71	0.90	0.79	0.99	0.86	0.79	0.70	0.88	0.77	0.95	0.81	0.75	0.65	0.84	0.73

KEY

PC	Portland Cement
GGBS	Ground Granulated Blast Furnace Slag
PFA	Pulverised Fuel Ash

Worst — **Colour coding** — **Best**

Cell contains value

TABLE 5.1 **Results for strength class RC30/37**

Mix	Strength	RC40/50 70mm																	
	Aggregate	100% Virgin Aggregate						25% Recycled Aggregate						100% Recycled Aggregate					
	Cement	100% PC		50% GGBS		30% PFA		100% PC		50% GGBS		30% PFA		100% PC		50% GGBS		30% PFA	
	Admixture?	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
	Name	**STANDARD**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
CO2 (kgCO2/m3)	Cement	323	259	169	135	265	212	323	259	169	135	265	212	323	259	169	135	265	212
	GGBS			14	11					14	11					14	11		
	PFA					2	1					2	1					2	1
	Virgin Coarse Aggregate	7	7	7	7	7	7	5	5	5	5	5	5						
	Sand	5	5	5	5	5	5	5	5	5	5	4	4	5	5	5	5	4	4
	Recycled Aggregate							2	2	2	2	2	2	8	8	8	8	8	8
	Admixture		3		3		2		3		3		4		3		3		4
	Water	0.05	0.04	0.05	0.04	0.05	0.04	0.05	0.04	0.05	0.04	0.05	0.04	0.06	0.05	0.06	0.05	0.06	0.05
	TOTAL	336	274	195	162	279	228	336	274	196	162	279	229	336	275	196	163	280	230
Water Extraction (m3/m3)	Water in mix	0.174	0.139	0.174	0.139	0.165	0.132	0.183	0.146	0.183	0.146	0.173	0.139	0.209	0.167	0.209	0.167	0.198	0.158
	TOTAL	0.174	0.139	0.174	0.139	0.165	0.132	0.183	0.146	0.183	0.146	0.173	0.139	0.209	0.167	0.209	0.167	0.198	0.158
Mineral Resource Extraction (kg/m3)	Cement	350	280	183	146.4	287	229.6	350	280	183	146.4	287	229.6	350	280	183	146.4	287	229.6
	GGBS			182	145.6					182	145.6					182	145.6		
	PFA					123	98.4					123	98.4					123	98.4
	Coarse Aggregate	1066	1066	1068	1068	1091	1091	790	790	791	791	808	808						
	Sand	773	773	760	760	690	690	763	763	751	751	681	681	734	734	722	722	656	656
	Recycled Aggregate							263	263	264	264	269	269	1013	1013	1015	1015	1036	1036
	Admixture		4.2		4.4		3.4		4.2		4.4		4.9		4.2		4.4		4.9
	Not included in TOTAL																		
	TOTAL	2189	2123	2011	1979	2068	2014	1903	1837	1724	1692	1776	1724	1084	1019	905	873	943	890
Waste Disposal (kg/m3)	Average Waste	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	TOTAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Normalised	**CO2**	1.00	0.82	0.58	0.48	0.83	0.68	1.00	0.82	0.58	0.48	0.83	0.68	1.00	0.82	0.58	0.48	0.83	0.68
	WE	1.00	0.80	1.00	0.80	0.95	0.76	1.05	0.84	1.05	0.84	1.00	0.80	1.20	0.96	1.20	0.96	1.14	0.91
	MRE	1.00	0.97	0.92	0.90	0.94	0.92	0.87	0.84	0.79	0.77	0.81	0.79	0.50	0.47	0.41	0.40	0.43	0.41
	WD	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	TOTAL	4.00	3.59	3.50	3.19	3.72	3.36	3.92	3.50	3.42	3.10	3.64	3.27	3.70	3.24	3.20	2.84	3.40	3.00
Weighted																			
0.43	**CO2**	0.43	0.35	0.25	0.21	0.36	0.29	0.43	0.35	0.25	0.21	0.36	0.29	0.43	0.35	0.25	0.21	0.36	0.29
0.23	**WATER**	0.23	0.18	0.23	0.18	0.22	0.17	0.24	0.19	0.24	0.19	0.23	0.18	0.28	0.22	0.28	0.22	0.26	0.21
0.19	**MRE**	0.19	0.18	0.17	0.17	0.18	0.17	0.17	0.16	0.15	0.15	0.15	0.15	0.09	0.09	0.08	0.08	0.08	0.08
0.15	**WASTE**	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	TOTAL	1.00	0.87	0.80	0.71	0.90	0.79	0.99	0.85	0.79	0.70	0.89	0.78	0.95	0.81	0.76	0.65	0.85	0.73

KEY

PC	Portland Cement
GGBS	Ground Granulated Blast Furnace Slag
PFA	Pulverised Fuel Ash

Worst — **Colour coding** — **Best**

Cell contains value

TABLE 5.2 **Results for strength class R40/50**

Mix	Strength	RC50/60 70mm																	
	Aggregate	100% Virgin Aggregate						25% Recycled Aggregate						100% Recycled Aggregate					
	Cement	100% PC		50% GGBS		30% PFA		100% PC		50% GGBS		30% PFA		100% PC		50% GGBS		30% PFA	
	Admixture?	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
	Name	**STANDARD**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
CO2 (kgCO2/m3)	Cement	388	310	206	165	304	243	388	310	206	165	304	243	388	310	206	165	304	243
	GGBS			17	14					17	14					17	14		
	PFA					2	2					2	2					2	2
	Virgin Coarse Aggregate	8	8	8	8	8	8	6	6	6	6	6	6						
	Sand	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	Recycled Aggregate							2	2	2	2	2	2	9	9	9	9	9	9
	Admixture		4		4		3		4		4		4		4		4		4
	Water	0.05	0.04	0.05	0.04	0.05	0.04	0.06	0.04	0.06	0.04	0.05	0.04	0.06	0.05	0.06	0.05	0.06	0.05
	TOTAL	400	326	235	194	318	259	400	326	235	194	318	261	401	327	236	195	319	261
Water Extraction (m3/m3)	Water in mix	0.175	0.140	0.175	0.140	0.165	0.132	0.184	0.147	0.184	0.147	0.173	0.139	0.210	0.168	0.210	0.168	0.198	0.158
	TOTAL	0.175	0.140	0.175	0.140	0.165	0.132	0.184	0.147	0.184	0.147	0.173	0.139	0.210	0.168	0.210	0.168	0.198	0.158
Mineral Resource Extraction (kg/m3)	Cement	420	336	223	178.4	329	263.2	420	336	223	178.4	329	263.2	420	336	223	178.4	329	263.2
	GGBS			223	178.4					223	178.4					223	178.4		
	PFA					141	112.8					141	112.8					141	112.8
	Coarse Aggregate	1180	1180	1180	1180	1180	1180	874	874	874	874	874	874						
	Sand	630	630	560	560	560	560	622	622	553	553	553	553	599	599	532	532	532	532
	Recycled Aggregate							291	291	291	291	291	291	1121	1121	1121	1121	1121	1121
	Admixture		5.0		5.4		3.9		5.0		5.4		5.6		5.0		5.4		5.6
	Not included in TOTAL																		
	TOTAL	2230	2151	1963	1924	2069	2007	1916	1837	1650	1611	1756	1696	1019	940	755	716	861	801
Waste Disposal (kg/m3)	Average Waste	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	TOTAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Normalised	**CO2**	1.00	0.82	0.59	0.49	0.79	0.65	1.00	0.82	0.59	0.49	0.79	0.65	1.00	0.82	0.59	0.49	0.80	0.65
	WE	1.00	0.80	1.00	0.80	0.94	0.75	1.05	0.84	1.05	0.84	0.99	0.79	1.20	0.96	1.20	0.96	1.13	0.91
	MRE	1.00	0.96	0.88	0.86	0.93	0.90	0.86	0.82	0.74	0.72	0.79	0.76	0.46	0.42	0.34	0.32	0.39	0.36
	WD	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	TOTAL	4.00	3.58	3.47	3.15	3.66	3.30	3.91	3.48	3.38	3.05	3.57	3.20	3.66	3.20	3.13	2.77	3.31	2.92
Weighted																			
0.43	**CO2**	0.43	0.35	0.25	0.21	0.34	0.28	0.43	0.35	0.25	0.21	0.34	0.28	0.43	0.35	0.25	0.21	0.34	0.28
0.23	**WE**	0.23	0.18	0.23	0.18	0.22	0.17	0.24	0.19	0.24	0.19	0.23	0.18	0.28	0.22	0.28	0.22	0.26	0.21
0.19	**MRE**	0.19	0.18	0.17	0.16	0.18	0.17	0.16	0.16	0.14	0.14	0.15	0.14	0.09	0.08	0.06	0.06	0.07	0.07
0.15	**WD**	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	TOTAL	1.00	0.87	0.80	0.71	0.88	0.77	0.99	0.85	0.78	0.69	0.87	0.76	0.94	0.80	0.74	0.64	0.83	0.71

KEY

PC	Portland Cement
GGBS	Ground Granulated Blast Furnace Slag
PFA	Pulverised Fuel Ash

Worst — **Colour coding** — **Best**

Cell contains value

TABLE 5.3 **Results for strength class RC50/60**

6 Discussion

The information presented thus far is intended to give a general perspective on the sustainable use of concrete. In practice each situation is different. While a certain situation may open doors for sustainability, another might close them. The properties of any particular mix need to be carefully controlled and that can change from day to day let alone from project to project. The intention of the assessment is to give a direct comparison of the effects that different decisions will have. For the use of cement replacements both typical and extreme measures have been included.

To start with, in this section, the key points that emerge from the assessment will be discussed with regard to the environmental effect of different decisions. Following on from this a more general approach is developed. Can an environmental calculator using data from this experiment be used? How can principles be applied in practice?

Assembling stacks based on weighted values for the four environmental criteria compares mixes. This visual allows differences to be presented clearly for the reader. Table 5.2 for C40/50 concrete will be the main basis for consideration.

6.1 Effect of water-reducing admixtures

Figure 6.1 shows the comparison between the Standard Mix and Mix 2 in Table 5.2.

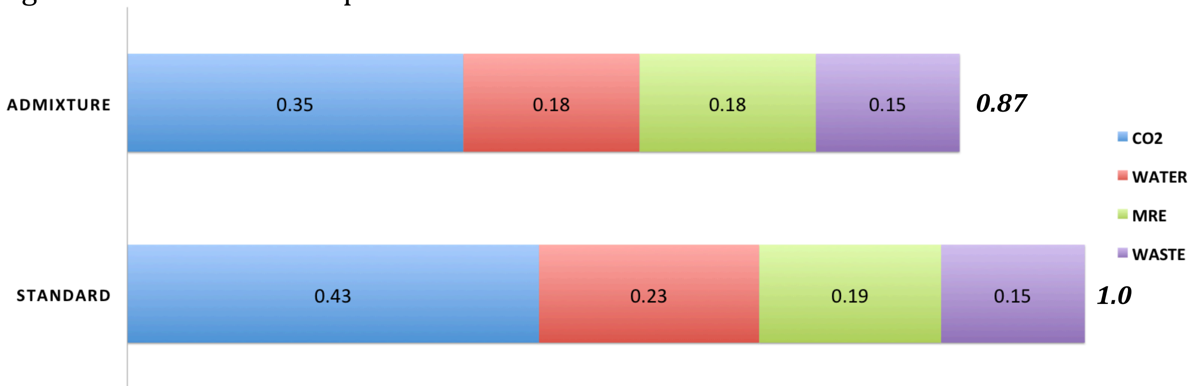


Figure 6.1: Effect of water reducing admixtures on environmental impact.
Source: Table 5.2

Overall, the weighted impact is 13% less. This results from the addition of 4.2kg/m^3 of admixture. The gains here are great and simple to achieve. This is due to the fact that water-reducing admixtures reduce the cement content (which has the biggest impact on the CO_2 of the mix) and water content. As can be seen in Figure 6.1, this is where the gains are made. The effect will be the same for every mix and so admixtures must be considered key to achieving more sustainable use of concrete. Especially as they become less expensive.

6.2 Effect of GGBS

Figure 6.2 compares the Standard Mix, Mix 3 and a mix using the maximum proportion of GGBS allowed in the codes (80%) for RC40/50 concrete.

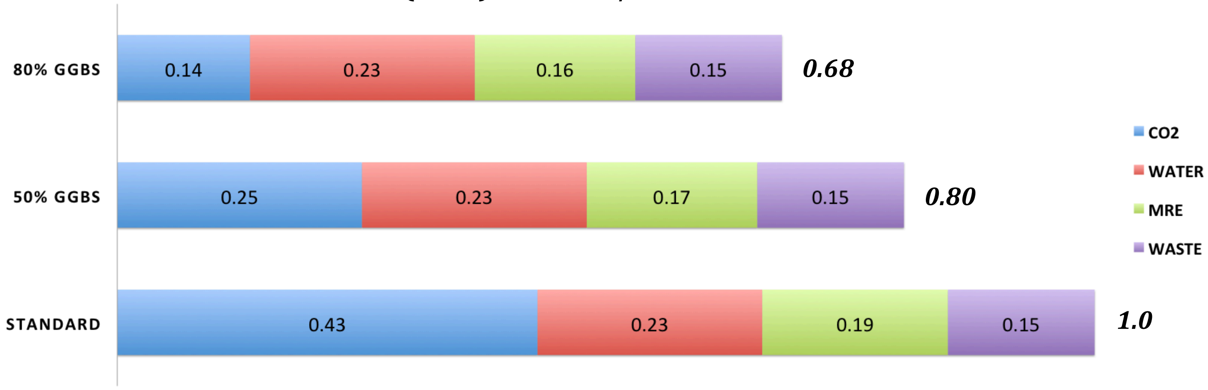


Figure 6.2: Effect of cement replacement by GGBS on environmental impact.
Source: Table 5.2

Here the total weighted impact is reduced by 20% for 50% GGBS and by 32% for 80% GGBS. The majority of this comes from the CO_2 reduction as a result of lessening the amount of Portland cement in the mix. While GGBS has some CO_2 associated with its use it is much less than that of Portland cement. GGBS is already widely used and the reason for this is backed up here. The improvement is significant.

Care must be taken when using GGBS and reference must be made to Section 3.3 where GGBS's effect on concrete properties are discussed. 50% is a typical quantity of GGBS in a mix but the codes allow for mixes to contain up to 80% if the conditions allow it (Clear & Sear, 2006).

6.3 Effect of PFA

Figure 6.3 compares the Standard Mix with Mix 5 in Table 5.2. The extreme of replacement by PFA allowed by the codes of 60% is also shown.

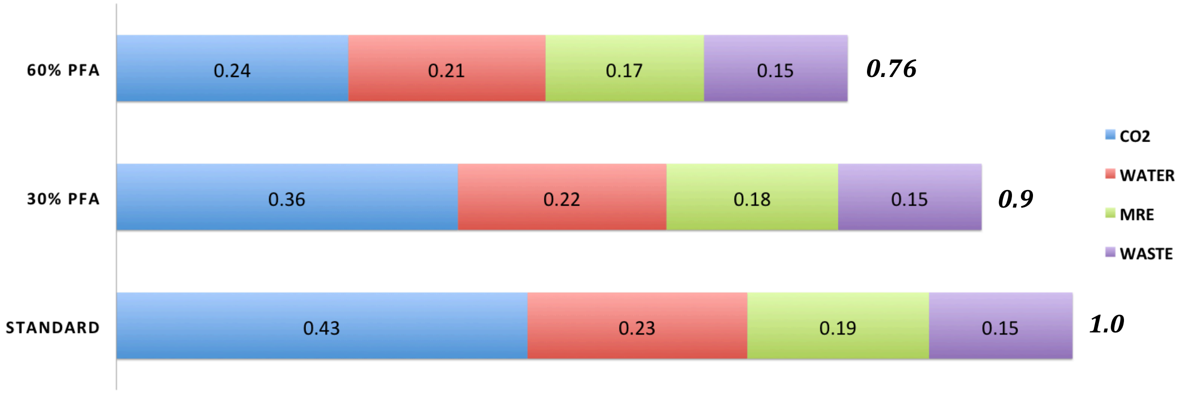


Figure 6.3: Effect of cement replacement by PFA on environmental impact

Source: Table 5.2

Typically, the environmental impact is reduced by 10% using 30% PFA. This is not quite as marked as for GGBS despite PFA having a much lower associated CO_2 content. The reason for this is that while PFA use does reduce the amount of cement in a mix, the total cementitous content has to go up. This is because strength is still being specified at 28 days for this mix and (as is shown in Figure 3.6) the strength of PFA replacement cement takes longer to develop. In order to get more benefit from the use of PFA, strengths should be quoted later on (for example, at 56 days).

The maximum replacement % of PFA as specified by codes is 60% (BSi, 2003). This has the effect of reducing the environmental impact by 24% as shown in Figure 6.3. This performs slightly better than 50% GGBS. Again this is due to the delayed strength gain effects. The more PFA that is included, the worse this becomes. The strength of this mix past 28 days will far exceed that for which it was designed.

PFA provides considerable advantages. The UK has large stockpiles that, if utilised, could help to improve the sustainable use of concrete across the country significantly. Benefits could be increased even more if strengths were specified at 56 days rather than at 28. This is not unrealistic. For example, in construction of a high-rise building the piles, raft slab and lower columns will not experience their full design load until the upper floors are constructed. They do not need full strength at 28 days, later strength development is realistically acceptable.

6.4 Effect of recycled aggregate

The best comparison is threefold, across the Standard Mix, Mix 7 and Mix 13.

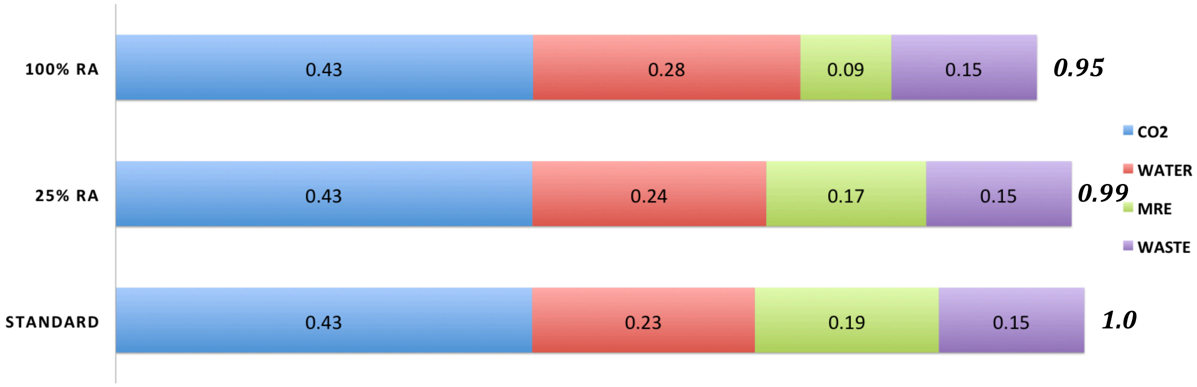


Figure 6.4: Effect of recycled aggregate on environmental impact.
Source: Table 5.2

The environmental impact is reduced by 1% and 5% respectively between mixes 7 and 13. This is very small because the effect on CO_2 content is negligible and both water and mineral resource extraction are conflicting. While use of recycled aggregate reduces the amount of virgin resources extracted, it results in a considerable increase in water content. The effect is very slightly positive overall.

Issues with the use of recycled aggregate have already been discussed in detail but it is worth highlighting that transport has not been taken into account here. On top of this, if the recycled aggregate is of relatively low quality the cement content may need to increase. This will certainly result in an adverse effect on the environmental impact of the mix.

The interactions with respect to recycled aggregate are somewhat complex and there are numerous factors involved. However, it must be noted that its use for structural concrete applications is not very sensible from an environmental point of view as supported by this investigation.

6.5 Effect of strength

Finally the effect of strength can be compared. This is inversely proportional to the water/cement ratio. Figure 6.5 shows the comparison using RC40/50 strength concrete as the reference for normalisation.

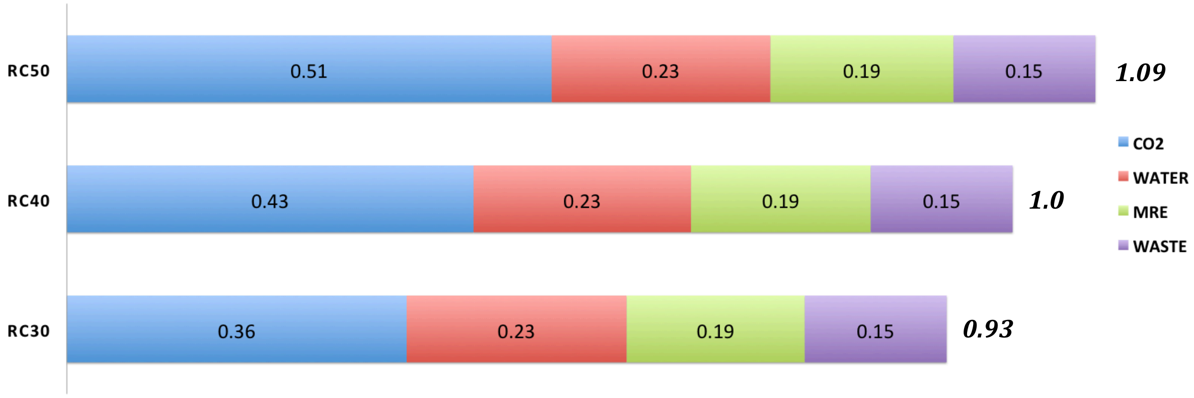


Figure 6.5: Comparison of the effects of concrete strength on environmental impact.
Source: Tables 5.1, 5.2 and 5.3

RC50/60 concrete is 9% less environmentally friendly and RC30/37 is 7% more environmentally friendly than RC40/50 concrete. This is as expected but it does reveal a trend that as concrete gets stronger its impact on the environment is more adverse.

There is not time to do a full analysis on whether using a higher strength concrete (requiring less material) will end up being more environmentally friendly despite the mix itself being worse per m^3. However, according to this investigation in order for use of RC50/60 concrete to make sense environmentally compared to RC40/50 it must be proved that the design will be 9% more material efficient.

It is specified in the codes that for strengths of over RC50/60 (such as RC90/105) there are numerous design rule changes. On top of this the mix design is increasingly complex, with use of extra fine material and Silica Fume needed to achieve the desired strength (Birkinshaw, personal communication, 2013). Traditional mix design does not apply. However, the high cement contents necessary to achieve these strengths are likely to result in a poor environmental performance.

6.6 The best mix

The best mix will be the one that combines the best elements of the above. That is Mix 6 with: 100% Recycled Aggregate, 50% GGBS and a water-reducing admixture. Across the 3 strength classes the total improvement is very similar. Figure 6.6 shows the comparison graphically.

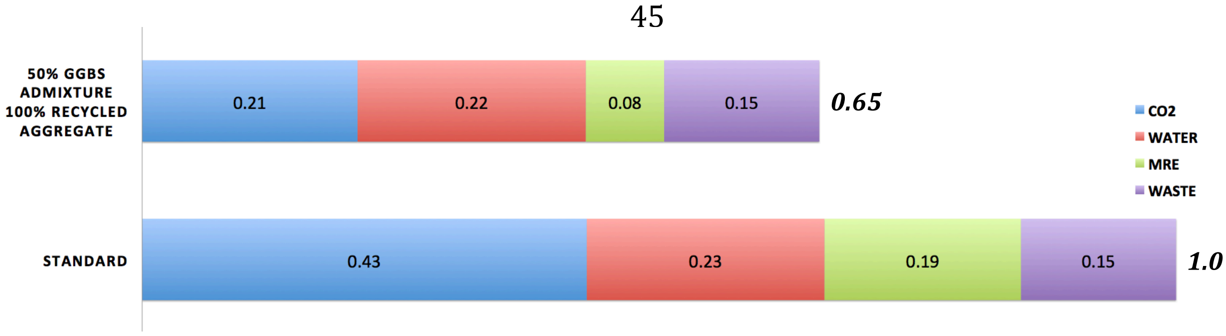


Figure 6.6: Comparing the most improved typical mix against the standard.
Source: Table 5.2

Thus, the total potential for improvement using typical values is by 35%. On top of this, if 80% GGBS replacement is considered alongside the potential of reduced waste onsite by 78% by using offsite construction methods (discussed in Section 3.5), the maximum possible improvement is shown in Figure 6.7.

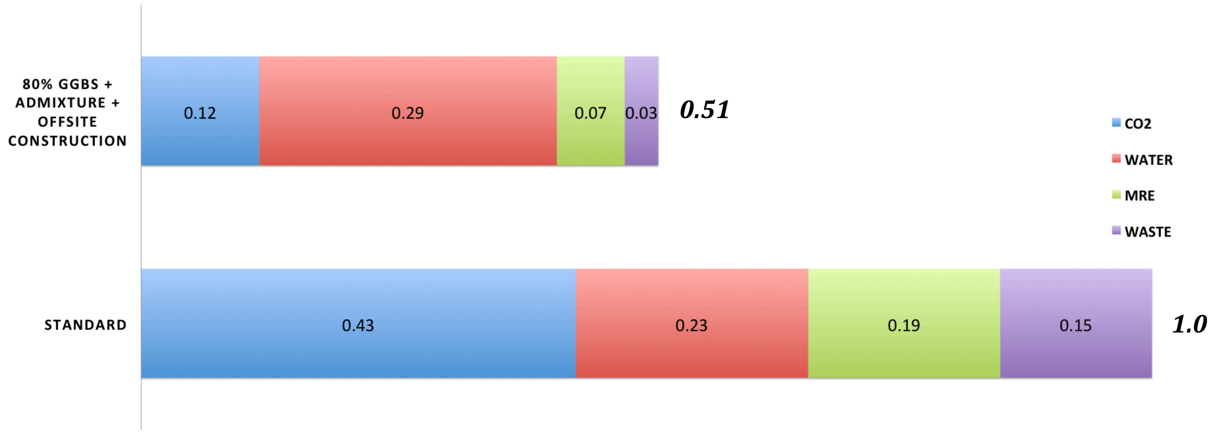


Figure 6.7: Comparison of the best possible performance against the standard.
Based on interpolated values from Table 5.2.

So, using this assessment the total potential improvement using these methods is just under 50%. Water extraction increases its impact but the considerable reduction of the other 3 criteria is enough to yield this result. Most notably the CO_2 impact is reduced to almost 25% of the standard value.

6.7 Generalising the assessment

Now that this assessment method has been developed, can it be used to help manufacturers to measure how environmentally friendly their mixes are? An environmental impact calculator has been created that implements the methodology described here for calculating the CO_2, water extraction, mineral resource extraction and waste disposal impacts of a concrete mix. These can be useful on their own. However, it is even clearer when these values are normalised and weighted as in this investigation. The issue lies in how to define a 'standard mix'.

In this document the base mixes were all derived from the same place with the information supplied by the same supplier, thus normalisation makes more sense and will work well. In practice, mixes change from day-to-day according to the weather and other factors. Does it make more sense to define a standard mix according to the conditions of that particular day?

	Strength	RC40		RC40		
	FROM APPENDIX A	STANDARD		40% GGBS		eCO2
Aggregate	Virgin	1786		1765		0.0066
kg/m3	Recycled					0.0079
Cement	Portland	380		240		0.924
kg/m3	GGBS			160		0.078
	PFA					0.015
Water		0.169		0.171		0.3
m3/m3						
Admixture	Water-Reducing	2.3		2.3		0.72
kg/m3						
Transport	Dist to site					0.0462
km						
TOTALS	CO2	365		248		
	WE	0.169		0.171		
	MRE	2168		2007		
	WD	1		1		
		TO TABLE 5.2	TO APPENDIX A	TO TABLE 5.2	TO APPENDIX A	
NORMALISED	CO2	1.09	1.00	0.74	0.68	
	WE	0.97	1.00	0.98	1.01	
	MRE	0.99	1.00	0.92	0.93	
	WD	1.00	1.00	1.00	1.00	
	TOTAL	4.05	4.00	3.64	3.62	
Weighted						
0.43	CO2	0.47	0.43	0.32	0.29	
0.23	WE	0.22	0.23	0.23	0.23	
0.19	MRE	0.19	0.19	0.17	0.18	
0.15	WD	0.15	0.15	0.15	0.15	
RATING		**1.03**	**1.00**	**0.87**	**0.85**	

	STANDARD
	TABLE 5.2
	RC40
CO2	336
WE	0.174
MRE	2189
WD	1

Table 6.1: Concrete environmental impact calculator.

Based on values obtained from Table 5.2 and from a typical Hanson concrete mix design (as issued on 14th May 2013). Certificate attached as Appendix A.

Table 6.1 shows a potential calculation. Results are shown for two RC 40/50 mixes specified on 14th May 2013 by Hanson (Birkinshaw, Personal Communication, 2013).

The certificate is attached in Appendix A. One mix uses 40% GGBS, the other is 100% Portland cement, which is analogous to the standard mix set up in this experiment.

The two mixes have been normalised according to the standard mix in Table 5.2 as well as to the standard mix as supplied by Hanson.

Interpolating the data for Mix 3 in Table 5.2, the equivalent values for a mix using 40% GGBS can be calculated. This is compared to the figures produced above in Figure 6.8 below.

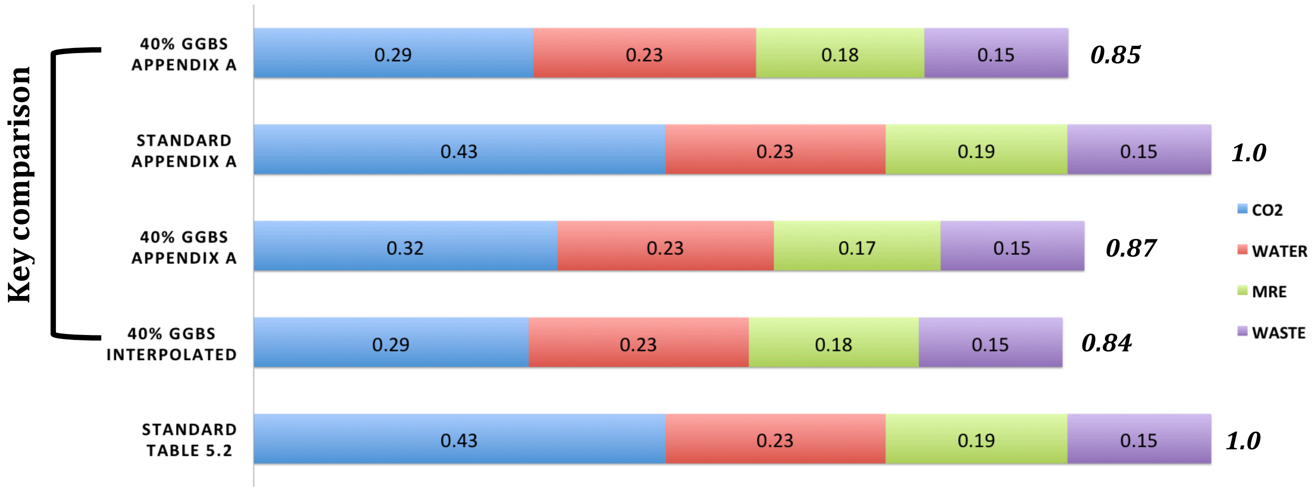


Figure 6.8: Comparison investigating the suitability of the environmental impact calculator
Based on values obtained from Table 5.2 and from a typical Hanson concrete mix design (as issued on 14th May 2013). Certificate attached as Appendix A.

The key comparison to make here is between the 40% GGBS mix normalised to the standard mix given by Hanson in Appendix A and the interpolated 40% GBS mix as normalised to the standard mix defined in Table 5.2.

This shows encouraging correlation. The 40% GGBS Mix given in Appendix A does not compare very well with the interpolated value from Table 5.2 but when compared to its own standard calculated at the same day, values are almost identical.

In order to confirm this as a valid method more examples would need to be investigated to see if the correlation is good enough. There is not time to pursue this here but there is some confidence in this method. If a particular condition meant that certain improvement methods couldn't be used, the flexibility here would allow for another solution to take up the slack. Realistically targets could be set at a 10-15% improvement (already 10-15 times better than BREEAM's 25% recycled aggregate credit).

6.8 Critical evaluation of BREEAM and other assessment methodologies

As already discussed, BREEAM awards a credit for use of a minimum of 25% recycled aggregate. The effect of this on the environmental impact of a mix has already been discussed in section 6.4. For 25% recycled aggregate it is measured at 1%. This is quite insignificant, especially when transport and the effect of additional cement is considered.

Using recycled aggregate is important for low strength concrete where quality is not of the utmost importance. Aggregate should not be sent to landfill. However, BREEAM should be incentivising more effective methods to improve the sustainability of concrete used for structural applications. If this is done right it can have a large effect on global CO_2 emissions. At the moment, BREEAM does not incentivise an effective way of achieving this and must consider improvement.

Other assessment methodologies such as the US Green Building Council's LEED system also focus on the use of recycled material. Again, this is important to reduce quantities taken to landfill but more must be done to promote the sustainability of concrete.

6.8 Is this long-term?

A well-known definition of sustainability is:

"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"

(Bruntland report for the world commission on environment and development, 1992)

In his book "Sustainable Materials: With Both Eyes Open" Julian Allwood considers the availability of cement and cement replacements on a long-term basis. He concludes that even if everything were done to make cement production more efficient, emissions would still increase by 18% by 2050. He also points out that cement production is in the region of 2,850Mt/year. Production of GGBS is around 200Mt/year and PFA is approximately 500Mt/year. These replacements cannot be the bedrock of a long-term strategy (Allwood & Cullen, 2011).

7 Conclusions

This investigation has flagged up many issues in the concrete industry and revealed areas in which current practice could be improved. The conclusions highlighted here can have an impact on how sustainable concrete is developed into the future and suggest ways in which the industry should change.

7.1 Implications for BREEAM

The use of 25% recycled aggregate has been shown to only improve the environmental credentials of structural concrete by 1%. The fact that a credit is awarded for this in BREEAM must be questioned. As a result of this investigation the following recommendations are suggested for BREEAM:

1. Change the specification that recycled aggregate is sourced within 30km in WST 02 to within a 14km radius of the site. It is still recommended that this credit be upheld to prevent aggregate going to landfill.
2. Consider using an environmental calculator for concrete as shown in section 6.7. This could be used to award credits for use of concrete instead of other more subjective methods.
3. Incentivise more use of cement replacements and admixtures.

7.2 Key methods that achieve more sustainable use of concrete

Admixtures and cement replacements are shown to be the most effective solutions to this problem, especially for reducing the CO_2 content of a mix. The use of offsite construction also has a significant impact on the waste produced. However, the use of this and of recycled aggregate must be carefully considered for each scenario. Excessive transport distances will often outweigh the gains from their use.

7.3 The future

Ultimately, to achieve the goal of long-term improvements the following steps should be taken:

1. Increased use of cement replacements – especially of PFA in the UK where there is much stockpiled ready for use.
2. Drive down the price of admixtures to make their use more accessible. As a result their use should be increased as much as possible.

3. Maintain recycled aggregate use for lower strength grades and other applications where aggregate quality is not of large concern. Its availability should be increased nationwide to limit transport costs.
4. Consider building more offsite concrete construction plants across the UK for large projects. Consider improving onsite construction methods. More efficient use of formwork and material can represent significant improvements for waste produced onsite.
5. Improve general awareness of specification of sustainable use of concrete, especially in consultant offices where sustainable mixes can be specified early in the decision making process.
6. Consider strength grades of concrete used with regard to the environment and material efficiency. If use of RC50/60 concrete results in a reduction of volume of 9% or more compared to use of RC40/50 concrete, construction will be more environmentally friendly.
7. Undertake research into the rate of concrete strength gain to balance the requirements for strength with the progress of construction. Piles, raft slabs and columns would be good starting points in the context of high-rise buildings. If cement replacements are used this can help to reduce the total cementitious concrete significantly.
8. Increase research and development work to create novel forms of cement that might completely replace the use of Portland cement.

7.4 Concluding remarks.

The assessment undertaken in this report has allowed for established methods of achieving more sustainable use of concrete to be quantified effectively. Areas of focus moving forward to continue improvement have been identified. It is key to note that, considering current trends and rates of usage, despite the best efforts of manufacturers, environmental impact due to concrete is still set to increase. Every avenue should be explored to minimise the effects and guarantee a sustainable future for concrete.

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CERTIFICATE OF MIX DESIGN

Appendix A
Page 1

Hanson
HEIDELBERGCEMENTGroup

Certificate No: 1950140291 14.05.2013 Page 1 of 2
Dated: 14.05.2013

Contractor:
HANSON
.
Shardlow
. .
UNITED KINGDOM

Site address:
{E ASHBY RD}
E ASHBY RD
SHEPSHED LE12 9BU
UNITED KINGDOM

Your Reference:

Customer Service Centre
Ashby Road East
SHEPSHED, LOUGHBOROUGH
Leicestershire
LE12 9BU
UNITED KINGDOM
Sales: 0845 845 6688
Orders:
East: 0845 451 0782
West: 0845 451 9787
Mortar: 0845 129 2747
www.hanson.com/uk

Supplying plant: 3071 Derby Concrete

MATERIAL	DESCRIPTION	SUPPLIER	SOURCE	ADMIXTURE UNITS
ADDITION1	GGBS	HANSON CEMENT	SCUNTHORPE	
CEMENT	CEMI	HANSON CEMENT	PADESWOOD	
Aggregate 1	GRAVEL QUARTZ 20	HANSON AGGREGATES	SHARDLOW QUARRY	
Aggregate 2	SAND	HANSON AGGREGATES	SHARDLOW QUARRY	
ADMIXTURE 1	SK160	SIKA LTD		l/100 kg cement

MIX SPECIFICATIONS

MIX/GRADE	RC20/25	RC32/40	RC40/50	
MAX AGG SIZE	20	20	20	
CEMENT TYPE	CIIIA+SR	CIIIA+SR	CIIIA+SR	
CONSISTENCE	S3	S3	S3	
MCC	240	300	340	
MAX W/C	0.70	0.55	0.45	

SSD MIX DESIGN kg/cubic metre

ADDITION1	98	128	160	
CEMENT	147	192	240	
Aggregate 1	991	1,026	1,056	
Aggregate 2	907	815	709	
WATER	171	167	171	

ADMIXTURE DOSAGES (SEE UNITS ABOVE)

Admix 1 & 2	0.575		0.575		0.575			
Admix 3 & 4								
Admix 5 & 6								
Admix 7 & 8								
W/C Ratio	0.70		0.52		0.43			
Alkali kg	1.30		1.64		1.99			
Cl % SO4 %	0.16	3.48	0.14	3.46	0.13	3.44		

Material sources and proportions may change subject to quality and availability. Concrete is supplied in accordance with the requirements of the current edition of BS8500.

THE QUALITY SCHEME FOR READY MIXED CONCRETE 009

Signed..
Hanson Concrete Technical Department

CERTIFICATE OF MIX DESIGN

Appendix A
Page 2

Hanson
HEIDELBERGCEMENTGroup

Certificate No: 1950140291 14.05.2013 Page 2 of 2
Dated: 14.05.2013

Contractor:
HANSON
.
Shardlow
. .
UNITED KINGDOM

Site address:
{E ASHBY RD}
E ASHBY RD
SHEPSHED LE12 9BU
UNITED KINGDOM

Your Reference:

Customer Service Centre
Ashby Road East
SHEPSHED, LOUGHBOROUGH
Leicestershire
LE12 9BU
UNITED KINGDOM
Sales: 0845 845 6688
Orders:
East: 0845 451 0782
West: 0845 451 9787
Mortar: 0845 129 2747
www.hanson.com/uk

Supplying plant: 3071 Derby Concrete

MATERIAL	DESCRIPTION	SUPPLIER	SOURCE	ADMIXTURE UNITS
CEMENT	CEMI	HANSON CEMENT	PADESWOOD	
Aggregate 1	GRAVEL QUARTZ 20	HANSON AGGREGATES	SHARDLOW QUARRY	
Aggregate 2	SAND	HANSON AGGREGATES	SHARDLOW QUARRY	
ADMIXTURE 1	SK160	SIKA LTD		l/100 kg cement

MIX SPECIFICATIONS

MIX/GRADE	RC20/25	RC32/40	RC40/50	
MAX AGG SIZE	20	20	20	
CEMENT TYPE	CEMI	CEMI	CEMI	
CONSISTENCE	S3	S3	S3	
MCC	240	300	340	
MAX W/C	0.70	0.55	0.45	

SSD MIX DESIGN kg/cubic metre

CEMENT	245	305	380	
Aggregate 1	991	1,020	1,050	
Aggregate 2	907	834	736	
WATER	171	168	169	

ADMIXTURE DOSAGES (SEE UNITS ABOVE)

Admix 1 & 2	0.575		0.575		0.575			
Admix 3 & 4								
Admix 5 & 6								
Admix 7 & 8								
W/C Ratio	0.70		0.55		0.45			
Alkali kg	2.04		2.48		3.04			
Cl % SO4 %	0.15	4.08	0.13	4.06	0.12	4.05		

Material sources and proportions may change subject to quality and availability. Concrete is supplied in accordance with the requirements of the current edition of BS8500.

THE QUALITY SCHEME FOR READY MIXED CONCRETE 009

Signed..
Hanson Concrete Technical Department

Appendix B

Risk Assessment Retrospective

This project was 100% research-based and the risks involved were minor and primarily related to prolonged computer use. Taking regular breaks from looking at screens and ensuring that a comfortable seating position was chosen were the main precautions taken.

The risk assessment handed in during October 2012, before the start of this project, laid out the possibility of being in contact with concrete and performing some tests. In reality this was not necessary as much of the experimental data needed for this report was already available in other reports and journals as cited in the bibliography.