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Reducing CO_2 : Optimum blend of binders in the UK

A.C. Heath and K.A. Paine
BRE Centre for Innovative Construction Materials
Department of Architecture and Civil Engineering
University of Bath
Bath, BA2 7AY, UK

ABSTRACT

Various strategies have been proposed for reducing the CO_2 emissions of cement manufacture. The Intergovernmental Panel on Climate Change (IPCC) stated that “Materials substitution, for example the addition of wastes (blast furnace slag, fly ash) and geopolymers to clinker” could be used to reduce global CO_2 emissions. Most current research on this area has focused on high fly ash / GGBS contents in Portland cement blends and geopolymers based on fly ash and GGBS with a view to produce materials with the lowest possible CO_2 emissions. Completed studies have not normally included the constraint of the availability of waste materials and geologic mineral precursors and the effect this can have on outcomes. This study investigated the CO_2 emissions based on UK binder requirements and the current and future production of waste materials. The effect of using limited fly ash / GGBS supplies, other waste materials and geologic minerals in both ternary PC blends and geopolymer binders was investigated and use patterns which produce the lowest CO_2 emissions proposed. A substantial reduction in CO_2 emissions from the current uncoordinated approach was found to be potentially achievable, but new technologies could have a greater impact.

1. INTRODUCTION

The UK’s 2008 Climate Change Act established the world’s first legally binding climate change target. The aim of the act is to reduce the UK’s greenhouse gas emissions by at least 80% (from the 1990 baseline) by 2050. Cement manufacture is responsible for approximately 5% of the global CO_2 emissions and it is unreasonable to believe that this industry will continue to produce CO_2 at current levels, particularly in light of likely increased future demand. While it is not necessary for all industries to achieve the 80% reduction by 2050, it is a useful target for comparative purposes. New materials or manufacturing techniques which meet the demand for cements but which have lower Global Warming Potential (GWP) are required.

The Intergovernmental Panel on Climate Change (IPCC) stated that “Materials substitution, for example the addition of wastes (blast furnace slag, fly ash) and geopolymers to clinker” could be used to reduce global CO_2 emissions [1]. The aim of this paper is to investigate whether these recommendations on material substitution are realistic for the UK, and what mix of binders could be used to minimize the GWP using current binder technology.

There have been a number of papers which have demonstrated the effect of reducing the clinker content in Portland cement (PC) based binders and data such as that in Figure 1 has been used to demonstrate the potential reductions in GWP by replacing clinker with mainly ground granulated blastfurnace slag (GGBS) and fly ash (FA) from coal-fired power stations [2]. These analyses have not, however, considered the availability of materials.

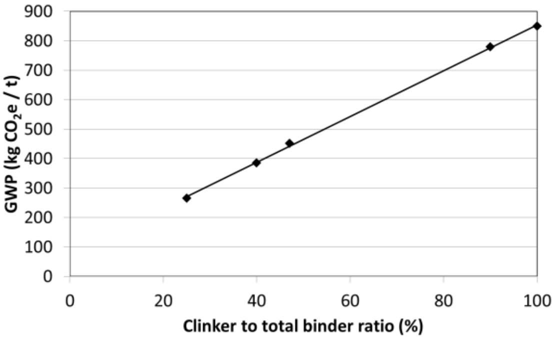


Figure 1. Effect of clinker substitution on binder GWP (data from [2])

2. METHODOLOGY

The analysis for this paper was performed by varying the UK binder mix composition and determining which produced the lowest GWP, based on the availability of raw materials. Any analysis which attempts to predict future trends will have a number of limitations and the conclusions should be considered with these in mind. One limitation to this study is that only PC based binders with added GGBS/FA, GGBS/FA based geopolymers and metakaolin (MK) based geopolymers were considered as these were the options recommended by the IPCC. For this analysis, mechanical properties were not determined and it was therefore assumed that all binder compositions considered could be used to produce concretes of equivalent mechanical performance and durability through appropriate mix design [3].

Throughout this paper, the GWP is presented as the 100-year CO_2 equivalent (CO_2e) according to the IPCC method [4]. This includes emissions associated with the infrastructure required to produce the material (i.e. the emissions associated with producing a cement plant are assigned to the cement produced, distributed over the lifetime of the plant). All figures are factory gate values for binders and do not include transport to sites or prefabrication plants, mixing with aggregates and water, placing or curing.

For by-products such as FA and GGBS, no emissions from steel / electricity production were allocated to the GGBS / FA, but emissions from any processing required were allocated to the material. This was because the goal was to calculate the reduction in GWP that can be achieved, and allocation of GWP has no impact on CO_2 emissions.

Data from the peer-reviewed literature using current technology / state of the art was used for the GWP of the different binders and is presented in Table 1. For the GGBS/FA based geopolymers, the data by Habert et al. [5] was modified to account for the use of sodium silicate with a modulus of 2.0 rather than the modulus 3.3 sodium silicate in the original paper as this produced an unrealistically high emissions profile [6]. Because of the assumptions and variability between plants, the figures in Table 1 should be considered indicative rather than definitive. As shown in the table, although a considerable reduction is possible, the binder with lowest GWP using the current state-of-the-art (GGBS/FA based geopolymer) does not achieve the goal of 80% reduction from PC.

For the geopolymers in particular there can be considerable variation in GWP based on the mix chemistry, and the GGBS / FA example is “representative” of mix designs in the literature [5] while the metakaolin geopolymer uses the ratios of SiO_2:Al_2O_3 = 4 and Na_2O:SiO_2 = 0.24 which can provide the maximum strength [7]. In both cases commercially available sodium hydroxide and silicate were used as activators.

Table 1. GWP of binders and clinker replacements

Binder / additive type	*Reference*	*GWP (kg CO_2e / t)*
PC	[2]	850
Fly Ash	[5]	5
GGBS	[5]	17
GGBS/FA geopolymer	[5]*	370
Metakaolin geopolymer	[7]	749

*recalculated as described above

The quantity of materials available was based on data for the UK [6] and considered both annual production and stockpiles available of suitable materials. The demand and production of materials was considered constant until 2050 with the exception of FA which was assumed to decrease from the current quantity suitable for binders of approximately 3.3 Mt / y to 0.5 Mt / y by 2035 as the UK energy mix moves from coal-fired power generation to increased renewable generation.

Table 2. Demand and available materials in the UK [6]

Material	*Approximate quantity*
Binder demand	10 Mt / y
Fly Ash	3.3 decreasing to 0.5 Mt / y
Fly Ash in stockpiles	57 Mt
GGBS	2 Mt / y
Metakaolin*	1.6 Mt / y

*assuming excess kaolin production capacity can be utilised for metakaolin production

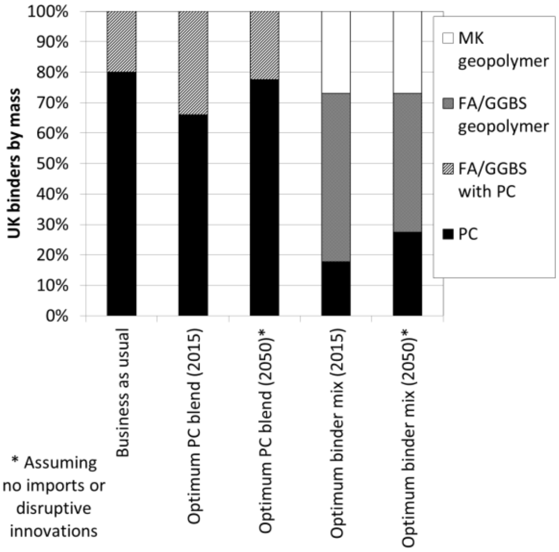
It was assumed that there is sufficient limestone and other raw materials required to meet PC clinker demands into the future and that there is capacity to produce sufficient geopolymer activator as the main raw materials for the commercial production of these are silica sand and sea water, both of which are abundantly available. For the purposes of calculating quantities, it was assumed the dry mass of the activators for the GGBS/FA geopolymers were 15% of the binder mass and that geopolymer mixes could be developed with the FA/GGBS which is suitable for PC blends.

It was assumed that all FA stockpiles would be used by 2050. Limits on the FA (25%) and GGBS (50%) contents of PC based mixes was imposed in the analysis, but these limits were not required because of the shortage of these materials. For the business as usual case, it was assumed an average of 10% FA and 10%

GGBS with 80% PC which returned a blended PC GWP similar to typical European values [7].

3. RESULTS

Figure 2 shows the "business as usual" UK binder mix (with negligible geopolymer use) along with optimised binder mixes with the lowest GWP based on available materials for both 2015 and the average until 2050.



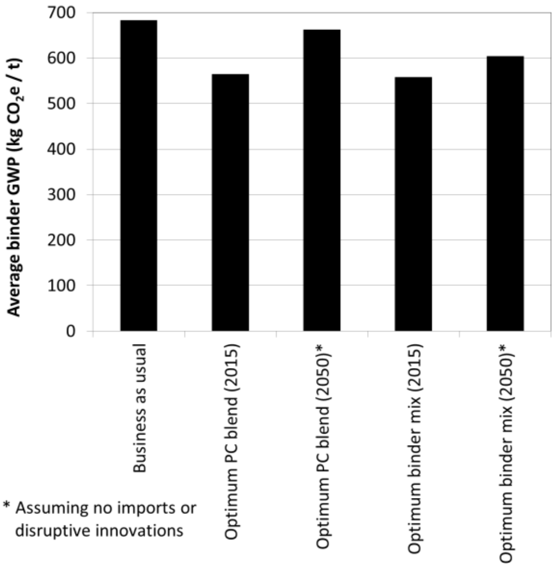
* Assuming no imports or disruptive innovations

Figure 2. UK binder mix for 2015 and until 2050

As shown in Figure 2, the "business as usual" case does not provide the lowest GWP and increases in FA/GGBS to approximately 35% are required to meet a goal of minimising the GWP in the likely event that PC based binders dominate in 2015. Because of the varying availability of some materials (particularly FA), the binder mix changes between 2015 and 2050. The effect of the binder mix on the average GWP of UK produced binders is presented in Figure 3.

As shown in Figures 2 and 3, if the PC based binder route is continued into the future, the shortage of FA/GGBS will mean we will effectively return to the "business as usual" situation for the mix blend by 2050 and the goal of substantially reducing the GWP will not be acheived.

As shown in the figures, a lower GWP can be achieved by using available FA and GGBS in geopolymers rather than in PC blends although additional metakaolin based geopolymers would be required to make up the binder demand. While the reduction in GWP from using geopolymers with PC based binder would be modest in 2015, by 2050 using geopolymers in the binder mix could lead to a reduction of approximately 9% in the average binder GWP. This reduction would be beneficial but should be considered in light of other savings that could be achieved.



* Assuming no imports or disruptive innovations

Figure 3. Average binder GWP for 2015 and until 2050

Because of improved efficiency measures, there was a reduction in GWP of clinker production of approximately 10% between 1990 and 2005 [8], which can be extrapolated to a reduction of approximately 17% by 2015. The combined reduction in GWP from the "business as usual" case is then 26% from 1990 to 2050 (assuming limited further efficiency savings), well below the desired 80% reduction.

5. FUTURE POTENTIAL

One or more of the following are therefore required:

- There is a substantial reduction in binder requirements;
- Geopolymer precursors are imported into the UK; or
- There are new binders or a step-change in technology for current binders.

It this point it appears unlikely that there will be a substantial reduction in cementitious binder use in the UK, and all indications are that global use is likely to increase until 2050. The issue of importing FA/GGBS is contentious as it would is likely to undermine the status of these materials as wastes or even by-products which could influence their use.

New binders [9] may have lower GWP than current binders, but the construction industry is notoriously conservative and it is unlikely that new binders will generally replace PC based binders by 2050. It is approximately 35 years since Davidovits first coined the term “Geopolymer” and a similar time until the 2050 deadline for 80% reduction in GWP. This indicates development and replacement with new binders must be faster than with geopolymers which still have a very small market share.

Disruptive innovations such as carbon capture and storage (CCS) [10] could allow substantial reductions in GWP, particularly for clinker based binders where the emissions are largely from single manufacturing facilities and exploration of this option should continue.

A substantial reduction in the GWP of both GGBS/FA and metakaolin based geopolymers could result if lower emission activators could be found. Sodium silicate production is responsible for the majority of the GWP for both GGBS/FA and metakaolin based geopolymers [3,5]. Although it is not currently common practice, it is possible to eliminate sodium silicate from geopolymers through the use of lower impact sources of amorphous silica such as silica fume, waste glass or rice husk ash in conjunction with lower impact alkaline activators [11]. It has been demonstrated this can lead to a reduction in GWP of approximately 40% for some geopolymer mixes [7], but the availability of these lower impact amorphous silica sources must also be considered.

4. CONCLUSIONS

While there are limitations in any analysis of this type, it has been shown that it is possible to reduce the average GWP of cementitious binders by optimising the binder mix for the UK. For example, PC as well as both FA/GGBS and metakaolin based geopolymers could play a role in future optimised binder blends. A lower GWP can be achieved if FA/GGBS is used in geopolymers rather than PC blends, but the technical properties of FA/GGBS in PC blends should also be considered.

The IPCC recommendations that geopolymers and high FA/GGBS Portland cement blends have potential to reduce CO_2 emissions are valid for the UK, but these recommendations will not result in an 80% reduction in GWP from cement manufacture by 2050 and new binders or a step change in current technology are required if this is to be achieved.

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