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Authors

Louise Keyte, National Research and Development Manager, Boral Innovation Factory Australia

Redmond Lloyd, General Manager – Innovation, Boral Innovation Factory Australia

Camille Holt, Research and Development Supervisor, Boral Innovation Factory Australia

Jason Chandler, Technical Services Manager – Concrete (Metro), Boral Australia

David Hocking, Technical Manager – Concrete, Boral Australia

Tony Thomas, Chief Engineer – Concrete – Boral Australia

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Louise Keyte,[1] Redmond Lloyd,[2] Camille Holt,[3] Jason Chandler,[4] David Hocking,[5] Tony Thomas[6]
[1]National Research and Development Manager, Boral Innovation Factory Australia
[2]General Manager – Innovation, Boral Innovation Factory Australia
[3]Research and Development Supervisor, Boral Innovation Factory Australia
[4]Technical Services Manager – Concrete (Metro), Boral Australia
[5]Technical Manager – Concrete, Boral Australia
[6]Chief Engineer – Concrete – Boral Australia

Abstract: Post-tensioning of concrete is recognised as a highly efficient construction solution, and yields significant benefits in structural performance, cost and embodied carbon through reduction of material volumes. Despite this, the concretes specified for post-tensioned construction usually have high Portland cement content and therefore relatively high embodied carbon relative to general structural concretes. As post-tensioned concrete typically makes up the majority of the volume in high-rise construction, there is significant potential to reduce embodied carbon in structures by reducing the Portland cement content of post-tensioned concretes. Reducing the Portland cement content of concrete reduces early strength, however, resulting in elongated construction cycle times. The time-sensitive nature of construction and the high cost to rectify anchor failures means that adoption of lower carbon concretes in post-tensioned applications is limited.

This paper examines recent advances in concrete materials technology that allow higher early age strengths to be achieved with significantly lower than average Portland cement contents. Together with recent advances in strength prediction using maturity methods substantial reductions in embodied carbon are now possible without increasing construction time and risk of failure. A case study of low carbon post-tensioned concrete is examined.

Keywords: keyword, keyword, keyword, keyword, keyword.

1. Introduction

Post-tensioned concrete members have become increasingly popular since the technology gained traction in the 1950's in Europe and America and has since found use in a number of applications including water tanks, bridges, dams, nuclear containment and most importantly in high-rise buildings where the reduction in weight of individual elements attained through the use of post-tensioning has facilitated increased building heights [1].

In general, post-tensioned concrete elements require less concrete and steel reinforcement than their reinforced concrete counterparts to achieve the same load bearing capability resulting in a reduction in the cost of materials. In addition, post-tensioned slabs are stiffer showing less deflection under load and are less susceptible to cracking with cracks that do form being less likely to allow ingress of water or other contaminants. Post-tensioning allows for the manufacture of larger slabs so fewer elements are required to construct a building. With fewer required elements there is a reduction in fabrication and installation times as well as a reduction in labour. On the other hand, post-tensioning requires specialized equipment and skilled labor for tensioning, and often has more stringent requirements for concrete early age performance [2]

According to guidelines issued by the Post-Tensioning Institute of Australia post-tensioning is usually performed in two stages. During the first stage approximately 25% of the total prestressing force is applied when the concrete attains a strength of 7 – 9 MPa. The remainder of the prestressing force is applied during the second stage once the concrete has attained a strength of 22 – 25 MPa depending on the diameter of the strands used. Delays due to concrete which is slow to gain strength can be costly and interfere with scheduled work. Concrete with high early strength is normally obtained using high cement contents. Accelerators can also be used to increase the rate at which the hydration reactions responsible for strength gain occur. [3]

Drying shrinkage is another important factor to consider in post-tensioned concrete. The Post-Tensioning Institute of Australia notes that maximum allowable shrinkage at 56 days is normally between 600 and 750 microstrain but this value varies across Australia. The shrinkage of concrete results in a loss of prestressing force due to axial shortening of the concrete [1].

The manufacture of Portland cement contributes between 5 - 7% of global CO_2 emissions. [4] Given that cement production is forecast to increase a further 50% between 2007 and 2050, reducing the amount of CO_2 that is generated by the manufacture of cement will be an important step towards meeting global CO_2 emission reduction targets. The embodied CO_2 of clinker is approximately 866 kg/tonne [4] arising from the consumption of fuel during the calcination and clinkering processes as well as from the decarbonation (or calcination) of limestone. For comparison, the embodied CO_2 of aluminium products is estimated to be as high as 10 000 kg/tonne. [4] It is the sheer volume of cement produced worldwide that makes the cement industry such a heavy emitter of CO_2.

Previously, improvements have been made to kilns in order to increase energy efficiency and decrease costs. Older vertical shaft and wet process kilns have been replaced by dry process kilns which achieve a 3 – 12% increase in energy efficiency. The addition of cyclone preheaters and precalciners has seen further increases in efficiency with a five stage preheater and precalciner delivering 20% greater energy efficiency than a dry process kiln without preheaters. Whilst phasing out and replacing older, inefficient technology will, over time, reduce carbon emissions this alone will not allow the industry to meet the necessary reductions in CO_2 emissions. Alternative fuels such as biomass or other waste materials can be used in place of fossil fuels in kilns thereby reducing the amount of CO_2 released during cement production. [4]

Probably the most effective manner in which the cement industry can reduce CO_2 emissions using already available resources and technology is through partial replacement of cement with supplementary cementitious materials (SCMs). The extent to which this can be achieved in a particular location is dependent on the availability and quality of SCMs so in some instances reduction of CO_2 emissions through cement replacement may not be as easily achieved. In the future, other technologies such as carbon capture and sequestration and alternate clinker chemistries, namely belite cements, may become commonplace. [4]

More than ever reducing carbon emissions, and environmental impact in general, is an important aspect of the design process and construction of new buildings, not just in cement manufacture. As discussed above, the amount of concrete and steel in a building can be decreased by employing more efficient construction methods, such as post-tensioned concrete, thereby decreasing the amount of CO_2 generated during the construction of a given building. Further improvements can also be achieved by partially substituting cement with SCMs. However, the combination of these two ideas does not always work well in practice. Partial replacement of cement with blast furnace slag, for example, normally results in a decrease in early strength proportional to the slag content because slag reacts more slowly than cement. [5] Whilst this is offset by an increase in overall strength relative to cement, the lower early strength makes use of slag for post-tensioned concrete difficult.

Boral has developed Envisia, a concrete with a high level of cement replacement which provides high early strength suitable for use in post-tensioning as well as low drying shrinkage. This paper compares strength and shrinkage data obtained during laboratory testing and on commercial high-rise applications in the field for Envisia, conventional Green Star compliant concrete and a typical concrete made without cement substitution.

2. Mix designs

This paper compares laboratory test data from three typical concrete mix designs with differing levels of cement reduction, then examines the performance of comparable mix designs sampled from 3 job sites where similar mixes have been supplied commercially. Each mix design was supplied to a certain job, over a similar time period in Sydney. Envisia is a new product wherein a certain level of cement is replaced by blast furnace slag and the other two concretes were chosen to represent products commonly sold by Boral, one a concrete with no cement replacement and the other a concrete with a moderate level of cement replacement, similar to that of Envisia.

2.1 Laboratory Mix Designs

The laboratory mix designs chosen for this study represent typical mix designs for 40 MPa concrete sold by Boral (Table 1). The level of cement reduction for Envisia is 51%, which is compared to a conventional high-substitution concrete designed to comply with the Green Building Council of Australia's Green Star [6] requirements with 41% cement reduction and addition of slag and fly ash. Although not presented here Envisia achieves similar strength and shrinkage performance with 60% cement reduction.

Table 1. Mix Designs Used In Laboratory Testing

	0% Reduction (Standard)	**41% Cement Reduction (Green Star)**	**51% Cement Reduction (Envisia)**
Portland Cement (kgm^{-3})	430	260	215
GGBFS (kgm^{-3})		77	
Fly ash (kgm^{-3})		93	
GGBFS# (kgm^{-3})			215
20 mm aggregate (kgm^{-3})	664	664	664
10 mm aggregate (kgm^{-3})	333	333	333
Coarse sand (kgm^{-3})	440	440	440
Fine sand (kgm^{-3})	318	318	318
Water reducer ($mL\ m^{-3}$)	1600	1600	1600
Water/cement ratio	0.44	0.44	0.44
Cement reduction*	0%	41%	51%

GGBFS indicates Ground Granulated Blast Furnace Slag.

GGBFS# indicates a proprietary ground granulated blast-furnace slag product.

Cement reduction is calculated according to the Green Building Council Australia MAT4 guide. [6]

2.2 Field Mix Designs

The field mix designs chosen for this study represent typical mix designs for post-tensioned concrete sold by Boral (Table 2).

Table 2. Mix Designs Used In Post-Tensioned Concrete

	18% Reduction (Standard)	**25% Reduction (Green Star)**	**51%Reduction (Envisia)**

Portland Cement (kgm^{-3})	360	330	215
GGBFS (kgm^{-3})		45	
Fly ash (kgm^{-3})	40	70	
GGBFS# (kgm^{-3})			215
20 mm aggregate (kgm^{-3})	762	765	704
10 mm aggregate (kgm^{-3})	292	283	303
Coarse sand (kgm^{-3})	529	495	460
Fine sand (kgm^{-3})	184	194	303
Water reducer (mL m^{-3})	1100	1700	1700
Water (kgm^{-3})	0.44	0.44	0.44
Cement reduction*	18%	25%	51%

GGBFS indicates Ground Granulate Blast Furnace Slag

GGBFS# indicates a commercial product consisting primarily of GGBFS.

Cement reduction is calculated according to the Green Building Council Australia MAT4 guide. [6]

It should be noted that for post-tensioning the requirements for concrete containing SCMs normally need to be changed so the nominated strengths at early age can be reached. In the case of Green Star concrete, a cement reduction of 41% is realised for 40 MPa concrete but the level of cement reduction needs to be lowered to 25% if the concrete is going to be used in post-tensioning applications. Envisia, on the other hand, is able to reach the necessary strength at early ages without decreasing the level of cement reduction.

3. Strength

3.1 Laboratory Performance

Envisia performs favourably in laboratory testing against Green Star concrete and reaches consistently higher strengths at 3, 7 and 28 days. Envisia compares well to standard concrete with no cement replacement attaining 12% and 5% lower strengths at 3 and 7 days and a strength parity at 28 days. Green Star concrete is 35 to 40% lower than the standard concrete at 3 and 7 days but the rate of strength development is higher between 7 and 28 days than the standard concrete, and 28 day strength is only 12% lower than the control. Lower rate of strength gain during the first 7 days of reaction is expected for concretes with cement replaced by fly ash and slag [5]. This is substantially overcome in Envisia concrete.

Table 3. Compressive strength of 40 MPa Concrete Produced In Laboratory Testing

Age (Days)	**0% Reduction (Standard) (MPa)**	**41% Reduction (Green Star) (MPa)**	**51% Reduction (Envisia) (MPa)**

3	32.0	18.6	28.1
7	37.7	24.8	35.8
28	46.3	40.7	47.1
Number of replicates	4	4	4

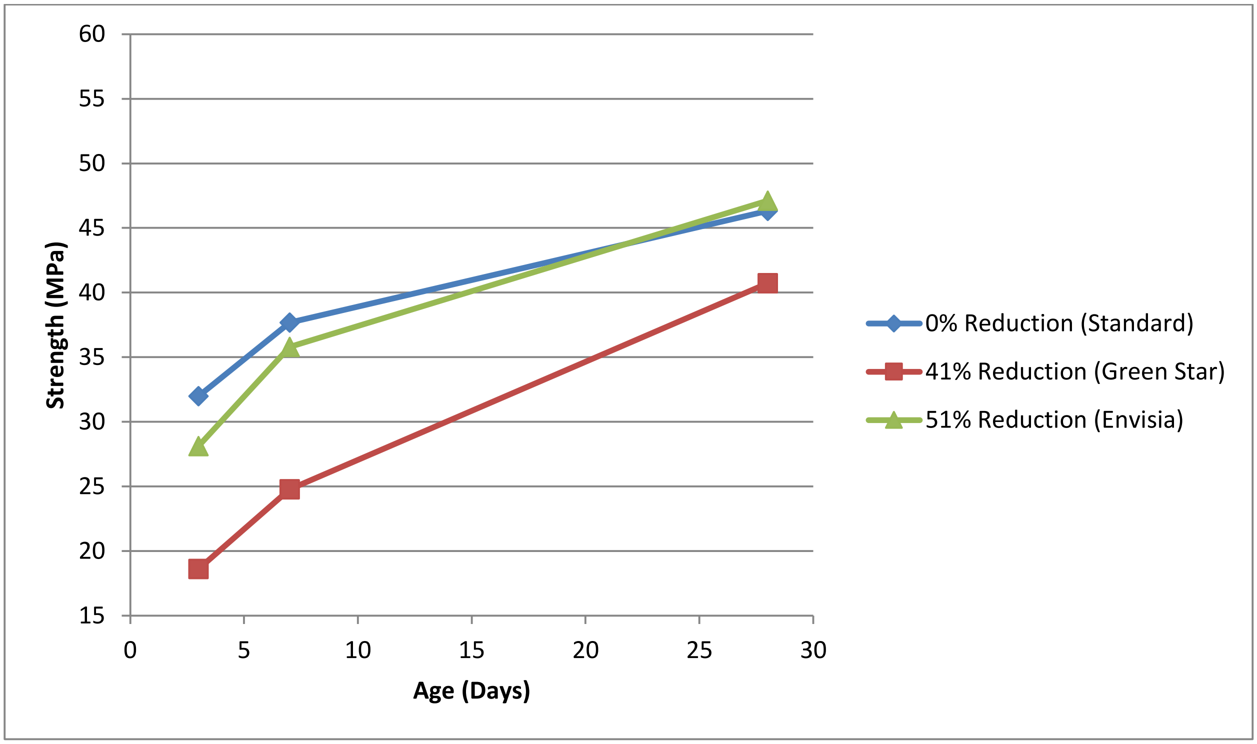

Figure 1. Strength of 40 MPa Concrete Produced In Laboratory Testing

3.2 Field Performance

Concrete for post-tensioning is normally designed to achieve a certain strength in a short period of time rather than with a particular later strength in mind. Concrete for post-tensioned applications typically requires high early age strengths to facilitate rapid stressing. Delays in stressing slow construction and therefore increase construction costs. For this reason concrete supplied for post-tensioning typically has low levels of cement replacement with SCM's as even a moderate level of cement replacement can result in slower strength gain at early ages. In section 3.1 Envisia and Green Star concrete were compared to standard concrete with no cement replacement. Whilst Envisia performed comparably to standard concrete Green Star concrete achieved lower strengths at all ages. To be able to use Green Star concrete in post-tensioning applications the laboratory 40 MPa mix design was changed and a smaller amount of cement was replaced with SCMs taking the level of cement reduction from 41% to 25%. No changes were made to Envisia concrete and the level of cement reduction remained constant at 51%.

All three concretes have a similar strength of approximately 27 MPa at 4 days, consistent with the need for the concrete to gain strength quickly before post-tensioning can take place. From 7 days onwards, the standard concrete realises strengths on average 3 MPa greater than Envisia. Green Star concrete used in post-tensioning applications reaches strengths of approximately 54 MPa at 28 days, much higher than the requirement of f'_c = 40 MPa due to the additional binder content which is necessary to reach the appropriate early strength (Figure 2). Due to the composition of the concrete, Envisia is able to realise acceptable strengths at both early and later ages while maintaining more than 50% cement reduction. The fact that Envisia concrete has appropriate properties for use in post-tensioning applications and still maintains a high level of cement reduction relative to other concrete products makes it an attractive option for customers seeking to reduce the amount of embodied carbon in a structure.

Table 4. Compressive Strength of 40 MPa Concrete Used In Post-Tensioning Applications

	Mean Compressive strength (n = # of individual results measured)		
Age (Days)	**18% Reduction (Standard) (MPa)**	**25% Reduction (Green Star) (MPa)**	**51% Reduction (Envisia) (MPa)**
4	27.1	26.6	27.6
	(n = 49)	(n = 102)	(n = 78)
7	38.5	36.1	35.4
	(n = 11)	(n = 110)	(n = 34)
28	48.7	54.1	45.9
	(n = 67)	(n = 476)	(n = 116)

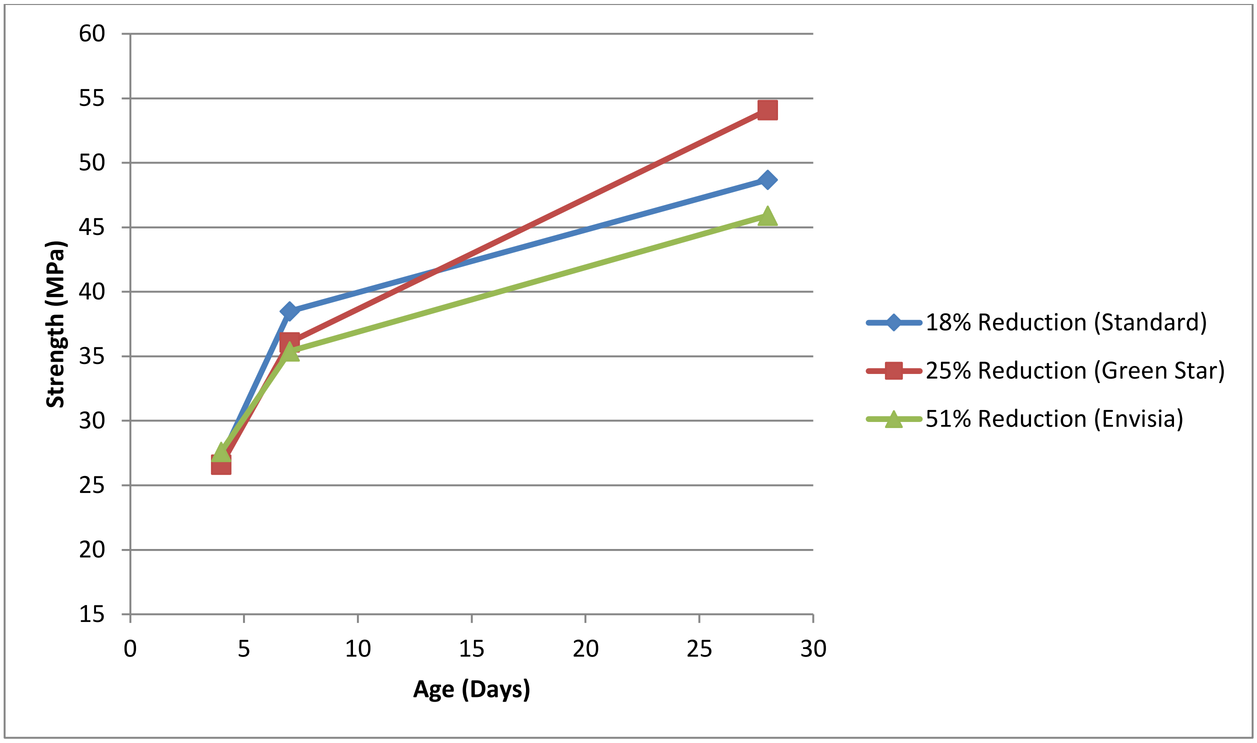

Figure 2. Field Sampled Compressive Strength of 40 MPa Concrete Used In Post-Tensioning Applications

4. Drying Shrinkage

Fresh concrete typically has water present in excess of that required for hydration. Evaporation of this water from the pore structure of concrete can cause shrinkage due to capillary forces [7]. Drying shrinkage needs to be kept within a reasonable range to avoid a decline in applied stress over time as the concrete dries and shrinks with age. The Post-Tensioning Institute of Australia recommends maximum shrinkage at 56 days of between 600 – 750 microstrain. Envisia, in addition to low cement content and comparable strength, also boasts low drying shrinkage. In laboratory testing according to Australian Standard AS1012.13 – 2015 [8] (Table 5) Envisia significantly outperforms concrete made with 100% Portland cement at all ages.

Table 5. Drying Shrinkage of 40 MPa Concrete Produced In Laboratory Testing

	0% Reduction (Standard)	**51% Reduction (Envisia)**
7 Day (microstrain)	230	120
14 Day (microstrain)	310	170
21 Day (microstrain)	380	210

28 Day (microstrain)	420	240
56 Day (microstrain)	530	330
n	1	1

Data obtained in the field for standard, Green Star and Envisia concretes shows Green Star concrete exhibits the greatest level of drying shrinkage at most ages (Table 6). At 56 days average drying shrinkage is 690 microstrain which is within acceptable levels and typical of good quality concrete made with Sydney aggregates. The drying shrinkage of standard concrete is better than Green Star concrete with an average 56 day shrinkage of 636 microstrain. The drying shrinkage of Envisia concrete is significantly lower than Green Star and standard concrete at all ages. At 56 days the average drying shrinkage of Envisia is 346 microstrain, half that of Green Star concrete.

Table 6. Drying Shrinkage of 40 MPa Concrete Used In Post-Tensioning Applications

	18%Reduction (Standard)	**25% Reduction (Green Star)**	**51% Reduction (Envisia)**
7 Day (microstrain)	254	327	134
14 Day (microstrain)	381	453	190
21 Day (microstrain)	466	523	232
28 Day (microstrain)	523	587	260
56 Day (microstrain)	636	690	346
n	8	3	5

5. CO_2-e reduction

Precise estimates of embodied carbon in concrete are difficult due to the heterogeneity in materials sourcing, cartage distances and so on. Using the methodology and data from Flowers and Sanjayan [9] the embodied CO_2-e for the concretes presented in section 3 were calculated and are presented in Table 7 and Figure 3. It is clear significant reductions in embodied CO_2-e relative to standard concrete and the equivalently performing Green Star concrete are achieved by replacing Portland cement in Envisia with slag. It should be noted that even more substantial reductions (up to 80% cement reduction) have been achieved with Envisia and are the subject of future development.

Table 7. CO_2-e Contribution of Green Star baseline, Standard, Green Star and Envisia Concrete

	Estimated Embodied CO_2-e contribution by source (using data and methodology from [9]) (kgm^{-3})			
CO_2-e source	**0% Reduction (Baseline)**	**18% Reduction (Standard)**	**25% Reduction (Green Star)**	**51% Reduction (Envisia)**
Portland Cement	360.8	295.2	270.6	176.3
Slag			6.4	30.7
Fly ash		1.1	1.9	
Other additives				5.1
Aggregates	52.8	52.8	54.4	49.9
Batching and cartage	21.0	21.0	21.0	21.0
Total	434.6	370.1	354.3	283.0
Reduction (% to baseline)	**0**	**15%**	**18%**	**35%**

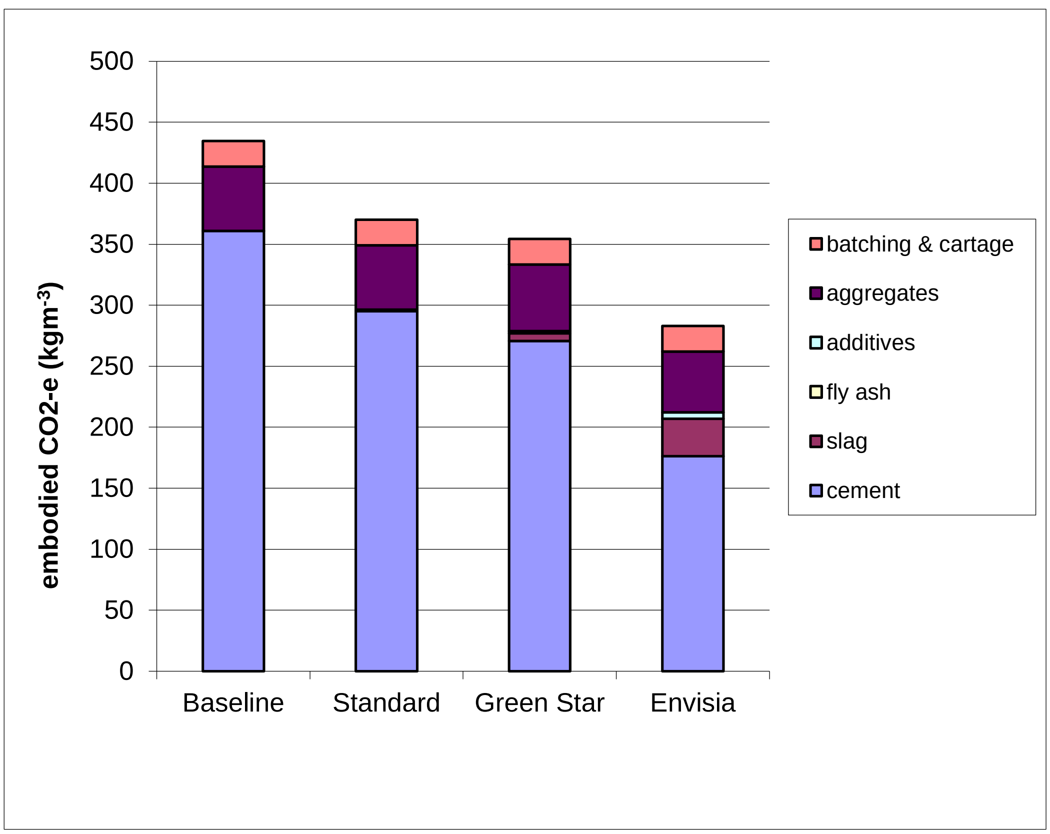

Figure 3. CO_2-e Contribution of Standard, Green Star and Envisia Concrete

6. Conclusions

Developments in concrete mix design have produced concretes suitable for post-tensioned applications with up to 25% cement reduction using the Green Star MAT-4 calculations. Due to the inherent limitations of SCM's on early age strength development it is difficult to achieve higher levels of cement replacement while still meeting early age strength requirements. The consequences of not meeting early age strength requirements are program delays which are usually not acceptable for cost reasons. Higher replacement levels have been achieved – for example Boral supplied high replacement concrete to Grocon for the Pixcel Building in Melbourne, which achieved 22 MPa for stressing after 5 days. For the majority of projects this elongation of stressing cycles presents an unacceptable cost escalation.

Envisia concrete has been shown to achieve the required strength for stressing in high-rise post-tensioned applications with significantly higher levels of cement reduction than current best practice, well in excess of the maximum awarded by Green Star. Envisia disrupts the usual trade-off between high early strength and high cement replacement, making very significant reductions in CO_2 emissions possible. The very low drying shrinkage achieved by Envisia concrete would be expected to reduce the loss of pre-stress due to drying shrinkage. Envisia concrete is compliant with all relevant Australian standards.

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