Investigation on the effect of low carbon, low shrinkage, high flexural strength ENVISIA® concrete on industrial floor and pavement application

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INVESTIGATION ON THE EFFECT OF LOW CARBON, LOW SHRINKAGE, HIGH FLEXURAL STRENGTH ENVISIA® CONCRETE ON INDUSTRIAL FLOOR AND PAVEMENT APPLICATION

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ABSTRACT

The key structural element in most industrial enterprises is the concrete floor slab. The aim of floor design is to select the most economical thickness while considering sufficient reinforcement to control the amount and size of cracks to a level consistent with the intended use of the floor. However, one of the most common causes of cracking in industrial floors is that the tensile stresses exceed the tensile strength of the concrete due to the shrinkage contraction. Therefore, there is a need for slabs that are reinforced with mesh to be saw cut in order to release the stresses due to the shrinkage. However, the distance between the sawn joints is related to the shrinkage of the concrete. Recently, considerable interest has been generated in the use of steel fibre reinforced concrete in order to control the tensile cracking of the composite material and reduce the number of joints especially in internal industrial floors.

Boral has developed a low carbon, low shrinkage and high flexural strength concrete, called Envisia®, with up to 60% cement replacement with specially milled ground granulated blast furnace slag (GGBFS) without compromising setting time or early strength. In this paper, a comprehensive experimental study was carried out to evaluate the influence of 40MPa Envisia® concrete on plastic and hardened properties of concrete industrial floors according to Concrete Society Report TR34 [1]. Finally, the results were compared with the results of conventional and fibre reinforced concrete mixes with the same strength grade.

1 Introduction

There is a general view amongst design engineers that the behaviour of concrete floor slabs is difficult to predict and cracking is very difficult to avoid. Whilst there is a degree of truth to this due to the number of variables involved in the behaviour of concrete floors, it is by no means an excuse for cracking and maintenance costs which should have been minimised by better design and detailing [2]. Studies undertaken on heavily trafficked concrete road surfaces show that a well-designed and constructed concrete floor incurs less than 10% of the maintenance costs per square metre than a poorly designed and constructed pavement. Add to this the costs due to damage to equipment (particularly hard forklift wheels), possible spinal injuries to personnel and trip hazards caused by poor joint detailing and it becomes clear why a floor slab needs adequate care and attention in design. As concrete cures, it undergoes chemical changes and loses capillary water causing it to reduce in size. At the same time, it is gaining structural strength due to the chemical bonds which are forming between its constituent materials. If at any point during this process a strain occurs due to the shrinkage being resisted by forces which exceed the increasing tensile or shear strength of the concrete a brittle failure will occur and a crack will form [3]. Therefore, for floor slab application, having a mix with lower shrinkage property, high abrasion resistance as well as high flexural strength would help designers to have more control on behaviour of concrete. In addition, the demand for high sustainability structures as well as the criteria determined by Green Building Council of Australia (GBCA) regarding Greenstar rating has led to the development of a number of sustainable products with higher dosages of Supplementary Cementitious Materials (SCMs). However, one issue with the higher use of SCMs is that they can lead to concrete with lower early strength gain and higher shrinkage than standard concretes, potentially compromising construction cycle times and element design outcomes. With this as a background, Boral Cement commenced an R&D program in 2008 to develop a binder system with a low carbon footprint, but able to provide strength gain similar to conventional concretes and lower shrinkage called Envisia®. This product contains a specially milled ground granulated blast furnace slag (GGBFS) which allows concretes that achieve high Portland cement replacement levels without compromising setting time or early strength. After a number of years of research and development, Boral first commercialised this concrete in July 2013 as a low carbon, high early strength concrete with low drying shrinkage aimed specifically at the high-rise post-tensioned market. Over the course of commercialization demand for other grades lead to the development of additional mix designs spanning many applications and for multiple performance benefits including industrial floor applications. This paper compares plastic properties, hardened properties such as strength, shrinkage, abrasion resistance as well as CO_2e emission data for Envisia®

concrete and a typical burnished concrete mix with equivalent strength grade for an industrial floor application.

2 Experimental programs

2.1 Material properties

2.1.1 Cementitious materials

Fly ash and GGBFS were used as SCMs. The shrinkage Limited cement (SL) was used for all concrete mixes. The physical properties of cement and SCMs and their chemical compositions using X-ray fluorescence (XRF) analysis are shown in Table 1 and Table 2 respectively.

Table 1: Physical properties of cement and SCMs

Materials	Median Particle Size (μm)	Specific Gravity (S.G)	Passing 45 μm sieve (%)	28-day strength index	Fineness index (m^2/kg)
SL Cement	16.3	3.15	94	100	395
GGBFS	10.2	2.90	99	103	420
Fly ash	13.2	2.10	89	94	370

Table 2: Chemical composition of cement and SCMs

Materials	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	TiO_2	Na_2O	P_2O_5
SL Cement	63.62	19.01	5.08	2.91	2.85	1.25	0.56	0.26	0.05	0.13
GGBFS	41.69	34.37	13.07	0.99	2.52	5.51	0.28	0.72	0.19	0.02
Fly ash	2.48	59.21	28.10	3.68	0.16	0.53	1.18	1.11	0.63	0.41

2.1.2 Aggregate and its grading

Fine sand with specific gravity of 2.59 and water absorption percentage of 0.40, and manufactured sand with specific gravity of 2.71 and water absorption percentage of 0.8 were used. Coarse aggregate, 20 mm and 10 mm gravel with specific gravity of 2.77 and water absorption percentage of 0.50 for both were used in all concrete mixes. From Table 3, all coarse and fine aggregates complied with requirements of the specification range listed in AS 2578.1 [4].

Table 3: Grading of coarse and fine aggregates

Coarse Aggregate			Fine Aggregate		
Sieve Size	20 mm	10 mm	Sieve Size	Manufactured Medium sand	Fine Sand
mm	Passing, %		mm	Passing, %	
19.00	98	100	4.75	99	100
13.20	52	100	2.36	83	100
9.50	11	89	1.18	58	100
4.75	1	18	0.600	40	98
2.36	1	4	0.300	25	47
1.18	0	3	0.150	14	2
			0.075	9	0

2.1.3 Admixtures

Low range water reducer (WR), High Range Water Reducer (HRWR) and Retarder (Re) and GGBFS activator were used in all concrete mixes.

2.2 Mix proportions

Two categories of concrete mixes with same grade of compressive strength were used in this research are shown in Table 4. Envisia® is a new product wherein a certain level of cement is replaced by blast furnace slag and another concrete was chosen to represent burnishing floor product. 35 kg of steel fibres were also added to each mix to investigate the effect of fibres in various properties of concrete especially in industrial floor application.

Table 4: Proportions of the concrete mixes

Concrete Mix	Water	Binder			Steel Fibre Content (kg/m3)
		SL	Slag	Fly ash	
Control	191	361	0	40	0
Control + Fibre	191	363	0	40	35
Envisia®	191	222	222	0	0
Envisia® + Fibre	191	222	222	0	35

2.3 Casting, curing and testing of specimens

The workability using the slump test, air content, fresh density, bleeding and setting time of the fresh concrete mixes were measured immediately after the mixing was completed according to AS 1012.3.1 [5], AS 1012.4.2 [6], AS 1012.5 [7], AS 1012.6 [8] and AS 1012.18 [9] respectively. Concrete cylinders of 100 mm diameter and 200 mm height were cast for compressive strength. The compressive and indirect tensile strength tests were performed on specimens stored in lime-saturated water for all concrete mixes up to 56 days in accordance to AS 1012.9 [10] and AS 1012.10 [11]. The flexural strength test was carried out on specimens with dimensions of 100 x 100 x 350 mm for all mixes after 7, 28 and 56 days curing in lime-saturated water according to AS 1012.11 [12]. Prisms of 75 x 75 x 280 mm in dimensions were cast for measuring the drying shrinkage according to AS 1012.13 [13]. The specimens were removed from moulds 24 hours after casting and then cured under lime water until the 7th day when the initial length was recorded. The samples were left for drying in laboratory at 23±2 °C and 50% relative humidity and length change was recorded up to 56 days. Determination of abrasion resistance of all concrete mixes was completed in accordance to BS EN 13892-4 [14] at the age of 28 and 56 days. Residual flexural tensile strength of metallic fibred concrete was measured according to BS EN 14651 [15] at 28 days.

3 Results and discussion

3.1 Plastic concrete properties

Plastic properties of all concrete mixes are presented in Table 5. It can be seen that the required slump and air content for both categories were achieved according to the TR34 [1]. It can be seen that Envisia® mixes had lower w/b ratio compared to control mix despite designing for similar 28-day compressive strength. The reason for these reductions is using higher binder content in slag mixes compared to control mix in order to get similar strength to control. It should be mentioned that the wet density of control mixes with 90% SL cement content as a binder are more than the Envisia® mixes with 50% replacement cement with slag which is due to differences in specific gravity between slag and cement. It can be seen that there is marginal difference on concrete setting time among all mixes. The effect of mix design on cumulative bleeding is presented in Figure 1. It can be seen that Envisia® concretes had less bleeding compared to control concretes which could be due to lower w/b ratio and higher binder content of Envisia® mix compared to control mixes. In addition, more water demand of slag due to higher fineness compared to cement as shown in Table 1 may be another reason for the lower bleed water in Envisia® mixes.

Table 5: Plastic property results for concrete mixes

Concrete Mix	w/b	Slump (mm)	Air Content (%)	Fresh Density (kg/m3)	Initial Set (min)	Final Set (min)
Control	0.47	90	1.6	2413	358	448
Control+Fibre	0.47	90	1.7	2450	370	465
Envisia®	0.43	95	1.5	2401	380	455
Envisia®+Fibre	0.43	95	1.5	2430	355	445

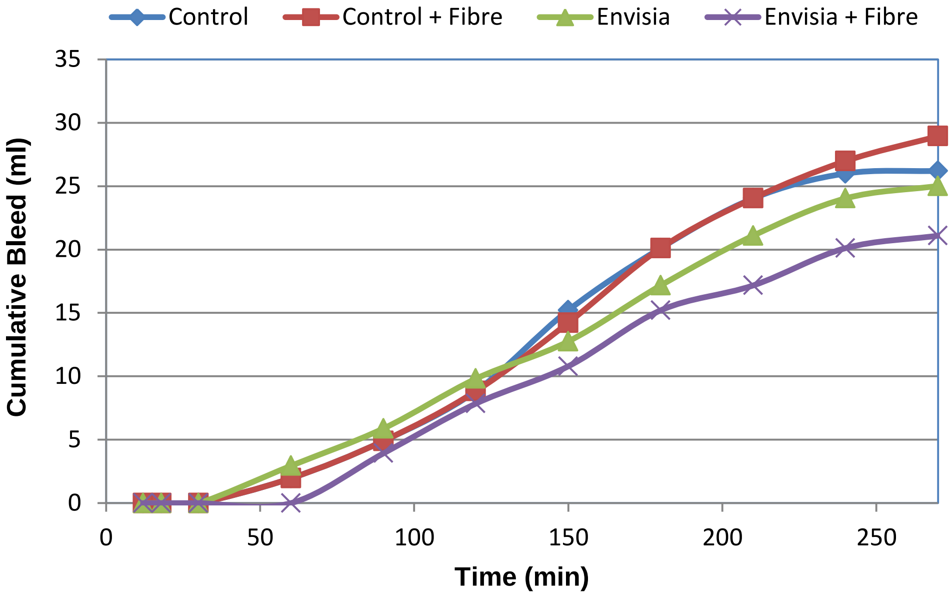

Figure 1: Cumulative bleeding in concrete mixes

3.2 Concrete strength properties

Compressive, indirect tensile and flexural strength developments for all concrete mixes are shown in Figures 2 to 4 respectively. The compressive strength results demonstrate the Envisia® concretes with and without fibres achieved lower later age strength as compared to control mixes due to high cement replacement level with GGBFS as well as the reduction of total quantity of cement which is responsible for early-age strength especially at higher cement replacement dosages. It is in agreement with findings of Teng, Lim [16] and Barnett, Soutsos [17]. However, Envisia® mixes achieved similar or even higher early age strength compared to control mixes due to activation of GGBFS particles and their contribution towards strength development much earlier than expected as shown in Figure 2.

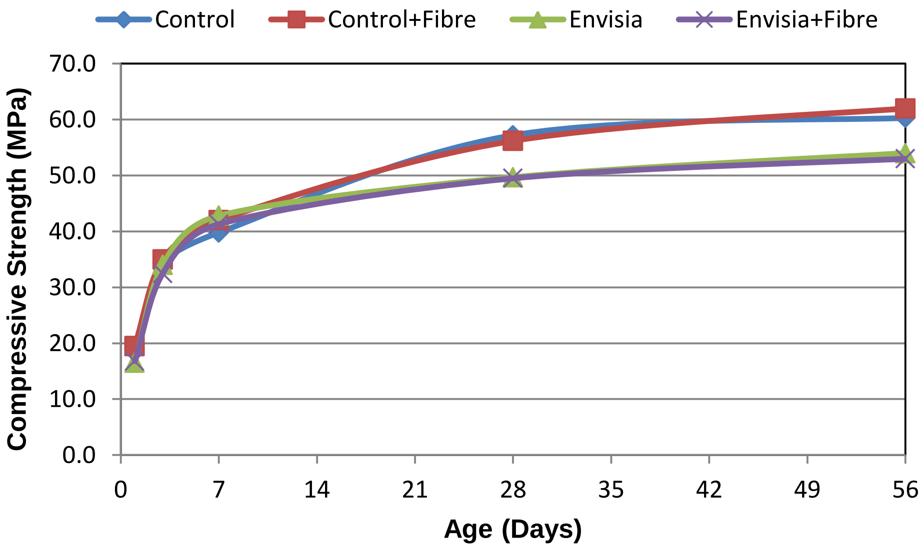

Figure 2: Compressive strength development in concrete mixes

Figure 3 demonstrates indirect tensile strength development results of al mixes up to 56 days. It can be seen that the mixes containing fibres works better than the mixes without fibres in all ages. However, control mixes gained slightly better results as compared to Envisia® mixes. Flexural strength developments for all concrete mixes are shown in Figure 4. It is noted that both Envisia® concrete mixes achieved approximately 20% higher flexural strength as compared to control mixes up to 56 days.

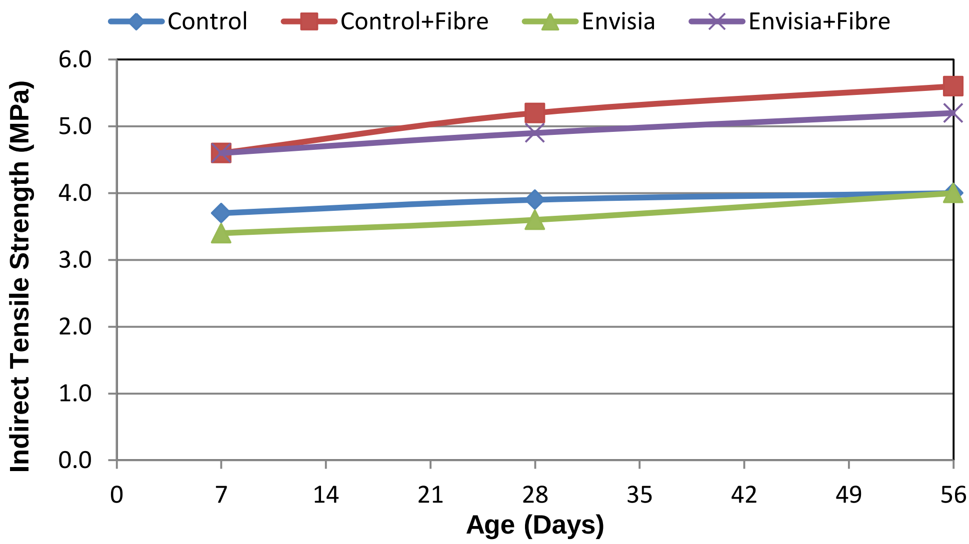

Figure 3: Indirect tensile strength development in concrete mixes

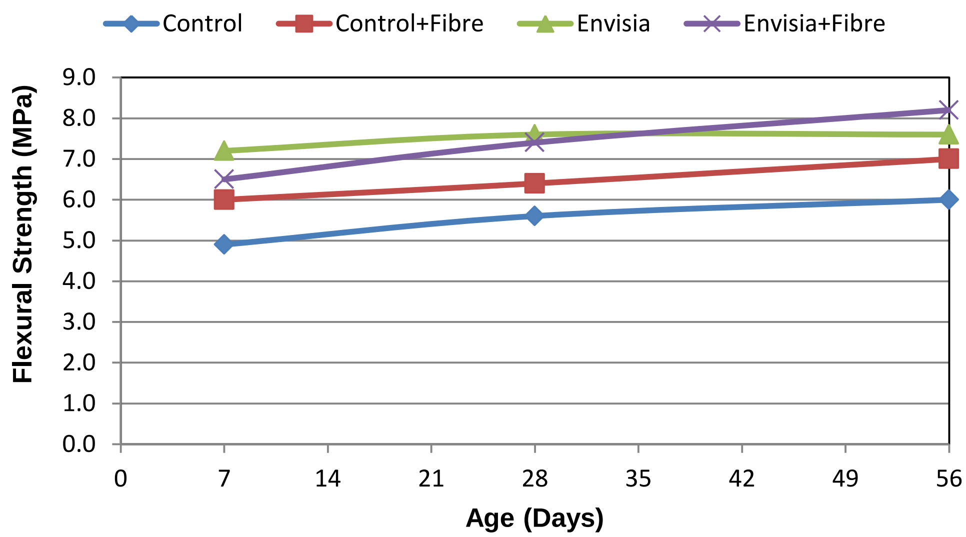

Figure 4: Flexural strength development in concrete mixes

The results of residual flexural tensile strength of both fibre reinforced concrete mixes at 28 days are presented in Figure 5. It can be seen that the limit of proportionality (L.O.P) of Envisia® concrete was higher about 22% compared to the control mix. However, residual flexural strength of both concrete mixes containing fibres for 1 to 4 mm crack mouth opening displacement (C.M.O.D) showed similar behaviour.

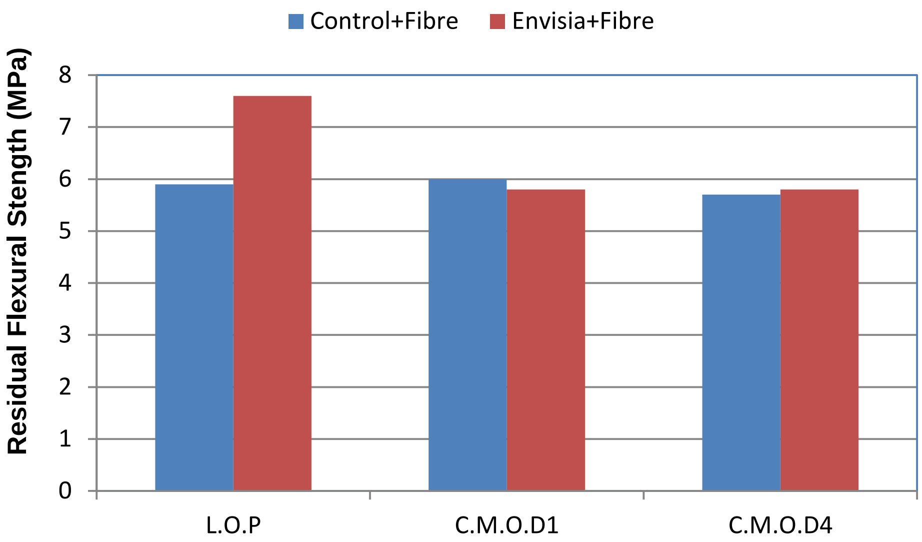

Figure 5: Residual flexural tensile strength of concrete mixes containing fibres

3.3 Drying shrinkage of concrete

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. 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 [18]. Drying shrinkage results of all concrete mixes are shown in Figure 6. An expected property based on previous work done for other concrete application shows the Envisia® concrete has a significant reduction in drying shrinkage. Figure 6 clearly demonstrates that Envisia® concretes developed significantly lower drying shrinkage, about 50% reduction at 28 days and 43% reduction at 56 days compared to control mixes. It could be due to the reduction of cement paste in unit volume of the concrete mix by 50% replacing cement with GGBFS as well as lower w/b ratio. In addition, increasing the amount of C-S-H gel hydrates and the density of hardened cement paste as well as the effect of activation of GGBFS in consuming the free water, which make concrete stronger and restricts the water evaporation could another reason in the reduction in drying shrinkage of Envisia concrete compared to control mix. It is in agreement with the findings of Li, Yao [19] and Atiş [20].

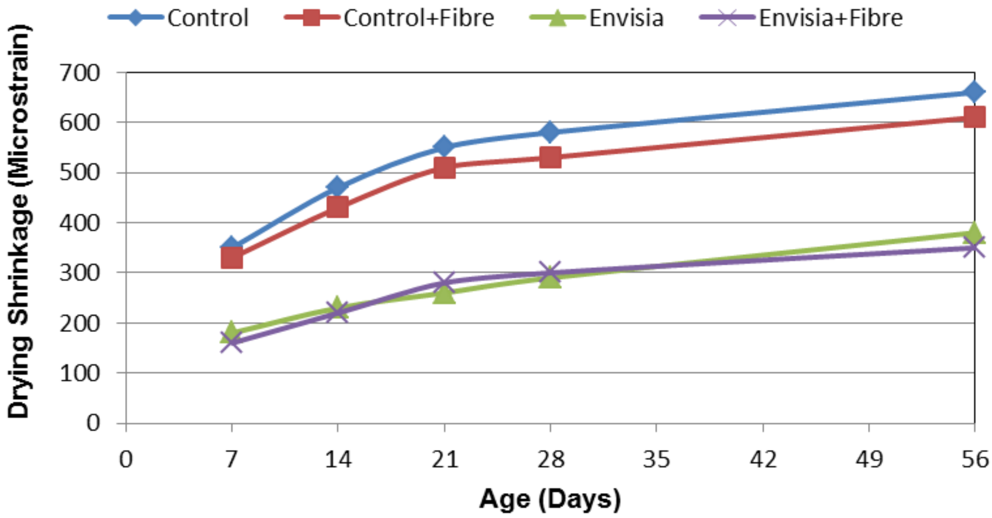

Figure 6: Drying shrinkage in concrete mixes

3.4 Abrasion resistance

Abrasion resistance of concrete is the ability of a concrete to resist wear caused by rubbing, scraping, skidding or sliding of objects on its surface. Wear, which is the removal of surface material, is a process of displacement and detachment of particles or fragments from the surface [21]. The wear resistance of the screed surface is assessed by measuring the mean depth of wear caused by a machine with three hardened steel wheels rotating over a ring shaped area for a fixed number of revolutions under a standard load according to BS EN 13892-4 [14] as shown in Figure 7. The mean depth of wear within the ring pattern is used to indicate the wear resistance of the screed surface at the test location. The primary factors affecting the abrasion resistance of concrete according to the literatures are: compressive strength, aggregate properties, finishing method, use of toppings, and curing. The abrasion resistance of concrete improved with the addition of steel fibres.

The results of the resistance to abrasion test performed at 28 and 56 days on specimens made with control and activated slag burnished concrete mixes with and without fibres are shown in Figure 8. It can be seen that depth of wear decreased by increasing the age of the samples from 28 days to 56 days especially for Envisia® mix due to 50% cement replacement with GGBFS. In addition, both control and Envisia® concrete mixes containing steel fibres showed better resistance to abrasion compared to plain concrete mixes as expected. However, Envisia® mixes with and without fibres improved abrasion resistance of concrete about 14% compared to both control mixes at 56 days. Investigation carried out by Atiş, Celik [22] revealed that the abrasion resistance increased as flexural tensile strength increased. They reported that the comparison between the relation of abrasion to compressive strength and abrasion to flexural tensile strength made in terms of R^2 of the linear regression showed that a stronger relation existed between abrasion and flexural tensile strength than that of abrasion to compressive strength of the concrete studied.

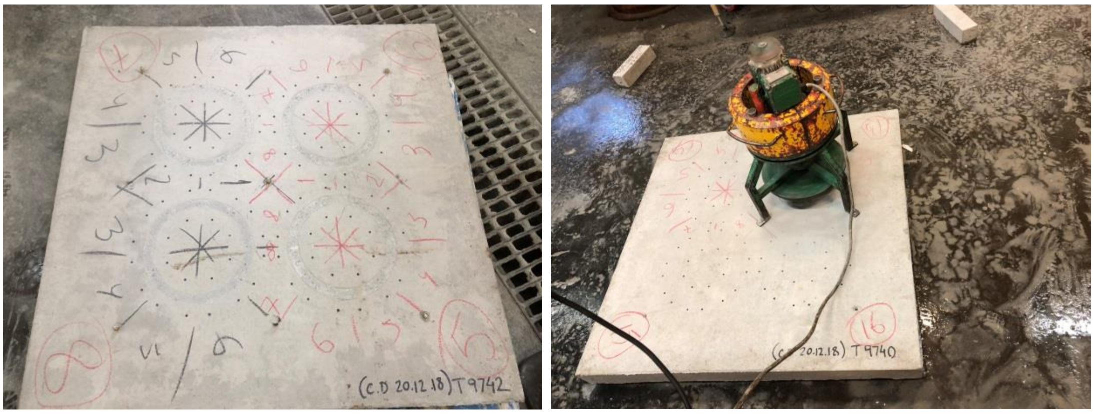

Figure 7: Abrasion resistance test sample and equipment

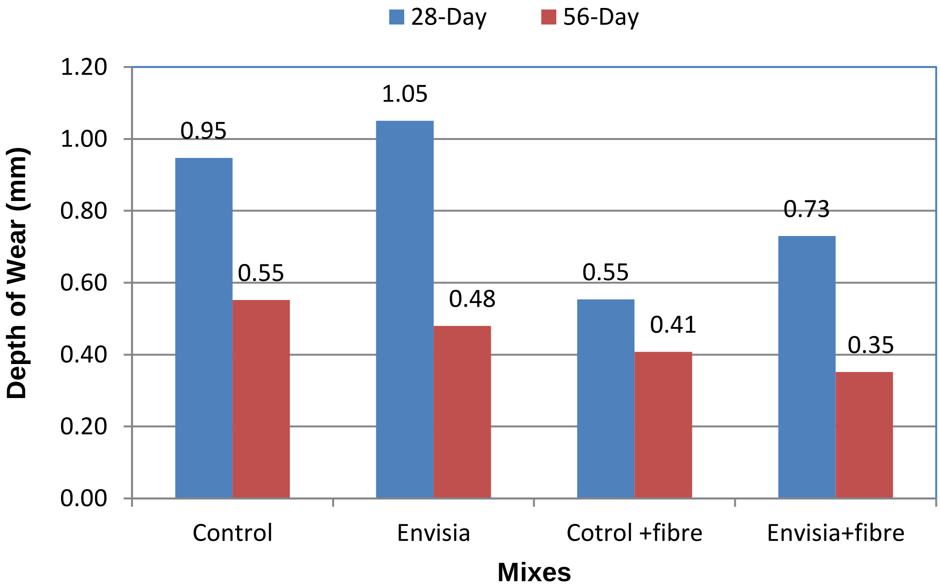

Figure 8: Depth of wear for mixes with and without fibres

3.5 CO_2-e reduction

This study quantified the carbon dioxide equivalent emissions (CO_2-e) generated by all the activities necessary to obtain raw materials, concrete manufacturing, and construction of one cubic metre of concrete based on the methodology and data presented by Turner, Collins [23]. Figure 9 demonstrations the CO_2-e footprint generated by Envisia® concrete compared to the control mix with the same grade. It is clear 20% reductions in embodied CO_2-e relative to control concrete are achieved by replacing 50% Portland cement with slag in Envisia® concrete.

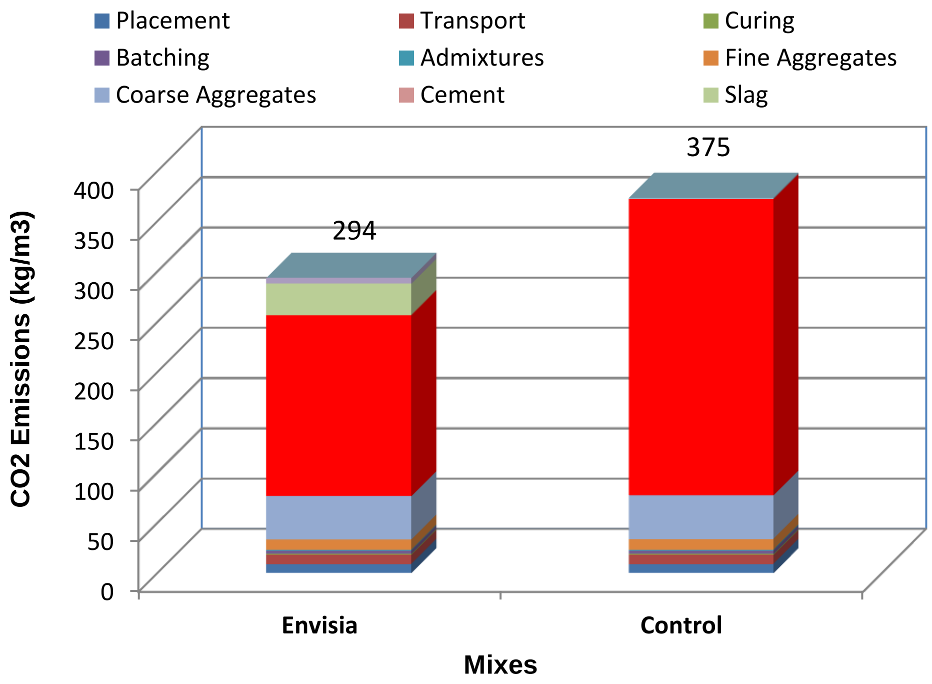

Figure 9: CO2-e Contribution of control and Envisia® Concrete

4 Conclusions

Based on the results of this study, the following conclusions can be drawn which are the comparison between Envisia® concrete with equivalent strength grade of conventional burnished OPC and 10% fly ash (SL/FA) concrete.

- Envisia® concrete exhibits higher early age strength gain, less bleeding water with the similar setting time compared to the control burnished mix.
- For the same grade of control burnished mix, 20% higher flexural strength is achieved by Envisia® concrete.
- Residual Flexural strength shows the activated slag burnished mix to have 20% higher peak flexural strength (Limit of proportionality – LOP), whilst similar post crack behaviour.
- Envisia® concrete exhibits significantly lower drying shrinkage. The 28-day and 56-day drying shrinkage results of Envisia® concrete showed 50% and 43% reduction respectively.
- Abrasion resistance of Envisia® concrete improved about 14% compared to control mix (at later age).
- A high proportion of activated GGBFS can be used to produce high performance concrete with lower carbon footprint due to reducing the Portland cement content. The embodied carbon emission reduced about 20% relative to control concrete

5 Acknowledgements

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