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SUSTAINABILITY IMPLICATIONS OF THE USE OF HYBRID POLYVINYL ALCOHOL FIBRE-REINFORCED FERROCEMENT AND FLY ASH

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Extensive research has been conducted on the use of fly ash as a partial replacement of cement in order to promote the sustainable use of cement. Most of these research has focused on the investigation of the cementitious properties of the blended cement and the engineering properties of the end products, such as fly ash concrete. The sustainability benefit of using fly ash is often qualitatively perceived without any quantitative assessment. A recent study on the performance of hybrid polyvinyl alcohol fibre-reinforced ferrocement (HPVAF) shows that adding moderate amounts of fly ash in the mixes could maintain the ultimate flexure and tensile strength of HPVAF. The increased service life/durability and the use of FA up to a 25% replacement for cement in HPVAF not only conserve virgin resources for producing energy-intensive construction materials but also avoid associated environmental impacts due to the manufacturing of these materials. This certainly offers socio-economic benefits in terms of cost saving, enhance affordability and guaranteed material supply for the people both in current and future generations. Life cycle sustainability assessment (LCSA) was conducted to determine these triple bottom line benefits associated with the use of HPVAF and FA in building construction.

Keywords: Ferrocement composite, Fly ash, Environmental impact, Life cycle cost.

1 INTRODUCTION

The construction industry is the main contributor to the greenhouse gas emission worldwide. Concrete which is the main construction material has a high carbon cost due to the production of cementitious materials. Another reason for concern is the depletion of resources such as sand and coarse aggregates which are heavily used in producing concrete. A recent study shows that the world is facing a global sand crisis because of the skyrocketing demand and sand mining is harmful to humans and the environment (Torres *et al.* 2017). A more efficient use of resources is therefore needed which requires innovative ideas and technologies in making concrete less resource-intensive. One of the improvement strategies is to use industry wastes or by-products a partial replacement of cement and/or aggregates (Kulasuriya *et al.* 2014). The main challenge is to maintain the engineering properties while using a cement replacement and/or recycled aggregates. Another strategy is on construction innovations, for example, to improve construction efficiency such as modular, prestressed and precast constructions, and to develop energy-efficient alternatives of conventional structural sections such as steel/concrete composites or other innovative composites (Banthia *et al.* 2012). Most of these research focused on the engineering aspects of the development to achieve desirable mechanical properties and durability requirements. The use of HPVAF in concrete could potentially reduce the amount of energy and carbon-intensive construction materials such as coarse aggregates, and also it enables the use of industrial by-product as a replacement of cementitious materials. Thus, cost as well as environmental saving opportunities will be resulted to achieve a sustainable built environment. The sustainability aspects in a sense of the triple bottom line benefits (i.e. environmental, social and economic) are often perceived achieve but not quantitatively measured. This paper presents a life cycle assessment of a new reinforced concrete composite which was recently proposed to improve eco-efficiency performance of the construction sector by providing the same output (i.e. concrete with a required level of compressive strength) with less cost and environmental impacts. In this new composite, fly ash was used as a cement replacement and engineered ferrocement was used as a permanent form that would lead to the reduction in construction cost and time-saving.

2 HPVAF COMPOSITE

A further development of HPVAF led to a combined use of hybrid polyvinyl alcohol (PVA) as fibre reinforcements in ferrocement panels (Abushawashi and Vimonsatit 2015), which was named hybrid PVA ferrocement, or HPVAF. The proposed HPVAF composite is made of an HPVAF panel, which is engineered with two types of PVA fibres, short (8 mm) and long (30 mm), at the tension part of the composite. HPVAF panels can be precast off-site to improve the productibility and quality control of the HPVAF fabrication. Thus, the HPVAF panels can be used as a permanent formwork in the construction of the HPVAF composite. The upper part of the HPVAF composite can be cast on-site and can be engineered further to achieve its weight efficiency, thus achieving a further reduction in materials use. Figure 1 shows the HPVAF composite and construction sequence. The main components of a typical HPVAF composite section are HPVAF panel, conventional concrete (CC) and steel reinforcements, with lightweight infill as optional.

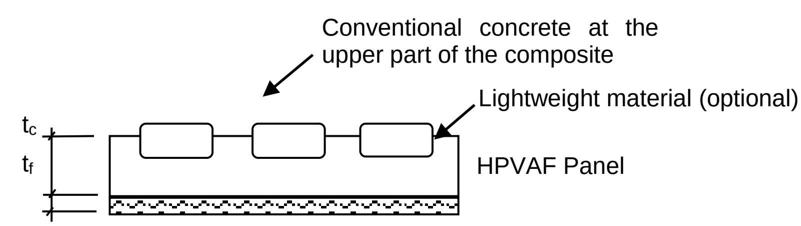

Figure 1. Section of HPVAF Composite.

The thickness, t_f, of the HPVAF panel is varied, from 20 mm to 40 mm. The thickness, t_c, of the upper concrete section can be designed to suit the design requirements for bending and shear using a conventional approach. A lightweight material can be used as an infill in the ineffective region of the upper concrete (Wahyuni *et al.* 2012) to achieve up to a 30% weight reduction when compared to a conventional reinforced concrete section with the same total depth ($t_f + t_c$). Using HPVAF panels as the permanent form of the composite section provides numerous construction benefits, especially for a large span construction. The permanent form eliminates the need for installing a temporary formwork and falsework system, thus reduces construction cost and time.

2.1 HPVAF Panel VS Conventional Concrete

Various mix proportions of HPVAF mortar have been tested for determining the compressive strength (Abushawashi 2015) using Ordinary Portland cement (OPC) and fly ash (FA) as the main binders of the mortar. The mortar mixture for the HPVAF panels used in the present study contained 400 kg/m^3 cement, with a ratio of 0.75:0.025:0.40:1:0.05 by weight of cement, FA, water, sand, and silica fume, respectively. The compressive strength of this mix was 46 MPa. The upper part of the HPVAF composite could be made of conventional concrete, with or without fibre reinforcement, depending on the design requirement. The cement:sand:aggregate ratio of the conventional concrete slabs was 1.0:2.1:3.2, and the water:cement ratio was 0.45. This mix was designed to have the compressive strength of 32 MPa at 28 days.

2.2 Mixtures of HPVAF Composites

Considering an HPVAF composite section which is made of a 40mm-thick HPVAF panel and a 115mm-thick of the upper concrete portion (Abushawashi and Vimonsatit 2014). Thus, the percentage of the HPVAF panel and of the CC are 26% and 74%, respectively. Table 1 shows the mixtures of the conventional concrete CC and the HPVAF and CC composites.

Table 1. Life Cycle Inventory of CC and HPVAF composites.

Energy and materials	**CC1**	**CC2**	**CC3**	**HPVAF +CC1**	**HPVAF +CC2**	**HPVAF +CC3**	**HPVAF +CC3+LW**
Mixture proportions							
OPC (kg/m^3)	400	350	300	374	337	300	264
Fly ash (kg/m^3)	0	50	100	26	63	100	100
Coarse agg. (kg/m^3)	1280	1280	1280	947	947	947	795
Sand (kg/m^3)	840	840	840	726	726	726	626
Water (kg/m^3)	180	180	180	175	175	175	147
Silica fume (kg/m^3)	0	0	0	3.9	3.9	3.9	3.9
PVA fibres (kg/m^3)	0	0	0	5	5	5	5
Wire mesh (kg/m^3)	0	0	0	13.7	13.7	13.7	13.7
Tensile steel bars (kg/m^3)	55	55	55	0	0	0	0
Lightweight (kg/m^3)	0	0	0	0	0	0	28
Total (kg/m^3)	2755	2755	2755	2271	2271	2271	1983
Transportation (tkm)	61	69	77	55	61	67	61
Manufacturing (kWh)	91	91	91	76	76	76	66

Note: LW = lightweight infill made up of 16% of the CC volume in the present case.

All materials were sourced locally in Western Australia. An estimate of the energy consumption at the concrete batching plant is 0.034kWh/kg of concrete (Nath *et al.* 2018). Two types of wire mesh were used, hexagonal woven wire mesh (chicken mesh) with a diameter of 1.4 mm and wire spacing of 40 mm, and flexible galvanized welded square mesh of 1.24-mm diameter and 25x25-mm holes. An estimate of the mesh production using a 2.2kW motor is 130 m^2 and 210 m^2 per machine hour for wire mesh and welded square mesh, respectively. The energy required for hot-dip galvanized steel is 2.5 GJ/tonne. The energy consumption during the construction (Biswas 2014) includes the off-site precast of HPVAF panels, transport operation from the casting site to the construction site, concrete ready mix, and concrete pouring. It should be noted that the consumption of other associated construction activities such as the installation of formwork and falsework are not included in this study. The HPVAF composites do not require the installation of formwork and falsework which means a significant reduction in the energy consumption compared to the CC construction. The environmental advantage of the avoidance of formwork and falsework savings that are resulted from the use of HPVAF in concrete is beyond the scope of this study and hence, will be considered in the future work.

A life cycle assessment (LCA) was carried out to estimate global warming, embodied energy consumption, solid waste, water consumption and land use of seven concrete mixtures following ISO14040-44 guideline (ISO 2006), which consists of four steps, namely: goal and scope, life cycle inventory (LCI), impact assessment and interpretation. We had considered the estimation of first two environmental indicators in this research as the construction industries contribute about 23% of Australia's annual GHG emissions and 20% of the total energy consumption (Nath *et al*. 2018). In addition, water is a scarce resource in WA and this construction sector produces a large amount of wastes (i.e. 19 million ton per year, (DoSEWPCQ 2011)). Finally, the land use changes due to quarrying and manufacturing of construction materials cause the loss of biodiversity (Biswas and Cooling 2013). The functional unit of this LCA study is 1 m^3 of concrete, which was used for conducting an inventory analysis to estimate energy and materials used during concrete life cycle (Table 1). Input and output data from the LCI in Table 1 were incorporated into SimaPro 8.4 LCA software (Pré Consultants 2017) and then relevant materials were linked to local Australian emission databases. In the absence of local databases, new libraries were created (i.e. wire mesh, lightweight). Australian emission databases were used for cement, fly ash, sand, electricity, transportation and water (Life Cycle Strategies Pty Ltd. 2015). The unit of tkm or tonne-kilometers was used to calculate the environmental impacts from the transportation of construction materials. Since the emission databases for coarse aggregate are unavailable, a new database was developed. The emissions associated with the combustion of diesel are available in the Australian databases. The foreign emission databases, such as Eco-invent and USLCI (US Life Cycle Inventory) that are available in the software, was used to calculate the impacts of silica fume and galvanized steel, respectively. It should be notable that PVA fibres only account for 0.2% of the total weight. Therefore, the exclusion of this chemical is not expected cause notable impact on the LCA results. Also its emission factor is not currently available. Finally, Australian indictor method has been used to calculate five aforementioned impacts (Life Cycle Strategies Pty Ltd. 2015).

3 RESULTS AND DISCUSSIONS

Table 2 presents five different environmental impacts resulting from mining, transportation and manufacturing of seven concrete classes. Global warming, land use, solid waste and embodied energy consumption are reduced from 573 kg CO_2 e-, 16.3 m^2, 1.3 kg and 3GJ to 488 kg CO_2 e-, 14.4 m^2, 1.4 kg and 2.8GJ due to the replacement of CC1 with CC3. The use of industrial by-products as a partial replacement for energy-intensive OPC has mainly reduced all these impacts. For example, Figure 2a confirms that OPC accounted for a significant portion of GHG emissions (i.e. 68%). These environmental impacts can further be reduced if HPVAF is added to these concrete classes. This is because of the use of HPVAF that increased the tensile strength of the concrete and thus completely eliminates the use of carbon-intensive tensile steel. Whilst overall GHG emissions are reduced due to use of HPVAF, Figures 2a and b show that OPC still remains as the hotspot.

CC3+HPVAF+LW was found to offer the higher environmental savings than other concrete classes (Figure 3) due to the reduction in 34% of OPC, 28% of coarse aggregates, 18% of water and complete replacement of tensile steel. Land use (i.e. 37- 48%) and water use (i.e. 37 – 46%) impacts decreased significantly when HPVAF is added to the conventional concrete. Firstly, the use of HPVAF composite completely reduces the use of steel which means that the land required for mining and processing of steel is reduced. Secondly, water consumption is reduced by 18% due to a reduction in the mixing of concrete ingredients (i.e. coarse aggregates, sand, and cementitious materials). Solid wastes are reduced quite considerably due to the avoidance of land clearing and inputs reduction for ingredient production. This means that inter-generational social equity aspect of sustainability can be enhanced by conserving land and non-renewable material resources for the future generations. The other indirect environmental impacts that could be avoided in due using HPVAF composite is the loss of biodiversity associated with quarrying and mining activities for concrete ingredients production. Reduction in expensive materials such as tensile steel and OPC is expected to reduce to the overall cost of HPVAF based concrete classes.

Table 2. Environmental impacts of seven concrete classes.

Impact category	CC1	CC2	CC3	HPVAF +CC1	HPVAF + CC2	HPVAF +CC3	CC3 +HPVAF+LW
Global Warming (kg CO_2e-)	573.6	525.2	478.4	488.3	453.8	419.2	374.0
Land use (m^3)	16.3	15.3	14.4	11.0	10.3	9.6	8.5
Water Use (m^3)	3.2	3.2	3.2	2.1	2.0	2.0	1.7
Solid waste (kg)	1.4	1.3	1.3	1.2	1.1	1.1	1.0
Cumulative energy demand (MJ)	3007.0	2880.4	2779.3	2512.2	2437.5	2362.7	2134.7

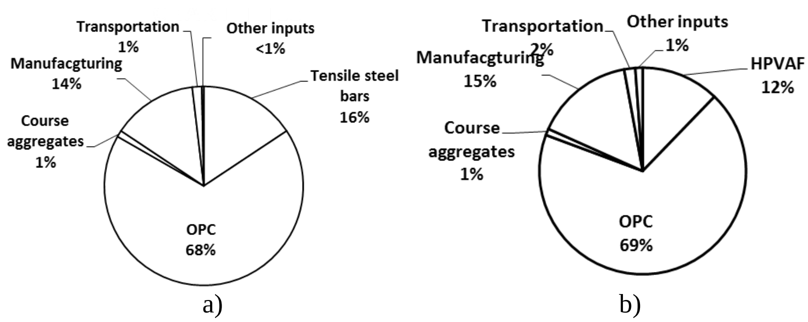

Figure 2. Breakdown of GHG emissions in terms of inputs a) CC1, b) HPVAF+CC3+LW.

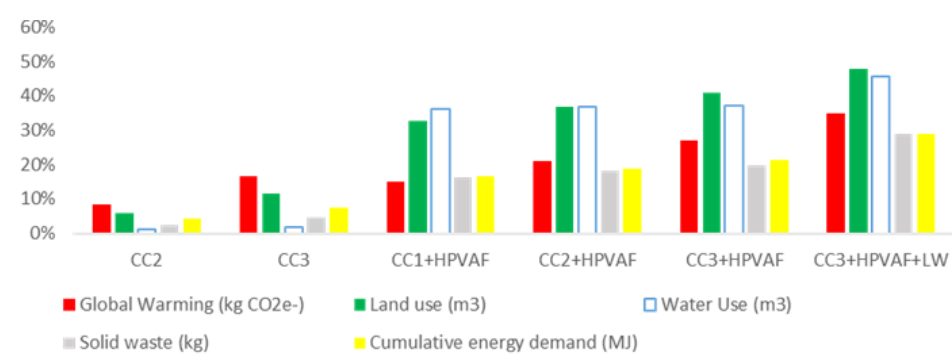

Figure 3. Environmental impacts saving associated with the use of HPVAF and industrial by-products.

4. CONCLUSIONS

There are environmental, social and economic implications associated with the use of HPVAF in concrete. The amount of conventional concrete that consists of energy and carbon-intensive construction materials can substantially be reduced due to the use of HPVAF in concrete. This ferrocement also maximizes the use of industrial by-products such as fly ash and silica fume without compromising the structural performance of concrete. The incorporation of these by-products with HPVAF could further increase sustainability benefits. A detailed economic analysis and the estimation of the service life of concrete classes of this study will be carried out to further highlight the sustainability benefits of these HPVAF concrete classes.

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