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A mechanical and environmental assessment and comparison of basalt fibre reinforced polymer (BFRP) rebar and steel rebar in concrete beams

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Abstract

This paper compares holistically the mechanical and environmental performance of basalt fibre reinforced polymer (BFRP) rebar against conventional steel rebar in concrete beams. This assessment involves material testing and life cycle assessment (LCA). The results show that BFRP tendons in reinforced concrete beams are stronger and lighter than steel with a better environmental profile and fewer embodied emissions, as fewer material and energy resources are required during production. The future market is expected to be within the precast industry, rather than in on-site construction, as precast BFRP concrete beams have approximately half the emissions of steel reinforced concrete beams.

Keywords: Basalt fibre reinforced polymer (BFRP); Mechanical performance; Life cycle assessment (LCA); Environmental performance; Concrete beam

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1. Introduction

In recent years, the use of fibre reinforced polymer (FRP) composite materials has been rapidly growing across numerous industries, for example the aerospace, automobile, marine, and construction industries [1]. Currently, a large proportion of industrial goods and mechanical parts are made from FRP composite materials as opposed to aluminium or steel. More specifically, the application of FRP is gaining acceptance, mainly because of its non-corrosive nature,

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high specific strength, high specific stiffness, and lower specific weight relative to conventional steel [1, 2]. Within the building sector, the adoption of FRP has been somewhat slower. In the last couple of decades, FRP materials have been used in retrofitting construction materials [1] such as, concrete beams [3] and masonry walls [4]. Nevertheless, FRP used as reinforcement bars, has found a place in the construction market, in terms of replacing traditional steel reinforcement [1, 2]. Further research and the development of guidelines for FRP reinforcements will support this transition, and will eventually open up new markets for potential FRP applications.

Glass fibre is the most widely used FRP material, because of its low cost and long-established availability on the market [5, 6]. However, manufacturers claim that carbon fibres are gaining a larger share, [7] insofar as carbon fibres are much stiffer than glass fibres, and have elastic modules identical to those of steel [5]. Another type of fibre that has gained popularity in the last two decades is basalt fibre [6, 8-10]. Various manufacturers have employed this fibre because of its low cost, high ecological compatibility during the production process, and functional properties [8-11]. The density of basalt (2600 kg/m^3) is approximately one third of the density of steel (7680 kg/m^3), which means BFRP is a lighter, stronger construction material compared to steel. It is expected that these mechanical properties will have implications on the environmental performance of BFRP as a construction material. Furthermore, it is easier and cheaper to produce basalt fibres, compared to other fibre types such as glass fibre [10, 12]. A previous study estimates the energy required for basalt fibre production to be around 5 kWh/kg in an electric furnace, whilst the energy required to produce steel is around 14 kWh/kg [13]. It is expected that this disparity in energy consumption will have an impact on the environmental performance of BFRP. BFRP reinforcement bars are therefore a promising material in concrete as a replacement for steel reinforcement bars [8-10, 14, 15].

Basalt fibre was originally developed in the Soviet Union during the 1960's to 1980's [6, 10]. Today, basalt fibre fabrication is mainly situated in Russia and China, with basalt mines located mainly in the Ukraine [6]. Few producers are situated in Western Europe. Basalt rock is principally composed of silica, alumina, with lime, magnesium oxide and ferric oxide found in lesser percentages [10]. For fabrication of continuous basalt fibre (CBF), the quantity of each material needs to be controlled [11]. Mineralogically speaking, basalt is primarily constituted of the minerals plagioclase, pyroxene and olivene [16]. To create basalt fibre, the basalt rock is mined and crushed into basalt fractures. Batches of basalt fractures are sorted and mixed in order to achieve the desired composition. These blended fractures are then melted in a furnace [10]. Once the basalt fractures are heated to an optimal temperature of between 1400 - 1600°C, the molten basalt is extruded into continuous filaments with a diameter of 12-18μm [17]. CBF may be formed into chopped basalt fibre strands, basalt fabrics, basalt wires or meshes, which can then be used in a wide range of application areas [10].

In order to convert the fibres into BFRP tendons, the CBF is glued together with resin. In some cases, sand is glued to the BFRP rebar surface to give a higher level of cohesion between the BFRP rebar and concrete. The total proportion of resin varies from 20 to 40% of the total product volume, and differs from manufacturer to manufacturer. However, epoxy resin is typically used [18]. The BFRP rebar is then pre-stressed to up to 50% of its ultimate strength, prior to inclusion in the concrete beam. BFRP tendons have a tensile strength in order of 1000 – 1300 MPa. In comparison, steel reinforcement has a tensile strength of around 500 MPa. The elastic module of basalt fibre is much lower than steel, of around 70 GPa [19, 20]. One of the main advantages of using BFRP as a strengthening material in concrete is that it is non-corrosive [21]. This property is advantageous in structures under severe attack from salty or damp environments, for example, the top layer of reinforcement in bridge decks, in concrete floors in multi-storey car parks, groundwork and foundations, or structures located by the coast. In conventional houses, BFRP bars offer the possibility of reducing the amount of concrete required, and may allow for thinner concrete members because of the strength and corrosion-resistant properties of basalt, which requires less passivating layers of concrete to limit the transport of oxidants towards the reinforcement bars. This may also in turn lead to a reduction in material consumption. Reduced material consumption will lead to a reduction in embodied energy and material emissions. On the other hand, the elastic module for BFRP tendons is much lower than that for steel. This disadvantage leads to excessive deformation at service limit state compared to steel bars, if the same cross-section area is used [14, 15, 18]. However, compared to steel, basalt fibre does not exhibit yielding during tension. The BFRP material is purely elastic. A relaxation test of the BFRP reinforcement bars has been ongoing at SEL since 2013. Reykjavik University estimate an expected final relaxation value of 6% after 50 years. This estimation is similar to glass fibre bars.

It should be noted that the effect of concrete admixtures in BFRP and steel rebar in concrete beams is outside the scope of this paper. However, it is expected that if the concrete is stronger with a larger cement content, than the BFRP rebar section will also be stronger, similar to the effect seen in steel reinforced concrete beams. A consequence of using a higher cement content is higher embodied emissions. It is acknowledged that the composite section strength of the BFRP rebar is heavily influenced by concrete strength; and is dependent on the admixtures, water content, and quality of sand and gravel used. As the concrete gets stronger the shear and compression stresses get higher and this leads to higher fracture bending moments.

Previously, only two studies have investigated the environmental impact of basalt aggregates in the production of concrete [22, 23]. To the authors' knowledge, no study has investigated both the mechanical and environmental performance of BFRP reinforcement bars in concrete. This study compares both of these aspects in a holistic approach. To start, the methodology for mechanical testing and life cycle assessment (LCA) are presented. Next, the strength and durability results from mechanical testing are presented, as well as the results from the LCA. The results are discussed together, in order to reflect on the mechanical and environmental findings in a holistic manner. Finally, concluding remarks and areas for further work are reported.

2. Methodology

The methodology section is divided into two parts. The first section documents the experimental procedure used for material testing, whilst the second section outlines aspects of the LCA methodology used.

2.1. Experimental procedure

Nine BFRP and three steel reinforced beams were tested in terms of strength and durability. The BFRP beams were pre-stressed and used 2 x 10mm diameter tendons. The basalt fibre tendons are glued with epoxy resin, and have a sanded finish to increase concrete bonding [24]. The BFRP pre-stressed beams were fastened with end anchors, and glued with threaded M24 bolts with steel plates at the end of the beams. Each tendon was pre-stressed to approximately 50% of its ultimate strength, as recommended by the ACI guidelines for FRP [25]. In comparison, steel wires are normally tensioned by up to 85% of their yield strength. The steel reinforcement tested was hot rolled B500 NC. The concrete strength was determined as the mean concrete strength of three tests on concrete cylinders carried out 28 days after casting, and averaged between 57.1 to 67.4 MPa for the BFRP and 31.4 MPa for the steel reinforced concrete. The average temperature in the lab was 20°C and relative humidity was 30% whilst the concrete was curing. The experimental setup and geometry of the beams are illustrated in Figure 1.

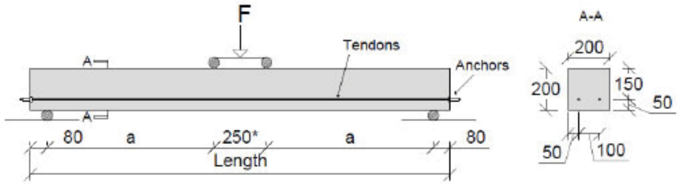

Fig. 1. Schematic drawing (not to scale) of the bending test setup and cross-section.

Tables 1 and 2 provide information on beam size, pre-stressing force (P) and total length to the point at which the shear force (F/2) is applied. All of the beams tested have the same equivalent amount of internal reinforcement, and a cross sectional area (A_f) of 156 mm^2. The bending ratio for the beams is $\rho = 0.0052$.

In all, five parameters are measured in the four-point bending test. Firstly, the maximum value of the shear force measured in a given test before fracture of concrete is referred to as V_{exp}, whilst $M_{\text{at failure}}$ is the maximum bending moment in the beam mid-span which is calculated by multiplying V_{exp} with a, the distance from the point load to the support. Thirdly, V_{cracking} is the shear force at which micro cracking is initiated. Fourthly, deflection (Δ) corresponds to failure load for each beam. Finally, two strain gauges, 30mm in length, were glued onto the compression site (at the top of the section) in the mid-span of the beam, in order to observe maximum strains. These values are given per mille (‰).

2.2. Life cycle assessment methodology

The goal of the LCA is to ascertain the environmental impacts of BFRP and conventional steel reinforcement bars in concrete beams. This comparative LCA has been carried out according to ISO 14040: 2006 and EN 15804: 2012 [26, 27]. The functional unit (FU) is defined 'per reinforced concrete beam', and an overview of the beam dimensions, together with the material inventory are provided in Table 1. Note that although nine BFRP and three steel reinforced beams are mechanically tested, the material inventory is the same for all steel reinforced beams, and can be divided into four inventories for the BFRP reinforced beams. A cradle-to-gate system boundary has been used, whereby 'raw material extraction and processing, processing of secondary material input (e.g. recycling processes), transport to the manufacturer, manufacturing' are included as part of the product stage [27]. The use stage is not assessed as emissions are expected to be close to zero in both scenarios. The end of life stage is not assessed as it is expected that the estimated service life of the beams will be more than 60 years. The LCA includes the acquisition of basalt rock from the mine, crushing basalt rock into fractures, transporting raw material to the factory and smelting basalt fractures in an electric furnace to create continuous basalt fibre (CBF). See Figure 2 for a more detailed diagram of the CBF production process. Epoxy resin is added to the CBF to extrude into pre-stressed BFRP tendons. The BFRP is then cast into concrete beams. Figure 3 depicts a flow diagram of the system boundary. Since specific manufacturer's data was not available for the resin composition used, it is assumed that 70% of the composite material is CBF and 30% epoxy resin. Life cycle inventory data has been collected from the Ecoinvent v3.1 database [28]. A Swiss process has been used for all concrete, and a European process has been used for reinforcing steel. Mass allocation is used for data collected on raw materials, energy, transport and direct emissions. The life cycle inventory model for BFRP production was developed in SimaPro Analyst v.8.0.5 [29]. For impact assessment, the ReCiPe Midpoint Hierarchist v1.11 method has been used, whereby all eighteen mid-point indicators have been assessed [30].

Table 1. Material inventory for reinforced concrete beams.

No.	Type of beam	Length (*mm*)	Width (*mm*)	Height (*mm*)	Volume of concrete (m^3)	Quantity of reinforcement (*kg*)
1	BFRP reinforced, pre-stressed	1200	200	200	0.05	0.40
2	BFRP reinforced, pre-stressed	2000	200	200	0.08	0.66
3	BFRP reinforced, pre-stressed	2700	200	200	0.11	0.89
4	BFRP reinforced, pre-stressed	3860	200	200	0.15	1.28
5	Steel reinforced	1250	200	189	0.05	4.44

In order to quality assure emission findings, the results from the LCA will be compared against life cycle emission data from environmental product declarations (EPD) for steel reinforced concrete beams, reinforcement steel and pouring concrete, representative of a Nordic market. Furthermore, since it is assumed that 30% of the BFRP tendons are made from epoxy resin, a sensitivity analysis on resins will also be completed to ascertain the impact resin has on embodied emissions in BFRP.

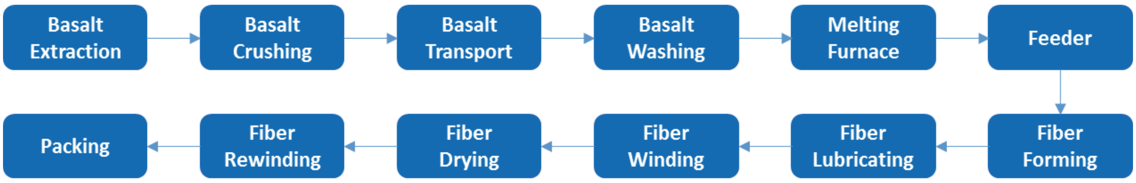

Fig. 2. Diagram of the CBF production process

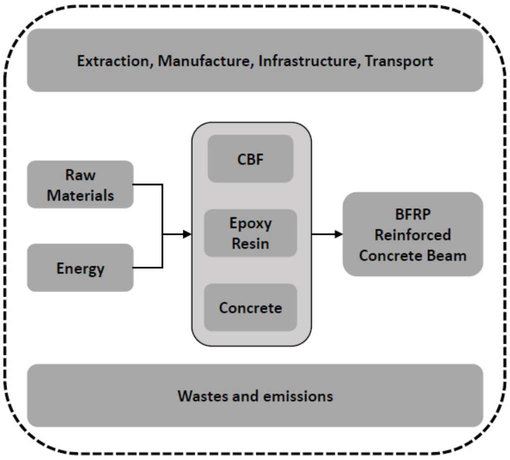

Fig. 3. Flow diagram showing the system boundary

3. Results

The results section is divided into two parts. The first section presents the results from material testing, whilst the second section presents the results from the LCA.

3.1. Mechanical performance

The failure mode of the beams pre-stressed by BFRP tendons was due to bending-shear failure. As shown in Table 2, the failure moment was nearly constant for all beams (from 23.1 to 30.6 kNm). The maximum shear force at failure varied depending on a/d ratio. This indicates that the a/d ratio has a significant effect on shear capacity although most shear equations in published standards and guidelines do not consider this.

Table 2. Experimental beams: Size, properties and results.

No.	Type of beam	Length (*mm*)	a (*mm*)	a/d	f'c (*MPa*)	P (*kN*)	A_f (*mm*^{2})	Bending ratio ρ	V_{exp} (*kN*)	$M_{at\ failure}$ (*kNm*)	$V_{cracking}$ (*kN*)	Deflection Δ (*mm*)	Strain at top face (‰)
1.1	BFRP	1200	395	2.63	67.4	84	156	0.0052	77.5	30.6	33	17	3.25
1.2	BFRP	1200	395	2.63	67.4	84	156	0.0052	72.0	28.4	38	15	2.90
2.1	BFRP	2000	795	5.3	60.4	78	156	0.0052	29.5	23.5	16.5	33	-
2.2	BFRP	2000	795	5.3	60.4	78	156	0.0052	33.5	26.6	17.5	35	-
2.3	BFRP	2000	795	5.3	60.4	78	156	0.0052	29.0	23.1	16.5	33	2.60
3.1	BFRP	2700	1145	7.63	61.7	84	156	0.0052	23.1	26.4	11.5	53	3.13
3.2	BFRP	2700	1145	7.63	61.7	84	156	0.0052	23.2	26.6	11.5	56	3.25
4.1	BFRP	3860	1600	10.67	57.1	78	156	0.0052	15.8	25.3	9	124	2.5
4.1	BFRP	3860	1600	10.67	57.1	78	156	0.0052	15.5	24.7	9	117	3.00
5.1	Steel	1250	390	2.39	31.4	0	452.4	0.0139	50	19.5	46.5	7.2	-
5.2	Steel	1250	390	2.39	31.4	0	452.4	0.0139	50.7	19.8	45.5	6.4	-
5.3	Steel	1250	390	2.39	31.4	0	452.4	0.0139	44.9	17.5	44.9	5.3	-

3.2. Environmental performance

The LCA results (see Table 3 and Figure 4) show that the 1200mm BFRP reinforced concrete beam performs better across all eighteen environmental indicators compared to the 1250mm steel reinforced concrete beam. The BFRP reinforced concrete beam experiences 14.7 $kgCO_{2eq}$/FU of climate change emissions, whilst the steel reinforced concrete beam experiences almost double the amount of embodied emissions at 23.7 $kgCO_{2eq}$/FU.

When emission factors from EPDs for precast steel reinforced concrete beams were implemented, it was found that the GWP product stage emissions ranged from between 25.1 to 27.9 $kgCO_{2eq}$/FU [31-33]. This is in-line with the findings of this study. However, when emission factors from EPDs for poured concrete [34] and 100% recycled reinforcement steel [35] were used, it was found that GWP emissions were at 11.3 $kgCO_{2eq}$/FU for steel reinforced concrete beams, compared to 14.6 $kgCO_{2eq}$/FU for a BFRP reinforced concrete beam of a similar size.

It was observed that the BFRP and reinforcement steel datasets have similar emission factors: 2.6 and 2.34 $kgCO_{2eq}$/kg respectively. However, since BFRP has a lower specific weight to steel, and is three times lighter, the overall embodied emissions are much lower in BFRP reinforced concrete beams. In the BFRP reinforced concrete beams, the largest contributor to emissions was concrete (93.7%), followed by resin (5.5%), furnace electricity consumption (0.4%), mining and transport (0.4%). In the steel reinforced concrete beams, the largest contributor to emissions was concrete (56.2%), followed by steel (43.8%).

When considered without concrete, the BFRP GWP results showed the largest contributor to embodied emissions was resin (86.8%), followed by furnace electricity consumption (6.7%), mining (6.3%) and transport (0.1%). It was found that epoxy resin has an emission factor of 6.73 $kgCO_{2eq}$/kg. In contrast, polyester resin has an emission factor of 7.64 $kgCO_{2eq}$/kg whilst organic chemicals emit 1.99 $kgCO_{2eq}$/kg. This range of emission factors resulted in a GWP result for BFRP tendons that ranged from 0.9 to 2.6 $kgCO_{2eq}$/kg. When the resin quantity was adjusted from 20 to 40%, GWP emissions ranged from 1.67 to 2.98 $kgCO_{2eq}$/kg.

Table 3. Mid-point results per functional unit.

Impact Category	Unit	Steel RC (1250 x 200 x 189mm)	BFRP RC (3860 x 200 x 200mm)	BFRP RC (2700 x 200 x 200mm)	BFRP RC (2000 x 200 x 200mm)	BFRP RC (1200 x 200 x 200mm)
Climate change	kg CO_2 eq	23.7	46.9	32.8	24.3	14.6
Ozone depletion	kg CFC_{-11} eq	1.19E-06	2.29E-06	1.6E-06	1.18E-06	7.11E-07
Terrestrial acidification	kg SO_2 eq	0.07	0.11	0.08	0.06	0.04
Freshwater eutrophication	kg P eq	5.71E-03	2.80E-03	1.97E-03	1.46E-03	8.76E-04
Marine eutrophication	kg N eq	0.012	0.023	0.016	0.012	0.007
Human toxicity	kg 1.4-DB eq	7.48	5.19	3.63	2.69	1.61
Photochemical oxidant formation	kg NMVOC	7.51E-02	0.13	0.09	0.07	0.04
Particulate matter formation	kg PM10 eq	4.65E-02	0.07	0.05	0.04	0.02
Terrestrial eco-toxicity	kg 1.4-DB eq	1.43E-03	2.2E-03	1.54E-03	1.14E-03	6.83E-04
Freshwater eco-toxicity	kg 1.4-DB eq	0.25	0.14	0.10	0.07	0.04
Marine eco-toxicity	kg 1.4-DB eq	0.25	0.14	0.10	0.07	0.04
Ionising radiation	kBq U235 eq	1.89	4.49	3.14	2.33	1.40
Agricultural land occupation	m^2a	0.42	0.70	0.49	0.37	0.22
Urban land occupation	m^2a	0.25	0.44	0.31	0.23	0.14
Natural land transformation	m^2	2.78E-03	5.71E-03	4.00E-03	2.96E-03	1.78E-03
Water depletion	m^3	0.25	0.60	0.42	0.31	0.19
Metal depletion	kg Fe eq	8.86	1.15	0.80	0.60	0.36
Fossil depletion	kg oil eq	3.52	5.89	4.12	3.05	1.83

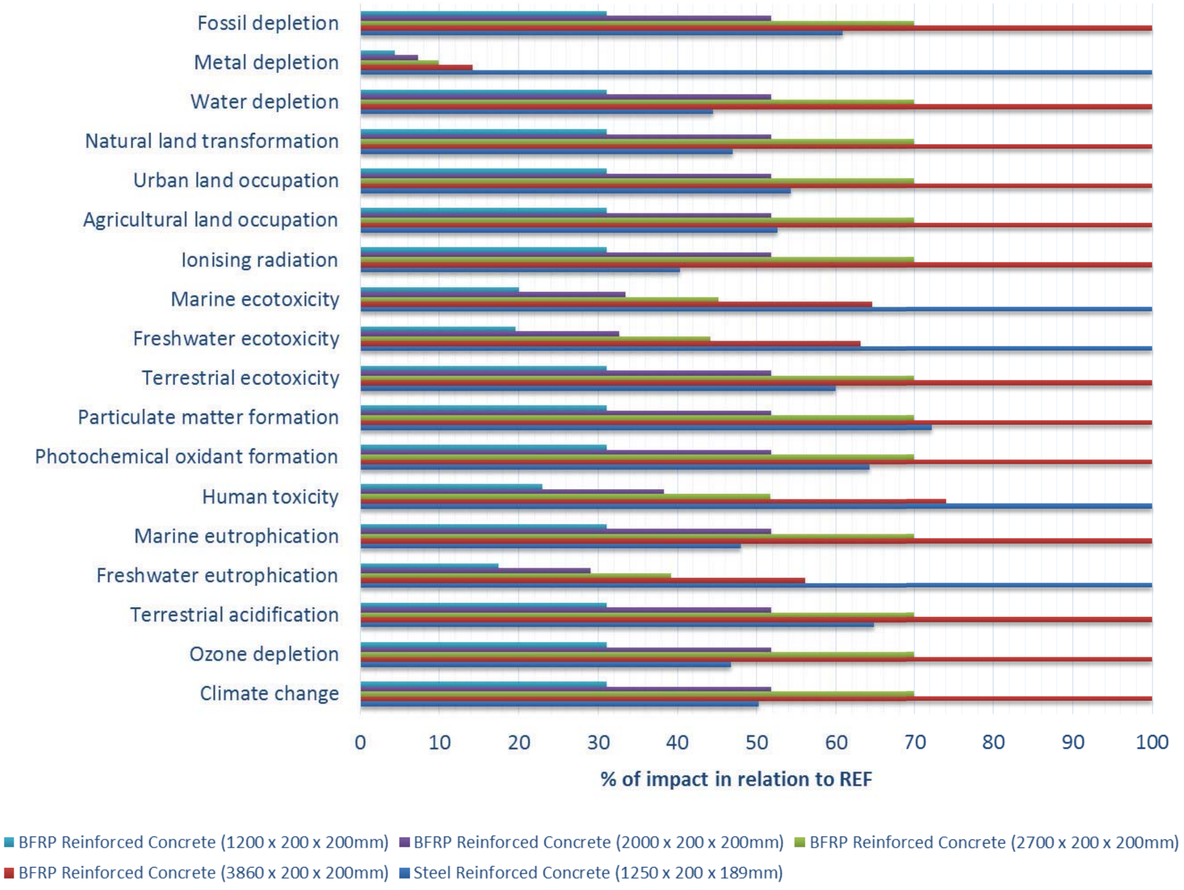

Fig. 4. Result comparison of reinforced concrete alternatives for each mid-point impact category

4. Discussion

For the first time, a holistic evaluation, combining both mechanical and environmental impact criteria, has been used to assess and compare two reinforcement materials for concrete beams namely steel rebar, which is traditionally used, and BFRP as an innovative rebar alternative. It should be noted that the latter has never been assessed with respect to both mechanical and environmental performance, as the only known publications dealing with environmental impact of basalt consider basalt aggregates used during the production of concrete [22, 23]. Two standardised methodologies have been used to assess and compare the mechanical and environmental performance of BFRP rebar and steel rebar in concrete beams; namely the mechanical experimental procedure and life cycle assessment. Nevertheless, these two methodologies are distinct and independent from one another. For example, although the mechanical testing results show that BFRP rebar has twice the strength of steel rebar, this is not reflected in the material inventory for LCA. In the future, the link between mechanical and environmental methodologies could be strengthened by using mechanical testing to design reinforced concrete, in order to optimise material use, and consequently reduce the amount of embodied material emissions measured in LCA.

The mechanical results show that strength is high for BFRP rebar, whereby tension strength is about twice the tension strength of steel reinforcement for the same cross section area. The drawback is the elastic modulus, which is only 50-80 GPa for BFRP tendons compared to 200 GPa for steel. This means that the full potential strength of BFRP was not reached especially when concerning crack widths and deflections. Essentially, BFRP reinforcement bars are purely elastic, with max elongation of around 3-4%. If the bars are unloaded, the elongation goes down to zero. For steel reinforcement bars, the elastic zone is up to 0.2%, whereby from that point it behaves like plastic.

The results show that BFRP pre-stressed beams without shear reinforcement are vulnerable to transverse loading even if the a/d ratio is high. A comparison of the experimental results show that the shear force and bending moment distribution along the span, as well as the slenderness of the beams needs to be considered in order to determine the shear capacity with accuracy and ensure safety.

The LCA results show that the 1200mm BFRP reinforced concrete beam performs significantly better across all eighteen environmental indicators compared to the 1250mm steel reinforced concrete beam. In terms of GWP, there is a 62% saving in climate change emissions when BFRP reinforcement is chosen over conventional steel.

When the BFRP environmental results are compared to EPD data, there are two core findings. Firstly, EPDs for precast steel reinforced concrete beams have a similar amount of GWP emissions, ranging from 25.1 – 27.9 $kgCO_{2eq}/FU$, compared to the steel reinforced concrete beams tested in this study, 23.7 $kgCO_{2eq}/FU$. Secondly, when the EPD data is replaced with in-situ pouring concrete and 100% recycled steel, embodied emissions are significantly reduced to 11.3 $kgCO_{2eq}/FU$. This result is competitive with the BFRP reinforced concrete beam that experiences 14.6 $kgCO_{2eq}/FU$. It was observed that both the BFRP tendons and reinforcement steel have similar emission factors: 2.6 and 2.34 $kgCO_{2eq}/kg$ respectively. However, since BFRP has a lower specific weight to steel, and is three times lighter, the overall embodied emissions are much lower in the BFRP reinforced concrete beams. This is because less material (per kg) is required to perform the same function.

In this study, the same quantity of concrete was used for both steel and BFRP reinforced concrete beam scenarios. It is thought that thinner concrete members could be implemented in the BFRP scenarios, since the mechanical results show that BFRP is much stronger than conventional steel reinforcement. This would lead to an overall reduction in material consumption, which would also lead to lower embodied material emissions. However, this aspect needs to be evaluated in conjunction with shear capacity in order to avoid transverse loading. Another measure to reduce the impacts originating from concrete could be to use a low carbon concrete alternative in both scenarios.

When considered without concrete, the LCA results showed the largest contributor to BFRP emissions was resin (86.8%), followed by furnace electricity consumption (6.7%), mining (6.3%) and transport (0.1%). It was therefore ascertained that the LCA results are sensitive to the type and quantity of resin used. When the type of resin was investigated, the BFRP LCA results varied by 65%. In addition, the results varied by 44% when the amount of resin was investigated. These results indicate that the amount of embodied emissions arising from resin are a significant driver of high emissions in BFRP tendons. This also indicates an area for optimisation in the future. BFRP manufacturers could therefore experiment with the composition and quantity of resin required during the BFRP production process with a view to reduce embodied emissions.

5. Conclusion

The findings have shown that BFRP rebar is a stronger and lighter alternative to steel reinforcement in concrete beams, and that it is a very promising building material for the future. Furthermore, fewer material and energy resources are required during the production process, which leads to a better environmental profile with fewer embodied emissions. In contrast, the mechanical testing part of this experiment showed that the BFRP reinforcement has a lower elastic module than steel reinforcement. This disadvantage leads to excessive deformation at service limit state compared to steel bars, if the same cross-section area is used. However, compared to steel, BFRP does not exhibit yielding during tension.

When the BFRP environmental results were compared to EPD data, there were two core findings. Firstly, EPDs for precast steel reinforced concrete beams have a similar amount of GWP emissions, ranging from 25.1 – 27.9 $kgCO_{2eq}/FU$, compared to the steel reinforced concrete beams tested in this study, 23.7 $kgCO_{2eq}/FU$. Secondly, when the EPD data for precast beams was replaced with EPD data for in-situ pouring concrete and 100% recycled steel, embodied emissions were significantly reduced to 11.3 $kgCO_{2eq}/FU$. This result is competitive with the BFRP reinforced concrete beam that experiences 14.6 $kgCO_{2eq}$/FU. These results highlight the environmental benefits to be gained from precast BFRP reinforced concrete beams. It is likely that the future market for basalt rebar will be within the precast industry rather than in on-site construction. This is because the handling of thinner and lighter precast basalt reinforced concrete members will be quicker and easier to install on-site than steel. This is advantageous from an environmental perspective, since precast BFRP concrete beams experience approximately half the emissions of precast steel reinforced concrete beams.

Another core finding was that both the BFRP tendons and reinforcement steel have similar emission factors: 2.6 and 2.34 $kgCO_{2eq}$/kg respectively. However, since BFRP has a lower specific weight to steel, and is three times lighter, the overall embodied emissions are much lower in the BFRP reinforced concrete beams. This is because less material (per kg) is required to perform the same function.

When considered without concrete, the LCA results showed the largest contributor to BFRP emissions was resin (86.8%). It was therefore ascertained that the LCA results are sensitive to the type and quantity of resin used, and that the amount of embodied emissions arising from resin are a significant driver of high emissions in BFRP tendons. This finding highlights an area for optimisation in the future. BFRP manufacturers could therefore experiment with the composition and quantity of resin required during the BFRP production process with a view to reduce embodied emissions. The development of new environmentally friendly resins could then be applied to all FRP composite materials.

In this study, the same quantity of concrete was used for both steel and BFRP reinforced concrete beam scenarios. It is thought that thinner concrete members could be implemented in the BFRP scenarios, since the mechanical results show that BFRP is much stronger than conventional steel reinforcement. This study highlights that BFRP is an advantageous construction material, and more specifically beneficial as a reinforcement material in concrete beams. The study highlights that BFRP may also be suitable in other construction applications, such as prefabricated sandwich panels, that require thin concrete facades and thin structural cores. It is expected that using BFRP in thinner concrete sections will have similar, low environmental emissions compared to conventional steel reinforced concrete elements. It is recommended that further work involves the investigation of thinner concrete members in BFRP reinforced elements, to find out which thickness is required for given performances. This body of work could help the future development of design guidelines and codes for BFRP in construction.

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References

[1] Masuelli MA. *Fiber Reinforced Polymers - The Technology Applied for Concrete Repair*. InTech; 2013.

[2] Lapko A, Urbański M. Experimental and theoretical analysis of deflections of concrete beams reinforced with basalt rebar. *Arch Civ Mech Eng* 2015;15:223-30.

[3] Kim HS, Shin YS. Flexural behavior of reinforced concrete (RC) beams retrofitted with hybrid fiber reinforced polymers (FRPs) under sustaining loads. *Compos Struct* 2011;93:802-11.

[4] Luccioni B, Rougier VC. Numerical analysis of fibre reinforced polymer retrofitted masonry panels. Engineering Structures 2013;49:360-72.

[5] Campbell FC. *Structural Composite Materials*. ASM International; 2010.

[6] Pico D, Steinmann W. Synthetic fibers for composite applications. In: Rana S, Fangueiro R, editors. *Fibrous and Textile Materials for Composite Applications*, Singapore: Springer; 2016, p. 135-170.

[7] Holmes M. Global carbon fibre market remains on upward trend. *Reinf Plast* 2014;58:38-45.

[8] Wang X, Shi J, Liu J, Yang L, Wu Z. Creep behavior of basalt fiber reinforced polymer tendons for prestressing application. *Mater Des* 2014;59:558-64.

[9] Elgabbas F, Vincent P, Ahmed EA, Benmokrane B. Experimental testing of basalt-fiber-reinforced polymer bars in concrete beams. *Compos Part B-Eng* 2016;91:205-18.

[10] Fiore V, Scalici T, Di Bella G, Valenza A. A review on basalt fibre and its composites. *Compos Part B-Eng* 2015;74:74-94.

[11] Ramakrishnan V, Panchalan R. A new construction material – non-corrosive basalt bar reinforced concrete. *ACI* 2005;229:253-270.

[12] Bashtannik PI, Kabak AI, Yakovchuk YY. The effect of adhesion interaction on the mechanical properties of thermoplastic basalt plastics. *Mech Compos Mater* 2003;39:85-8.

[13] Fazio P. Basalt fibra: from earth an ancient material for innovative and modern application. *EAI* 2011;3: 89-96.

[14]Thorhallsson ER, Snaebjornsson JT, Basalt Fibers as New Material for Reinforcement and Confinement of Concrete. Solid State Phenomena 04/2016; 249. DOI:10.4028/www.scientific.net/SSP.249.79

[15] Gunnarsson A, Thorhallsson ER, Snæbjornsson JT. Simulation of experimental research of concrete beams prestressed with BFRP tendons. In proceedings of the XXII Nordic Concrete Research Symposium Reykjavik, Vodskov: 2014,p. 153-156 .

[16]Schilling JG, Sigurdsson H, Kingsley RH. Skagi and western neovolcanic zones in Iceland: 2. Geochemical variations. *J Geophys Res B: Solid Earth* 1978;83:3983-4002.

[17] Novitskii A, Efremov M. Some aspects of the manufacturing process for obtaining continuous basalt fiber. *Glass Ceram* 2011;67:361-5.

[18] Thorhallsson ER, Gudmundsson SH. Test of prestressed basalt FRP concrete beams with and without external stirrups. In: Dancygier AV, editor. Proceedings of Fib symposium Engineering a Concrete future: Technology, modelling & Construction, Tel Aviv; 2013, p. 393-396

[19] Thorhallsson E, Zhelyazov T, Gunnarsson A, Snaebjornsson JT. Concrete beams reinforced with prestressed basalt bars. In: Stang H, Braestrup M, editors. Proceedings of Fib Symposium. Concrete - Innovation and Design, Copenhagen; 2015, p. 277-278.

[20]Sim J, Park C, Moon DY. Characteristics of basalt fiber as a strengthening material for concrete structures. *Compos Part B-Eng* 2005;36:504-12.

[21] Lopresto V, Leone C, De Iorio I. Mechanical characterisation of basalt fibre reinforced plastic. *Compos Part B-Eng* 2011;42:717-23.

[22] Ingrao C, Lo Giudice A, Tricase C, Mbohwa C, Rana R. The use of basalt aggregates in the production of concrete for the prefabrication industry: Environmental impact assessment, interpretation and improvement. *J Clean Prod* 2014;75:195-204.

[23] Ingrao C, Lo Giudice A, Mbohwa C, Clasadonte MT. Life Cycle Inventory analysis of a precast reinforced concrete shed for goods storage. *J Clean Prod* 2014;79:152-67.

[24] MagmaTech. Rockbar 2016 [Available from: http://magmatech.co.uk/index.php/products/rockbar].

[25] ACI Committee 440.1R-15 Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars. ACI; 2015.

[26] ISO 14040: 2006. Environmental management -- Life cycle assessment -- Principles and framework; 2006.

[27] NS-EN 15804: 2012 + A1: 2013. Sustainability of Construction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products. Standard Norway, European Standard; 2013.

[28] Ecoinvent. Ecoinvent database version 3.1. In: Centre E, editor. www.ecoinvent.org, Zurich, Switzerland; 2013.

[29] PRé Consultants. SimaPro Analyst LCA Software v. 8.0.5. Netherlands: PRe; 2015.

[30] Goedkoop M, Heijungs R, Huijbregts M, Schryver AD, Struijs J, Zelm Rv. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation; 2013.

[31] EPD Norge. EPD 284E: Skonto Prefab: Concrete Beam. The Norwegian EPD Foundation; 2014.

[32] EPD Norge. EPD 12-223-NO: Spenncon: Prestressed Concrete Beam B45 M45. The Norwegian EPD Foundation; 2015.

[33] EPD Norge. EPD 398-280-EN: UPB: Precast Concrete Beam. The Norwegian EPD Foundation; 2016.

[34] EPD Norge. EPD 328-210-NO: Velde Betong: In-Situ Concrete B30 M60. The Norwegian EPD Foundation; 2015.

[35] EPD Norge. EPD 348-237-EN: Leif Hubert Stål: Wire Mesh Reinforcement Steel. The Norwegian EPD Foundation; 2015.