ENVIRONMENTAL AND COST BENEFIT OF VERY HIGH PERFORMANCE CONCRETE SOLUTION IN INDUSTRIAL BUILDING DESIGN

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Abstract

This paper aims to compare the traditional building designed with the current construction technology towards the same structure designed with a new composite solution based on Very High Performance Concrete (VHPC) reinforced with fibres. Both the Cost Calculation Analysis and the Life Cycle Analysis have been developed: as main conclusion, the new composite contributes to decrease the entire building cost and the environmental impact, while the service life of the structure increases.

Very High Performance Concrete (VHPC) is a concrete with very dense matrix. Its combination with carbon steel fibres allows to achieve both high mechanical properties and high durability, offering new opportunities to designers and improving the overall sustainability of the construction.

Keywords: VHPC, concrete, fibre, durability, cost calculation, life cycle analysis

1. Introduction

Fibre Reinforced concrete is a well-established material in the construction sector. Generally, the fibres (both polymeric and metallic) are introduced in the matrix in order to guarantee a post-cracking residual strength, but in most of the cases the softening behavior of the composites limits their structural applications. However, combining specific cement-based raw materials and the last generation of superplasticizers, very high mechanical properties can be achieved both in compression and in bending; this material, called Fibre Reinforced VHPC (Very High Performance Concrete), is characterized by a very low water/binder ratio and the presence of a rather high content of steel micro fibres. Since the principle of cost-effectiveness has long been one of the principal demands in civil engineering practice, and the social requirement of sustainability have been strongly considered in the last decades [1], the two above mentioned characteristics might play very important roles: the first property increases the durability of the composite/structures,

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while the second guarantees a hardening behavior in bending, opening new possibilities in the design of industrial buildings.

2. Material characterization

The composite was selected by comparing different solutions starting from the aggregates generally used by the precast producer and limiting their maximum size to 4 mm. The material presents the typical proportioning of a self-compacting concrete. The mix design of the Fibre Reinforced VHPC material is reported in Table 1. The binder was a mix of cement (CEM I 52.5 R) and ground granulated blast furnace slag (GGBS); the straight high carbon steel micro fibres (MasterFiber® 482) were 13 mm long, with a 0.16 mm diameter and their content was set equal to 100 kg/m^3; the polycarboxilate ether based MasterGlenium® ACE superplasticizer was introduced in order to achieve a self-compaction consistency [2].

Tab. 1: Material mix design.

CEM I 52.5 R (kg/m^3)	GGBS (kg/m^3)	Sand 0/2 (kg/m^3)	MasterFiber® 482 (kg/m^3)	MasterGlenium® ACE (kg/m^3)	Water (kg/m^3)
600	500	983	100	33	200

The results (Table 2) confirmed a self-compacting concrete consistency (Fig. 1): (a) slump flow; (b)V–funnel; (c) L-shape box and (d) J-ring tests.

(a) (b) (c) (d)

Fig. 1: Fresh State Characterization

Tab. 2: Average fresh state properties

Slump Flow (mm)	V-Funnel (sec)	L-Box (%)	J-Ring (mm)
752	27	75	750

An average cubic compressive strength R_{cm} of 116.5 MPa and an elastic modulus E_c close to 40 GPa characterized the material. Three different orientations of fibres, caused by the casting procedures, were taken into consideration and were strongly influencing the post-peak behaviors of Fibre Reinforced VHPC.

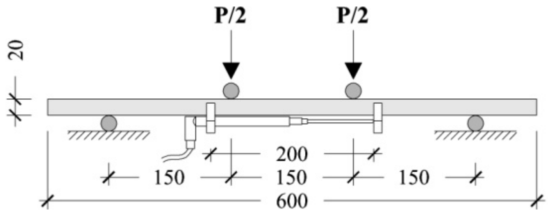

Fig. 2a: Bending Test Scheme (set B)

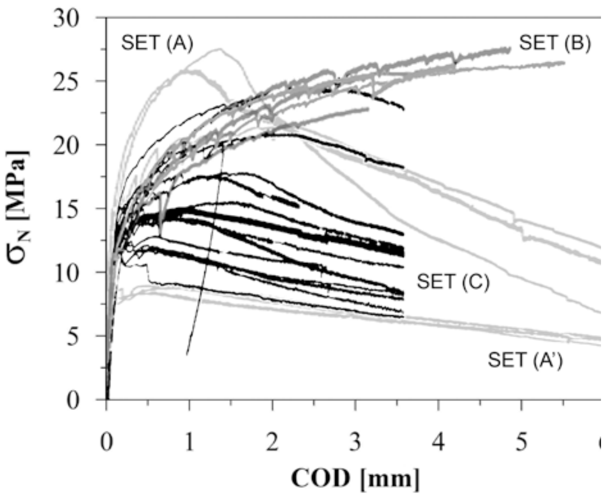

Fig. 2b: Nominal stress-COD experimental results with different fibre orientations

1000x30x500mm slabs were cast, favoring a fibre orientation parallel to the casting flow; later on, the slab was cut according to different orientations, with respect to the concrete flow (sets A and A') [3]. 150x30x500mm specimens were sawed, in order to characterize the material behavior by means of four point bending tests. Regarding set B, five nominally identical 150x20x600mm beam specimens were cast by means of an EN14651 beam mould and tested, according to the same bending setup (Figure 2a) [4]. Set C was inherent with beam elements extracted from a plate (1200x25x2500 mm) cast without any attempt of maximizing fibres orientation [5]. Nominal stress vs. Crack Opening Displacement (COD) experimental curves are presented in Figure 2b. The influence of fibres orientation is clearly visible: the set C material (randomly distributed fibres) was identified as a 10b FRC class according to the *fib* Model Code 2010 and was taken into account in the structural design.

3. Case study: Industrial building design

The considered industrial building (length 24m, width 19,45m, height 7,8m) is hereby presented. It consisted of six columns, four main beams (span 12m), five secondary beams (span 19.45m) and a roofing panel with a 5 m span. Figure 3 shows the structural layout, in the case of a traditional precast structure.

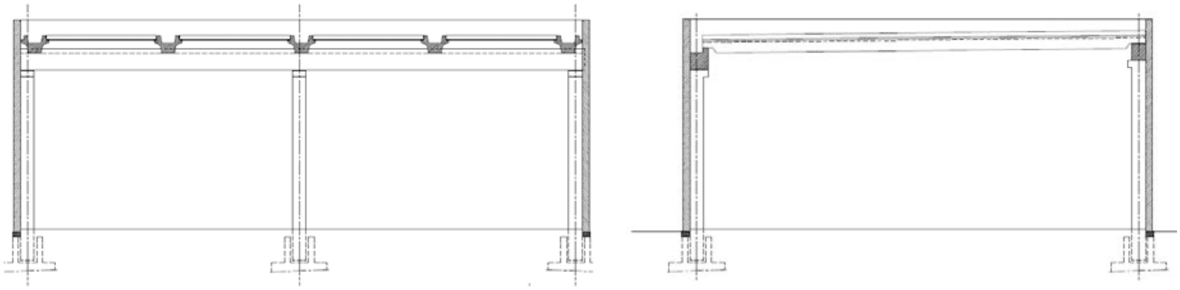

Fig. 3: Structural layout - traditional precast structure (longitudinal & transversal section)

The construction site was identified (northwestern Italian region), and the environmental actions and the live loads were determined, according to the Italian code:

- Snow load: 1.2 kN/m^2
- Wind load: 0.64 kN/m^2
- Distributed maintenance load: 0.5 kN/m^2
- Seismic acceleration: S_d = 0,07 g

New Elements Design

The main characteristics of Fibre Reinforced VHPC (self-compactability and remarkable toughness) give to the designers the possibility to prefigure new and advanced shapes: the new roofing element and the new secondary beam are shown in Figure 4.

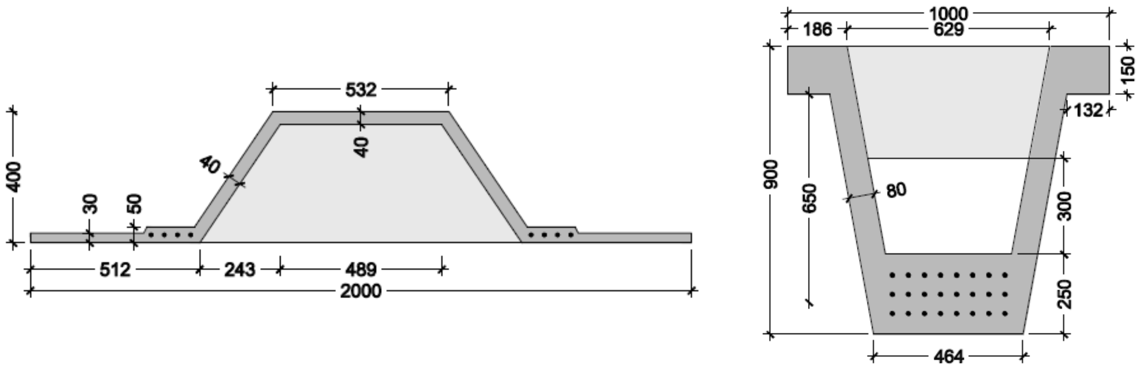

Fig. 4: Roofing Element (left) and Secondary Beam (right) (dimensions in mm)

The longitudinal reinforcement of the roofing element consisting of 4+4 ϕ 10 was designed for a 10 m span; the fact that the traditional precast system had only 5 m long elements, leads to a first conclusion: thanks to the innovative cementitious composites mechanical performances, the roofing elements span can be doubled.

Figure 5a shows the design load-displacement curve inherent with the roofing element; the white dot represents the Serviceability Limit State (SLS), while the black one represents the Ultimate Limit State (ULS) condition.

The longitudinal reinforcement of the secondary beam consisted of three rows of 8 tendons (diameter 0,5”), prestressed at 1395 MPa (pretension losses were considered and preliminary fixed at 18%) while its span was set equal to 19.45 m; also in this situation, both the SLS and ULS (Fig. 5b) were characterized by adequate safety factors.

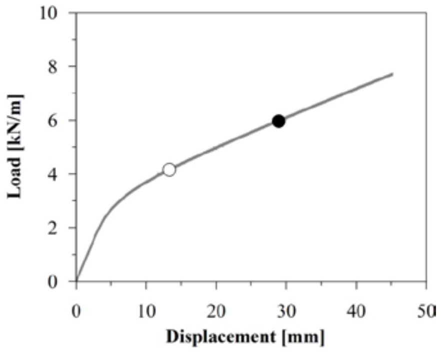

Fig. 5a : Roofing element: load / displ. curve

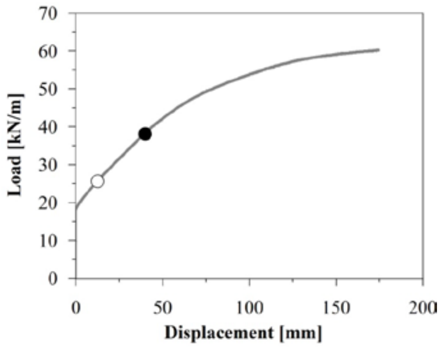

Fig. 5b : Beam: load / displ. curve

Principal Beams and Columns

In the proposed configuration, the principal beam is devoted to the preservation of a frame effect designed to ensure adequate stiffness and resistance towards horizontal actions. A simply supported scheme was considered, together with a medium-strength (C40) fibre-reinforced concrete material (FRC class 2a). The proposed transverse section was 400x300 mm in size and was reinforced with a minimum amount of longitudinal bars (3 Φ 10mm). The contribution of fibres provided adequate shear resistance and, therefore, it was not necessary to adopt a specific shear reinforcement.

For the columns, a traditional reinforced concrete solution was chosen. The columns were characterized by combined compression and bending, as they took part in the frame effect. Since the rather high effective length of these structural elements, significant mass reductions could not be achieved by material change. Nevertheless, the column section which was dependent of the weight of the rest of the structure was significantly reduced in the case of the new building design solution as they were benefiting from the weight reduction of the roofing elements and the beams thanks to the use of fibre reinforced VHPC. As a consequence, it followed a 500 x 500 mm section, reinforced with 12 ϕ 18 regular steel bars.

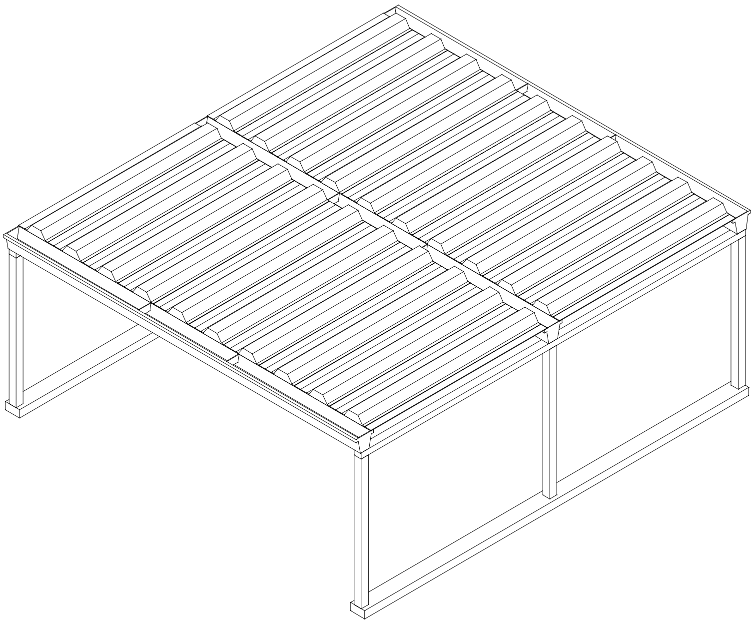

Fig. 6: Structural layout - proposed precast structure

Cost analysis: comparison between conventional and Fibre Reinforced VHPC solutions

In order to fully estimate the potential of the new material, a detailed comparison was performed by considering materials costs (cements, aggregates, admixtures, fibres, steel bars and tendons), transportation costs (the building yard was considered 100 km far away from the production site), installation costs (including the crane rental), labor costs (related to both the element production and the installation), and storage costs. Table 3 summarizes the materials costs.

Tab. 3: Materials costs

Conventional C50/60 (€/m^3)	Fibre Reinf. VHPC (€/m^3) (fibres incl.)	Steel Bars (€/kg)	Prestressed Tendons (€/kg)	Fibre Reinf. Concrete (€/m^3) (fibres incl.)
50	440	0.65	1.00	150

Fibre Reinforced VHPC is definitely characterized by a higher cost, if related to the one inherent with traditional concrete, since high carbon steel fibres have a significant impact on the total estimation.

The volume and weight entries of each element were taken as a starting point in the cost estimation of the entire structure: Table 4 summarizes the physical characteristics of each element. The overall material cost for the entire building, for each precast element type, is shown in Table 5.

The total cost of Fibre Reinforced VHPC turned out to be higher than the one related to a traditional construction technique, even though the higher roofing elements span (10m instead of 5m) allowed the suppression of two secondary beams. It has to be noted that the beneficial influence of the new technology can be clearly seen from the other above mentioned costs: in Table 6, the production labor cost is drastically reduced. The labor incidence was assessed by data supplied by technical manuals. The hourly cost (22,0 €/h) was indicated by prefabrication experts.

Tab. 4: Element Characteristics

Element	Structural Solution	Element Length (m)	Element Weight (kg)	Specific Weight (kg/m^2)	Material Volume (m^3/m^2)	Rebars (kg/m^2)	Tendons (kg/m^2)	Grid (kg/m^2)
Roofing Element	Concrete	5	2200	166	0.07	5.3	0	4.7
	Fibre Reinf. VHPC	10	2282	114	0.05	2.5	0	0
Secondary Beam	Concrete	19.45	16800	864	0.34	29.8	24.3	13.3
	Fibre Reinf. VHPC	19.45	13055	671	0.27	0	26.4	0
Principal Beam	Concrete	12.5	14300	1144	0.46	33.5	24.5	0
	Fibre Reinf. Concrete	12.5	3750	300	0.12	2	0	0
Column	Traditional design	7.8	7500	962	0.38	73.3	0	0
	New design	7.8	4875	625	0.25	31	0	0

Tab. 5: Overall material Costs

	Roofing (€)	Sec. Beams (€)	Pr. Beams (€)	Columns (€)	Foundations (€)	**Total Cost (€)**	Cost/Surface (€/m^2)
Concrete	4.568	6.755	3.454	3.125	4.500	**22.401**	48
Fibre Reinforced VHPC	10.123	8.434	960	1.521	3.000	**24.037**	52

Tab. 6: Labor costs (production phases)

	Traditional				New Solution			
Element	Concrete Volume (m^3)	Labor Incidence (h/m^3)	Labor (hours)	Cost (€)	Concrete Volume (m^3)	Labor Incidence (h/m^3)	Labor (hours)	Cost (€)
Roofing	30,6	7	214,1	4.709	21,3	4	85,2	1.875
Sec. Beams	33,5	9	301,5	6.633	15,7	6	94,0	2.068
Pr. Beams	22,8	8	182,4	4.013	6,0	5	30,0	660
Columns	17,9	6	107,3	2.360	11,7	6	70,2	1.544
Foundations	22,8	8	182,4	4.013	15,4	6	92,2	2.027
TOTAL	127,6			21.728	70,1			8.175

By calculating the ratio between the material volumes used in each solution (0,55), it was possible to define a reduction coefficient that might be applied to the transport and storage costs, as a rough preliminary approximation.

Starting from a specific ordinary structure cost (per square meter) provided by a precast concrete industry (150€/m^2), it was possible to estimate the total, first tentative cost of the traditional concrete bearing structure (excluding floors, infill panels and finishes); we have: 466,8 m^2 x 150 €/m^2 = 70.020 €.

The cost incidence of Transport (8%), Storage (9%) and Installation (10%) on the total cost was estimated by the experience of the precast producer: the global building cost calculation is presented in Table 7.

As previously shown, although the impact of the Fibre Reinforced VHPC on the structure cost was found to be relevant in the material estimation, a positive influence on the overall cost reduction was achieved due to a significant volume, ordinary reinforcement and mass reduction.

Tab. 7: Structure costs

	Material Cost (€)	Labor Cost (€)	Transport Cost (€)	Storage Cost (€)	Assembly Cost (€)	**Structure Cost (€)**
Traditional	22.401	21.728	5.601	6.301	7.002	**63.033**
New Solution	24.037	8.175	3.075	3.459	7.002	**45.748**

4. Life Cycle Assessment

The Life Cycle Assessment consists in the compiling and the evaluation of the input, the outputs and the potential environmental impacts of a product, throughout its lifetime (DIN ISO 14040). Fibre Reinforced VHPC is not only able to reduce the overall cost, but its own properties can also extend the construction lifetime, thanks to its very low water/cement ratio - able to create a very dense and waterproofing matrix - and the crack bridging effect provided by the steel fibres [6].

The life expectancy of Fibre Reinforced VHPC should be considered higher than the one of traditional concrete and the global costs can be hence further reduced due to the postponement of the ordinary maintenance.

Figure 7 indicates the environmental impact of the concrete materials used in the abovementioned design: a reduction of the Ozone Depletion Potential (ODP) was observed in Fibre Reinforced VHPC, while both the Global Warming Potential (GWP) and the not renewable Primary Energy Demand (PED n-r) were definitely higher, if related to the production of the new material. This result was due to the higher amount of cement and the presence of the steel fibres.

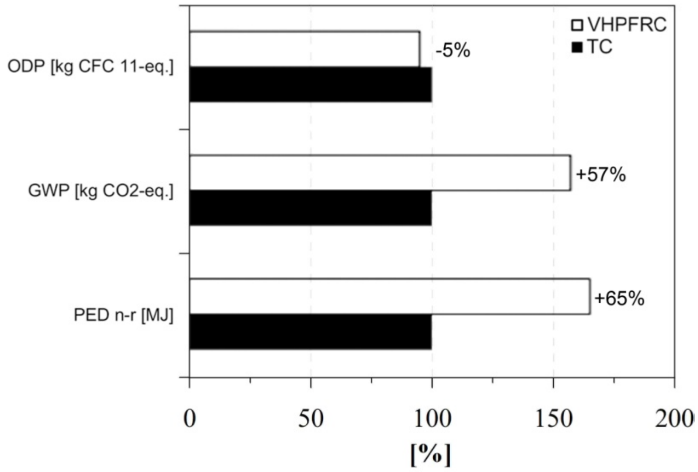

Fig. 7: Environmental impact of the materials

On the contrary, the environmental impact calculation of the entire structure - just considering the material (volume) and the improved durability of Fibre Reinforced VHPC - led to different results: by assuming a 50 years construction lifetime, a 50 years concrete life expectancy for traditional concrete, and a 100 years concrete life expectancy (durability) for Fibre Reinforced VHPC, the results show the positive influence of the new technology (Figure 8). In conclusion, it is important to remark that all the environmental indicators exhibited a reduction, with respect to the traditional construction.

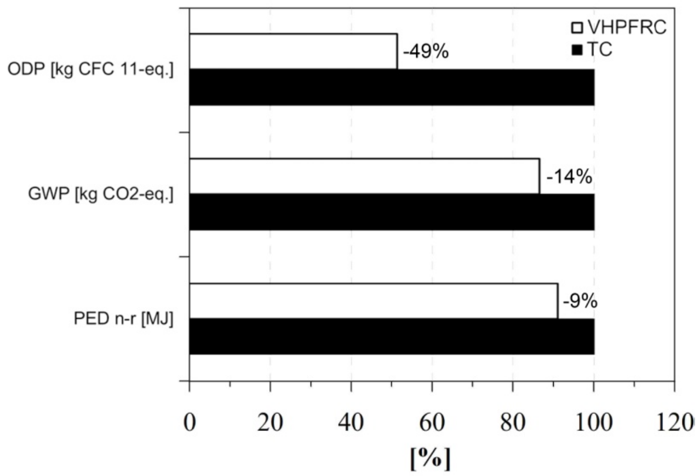

Fig. 8: Environmental impact of the materials (whole structure)

5. Conclusions

The new technologies open new frontiers in the construction world: the establishment of Fibre Reinforced VHPC in the construction market gives new possibilities to the designers. The higher material cost and environmental impact should not restrain the precast producers, but the overall evaluation has to be measured and balanced in order to establish the right opportunities.

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