International Journal of Students Research in Technology & Management
Vol 2 (03), May 2014, ISSN 2321-2543, pg. 113-120

Assessment of Embodied Energy in the Production of Ultra High Performance Concrete (UHPC)

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***ABSTRACT* - There is a growing interest towards quantifying the direct and indirect emission of carbon (embodied energy) in the production and utilization of new types of concrete. Advanced technological development of concrete and demand for high strength and high performance construction materials have lead to the evolution of Ultra High Performance Concrete (UHPC). This material is primarily characterized with high strength and durability and when reinforced with steel fibers or steel tubes exhibits high ductility. Existing UHPC preparation methods involve costly materials and classy technology. This may increase the embodied energy of UHPC, which is not in favor of green environment for a sustainable technology and development.**

Embodied energy is the energy required to produce any goods or services, which is incorporated or embodied in the product itself. Embodied energy assessment aims in finding the sum of total energy necessary for an entire product life-cycle. To make UHPC an eco-friendly material, the embodied energy involved in its production should be reduced by the application of simple technology. Many research works are being done in replacing certain amount of cement with silica fume (SF), fly ash (FA), ground granulated blast furnace slag (GGBS) etc. in order to achieve an environmental friendly UHPC of high strength of more than 150 MPa and an elevated level of durability. This study is focused on the assessment of embodied energy involved in the production of UHPC with alternate cementitious material. With the knowledge of embodied energy for UHPC, implications can be deliberated by varying the constituents and replacing cement with certain amount of eco-friendly materials, so as to reduce the environmental impact of construction with UHPC.

***Key Words* - embodied energy, fly ash, GGBS, sustainable concrete, UHPC.**

I. Introduction

The net cement production in the world has increased from about 1.4 billion tonnes in the year 1995 to almost 2 billion tonnes in the year 2010. This has lead to the emission of about 2 billion tonnes of CO2 in the atmosphere every year [1]. The global cement industry has reduced its specific net CO2 emissions per tonne of product by 17 % since 1990, from 756 kg/tonne to 629 kg/tonne. Meanwhile, cement production increased by 74 % between 1990 and 2011, according to the World Business CSI, which released its 2011 data update to the project Council for Sustainable Development's Cement Sustainability Initiative (CSI).

"Getting the Numbers Right" or GNR, which tracks global CO_2 emissions for participating companies in the cement industry, reports the evidence of significant reduction of CO_2 emissions and improved efficiency. According to CSI, the four main drivers for the reduction in emissions are (i) investment in more efficient kiln technology, (ii) increasing the use of alternative fuels such as biomass, (iii) reduction in clinker content and (iv) 8 % decrease in electricity use per tonne of cement since 1990. Between 2010 and 2011, cement production volume covered by the GNR increased from 840 million tons to 888 million tons, and specific net CO_2 emissions decreased from 638 kg/ton to 629 kg/ton of product.

As a building material, concrete is the most used man-made material in the world, utilized at double the rate of all other building materials, according to CSI. There are several essentials which can reduce the environmental impact factor and CO_2 intensity of concrete used for construction, which include maximizing the concrete durability, conservation of materials, use of waste and supplementing cementing materials and recycling of concrete [3]. Partial replacement of cement with waste and supplementary cementitious materials such as fly ash, GGBS, silica fume, rice husk ash and metakaolin not only improves the concrete durability and reduce the risk of thermal cracking in mass concrete but also emits less CO_2 than cement. By doing so, it ensures the proper utilization of such waste materials in an effective manner which otherwise are being dumped creating hazard to the environment.

II. Research Significance

Ultra high performance concrete belongs to the family of engineered cementitious composites (ECC) and is defined as cement based concrete with compressive strength equal to or greater than 150 MPa. The ductility of UHPC is attained by adding steel fibres to it and these generally transform the developed cracks into larger number of small width cracks, which increases the strength and durability of UHPC members. It is a high strength ductile material formulated from a special combination of constituent materials which include Portland cement, silica fume, quartz powder, fine sand, high range water reducer, water and steel fibres. With the present focus on sustainability, green concrete is achieved by optimizing the mixture proportions and material substitutions, so that energy and CO_2 impact can be reduced

Replacement of certain amount of cement with silica fume and other cementitious materials in the production of UHPC itself leads to lesser consumption of cement. UHPC, being a highly efficient material with good mechanical and durability characteristics is used in the production of thinner elements which in turn consumes less volume of cement. Hence, UHPC employs lesser volume of cement both in the production and utilization phases. The present study focuses on the assessment of embodied energy of UHPC, with partial replacement of cement with eco friendly materials like silica fume, fly ash, GGBS etc. Also, an optimum UHPC mix proportion with less embodied energy, without compromising the strength and durability criteria are obtained.

III. Sustainable Construction

The principles of sustainable development and green buildings have penetrated the construction industry at an accelerating rate in recent years. The concrete industry in particular, because of its enormous environmental footprint, has a long way to go to shed its negative image [4]. Sustainability is given prime importance in the field of construction for the social progress which recognises the needs of everyone, effective protection of the environment, prudent use of natural resources and maintenance of high and stable levels of economic growth and employment. The use of GGBS or fly ash in concrete, either as a mixer addition or through a factory made cement can significantly reduce the overall greenhouse gas emissions associated with the production of concrete, and thereby reducing the embodied energy.

A. Embodied Energy

Embodied energy is an accounting method which aims to find the sum of the energy necessary for an entire product life-cycle, which constitutes assessing the relevance and extent of energy into raw material extraction, transport, manufacture, assembly, installation, disassembly, deconstruction and/or decomposition as well as human and secondary resources as shown in Fig. 1. Materials that have a lower embodied energy are more sustainable than those with a higher embodied energy. Energy inputs usually entail greenhouse gas emissions in deciding whether a product contributes to or mitigates global warming. Different methodologies produce different understandings of the scale, scope of application and the type of energy embodied. Typical embodied energy units used are MJ/kg (mega joules of energy needed to make a kilogram of product).

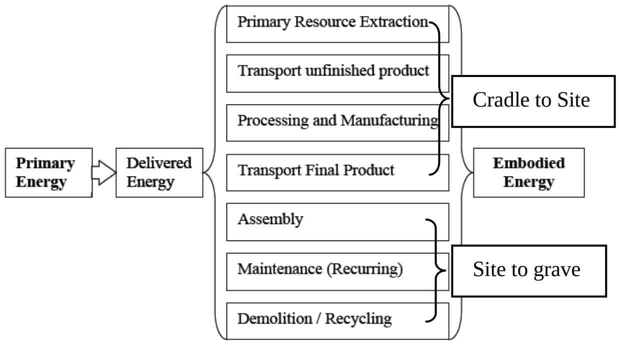

Fig. 1 Breakdown of embodied energy calculations

1) Embodied Energy Methodologies: Different methodologies use different scales of data to calculate the energy embodied in products and services of nature and human civilization. International consensus on the appropriateness of data scales and methodologies is still pending. This difficulty can give a wide range in embodied energy values for any given material. In the absence of a comprehensive global embodied energy public dynamic database, embodied energy calculations may omit important data. Such omissions can be a source of significant methodological error in embodied energy estimations. The following are the widely used methodologies, 1. Input-Output embodied energy analysis and 2. Process life cycle assessment.

2) Standards on Embodied Energy: The UK Code for Sustainable Homes and USA LEED are methods in which the embodied energy of a product or material is rated along with other factors, to assess a building's environmental impact. Embodied energy is a concept for which scientists have not yet agreed absolute universal values because there are many variables to take into account, but most agree that products can be compared to each other to see which has more and which has less embodied energy.

B. Supplementary Cementitious Materials

There are some materials obtained as industrial by-products, which is actually a waste, but can be used as a supplementary cementitious material, by partially replacing the cement. In this study, the analysis of embodied energy of UHPC is undertaken, by partial replacement of cement with silica fume, fly ash and ground granulated blast furnace slag (GGBS).

1) Silica Fume: This siliceous material is a by-product of the semiconductor industry. When added to concrete, this greatly improves both strength and durability, and hence modern high performance concrete mix designs as a rule call for the addition of silica fume. There have been several research works, which have identified the benefits of silica fume both as a pozzolanic and a filler material [5], [6]. Nowadays silica fume is produced specifically for the concrete industry, apart from that available as an industrial by-product due to its massive usage. The beneficial aspect of silica fume is the presence of around 98 % of SiO_2.

2) Fly Ash: The utilization rates of fly ash vary greatly from country to country, from as low as 3.5% in India to as high as 93.7% in Hong Kong [7]. Fly ash, an important pozzolanic material has numerous advantages when compared with regular Portland cement. Firstly, lesser heat of hydration makes it a popular cement substitute for mass structures, resulting in the development of high volume fly ash concrete mixes. Perhaps, the most significant advantage of fly ash is that it is a byproduct obtained from coal combustion, which otherwise involves the greater cost for disposal of the waste product. Moreover, concrete produced with fly ash can have better strength and durability. After all, the cost of fly ash is lesser than Portland cement. The main disadvantage of fly ash is its slow rate of strength development and hence accelerators are used to speed up the hydration rates of fly ash concrete mixes. The quality of fly ash is an important issue, because of considerable variation in the physical and chemical properties, since the primary source of coal varies widely. In recent years, after the increased usage of fly ash, technologies have developed to separate the unburned residues for the quality improvement.

3) Ground Granulated Blast Furnace Slag: This is a glassy granular material, which is a by-product of the steel industry, formed when molten blast furnace slag is rapidly chilled, when immersed in water [8]. Like fly ash, GGBFS improves mechanical and durability properties of concrete and generates less heat of hydration. GGBFS is not only used as a partial replacement for portland cement, but also as an aggregate. The optimum cement replacement level is often quoted to be about 50% and even sometimes as high as 70% to 80%. The cost of slag is generally same as that of portland cement, but is being extensively used due to its beneficial properties [5]. Many suggest that the concrete industry offers ideal conditions for the beneficial use of such slag and ashes because the harmful metals can be immobilized and safely incorporated into the hydration products of cement.

IV. METHODOLOGY

For the assessment of embodied energy of UHPC, initially a base mix with quartz powder (40% of cement) designated as UHPC-I is taken into consideration, whose mix proportions are given in Table I. The optimum mix proportion of the base mix is obtained from various trials at the laboratory, satisfying the criteria of UHPC. The main constituents of the base mix are cement, silica fume, quartz powder, sand, water, superplasticizers and steel fibres. The mix developed is a kind of reactive powder concrete, whose material proportions are determined in part by optimizing the granular mixture. The basic idea is to completely eliminate the coarse aggregate to attain greater homogeneity. The cost effective optimal dosage of steel fibres is 2% by volume of concrete. The fine sand used in this case acts as a filler material and superplasticizer is added to improve the workability of the mix. The compressive strength of this base mix with silica fume (25% of cement) is found to be 196 MPa with hot air curing at 200°C. The embodied energy of the base mix is ascertained by replacing 25% of cement with silica fume (SF), fly ash (FA) and ground granulated blast furnace slag, GGBS (BS).

Also, in order to arrive at the optimum value of embodied energy of UHPC with varying percentage of silica fume, fly ash and GGBS, several literature [9]-[16] are identified to obtain the mix proportions of UHPC with higher strength and durability criteria. Out of those literature, three are finally chosen [10], [15] & [16], and the mix proportions of UHPC taken from those literatures are presented in TABLE II (UHPC-II), TABLE III (UHPC-III) and TABLE IV (UHPC-IV) respectively. The mixes are so identified, that one set of mix contained steel fibres but no coarse aggregate; the other set contained coarse aggregate but no steel fibres and the third set contained neither steel fibres nor coarse aggregate. All the three sets of mixes had varying percentage of silica fume, fly ash, GGBS and quartz powder, to achieve several mix proportions having higher strength and durability, satisfying the UHPC norms. The embodied energy of all the three set of mixes with varying combinations of silica fume, fly ash and GGBS are ascertained. A comparative analysis is made with the embodied energy and compressive strength of all the mixes, and the influence of the compressive strength on the embodied energy of a particular mix is also studied.

V. MATERIAL DESCRIPTION

The supplementary cementitious materials silica fume, fly ash and GGBS are abbreviated as SF, FA and BS respectively. Three mix proportions of UHPC-I with silica fume, fly ash and GGBS are designated as UHPC-I-SF, UHPC-II-FA and UHPC-III-BS respectively.

UHPC-II mixes have 6 different mix proportions containing varying percentage of fly ash and GGBS, which are given in TABLE II. In addition to the basic materials, it contained steel fibres, silica fume and quartz powder, but no coarse aggregate. The mix denoted as BS0FA0 contained neither GGBS nor fly ash; BS10FA10 contained 10% GGBS as well as 10% fly ash; BS10FA20 contained 10% GGBS, 20% fly ash; BS10FA30 contained 10% GGBS and 30% fly ash; FA20 contained no GGBS but 20% fly ash and BS40 contained 40% GGBS but no fly ash.

TABLE I

MIX PROPORTION of BASE MIX UHPC-I WITH DIFFERENT % of SILICA FUME, FLY ASH and GGBS

S. No	Material	Embodied energy (MJ/kg)	Quantity (kg/m^3)			Total Embodied energy (MJ/m^3)		
			UHPC-I-SF	UHPC-I-FA	UHPC-I-BS	UHPC-I-SF	UHPC-I-FA	UHPC-I-BS
1	Cement	5.50	788.00	788.00	788.00	4334.00	4334.00	4334.00
2	Fly ash	0.10	0.00	197.00	0.00	0.00	19.70	0.00
3	GGBS	1.60	0.00	0.00	197.00	0.00	0.00	315.20
4	Silica fume	0.036**	197.00	0.00	0.00	7.09	0.00	0.00
5	Quartz powder	0.850*	315.00	315.00	315.00	267.75	267.75	267.75
6	Coarse aggregate	0.083	0.00	0.00	0.00	0.00	0.00	0.00
7	Fine aggregate	0.08	866.80	866.80	866.80	70.21	70.21	70.21
8	Water	0.01	173.00	173.00	173.00	1.73	1.73	1.73
9	Superplasticizer	9.00**	14.77	14.77	14.77	132.93	132.93	132.93
10	Steel fibres	36.00***	157.00	157.00	157.00	5652.00	5652.00	5652.00
Total value of each mix (MJ/m^3)						**10465.71**	**10478.32**	**10773.82**

* Green Building Challenge Handbook, 1995.

** Minerals Products Association, The Concrete Industry Sustainability Performance Report, 1st Report

*** Steel Wires (Virgin) from ICE Database.

Others – The Inventory of Carbon & Energy Database (ICE)

TABLE II

MIX PROPORTIONS of UHPC-II WITH DIFFERENT % of FLY ASH and GGBS (WITH STEEL FIBRES and WITHOUT COARSE AGGREGATES)

S. No	Material (kg/m^3)	BS0FA0	BS10FA10	BS10FA20	BS10FA30	FA20	BS40
1	Cement	830.00	664.00	581.00	498.00	664.00	498.00
2	Fly ash	0.00	83.00	166.00	249.00	166.00	0.00
3	GGBS	0.00	83.00	83.00	83.00	0.00	332.00
4	Silica fume	291.00	205.00	157.00	141.00	195.00	173.00
5	Quartz powder	244.00	260.00	266.00	264.00	257.00	269.00
6	Coarse aggregate	0.00	0.00	0.00	0.00	0.00	0.00
7	Fine aggregate	733.00	781.00	800.00	794.00	773.00	810.00
8	Water	151.00	151.00	151.00	151.00	151.00	151.00
9	Superplasticizer	55.00	35.00	34.00	33.00	38.00	35.00
10	Steel fibres	234	234.00	234.00	234.00	234.00	234.00

TABLE III

MIX PROPORTION of UHPC-III WITH DIFFERENT % of SILICA FUME and GGBS (WITHOUT STEEL FIBRES and WITH COARSE AGGREGATES)

S. No	Material (kg/m^3)	1-SF10	2-SF10	3-SF10	SF10BS20	SF10BS40
1	Cement	450.00	630.00	810.00	630.00	450.00
2	Fly ash	0.00	0.00	0.00	0.00	0.00
3	GGBS	0.00	0.00	0.00	180.00	360.00
4	Silica fume	50.00	70.00	90.00	90.00	90.00
5	Quartz powder	0.00	0.00	0.00	0.00	0.00
6	Coarse aggregate	1195.00	1073.00	923.00	923.00	923.00
7	Fine aggregate	797.00	715.00	616.00	616.00	616.00
8	Water	90.00	126.00	162.00	162.00	162.00
9	Superplasticizer	18.00	18.00	18.00	18.00	18.00
10	Steel fibres	0.00	0.00	0.00	0.00	0.00

TABLE IV

MIX PROPORTION of UHPC-IV WITH DIFFERENT % of FLY ASH and GGBS (WITHOUT STEEL FIBRES and COARSE AGGREGATES)

UHPC-III mixes have 5 different mix proportions containing

S. No	Material (kg/m^3)	FA0BS0	FA20	FA40	FA60	FA80	BS20	BS40	BS60	BS80
1	Cement	850.00	680.00	510.00	340.00	170.00	680.00	510.00	340.00	170.00
2	Fly ash	0.00	170.00	340.00	510.00	680.00	0.00	0.00	0.00	0.00
3	GGBS	0.00	0.00	0.00	0.00	0.00	170.00	340.00	510.00	680.00
4	Silica fume	260.00	260.00	260.00	260.00	260.00	260.00	260.00	260.00	260.00
5	Quartz powder	212.00	212.00	212.00	212.00	212.00	212.00	212.00	212.00	212.00
6	Coarse aggregate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	Fine aggregate	850.00	787.00	724.00	661.00	598.00	838.00	826.00	814.00	802.00
8	Water	170.00	170.00	170.00	170.00	170.00	170.00	170.00	170.00	170.00
9	Superplasticizer	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00
10	Steel fibres	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

varying percentage of silica fume and GGBS, which are given in TABLE III. In addition to the basic materials, it contained coarse aggregate but no steel fibres, fly ash and quartz powder. The mix represented as 1-SF10, 2-SF10 and 3-SF10 comprised only 10% silica fume with varying quantity of cement as presented in Table III. The mix symbolized as SF10BS20 consisted of 10% silica fume, 20% GGBS and SF10BS40 comprised 10% silica fume, 40% GGBS.

UHPC-IV mixes have 9 different mix proportions containing varying percentage of fly ash and GGBS, which are given in TABLE IV. In addition to the basic materials, it contained silica fume and quartz powder, but no coarse aggregate and steel fibres. The mix symbolized as FA0BS0 has neither fly ash nor GGBS; FA20 included 20% fly ash; FA40 included 40% fly ash; FA60 included 60% fly ash; FA80 included 80% fly ash; BS20 included 20% GGBS; BS40 included 40% GGBS; BS60 included 60% GGBS and BS80 contained 80% GGBS.

IV. Results And Discussions

The embodied energy of the UHPC mixes are calculated based on the embodied energy values of each constituent material in terms of Mega Joules per kilogram (MJ/kg). These embodied energy values for different constituents are taken from three different sources for this study [17]-[19]. The quantity of the constituent materials in terms of kilogram per cubic metre (kg/m^3) is multiplied with the basic embodied energy values to get the total embodied energy of the constituent material in MJ/m^3. The sum of all the embodied energy values of the constituent materials in the mix would represent the final embodied energy of the mix in terms of MJ/m^3. The embodied energy value for steel fibres is not found in any source, and hence the value of steel wires (virgin) from ICE database is taken as the embodied energy value for steel fibres, as far as this study is concerned.

The embodied energy values of UHPC-I mixes presented in TABLE I, represents that the embodied energy is lesser for the mix with silica fume with superior strength of 196 MPa than the mix with GGBS with comparatively lesser strength. This is because the embodied energy value of GGBS is higher than that of silica fume.

From Figs. 2, 3 and 4, it is evident that the embodied energy as well as the compressive strength of UHPC-II mixes is very high when compared with the other two mixes. This is obvious due to the presence of steel fibres in the mix, for which the embodied energy is very high about 36 MJ/kg (Steel wires – ICE data base). The steel fibres are included in the mix to impart ductility, because it is certain that the high strength mixes are very brittle in nature. This type of ultra high performance mix is used for specific purpose, where strength and durability are the governing factors.

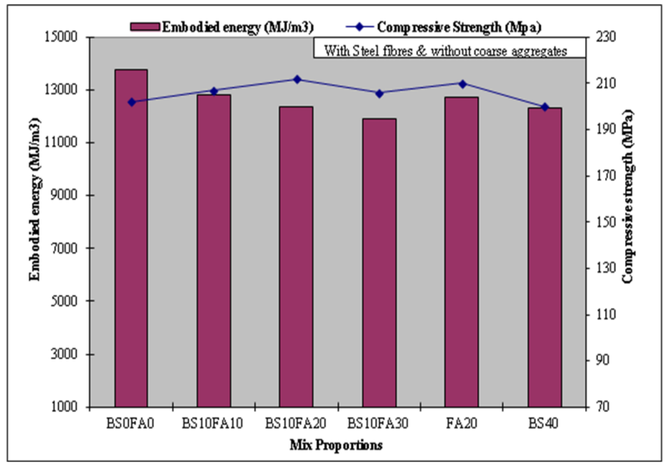

Fig. 2 Embodied energy Vs Compressive strength for UHPC mix with steel fibres and without coarse aggregates

The embodied energy of the other two mixes UHPC-III and UHPC-IV without steel fibres is in the range of 1500 to 5000 MJ/m^{3}depending upon the mix proportions. Their compressive strength is in the range of 70 MPa to 140 MPa, which is less compared to UHPC-II mixes, whose compressive strength is more than 200 MPa. These mixes satisfy the criteria of UHPC and also have a less embodied energy, which can be termed as “high strength green concrete”.

From Fig. 2 and TABLE II (with steel fibres and without coarse aggregate), it is recognized that the embodied energy is highest of about 13763 MJ/m^3 for the mix without fly ash and GGBS and the compressive strength is highest of about 212 MPa for the mix with 20% fly ash and 10% GGBS. The optimum mix among the UHPC-II mixes would be the mix with 10% GGBS and 30% FA, having an embodied energy of 11913 MJ/m^3 and a compressive strength of 206 MPa. Similar strength of 202 MPa is achieved with the mix without fly ash and GGBS but with the highest embodied energy of 13763 MJ/m^3, which is actually not a good proportioning in embodied energy perception. Hence, this mix would require partial replacement of cement with optimum levels of fly ash and GGBS.

From Fig. 3 and TABLE III (without steel fibres and with coarse aggregates), it is apparent that the embodied energy as well as the compressive strength is highest for the mix with 10% of silica fume (with 810 kg/m^3 of cement) of about 4748 MJ/m^3 and 137 MPa respectively, which is due to the presence of high cement content. The optimum mix among the UHPC-III mixes would be the mix with 10% of silica fume (with 450 kg/m^3 of cement), having an embodied energy of 2803 MJ/m^3 and compressive strength of 131 MPa. The weakest mix would be the mix with 10% SF and 40% GGBS, having the least compressive strength of about 110 MPa and high embodied energy of 3345 MJ/m^3.

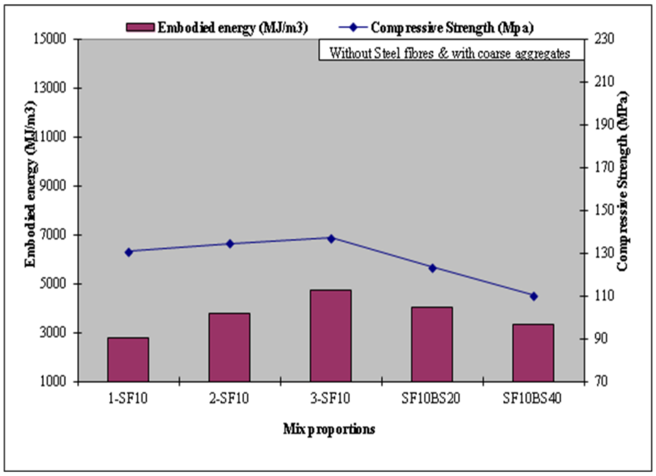

Fig. 3 Embodied energy Vs. Compressive strength for UHPC mix without steel fibres.

From Fig. 4 and TABLE IV (without steel fibres and coarse aggregate), it is evident that the embodied energy is highest for the mix without fly ash and GGBS of about 5340 MJ/m^3 and the compressive strength is highest for the mix with 40% fly ash and no GGBS of about 126 MPa. The optimum mix among the UHPC-IV mixes would be the mix with the highest compressive strength of 126 MPa and an embodied energy of 3494 MJ/m^3 containing 40% fly ash and no GGBS. The mixes which would require a re-proportioning are, 1) The mix containing 80% of GGBS, with an embodied energy of 2684 MJ/m^3 and a low compressive strength of 82 MPa and 2) The mix with the highest embodied energy of 5340 MJ/m^3 and a compressive strength of 113 MPa having no fly ash and GGBS, because the same strength of 113 MPa is achieved with a lesser embodied energy of 2570 MJ/m^3 with the mix containing 60% of fly ash. This reduction in embodied energy with considerable strength can be due to the replacement of high volume of cement with fly ash.

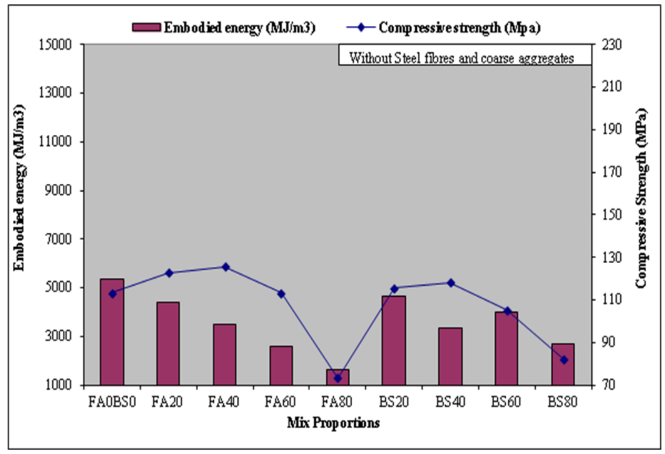

Fig. 4 Embodied energy Vs. Compressive strength for UHPC mix without steel fibres and coarse aggregates.

V. CONCLUSIONS

Basically, all the UHPC mixes contain silica fume as a base material, which has very low embodied energy value of 0.036 MJ/kg, when partially replaced for cement produces a high strength low embodied energy ultra high performance concrete. An efficient mix is identified as the mix with partial replacement of cement by 10-25% of silica fume, 20-40% of GGBS and 30-60% of fly ash, which results in the reduction of cement usage and in turn results in lesser embodied energy without compromising the strength. To obtain the most favorable UHPC mix, the proportioning of the cementitious materials needs to be taken utmost care, because higher percentage of replacement of supplementary cementitious materials can lead to a poor mix having higher embodied energy and lower strength. Hence, the optimum levels of cementitious materials as a replacement for cement can be arrived by trial and error only.

ACKNOWLEDGEMENT

We acknowledge with thanks the technical support provided by the Computational structural mechanics group (CSMG), CSIR-SERC. This paper is being published with the kind permission of the Director, CSIR-SERC, Chennai, India.

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