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Effective Use of Structural Materials in Sustainable Design

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ABSTRACT

Nowadays, several materials are used in construction sector. The main aim of this paper is to investigate energy consumptions, CO_2 emissions and cost during the production and life-cycle of structural materials (e.g. steel, aluminium, timber, cement, aggregate, waste mineral additives). These materials have different environmental impacts andthe reuse of waste structural materials (e.g. recycled aggregate, steel and aluminium) as well as waste minerals in concrete (fly ash, slag etc) save energy consumption, CO_2 emissions and costs. Thus, the importance and effectiveness of recycled materials will be evaluated via energy consumption, carbon footprint, ultimate strength and their ratios. Embodied energy to ultimate strength or embodied carbon to ultimate strength ratios may emphasize the effectiveness ofa sustainable material. The most effective materials in this study indicate the recycled steel and C50 concrete with 50 % fly ash or slag.

Keywords. CO_2, building materials, energy, strength, recycle

INTRODUCTION

Sustainability is the intersection of economic, social and environmental necessities. By enhancing the environmental performance, sustainability concept is to leave a better world to live for future generations. If the people, government and companies consider economic, social and environmental impact together, this intersection (Figure 1) will provide a cleaner and more liveable planet without compromising to meet their own needs of the future generations.

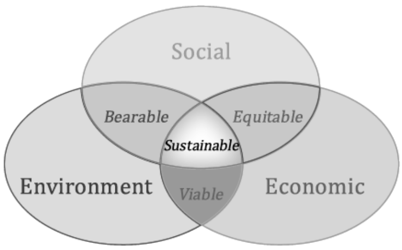

Figure 1 Description of Sustainability (Sabnis, 2012)

Sustainability in construction sector is the main theme of this paper. About 40% of the total natural resources used in industrial countries are consumed by construction sector and about 25% of energy is used in housing. This large consumption of resources and energy in the building sector has deep impacts on the environment. Reinforced concrete buildings are commonly built all over the world due to the economic and local reasons.However,cement production is one of the most energy-intensive industrial processes in the world. For each one ton cement production,930 kg CO_2 is emitted (Higgins, 2006) and theseemissions are estimated at about 7% of the worldwide CO_2emissions. The world also needs to learn more about the effective use of cement and concrete to make stronger, more durable, energy-efficient and economic structures. At the end of lifetime, debris after demolition is still used as a filling material in many places. Whereas the recycling of coarse aggregates and to reuse in road or pavement concrete provide economical solutions.As for the metals in construction sector, 33 % less energy is required to recycle steel than to make it from iron ore; and recycled aluminium means to consume about 95% less energy.

The effect of concrete to sustainability comes from its ingredients (e.g. cement, water to cement ratio, aggregates and types, waste additives) and their impacts to the structure during the life. Concrete should be desirably strong and durable to any environmental factors causing its damage or deterioration. The partial replacement of waste mineral additives (fly ash, slag etc.) with cement provides an important contribution for the green, durable and energy efficient concrete design. Depending to durability and strength demand, the by-products fly ash and slag can be replaced up to 70 % with cement.

EMBODIED ENERGY AND CO_2 EMISSIONS

Sustainable materials to be used in the buildings should have some specifications; i.e renewable, reusable and recyclable as much as possible; low embodied energy and CO_2 emissions; locally resourced, minimum waste, and non-polluting. The constructors must also take the cost for sustainable building into account. Embodied energy of building materials is the sum of all energy consumption which includes the energy used for material exploitation, production, construction, installation, maintenance and demolition. Embodied carbon data is generally predicted from life cycle assessment. The data of embodied energy may have higher accuracy than those of embodied CO_2.

Embodied energy, embodied CO_2 data and average prices of structural materials in Turkey, EU and US are given are displayed in Table 1. Aluminium has the highest embodied energy and carbon values, steel is in the second rank as well. Embedded energy (EE) and carbon (EC)data are given in Figure 1, a simple linear relationship (Eq.1) with very high correlation coefficient (R)is developed for 10 data (waste materials were not displayed in Figure but added to correlation relationship).

$$EC = 0.5\ EE\ ,\ R = 0.995 \qquad (1)$$

Embodied carbon emissions per embodied energy were investigated as well; a change different from Figure 1 exists for these ratios. In Figure 2, cement has the highest carbon emission ratio within structural materials. Because about 60% of CO_2 produced in cement manufacturing arises from the calcination reaction to liberate CaO from $CaCO_3$. CO_2 emissions, e.g. for C30 concrete production, is directly proportional to the cement content used in the concrete mix and only cement use leads high carbon value and carbon emission ratio. To decrease CO_2 footprint of concrete the utilization of waste mineral additives such as fly ash, silica fume and slag to some extent in concrete should be used preferably to save energy consumption and carbon emissions in the highest level. For example, 50 % fly ash (f.a) or slag replacement with cement provides about 50 % decrease in CO_2 value and about 20 % decrease in carbon emission ratio of C30 concrete (Figure 2).

Table 1. Embodied Energy and Carbon Data of Main Structural Materials

Building Materials		Embodied Energy (EE) & Carbon Data (EC)*		Average Price, $**			
Materials	Type	EE MJ/Kg	EC Kg CO_2/Kg	Turkey	Europe	US	
Wood	glue laminated timber (glulam)	12	0.65	250	300		($/m^3)
Steel	ribbed bar	24.6	1.71	730	1500		($/mt)
	profile	25.4	1.78	900			
Aluminium	alloyed	155	8.24	2275	2300	2400	($/mt)
Cement	Ordinary portland	4.6	0.83	69	110	105	($/mt)
Fly ash	F or C type	0.1	0.01	40	12	15	($/mt)
Silica fume		0.1	0.014	490	200	150	($/mt)
Slag (GBBS)		1.33	0.07	62	30	25	($/mt)
Concrete (No wasteminerals)	C20	0.95	0.128	55	95	100	($/m^3)
	C25	0.99	0.136	57	100	105	($/m^3)
	C30	1.08	0.153	60	120	110	($/m^3)

* The reference of Embodied Energy and Carbon data is Hammond and Jones (2008). Steel, aluminium havegeneral data recycled to some extent.
**The prices -transport cost not included by excluding Turkey fly ash and slag data-were investigated from several internet sources and personal communications.International prices are variable, the average values were used.Silica fume price for Turkey is based on imported Norwegian one andthe transported cost of fly ash increased about four times in the last years.Concrete and wood prices belong to ready mix concrete and pine tree logs, respectively.

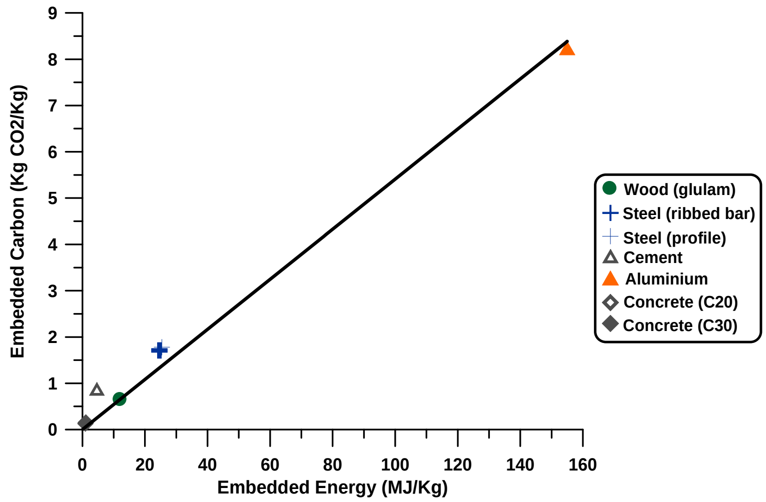

Figure 1. The relationship between embedded carbon and embedded energy

As per waste minerals or by-products in concrete; fly ash is the finest particles rising with the flue gasesfromthe combustion of coal (F type) or lignite (C type) in power plant. Fly ash is captured by preventing to enter the atmosphere. 20-50% fly ash rises during the combustion from 1 ton coal or lignite. Blast furnace slagas molten ash arises as a by-product from pig iron production and is collected, granulated by cooling and ground to reach the sufficient fineness.25% of one ton iron is slag. Silica fume is a by-product ofsilicon and ferrosilicon alloy production. As a nanomaterialit is a very effective material against to high price (Table 1). By adding silica fume, fly ash or slag into the concrete during the construction, designers aim a long service life for reinforced concrete structure.In high-rise buildings silica fume is an indispensable ingredient of very high strength concrete especially in the compressive strengths higher than 70 MPa and alsoto achieve high early strength for mould removal. Fly ash is a cheap material for sustainable and durable concrete.Fly ash and slag are needed for controlled temperature increase in hydration, to increase impermeability and later strength gain. The waste minerals are used around the world for durability requirements and economy in concrete more and more.

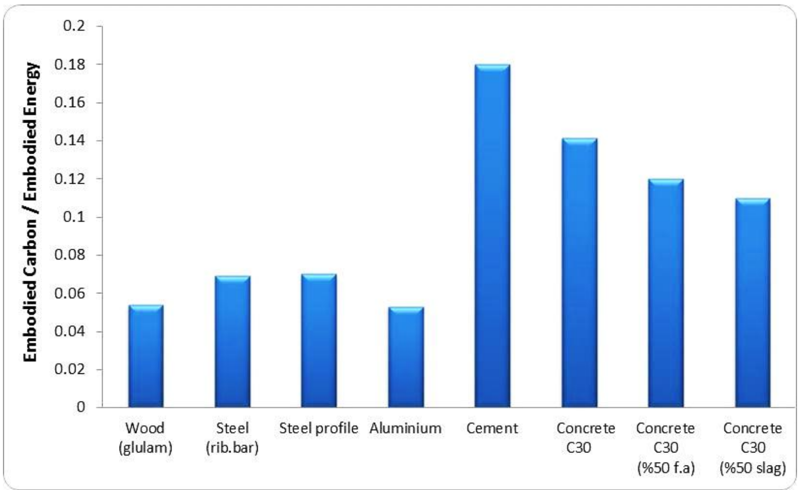

Figure 2. Embodied carbon to embodied energy ratios in structural materials

ENERGY,CARBON AND COST EFFECTIVE DESIGN

Reuse and recycling should be used in a high content to save the resources, to decrease energy consumptions, CO_2 emissions and cost. As a kind of effectiveness, the embodied CO_2 values to strength ratios (Figure 3) and the embodied energy values to strength ratios (Figure 4) of structural materials (e.g. steel, aluminium, wood and concrete types) wereclassified to be virgin and fully recycled. Channel type extruded aluminium (6061-T6), ASTM A36 steel, glulam from douglas fir, concrete C20 and C50 are chosen for comparison. Ultimate strengths are taken into consideration and these strengths are tension (400 MPa for steel, 310 MPa for aluminium) or compression (50 MPa for laminated composite beam, C20 and C50 for concrete). As seen from Figure 3 and 4, recycled steel and aluminium are competitive with concrete. Compressive strengths in concretes are based on 28 days but it should be remembered the concretes including high level (50 %) fly ash and slag replacement will have higher strength gains in 90 days, 365 days, 5 years etc. Thus the ratio under consideration will decrease more and more to be different from usual concrete (0%).High level fly ash or slag replacement environmentally and competitively gives the most proper solution in view of later strength gains and durability.

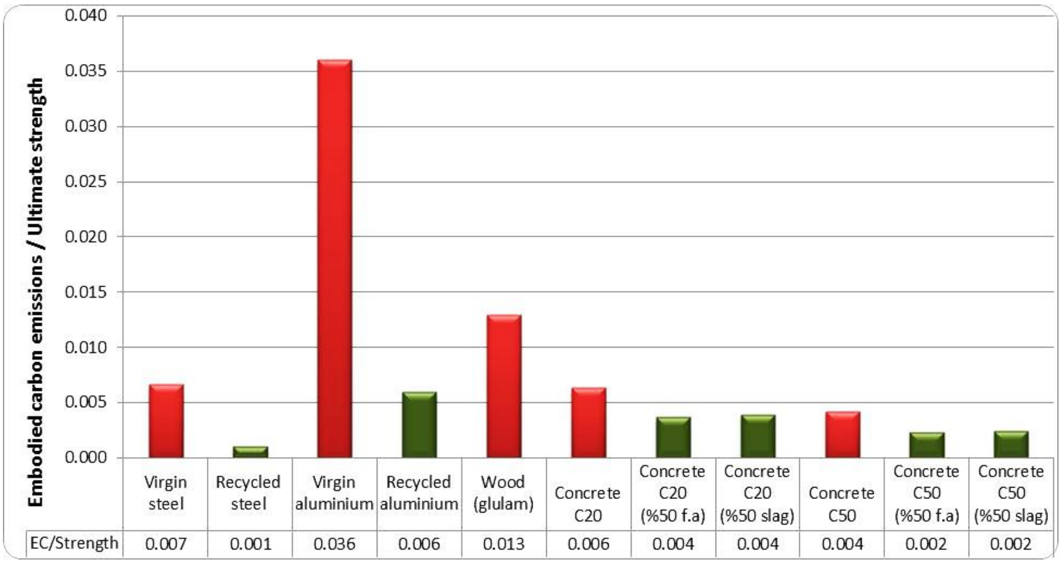

Figure 3. Embodied carbon emissions to strength ratios in structural materials

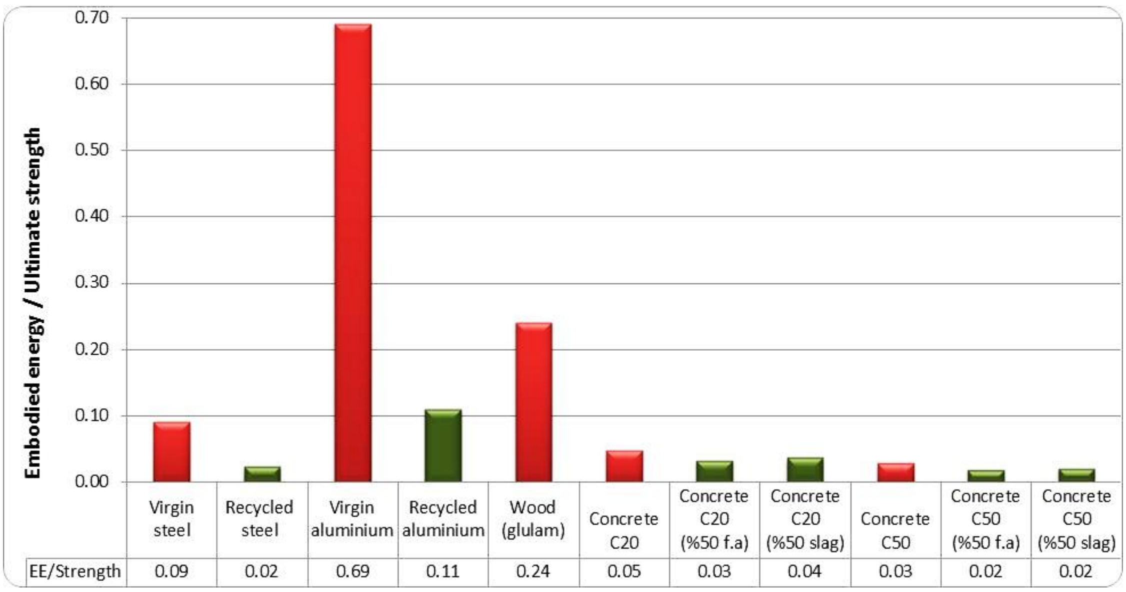

Figure 4. Embodied energy to strength ratios in structural materials

In Figure 5, 28-days compressive strength decision in concrete is investigated from a different view. From a few-story buildings to high-rise buildings,the compressive strengths of C20 to C120, costs andcost effectiveness in terms of cost to compressive strength ratios are displayed based on the actual material costs (i.e. cement, crushed aggregate, natural sand, high range water reducer) of relevant concrete class in Istanbul without transportation. Cost to compressive strength ratio decreases upto C60 concrete rapidly, however, then (> C60) almost stable due to possibly silica fume content in very high strength concrete.

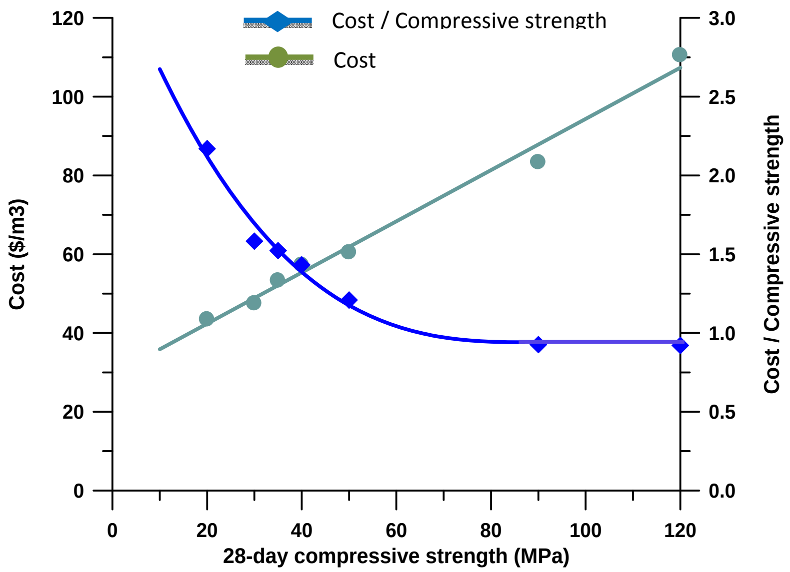

Figure 5. Concrete strength classes and cost effectiveness

CONCLUSION

The world needs to learn the effective and better use of structural materialsand to construct stronger, more durable, sustainable and energy-efficient structures. The following results can be given:

•Engineers, architects, planners, and builders should use industrial wastes and recycled aggregates from demolition.

• Embodied energy and carbon values should be compared with strength gain. Recycled metals instead of virgin ones and waste minerals such as fly ash, slag in concrete increases the effectiveness and decrease the costs. Recycled steel or C50 concrete with higher content of fly ash or slag (50 %) gives the best performance. The cost effectiveness increases with the compressive strength.

• In environmentally friendly concrete mix design, theingredients must be determined according to strength, durability and cost requirements.

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