LOW ENERGY CONCRETE

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ABSTRACT

The escalating demand on energy consumption as well as the scarcity of non renewable energy resources represents a major concern worldwide. Hence, efforts are being exerted to resort to lower energy alternatives in almost all aspects of life. Portland cement concrete has been known as an energy intensive material that emits large amount of CO_2 during its various stages of manufacturing. While concrete has been classified over the decades based on its performance, it has seldom been assessed and evaluated based on its embodied energy.

This work aims at evaluating concrete mixtures based on energy and CO_2 emission together with strength and durability characteristics. Alternative mixtures were targeted for both normal as well as moderate strength concrete as ones potentially having less energy and less CO_2. The results were used to establish a simplified user-friendly model for this process. Results reveal that concrete that is somewhat environmental-friendly can be prepared while fulfilling performance criteria and at a relatively less cost.

Keywords: Low Energy, Concrete, Cement, CO_2, Environmental-friendly

1. INTRODUCTION

One of the main impediments nowadays worldwide is the shortage of energy. The construction industry in Egypt is no exception in the sense that it incorporates energy intensive constituents such as ceramics, steel, brick and cement (Sherif, and Mohammed 2014). If the amount of energy required to crush, heat, mix, and transport concrete is considered, a statement can be made that the use of conventional concrete in green building is not effective in terms of decreasing the energy consumed and the carbon emission produced from the construction industry (Evans, 2008).

In Egypt, Portland cement market is considered as one of the largest in the world with twenty-one producers, twenty four plants and forty three kilns. Providing work for more than 50,000 people and indirectly supporting 200,000 others, it is also one of the most "economic drivers" (Saad, 2014). While cement is, indeed, an effective economic driver, yet the energy consumption should also be considered in its manufacturing. As and evidence, a 5% of the total global industrial energy consumption is estimated to be on the cement manufacturing. Another important point that should also be taken into consideration is that the cement production itself increases by about another 5% annually (Hendriks et al., 2004). Thus as energy saving is indeed in concrete production, the Portland cement amount should be reduced since 80% of the greenhouse emissions are released during its production (Flower and Sanjayan 2007). Also according to the U.S. Environmental Protection Agency, cement is rated as the third material for gas greenhouse pollution in the U.S. Whenever the cement is produced; it releases a huge amount of CO_2 in addition to greenhouses gases which are considered to be an essential by-product of the freshly produced cement. Furthermore, in cement industry, the heating and the mixing processes consume a marvelous amount of energy that can never be ignored (Hanle et al., 2010). That's why it is very important to decrease the amount of Portland cement used in the concrete to reach the optimum strength needed in the concrete with the lowest energy used.

The effort to reduce the energy consumption in the concrete industry should thus consider classifying various factors affecting concrete production. It is continued by taking a closer look at each component alone then defining stages necessary in order to find energy efficient solutions that could reduce energy consumption. Starting by the aggregates, for instance, previous work demonstrates that recycled aggregates can be used successfully in most of concrete mixes. In addition, polymers could be added to light weight aggregate. The cement consists of many stages and energy efficiency can be tackled in each stage. For example, the gyratory crusher can be used in the mining stage to reduce the mining energy and the dry process can be used to reduce energy in the cement clinker stage (Hendriks et al., 2004). Moreover, the self-compacting concrete can save the compaction energy. Furthermore, adding mineral plasticizers and liquid plasticizers can help enhance the workability and quality leading to the reduction of water to cement ratio or even replacing the cement which is the main energy intensive material in the concrete. Figure 1 shows a representation of the cement industry and the associated energy consumption in the U.S. This is also demonstrated by the fact that it produces services and goods by 1/10 the energy it is consumes.

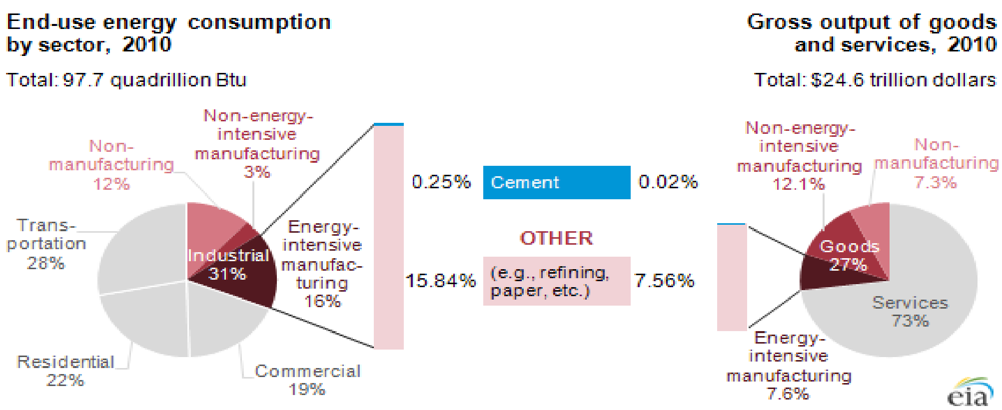


Figure 1: Percentage of energy consumption in the US (U.S. Energy Information Administration, 2013)

There are several articles in the literature that introduced substances which replace cement in concrete and are more energy efficient. With the increasing awareness of the importance of green building, some concrete alternatives are also available in the international market that might help generate a less energy consuming concrete.

The main objective of this study is to produce concrete mixtures that meet strength and quality criteria with less energy consumption at various stages of production. This is achieved by conducting an experimental program as well as a developing a simplified numerical model. The experimental program focuses on how to produce concrete mixes that satisfy the strength and quality criteria with less energy consumption at various stages of production. While the model focuses on the means to reduce energy in each stage of concrete formation process starting with the raw material until the final mixing phase.

2. EXPERIMENTAL PROGRAM

Twelve concrete mixes were designed. The twelve mixes were divided into two categories or types, which are normal strength concrete (20–30 MPa) and higher strength concrete (30–40 MPa). Six concrete mixes were prepared for each one of these two categories as follows:

2.1 Normal Concrete Mixes

a) **Conventional concrete mix (control mix for this group)**: with water to cement ratio (w/c) = 0.50.

b) **Conventional mix with reduced w/c ratio (0.45) and added admixtures (plasticizer):** reducing the water to cement ratio in a mix can save energy since cement is one of the most energy consuming components. While plasticizers are chemical admixtures that can be added to concrete mixtures in order to enhance workability, it reduces "the water content by 12 to 30 percent and can be added to concrete with a low-to-normal slump and water-cement ratio to make high-slump flowing concrete" (PCA, 2015).

c) **Self-Compacting Concrete mix (SCC):** Compaction consumes a significant amount of energy; thereby reducing the compaction energy required for concrete will reduce energy consumption. According the concrete portable, Self-Compacting Concrete is fit for several construction conditions even the severe ones with much less time compared to the conventional one and this is due to its ability to consolidate under its own weight. Use of SCC can also help minimize hearing-related damages on the worksite that are induced by vibration of concrete.

d) **Partially replacing cement by Arc Electric Slag (mineral admixtures)**: According to Hakkari (2015), Slag is a byproduct obtained by industrial wastes and the objective for using it to take account of the economic benefits and environmentally safe recycling of industrial and other waste by-products"

e) **Replacing Coarse Aggregates with Recycled Aggregates**: Natural coarse aggregate are fully (100%) replaced by recycled concrete aggregate obtained from crushed test cubes in the lab.

f) **Adding Silica Fume admixture to the mix**: According to Rezaei-Ochbelagh et al. (2012) silica fume is the best choice as addictive "When additives are utilized as partial replacements for Portland cement, apart from reduced cement use, an improvement in concrete properties such as strength, permeability, corrosion resistance and durability results and concrete cost is minimized.

The mix design for each of these six mixes is shown in Tables 1.

Table 1: Normal strength concrete mix design

Mix Type And Code	Constituents of the Mix (kg/m^3)							
	Cement	Water	w/c	Fine Aggregate	Coarse Aggregate	Electric Arc Slag	Silica Fume	Chemical Admixture.
Mix (a) (N1CM)	350	175	0.50	600	1208	0	0	0
Mix (b) (N2P)	300	135	0.45	658	1316	0	0	2L of Plasticizer (A)
Mix (c) (N3FS)	280	126	0.45	601	1201	70	0	0
Mix (d) (N4SF)	315	142	0.45	606	1212	0	35	0
Mix (e) (N5RA)	300	135	0.45	609	1218	0	0	2L of Plasticizer (A)
Mix (f) (N6SC)	450	135	0.30	905	905	0	0	15Lof Plasticizer (F) + 5L of Visc..Mod..

2.2 Higher Strength Concrete Mix

The following mixes were used for the investigation of a higher strength concrete:

g) Conventional concrete mix (Control Mix for this group). Mix code H1CM
h) Conventional mix with reduced w/c ratio and added admixtures (Super Plasticizer). Mix code H2P
i) Partially replacing cement by arc electric slag (mineral admixtures). Mix code H3FS
j) Adding Silica Fume admixture to the mix. Mix code H4SF
k) Replacing coarse aggregates fully with recycled aggregates obtained from crushed test cubes in the lab. Mix code H5RA
l) Self-compacting concrete mix (SCC). Mix code H6SC

The mix design for each of these six mixes is shown in Tables 1.

2.3 Material Properties

Cement: type I normal Portland cement was used with a specific gravity of 3.14 and a specific surface area (Blaine fineness) of 375 m^2/kg. Typical Bogue compounds of the cement were as follows: C_3S = 53.7 percent, C_2S = 27.6 percent, C_3A = 6.1 percent and C_4AF = 10.1 percent. The alkali content (as Na_2O equivalent) was 0.45 mass percent.

Fine Aggregates: Natural siliceous river sand was used as fine aggregates in the present research program.

Coarse Aggregates: Crushed dolomite was used as coarse aggregates in present research program.

Water: Typical municipal tap water was used in all concrete works in the present experimental program.

Mineral Admixtures: Two types of mineral admixtures were used in this experimental program a) Silica fume and b) Electric Arc Slag.

Table 2: Higher strength concrete mix design

Mix Type And Code	Constituents of the Mix (kg/m^3)							
	Cement	Water	w/c	Fine Aggregate	Coarse Aggregate	Electric Arc Slag	Silica Fume	Chemical Admixture.
Mix (g) (H1CM)	480	216	0.45	580	1044	0	0	0
Mix (h) (H2P)	400	105	0.35	699	1258	0	0	8L Plasticizer (F)
Mix (i) (H3FS)	360	203	0.45	582	1047	90	0	8L Plasticizer (F)
Mix (j) (H4SF)	405	203	0.50	589	1061	0	45	8L Plasticizer (F)
Mix (k) (H5RA)	400	140	0.35	630	1120	0	0	8L of Plasticizer (F)
Mix (l) (H6SC)	550	197	0.30	825	825	0	0	15L Plasticizer (F) + 5L Visc..Mod..

Silica Fume: Silica fume was used as a supplementary cementitious material in some mixes as shown in Table 3. The used silica fume had SiO2 content of 93% and an average particle size of 0.15 μm.

Electric Arc Slag: arc slag produced during the manufacture of crude steel by the melting of steel scrap with additions of fluxes. It is non porous, dense and can resist polishing and enhances the mix durability.

Water reducing Admixtures: Commercially-available water-reducing and high-range water-reducing admixture (super plasticizer and plasticizers) were used to produce concrete mixes with lower water to cement ratios. The two types were complying with ASTM C 494 Types A and F respectively. The Type A was lignin based while the type F was naphthalene based. Both had a specific gravity in the range of 1.18.

Viscosity Modifier: It Improves stability and segregation resistance of concrete mixes without significant reduction of slump or flow, resulting in improved surface quality and aesthetics. The ViscoCrete used in some mixes was obtained from one of the local companies in Egypt and it has a pH value of 4,40% solid content, and a density of 1.08 kg/lt.

2.4 Lab Tests

The experimental program included the flowing set of standard tests:

- Slump test according to ASTM C143: Cone slump test for normal concrete and flow slump test for self-compacting concrete.
- Air content according to ASTM C231.
- Compressive strength after 7 and 28 days according to BS EN 12390-3:2009.
- Flexure strength after 28 days according to ASTM C78.
- Chemical durability test according to ASTM STP 169.

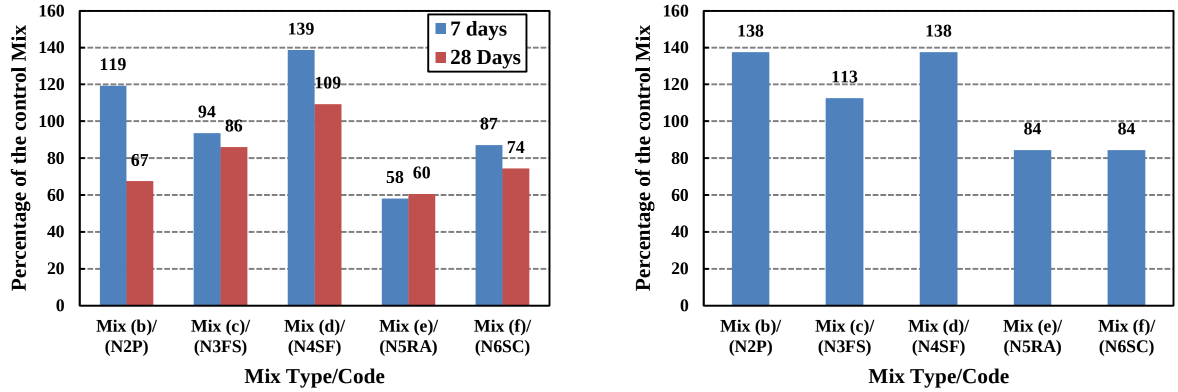
3. TEST RESULTS AND DISCUSSIONS

The fresh and hardened concrete test results for the normal and higher strength concrete mixes are shown in Table 3. Figure 2a shows the compressive strength at ages 7 and 28 days as percentage of the conventional concrete strength at the corresponding age and Figure 2b shows flexural strength as percentage of those of the control mix for normal strength concrete mixes.

Figure 3a shows the compressive strength at ages 7 and 28 days as percentage of the conventional concrete strength at the corresponding age and Figure 3b shows flexural strength as percentage of those of the control mix for higher strength concrete mixes.

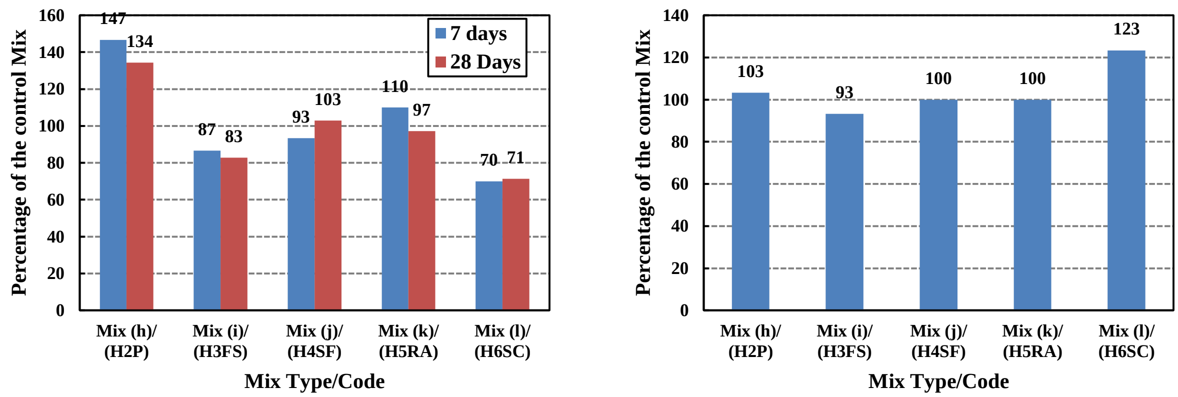
Table 3: Fresh and hardened concrete test results for the normal and higher strength concrete mixes

Group Type	Mix Type/Code	Slump/ *Flow Slump* (mm)	Unit Weight (kg/m³)	Compressive Strength 7/days(MPa)	Compressive Strength 28/days(MPa)	Flexure Strength 28/days (kN)
Normal Strength Group	Mix (a)/ (N1CM)	25	2501	31	43	32
	Mix (b)/(N2P)	30	2527	37	29	44
	Mix (c)/(N3FS)	35	2461	29	37	36
	Mix (d)/(N4SF)	65	2390	43	47	44
	Mix (f)/(N5RA)	0	2257	18	26	27
	Mix (e)/(N6SC)	450	2304	27	32	27
Higher Strength Group	Mix (g)/ (H1CM)	15	2261	30	35	30
	Mix (h)/ (H2P)	20	2347	44	47	31
	Mix (i)/(H3FS)	30	2440	26	29	28
	Mix (j)/(H4SF)	170	2343	28	36	30
	Mix (k)/(H5RA)	15	2270	33	34	30
	Mix (l)/(H6SC)	500	2351	21	25	37



a) Compressive strength b) Flexural strength

Figure 2: Compressive and flexural concrete strength results for normal concrete mixes



a) Compressive strength b) Flexural strength

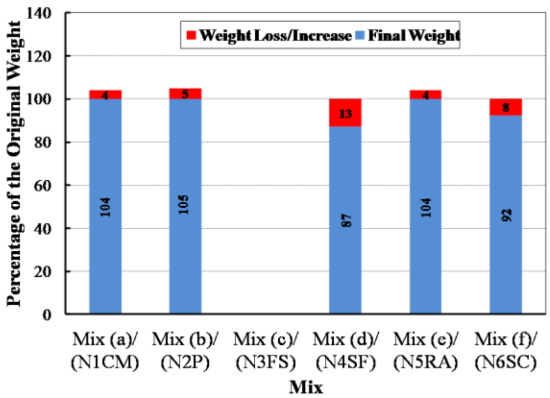
Figure 3: Compressive and flexural concrete strength results for higher strength concrete mixes

Generally there was no wide variation between the tests results when compared to the conventional mixes. All slumps were within the accepted region except for normal strength mix with recycled aggregates as a result of the materials additional water absorption. The unit weight variation trend was different in normal and higher strength mixes; all mixes except the plasticizer mix had a relatively less unit weight while all the higher strength mixes had a heavier unit weight than the conventional mix. All mixes were in the acceptable range of compressive and flexure strength. The silica fume mix obtained the highest strength and flexure results along with the plasticizer.

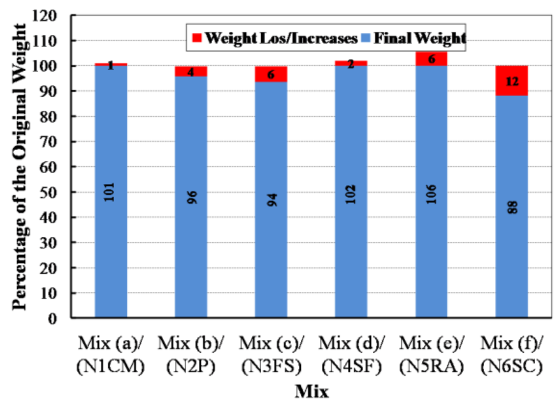
The durability test results are summarized in Table 3 and Figures 4 and 5 for the normal strength concrete mixes and higher strength concrete mixes. There is a wide variation in the chemical durability results because the mixes were not subjected to equal number of cycles but where tested at equal intervals. Some mixes had an increase in weight which is due to crystallization of salt. The Normal strength silica fume mix was the closest to the conventional mix behavior. The magnesium sulfate effect on the super plasticizer mix was similar to the conventional. Generally the Slag mixes had a better durability than the conventional mixes.

Table 3: Durability test results for the normal and higher strength concrete mixes

Group Type	Mix Type/Code	Initial Weight (kg)	Weight after sulfuric acid (kg)	Reduction (%)	Initial Weight (kg)	Weight after Magnesium sulfate (kg)	Reduction (%)
Normal Strength Group	Mix (a)/N1CM)	257	268	-4	264	267	-1
	Mix (b)/(N2P)	247	260	-5	261	250	4
	Mix (c)/(N3FS)	294	N/A	--	318	298	6
	Mix (d)/(N4SF)	264	230	13	254	258	-2
	Mix (e)/(N5RA)	275	286	-4	265	280	-6
	Mix (f)/(N6SC)	278	257	8	287	253	12
Higher Strength Group	Mix (g)/(H1CM)	242	229	5	233	240	-3
	Mix (h)/ (H2P)	317	283	11	306	314	-3
	Mix (i)/(H3FS)	275	265	4	290	282	3
	Mix (j)/(H4SF)	280	276	1	352	292	17
	Mix (k/(H5RA)	271	N/A	--	278	266	4
	Mix (l)/(H6SC)	284	261	8	290	252	10

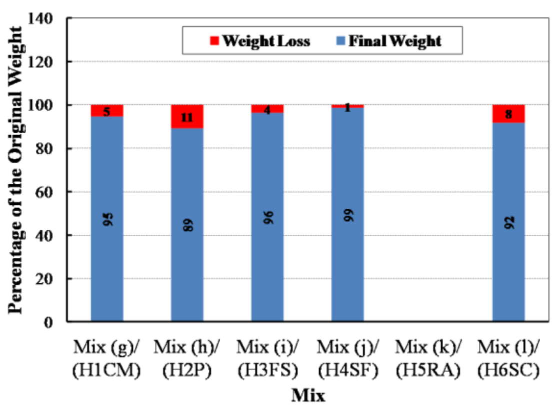


a) Sulphuric Acid

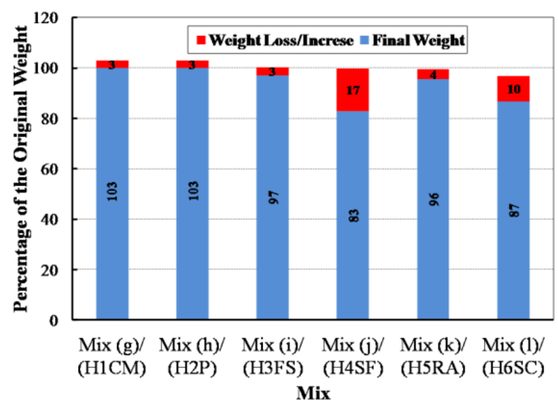


b) Magnesium Sulphate

Figure 4: Normal strength chemical durability test results



a) Sulphuric Acid



b) Magnesium Sulphate

Figure 5: Higher strength chemical durability test results

4. ENERGY MODEL

4.1 Methodology

The process of preparation and casting concrete is divided into stages. The energy consumed in each stage is obtained from the literature. These stages are:

a) Material preparation: coarse and recycled aggregate crushing, sand preparation, cement production.
b) Transportation: aggregate: aggregate, sand, and cement.
c) Concrete mixing: ready mix and transportation of the ready mix concrete.
d) Pumping
e) Compaction

A computer software is developed to perform the calculation of developed energy model. It consists of input module by the user to define the quantities of the constituents of the concrete, whether or not compactions will be used, the unit weight of the produced concrete, whether mixing on the site or ready mix will be used. Sample for this module is given in Table 4.

The computer processes the input data using the energy consumption values as stored in the data bank of the software for each of the defined material/process. Sample of the processed results is given in Table 5

The computer program responds as an output with the total energy consumption/ton (MJ/T) for the specified concrete mix and production method. Sample of the computer output is given in the last two lines in Table 5.

Table 4: Sample of the input module of the energy model

Input 1: Define the proportions and conditions of mix		
Name of mixture	HS Self Compacting Concrete	
Constituents	Quantity	Units
Cement	550	kg/m^3
Water	165	kg/m^3
Sand	825	kg/m^3
Coarse aggregates	825	kg/m^3
Recycled aggregates	0	kg/m^3
Unit Weight	2351	kg/m^3
Compaction	No	
Mixing	Mixing plants	

Table 5: Sample of the energy consumption for the material/processing

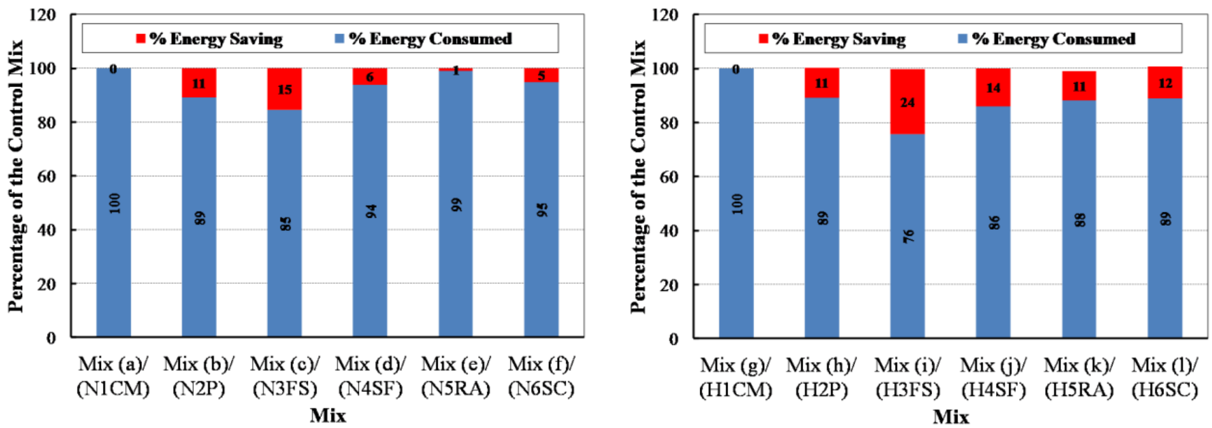
Energy consumption (MJ/m^3)			
Materials		**Transportation to plants**	
Aggregates crushing	23.76	Aggregates transportation	7.11
Cement production	2178	Cement transportation	4.74
Sand manufacturing	43.725	Recycled aggregates transportation	0.00
Recycled aggregates crushing	0.00	Sand transportation	7.11
Subtotal energy consumed	**2245.485**	**Subtotal energy consumed**	**18.96**
Transportation to factories		**Concrete mixing**	
Coarse aggregates transportation	177.79	In plant mixing (Ready mix)	0.04
Cement transportation	118.53	Transportation mixers	0.00
Recycled aggregates transportation	0.00	Pump	3.50
Sand transportation	177.79	On site mixing	0.00
Subtotal energy consumed	**474.10**	**Subtotal energy consumed**	**3.55**
Compaction energy			
Standard lab test	0.00		
Subtotal energy consumed	**0.00**		
Total energy consumed (MJ/m^3)	2742.09	**Total energy consumed (MJ/T)**	1166.35

4.2 Energy Model results

The Energy model was applied on all the mixes for normal strength concrete and higher strength concrete. The results are given in Table 6 and Figure 6.

Table 6: Energy consumption results for the different concrete mixes

Normal Strength Group			Higher Strength Group		
Mixes Number / Code	MJ/T	Reduction %	Mixes Number / Code	MJ/T	Reduction %
Mix (a) / (N1CM)	1031.7	--	Mix (g) / (H1CM)	1312	--
Mix (b) / (N2P)	919.9	11	Mix (h) / (H2P)	1172.6	11
Mix (c) / (N3FS)	873.6	15	Mix (i) / (H3FS)	994.8	24
Mix (d) / (N4SF)	968.9	6	Mix (j) / (H4SF)	1129.3	14
Mix (e) / (N5RA)	982.5	1	Mix (k / (H5RA)	1156.9	11
Mix (f) / (N6SC)	1026.9	5	Mix (l) / (H6SC)	1166.4	12



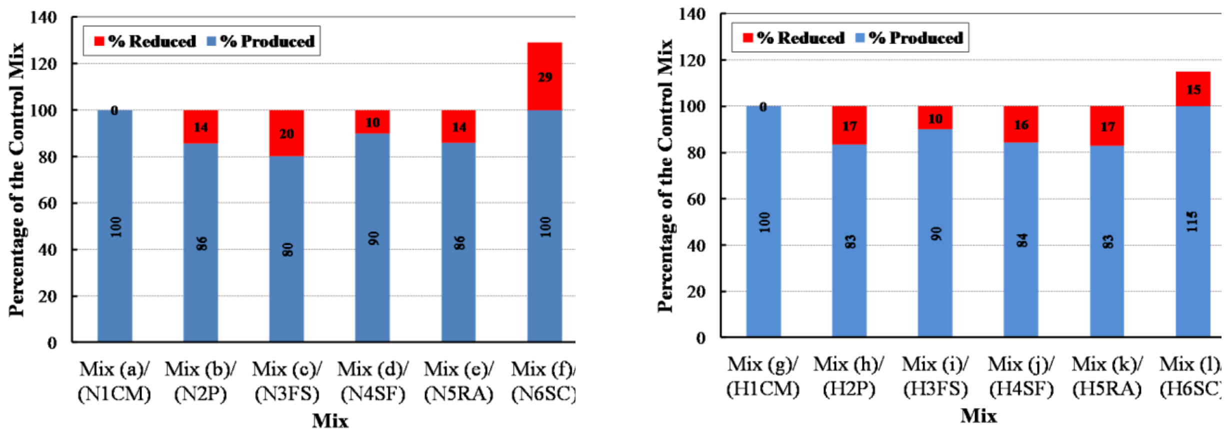
a) Normal strength concrete b) Higher strength concrete

Figure 6: Energy consumption results

5. CO_2 EMISSION

A CO_2 emissions model, that was designed earlier by Saada (2015), was used to calculate the carbon dioxide produced by the mixes in addition to calculating the environmental merits in terms of the saving in the produced carbon dioxide. The model takes into account the effect of mix constituents and transportation on the produced CO_2.

The results of the CO_2 emission model for the normal and higher strength concrete mixes are show in Figure 7. It can be seen from this figure that for higher strength mixes, recycled aggregate and the super plasticizer mixes produced the least CO_2 followed by the Silica fumes mix while the self compacting concrete mix produces more CO_2 than the conventional mix. This increase occurred mainly due to the extra amount of cement added in the mix.



a) Normal strength mixes b) Higher strength mixes

Figure 7: Results of the CO_2 emission model

6. COST ESTIMATE

The direct cost estimate of this research consists of the calculated cost for each of the designed mixes/m^3. The cost is calculated according to the prices in the Egyptian construction market in the fifteenth of August 2015. It includes the cost of the materials only and excludes the labor and equipment costs. Based on the United States Environmental Protection Agency, there is a benefit of saving carbon dioxide that benefits the mix costs. The social cost of carbon in USA is 40$/ metric tonne. This cost is equivalent to about 300 L.E according to the current currency exchange rate. Table 7 shows the results of the cost estimate. It includes all the used prices in the cost calculations.

Table 7: Results of the cost estimate

Group Type	Mixes Number / Code	Materials Cost (L.E/m^3)	Social Cost of Carbon (L.E/m^3)	Total Cost (L.E/m^3)	% Reduction
Normal Strength Group	Mix (a) / (N1CM)	314	1899	2213	--
	Mix (b) / (N2P)	307	1628	1935	13
	Mix (c) / (N3FS)	270	1520	1790	19
	Mix (d) / (N4SF)	551	1709	2260	-2
	Mix (e) / (N5RA)	299	1628	1927	13
	Mix (f) / (N6SC)	619	2441	3060	-38
Higher Strength Group	Mix (g) / (H1CM)	382	2603	2985	--
	Mix (h) / (H2P)	444	2170	2614	12
	Mix (i) / (H3FS)	402	1953	2355	21
	Mix (j) / (H4SF)	764	2197	2951	1
	Mix (k) / (H5RA)	433	2164	2597	13
	Mix (l) / (H6SC)	732	2969	3701	-24

7. CONCLUSIONS AND RECOMMENDATIONS

Based on the materials, methodology and other parameters associated with this study, the following conclusions and recommendations can be stated:

- Producing concrete through the conventional materials and techniques results in huge energy consumption and large emission of carbon dioxide.
- Portland cement is confirmed to be the largest contributor of the environmental non-friendless of concrete. Hence, its reduction and/ore replacement needs to be a major goal in the construction industry.

- Together with strength and durability, energy needs to be one of the criteria in classifying and categorizing Portland cement concrete mixtures.
- Producing good quality concrete mixtures with low energy is possible and in fact can be considered feasible on even the direct cost only. This feasibility is enhanced when considering the indirect costs and negative environmental impacts of conventional approach.
- The model used herein seemed helpful in guiding users into classifying the concrete energy emission. This model needs to be upgrades and validated.
- The construction industry as well as the codes of practice needs to join forces in introducing provisions in the codes and in project criteria that explicitly target low energy concrete.
- Further studies need to be conducted using wider range of materials and applications to expand and adjust the proposed model herein and possibly open the door for its implementation by the industry.

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