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A Proposed Method for Safe Disposal of Consumed Photovoltaic Modules

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ABSTRACT
The growth of domestic and large-scale applications of solar energy, especially photovoltaic (PV) cells which reaches annually up to 40 % worldwide since 2000, means that the technology has stepped out from demonstration phase to large-scale deployment. Several countries have started to exploit this huge potential as part of their future energy supply. Photovoltaic cells are manufactured from various semiconductors; materials that are moderately good conductors for electricity but harmful to the environment. End-of-life disposal of PV modules can be an environmental issue. However, due to the long lifespan of PV modules (25 to 30 years), currently most PV modules have not reached the disposal stage. As a result, there is very little experience and knowledge with the disposal and/or recycling techniques of PV modules. This paper proposes a method for safe disposal of solar panels after the end of their life by burying the PV cells into concrete blocks that may be used in different civil applications. Two types of PV cells (mono-crystalline & multi-crystalline) are selected to be mixed with concrete components to investigate their effect on properties of concrete. The experimental results showed that the PV cells have an effect on the concrete properties. Reduction of concrete compressive strength and density, while an increase in the concrete porosity were observed. In General, this study showed the validity of the proposed method to be further investigated for safe disposal of consumed photovoltaic modules.
Keywords:Photovoltaic cells recycling, PV cells recycling, PV cells disposal, photovoltaic cells disposal

I. INTRODUCTION

The growth of domestic and large-scale applications (annual growth of more than 40% in the world since 2000), photovoltaic (PV) cells demonstrates that the technology has evolved from the demonstration phase to large-scale deployment. Currently, it creates an emerging, stimulating and innovative market. Several countries have begun to exploit this enormous potential as part of their energy supply in the future. The photovoltaic cells are manufactured from various semiconductors; materials that are moderately good conductors of electricity but harmful to the environment. The most commonly materials used in manufacture are silicon (Si), the compound cadmium sulfide (CdS), copper sulfide (CuS) and gallium arsenide (GaAs). These PV cells are packaged in modules that produce specific voltage and current when illuminated.

End-of-life disposal of PV modules can be an environmental issue. However, due to the long lifespan of PV modules (25 to 30 years), currently, most PV modules have not reached the disposal stage. As a result, there is very little experience and knowledge with the disposal and/or recycling of PV modules. Recycling PV modules presents a number of challenges because of the lamination-nature of the module layers [1]. As with other laminated, layered and mixed-material items, it can be difficult to separate the various components safely and efficiently.

McMonagle [1] concluded that decommissioning waste for PV cells is the stage expected to result in the largest environmental impact when PV modules is evaluated on a full life-cycle basis. Heavy metals and organic substances found in the capsule material may leach from modules and may exceed the environmentally safe limits [1], [2]. Rare and valuable materials (including rare metalloids such as tellurium, indium and gallium) are also waste material from the life cycle of a PV module [3].

For crystalline silicon modules, the toxic materials contained in the actual semiconductor material are below the levels regulated by the European Photovoltaic Industry Association EPIA [4]. However, arsine has been reported as being used in the manufacturing of amorphous silicon modules. CdTe, CIS and CIGS PV modules all contain cadmium compounds, which are considered toxic to the environment and human health. CIS and CIGS PV modules also contain selenium, a regulated substance that bio-accumulates in food chains and forms hydrogen selenide, which is highly toxic and carcinogenic [4]. So these PV cells also pose an environmental concern because of the presence of heavy metals and other chemicals in the encapsulated materials.

Should these modules inadvertently end up in municipal waste incinerators, the heavy metals would gasify and a fraction of them would be released into the atmosphere and electrostatic precipitators can reduce this release to less than 0.5%. The remaining heavy metals would end up in the incinerator ash, which would be disposed of in a controlled landfill [5]. Disposal of large quantities of modules in a single landfill could lead to increased potential risks to humans and biota. The leaching of chemicals and heavy metals from these landfilled-modules has the potential to contaminate local ground and surface water.

This paper proposes a method for safe disposal of solar panels at the end of their life. The proposed technique depends on crushing these panels into small pieces and locking them in large concrete blocks that may be used as battering ram of the waves on beaches or as barriers to fine soil on the shores of valleys and rivers against erosion or in the construction of dams, bridges etc. So, this way is promising in preserving the environment from expected damage from the accumulation of these panels with an additional benefit from using it as rubble inside the concrete mixtures.

II. RESEARCH METHODOLOGY

Because the most widely spread of solar cells in the world are the mono-crystalline photovoltaic cells and poly-crystalline photovoltaic cells, so in this research these two types of photovoltaic cells have been chosen to be mixed with concrete to investigate their effect on the properties of concrete. These two sets of solar cells are crushed individually to small sizes and added as a percentage in the concrete mix. These percentages are 0.5%, 1% and 2% of the mix as replacement of sand. Then, standard tests for concrete have been performed to detect the influence of adding these materials on concrete properties such as strength, voids ratio and quality.

III. CONCRETE COMPOSITION AND STANDARD TESTS

According to the bulletin of the American Concrete Institute (ACI) [6], reapproved in 2009, the concrete is composed principally of aggregates, Portland cement, water, and many contain other cementitious materials and/or chemical admixtures. Typically, concrete also contains some amount of entrapped air and may also contain purposely entrained air obtained by use of admixture or air-entraining cement. [9] Chemical admixtures are frequently used to accelerate, retard, improve workability, reduce mixing water-cement ratio, increase strength, or alter other properties of the concrete [7]. The selection of concrete proportions involves a balance between economy and requirements of placeability, strength, durability, density, and appearance. [8]

Sand:

Sand is defined as a natural material that is available in our environment and typically used in concrete mixes. It is characterized by its very low cost, retained on sieve no 100 and passing from sieve no 4. The sand passing from sieve No 4 and retained on sieve No 100; is less than 4.75 mm in diameter and has a specific gravity of 2.67.

Coarse aggregate:

Coarse aggregate is a naturally crashed stone used as an inexpensive material that is retained on sieve no 4. Coarse aggregate is responsible for strengthening the concrete. It has a unit weight 1.65 t/m3

Cement:

Cement is a binder material used in concrete to harden the concrete mixture. The main compounds of cement are the silica, and calcium; it has a specific gravity of 3.15. There are different types of cement, the most common ones are the Portland, and the Super Sulfate-cement

Water:

Drinking water is considered in the concrete mixture. Water should be clean and free of acids, alkenes, and any harmful materials. Water is responsible for the hydration of cement and the workability of concrete

Crushed photovoltaic cells:

Photovoltaic cells are made of various semiconductors, which are materials that are moderately good conductors of electricity. The materials most commonly used in manufacturing these cells are silicon (Si) and compounds of cadmium Sulphide (CdS), cuprous sulphide (CuS), and gallium arsenide (GaAs).

IV. EXPERIMENTAL PROCEDURE

A concrete mixture was prepared for performing the experimental procedure as following:

1- The sieve analysis test was conducted for specimens of sand and coarse aggregate; the results are shown in Table 1. The results show that both specimens are approved as per American Society of Testing and Materials ASTM standards C33 [10] as shown in Fig 1.
2- The maximum nominal size of the coarse aggregate used was 20 mm.
3- The super-sulfate cement was used; as most probable applications for the proposed concrete blocks will be in contact with soil.
4- Two types of PV cells were used; mono-crystalline silicon and multi-crystalline silicon.
5- The PV cells were crushed and added to the concrete mixture as a filler material with

percentage of 0.5%, 1%, and 2% of the total weight of concrete specimen for each PV type.

6- For each percentage of PV cells, three specimens of concrete mixture were tested. In addition a specimen with 0% of PV cells was tested as reference for the six PV specimens.

7- The concrete mixture for both types of PV cells was mixed with a ratio of 0.57 : 1 : 1.5 : 3, by weight, for water, cement, fine aggregate (sand+ crushed PV cells), and coarse aggregate respectively.

8- Concrete mixtures were poured in cylindrical molds with 150 mm in diameter and 300 mm height have been used for casting the specimens.

Table 2 shows the details of specimens' contents while Fig. 2 shows photos of concrete-cylinders sample preparation.

V. RESULTS AND DISCUSSION

1. Compressive strength of concrete

All concrete specimens have been tested after 7 days of casting, a correction factor was applied to get the

Table 1: Results of sieves analysis test of sand and coarse aggregate specimens

Sieve NO.	weight (gm)	Total weight (gm)	Retained(%)	Passing(%)	ASTM C33
2	5.3	5.3	0.53	99.47	100
4	29	34.3	3.43	96.57	95 to 100
8	152	186.3	18.63	81.37	80 to 100
16	184	370.3	37.03	62.97	50 to 85
30	169	539.3	53.93	46.07	25 to 60
50	281	820.3	82.03	17.97	5 to 30
100	97	917.3	91.73	8.27	0 to 10

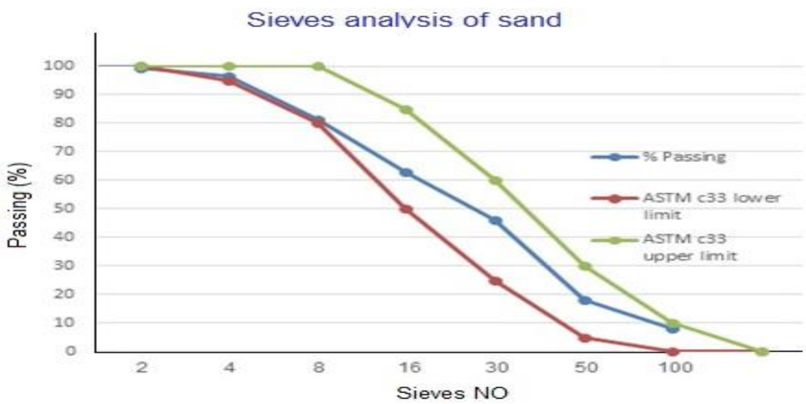

Fig. 1: Results of sieve analysis test of sand specimen

Table 2: Details of specimens' content

Type	%ofPV cell	Water (Kg)	Cement (Kg)	Fine Aggregate		Coarse Aggregate (Kg)	Total Weight (Kg)
				Sand (Kg)	PV Cell (Kg)		
Mix Proportion	-	0.57	1	1.5		3	6.07
Control Specimens	0	4	7	10.5	0	21	42.5
Multi-Si PV Specimens	0.5	4	7	10.29	0.21	21	42.5
	1	4	7	10.08	0.42	21	42.5
	2	4	7	9.66	0.84	21	42.5
Mono-Si PV Specimens	0.5	4	7	10.29	0.21	21	42.5
	1	4	7	10.08	0.42	21	42.5
	2	4	7	9.66	0.84	21	42.5

compressive strength after 28 days according to the specification of American Concrete Institute No. 209 (ACI 209) as follows [11]:

$$f_c' = f_{cm}(t) \times CF \quad , \qquad CF = \left(\frac{4+0.85t}{t}\right)$$

Where:
t: Time in days
f_{cm}: Mean compressive strength at a certain time
fc': Compressive strength after 28 days.

Inspecting the results of compressive strength for all specimens of concrete cylinders, it is observed that there is a reduction in the compressive strength due to adding a small amount of crashed photovoltaic cells to the fine aggregate. We refer this reduction in the compressive strength to the chemical reaction between cement and photovoltaic cells. As a result of this chemical reaction, an amount of air voids were produced in the cylinder which led to increase in the volume of concrete. Fig. 3 shows the shape of failure in the specimens, it is noted that the failure of specimens with 2% and 1% of both types of photovoltaic cells occurs at the top of specimens, this is due to the big amount of voids in the upper part of cylinder which is higher than the 0.5 % specimens. The maximum reduction in the compressive strength was 40 % compared to the control specimens (0 % of PV cells), Table 3 illustrates the recorded results for all types of specimens including control ones, while Fig. 4 shows the ratio of the average values of compressive strength for all tested specimens to that of the control one.

2. Porosity and density of concrete

The density of concrete was calculated for all specimens prepared with the both types of PV cells. A decrease in the density was observed for all specimens prepared with both types of PV cells. Also, it was observed that the cement dough leaked at the top of cylinders which means that the voids often have been produced at the top part of the cylinders. This phenomena may be considered as an indicator for the increase in the porosity of concrete dough which leads to reduction in concrete density for both types of photovoltaic cells. The maximum reduction in concrete density was 8 % in the 2 % specimens of mono-crystalline PV cells compared to that of the control specimens as illustrated in Table 3. Fig. 5 shows the ratio of the average values of concrete density for all specimens to that of the control one.

Fig. 2: Photos of concrete-cylinders sample preparation

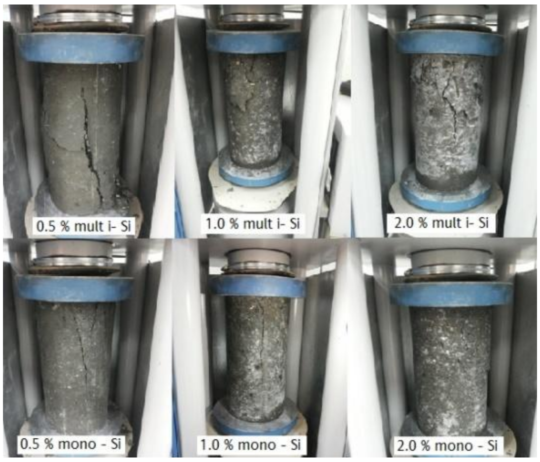

Fig. 3: Failure shape in concrete specimens for both types of PV cells

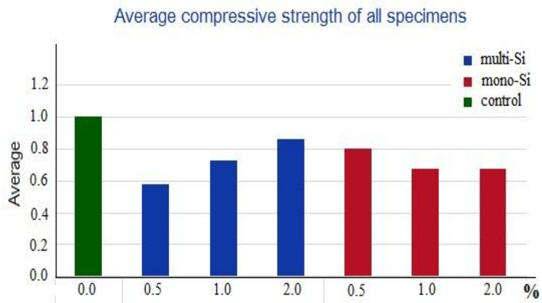

Fig. 4: Ratio of average compressive strength for all specimens to the control specimen

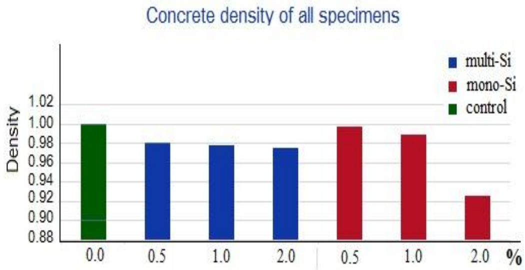

Fig. 5: Ratio of the average values of concrete density for all specimens to the control one

VI. CONCLUSION

The Experimental results showed that adding the crushed photovoltaic cells to the concrete components affect the properties of the resulted concrete mixtures, especially its compressive strength and its density. Two types of PV cells have been added separately with percentages of 0.5 %, 1.0 % and 2.0 %, by weight, of the concrete mixture. The results of compressive strength test showed that the maximum reduction in compressive strength may reach up to 40 % in the specimens mixed with 2.0 % of mono-crystalline PV type. While the density test showed that the maximum reduction in the density of concrete was 8% also in the specimens mixed with 2.0 % of mono-crystalline PV type. It is concluded from these results that the PV cells may be used as a filler material in addition to sand and coarse aggregate in concrete mixtures for non-structural applications only where the compressive strength does not play the main role such as concrete barriers, concrete slabs, concrete bumpers for sea waves or dunes, etc. In addition, due to the high porosity of these concrete mixtures, it may be used in heat isolation applications. In general, the results showed the validity of the proposed method for safe disposal of consumed photovoltaic modules.

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Table 3: Results of compressive strength tests for all specimens

Type	Item	Area (mm^2)	Weight (kg)	Unite Weight (Kg/m^3)	Failure Load (KN)	$f_{c\ 7day}$ (N/mm^2)	Tested After (Days)	CF	f_c' (N/mm^2)
Control	c1	17671.46	11.75	2216.38	180.00	10.19	7.00	1.42	14.48
	c2	17671.46	11.81	2227.70	140.00	7.92	7.00	1.42	11.26
	c3	17671.46	11.77	2220.15	176.00	9.96	7.00	1.42	14.16
0.5% Multi-Si	m31	17671.46	11.28	2127.72	100.00	5.66	7.00	1.42	8.04
	m32	17671.46	11.67	2201.29	96.00	5.43	7.00	1.42	7.72
	m33	17671.46	11.70	2206.95	90.00	5.09	7.00	1.42	7.24
1% Multi-Si	m11	17671.46	11.50	2169.22	120.00	6.79	7.00	1.42	9.65
	m12	17671.46	11.60	2188.09	128.00	7.24	7.00	1.42	10.30
	m13	17671.46	11.46	2161.68	114.00	6.45	7.00	1.42	9.17
2% Multi-Si	m21	17671.46	11.46	2161.68	144.00	8.15	7.00	1.42	11.58
	m22	17671.46	11.46	2161.68	144.00	8.15	7.00	1.42	11.58
	m23	17671.46	11.54	2176.77	140.00	7.92	7.00	1.42	11.26
0.5% Mono-Si	o31	17671.46	11.74	2214.49	124.00	7.02	7.00	1.42	9.97
	o32	17671.46	11.81	2227.70	152.00	8.60	7.00	1.42	12.23
	o33	17671.46	11.68	2203.18	122.00	6.90	7.00	1.42	9.81
1% Mono-Si	o11	17671.46	11.75	2216.38	118.00	6.68	7.00	1.42	9.49
	o12	17671.46	11.54	2176.77	100.00	5.66	7.00	1.42	8.04
	o13	17671.46	11.66	2199.40	116.00	6.56	7.00	1.42	9.33
2% Mono-Si	o21	17671.46	10.86	2048.50	120.00	6.79	7.00	1.42	9.65
	o22	17671.46	11.04	2082.45	100.00	5.66	7.00	1.42	8.04
	o23	17671.46	10.80	2037.18	116.00	6.56	7.00	1.42	9.33