Computer-Aided Measurements of the Electrical Resistivity Fields in Concrete Mixtures with and without Polyethylene Terephthalate

Khoury, N., Ph.D.[1], P.E., Maalouf, Y., M.S., Ghanimeh, S., Ph.D., and Zéhil G-P, Ph.D.
Department of Civil and Environmental Engineering
Notre Dame University-Louaize
Zouk Mosbeh, Lebanon
[1]e-mail: nnkhoury@gmail.com

Abstract—**This study aims at determining the electrical resistivity and mechanical properties of concrete mixes with and without polyethylene terephthalate (PET). 2-D Electrical Resistivity Tomographies (ERTs) were obtained using 14 electrodes spread on the surface of the concrete cylinder. AGI Supersting R1/IP was used for data acquisition and data were processed by an iterative finite element based inversion algorithm with EarthImager 2D. 1D testing was also performed on concrete cylinders with two stainless steel plates located at the ends acting as a source and a receiver. ERTs and 1D results showed that the electrical resistivity of concrete was lower in specimens with PET than in those without PET. After ERT testing, compressive strength tests were conducted on specimens. Findings revealed an increase in the compressive strength up to a PET content of 5% then a decrease up to a PET content of 20%. Findings also showed that the inclusion of PET increased the probability of corrosive action in PET concrete.**

Keywords—Electrical Resistivity; Numerical Inversion; Finite Element Method; Concrete; PET; Compressive Strength.

I. INTRODUCTION

Portland Cement Concrete (PCC) is considered an essential construction material, with between 21 and 31 billion tons used in 2006 (European Concrete Platform, 2009). PCC is a mix of coarse aggregates, fine aggregates, water, Portland cement and admixtures. The growing population has resulted in an increase demand for concrete and a consequent rise in the consumption of aggregates. For example, it is predicted that the US demand for aggregates will reach more than 2.5 billion tons per year by 2020 (Malesev et al., 2010).

In order to improve the sustainability of the construction industry, recent studies focused on substituting aggregates with low value, readily available material including, among others, crushed concrete, natural fibers and polyethylene terephthates (PET) (Malesev et al., 2010, Sadrmomtazi et al., 2016, Batayneh et al., 2007 and Awwad et al., 2011). While in some applications the results showed improvements in concrete quality vis a vis strength, ductility, durability and erosion (Awwad et al., 2011, Mishra, 2013, and Irwan et al., 2013), substituting aggregates with PET often resulted in a lower strength concrete (Araghi et al., 2015).

PCC structures are known to be vulnerable to several conditions including, but not limited to, extreme weather, acidic soils, acid rain and air pollution. Furthermore, the rate of deterioration has been increasing lately due to the rise of temperature and CO_2 atmospheric levels under the changing climate (Wang et al., 2010). The impact is more pronounced on the aging, already deteriorated, concrete infrastructures leading to a pressing global need for monitoring and repair. An increasing interest has been noted in developing methods capable of determining structural characteristics and damage potential. Commonly, PCC testing is categorized as destructive (e.g. pull out tests, pull off test, penetration resistance test and core samples) or non-destructive (e.g. acoustical waves, electrical resistivity, electromagnetic techniques, and different types of radiations (Karhunen, 2013, Rybak et al., 2010 and Obad, 2014).

This study focuses on the use of both destructive and nondestructive methods to monitor the effect of PET in PCC. 2D ERTs and 1D resistivity testing will be conducted on the cylinders to depict the impact of aggregate substitution with different proportions of PET. In addition, cylinders will be crushed to determine the effect of PET on compressive strength.

II. METHODOLOGY

The composition of the concrete mix is shown in Table 1. The PET material consisted of shredded bottles (Figure 1) and had a final particle size of 10 to 20 mm with a well-graded distribution (Figure 2). The materials were mixed using a mechanical mixer. A slump test in accordance with ASTM C143 was performed to determine the method of cylinder preparation. The concrete mixtures were formed into cylinders and cured for 28 days according to ASTM C192. Selected specimens were removed from the water tank after 28 days of curing for testing.

Figure 1 A Photographic view of PET particles

Electrical resistivity consists of injecting current from electrodes and measuring the potential difference created in the material with two other electrodes (Lataste et al., 2013). Differences in the apparent resistivity values are analyzed to determine the presence of cracks (Lataste et al., 2013) and corrosion of steel bars in concrete (Morris et al., 2002). 2D electrical resistivity was performed on the specimens by placing 14 electrodes, spaced 2 cm, on the cleanest surface of each tested cylinder. Dipole-dipole array was used for current injection and potential measurement. Figure 3 shows how the electrodes were placed on the concrete cylinder to decrease the contact resistance as much as possible. The contact resistance varied from 1,000 ohm to 2,000 ohm. The results were consistent with the literature and considered acceptable for accurate ERTs.

Table 1 A summary of mix designs

Materials	Control mix	2% PET	5% PET	8% PET	10% PET	15% PET	20% PET
Cement	13.1 kg	13.1 kg	13.1 kg	13.1 kg	13.1 kg	13.1 kg	13.1 kg
Water	7.3 kg	7.3 kg	7.3 kg	7.3 kg	7.3 kg	7.3 kg	7.3 kg
Gravel	33.8 kg	33.1 kg	32.1 kg	31.1 kg	30.4 kg	28.7 kg	27.0 kg
Sand	25.8 kg	25.8 kg	25.8 kg	25.8 kg	25.8 kg	25.8 kg	25.8 kg
PET	-	0.2 kg	0.5 kg	0.8 kg	1.0 kg	1.5 kg	2.0 kg

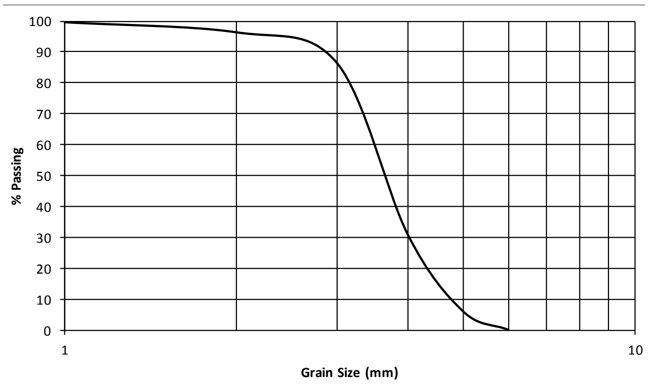

Figure 2 Grain size distribution used in the control mix

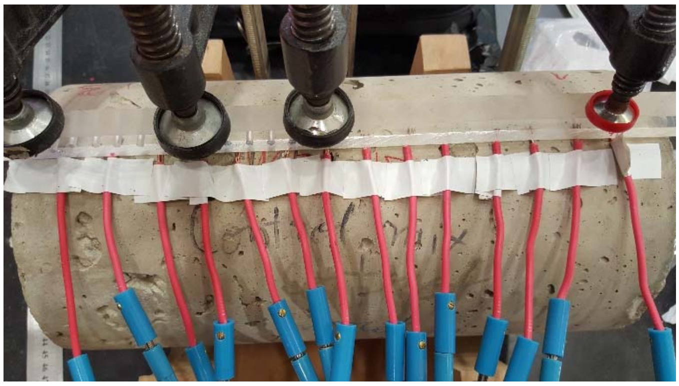

Figure 3 2D ERT Setup

1D resistivity testing, illustrated in Figure 4, consisted of placing two stainless steel plates with diameters equal to the diameter of the cylinder at each end of the cylinder. In order to decrease the contact resistance, a wet cloth was placed between the stainless plates and the concrete surface. This method ensured a lower contact resistance thereby enhancing accuracy in the calculation of apparent resistivity.

Figure 4 1D Setup

The cylinders were tested for compressive strength by applying an axial load at a constant rate according to ASTM C39 as shown in Figure 5. Neoprene pads were used for capping; the load cell capacity was 2,000 kN.

Figure 5 Loading-frame used in compressive strength testing

III. DATA PROCESSING

The data collection phase of an ERT corresponds to imposing electrical boundary conditions to a physical domain of known geometry – the concrete cylinders in this case – but of unknown material properties, and measuring its response. The objective of the data processing phase is to determine numerically – to the best possible level of accuracy – the spatial distribution of material properties that is consistent with the response previously observed experimentally. This is typically called an inverse boundary value problem. To perform the inversion, a so called shooting method is used: the physical domain is modeled and meshed into finite elements, and a value of resistivity is assigned to each cell as an initial guess. The response predicted by this "forward" model is compared to the measured response and the resistivity field is updated iteratively, in the model, so as to minimize an objective function corresponding to a least-square prediction error (RMS).

The two-dimensional resistivity inverse problem is, however, underdetermined and ill-posed. This means that several spatial distributions of resistivity exist that would predict the same response. Additional constraints must therefore be imposed to identify the optimal solution. To this aim, an objective function corresponding to the smooth model inversion is used. Smooth model inversion is based on the assumption that data errors are normally distributed.

IV. PRESENTATION AND DISCUSSION OF RESULTS

A. Slump Results

The slump test results showed a general decreasing trend with increasing PET content (Table 2), which is in accordance with reported findings (Siddik et al., 2007). The results for the 8% and 10% PET content showed an unexplained shift from the overall trend thus requiring further investigation.

Table 2 A summary of slump test results

PET Content	Slump (cm)
0%	3.7
2%	3.2
5%	2.5
8%	3.2
10%	3.5
15%	1.8
20%	1.6

B. Electrical Resistivity

Figure 6 shows the 2D ERT of the specimen with 0% PET – the baseline value. Electrical Resistivity (ER) values varied from approximately 10 ohm.m to 179 ohm.m. RMS value was approximately 3.8 for the investigated profile which indicated that the data fit with the computed response.

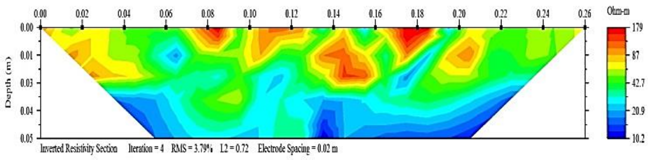

Figure 6 ERT of the control specimen

Figure 7 shows the 2D ERT of a specimen with 5% PET. An overall decrease in resistivity is seen, values ranged from 12.9 ohm.m to 116 ohm.m. RMS was also within acceptable ranges, an indication that the data fit well the computed response. An additional 2D ERT was obtained on specimens with 15% and 20% PET, refer to Figures 8 and 9. It is evident that ER decreased with increased percentages of PET. The RMS values were found to be approximately 5.12%. Laboratory observation revealed that the area with a high ER value was associated with aggregate and PET in specimens. Specimens were visually inspected after the compressive strength testing. Figure 10 shows the presence of PET at a location with high ER values. Based on the aforementioned data, it is clear that the inclusion of PET in concrete decreased its ER. It is important to note that 2D can also be used to detect PET in concrete specimens.

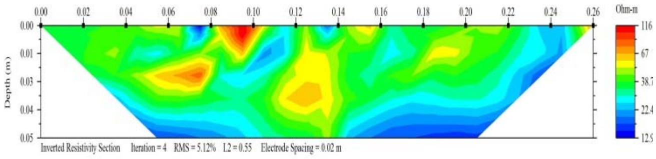

Figure 7 ERT of specimen prepared with 5% PET

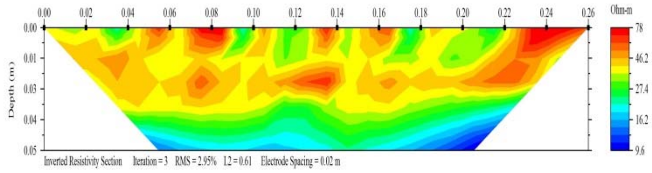

Figure 8 ERT of a specimen with 15% PET

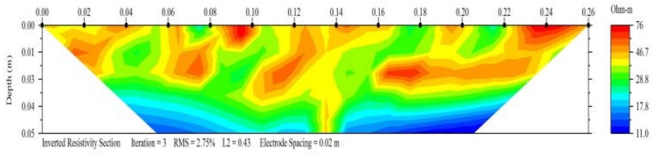

Figure 9 ERT of a specimen with 20% PET

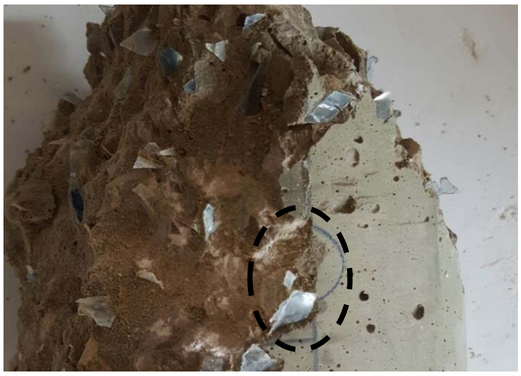

Figure 10 Concrete cylinder inspected after failure, showing the presence of PET flakes

1D ER testing was conducted on the same specimens; the results are summarized in Table 3. ER value decreased from 135 ohm.m for the control specimen to 49 ohm.m for the 5% PET specimen then increased gradually to 85 ohm.m for the 20% PET specimen (Figure 11). The observed pattern is consistent with the findings of Sadrmomtazi et al. (2016). Overall, the 2D and 1D results showed the ER values are lower in PET specimens compared to control mix, also consistent with the reported results of Sadrmomtazi et al. (2016).

Table 3 ER Values with different percentages of PET

PET Content	ER
0%	135
2%	67
5%	49
8%	55
10%	54
15%	57
20%	85

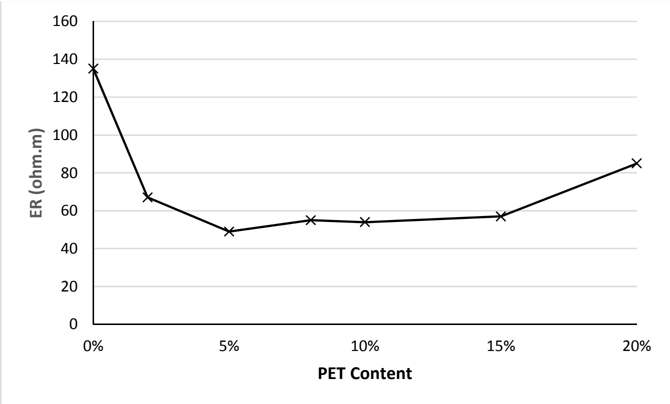

Figure 11 1D ER versus percent of PET

Table 4 shows the ranges of ER and the corresponding probabilities of corrosion. Based on this table and on the aforementioned ER results, it can be deduced that the inclusion of PET particles increases the probability of corrosive actions in the concrete mixes that were tested. This outcome is consistent with the findings of Sadrmomtazi et al. (2015) who reported that ER was reduced in concrete mixtures containing PET.

Table 4 Electrical Resistivity versus Probability of Corrosion by Sadowski et al. (2013)

Electrical Resistivity (Ω.m)	Probability of Corrosion
>120	Not probable
50 - 120	Probable
<50	Inevitable

C. Compressive Strength Results

The compressive strength increased from 23.7 MPa to 27.8 MPa as the PET content increased from 0% to 5% then gradually decreased at higher PET contents to reach 12.5 MPa at 20% PET (Figure 12). Similar findings were reported by Mishra (2016) and Chawdhury et al. (2013). The observed increase in strength at PET content of less than 5% can be attributed to a lower void ratio at low PET content, leading to strong bonds between the natural and PET aggregate and the cement paste, as reported by Sadrmomtazi et al. (2015).

While conducting the compressive tests, it was noted that a higher PET content caused a columnar vertical cracking of the concrete cylinders (Type 3 according to ASTM C39/C39M − 14). Thus a higher content of flat shredded PET flakes in the concrete mix appeared to render the corresponding samples more fragile in the sense that their rupture was more likely to take place over vertical planes where the maximum tensile stresses act. More ductile samples containing less PET flakes typically rupture over inclined planes where the maximum shear stresses occur (Type 1-2 according to ASTM C39/C39M − 14). This finding could be explained by poor adhesion of the concrete matrix to the smooth flat sides of the shredded PET flakes. Future studies could focus on optimizing the average size and improving the shape of the PET waste particles to better control this adverse effect.

Table 5 Compressive strength of PET mixtures

PET Content	Compressive Strength (MPa)	Standard Deviation	Coefficient of Variation (%)
0%	23.7	-	-
2%	24.7	0.6	2.2
5%	27.8	1.0	3.7
8%	17.9	0.8	4.6
10%	18.1	0.1	0.6
15%	18.8	1.5	12.1
20%	12.5	0.02	0.1

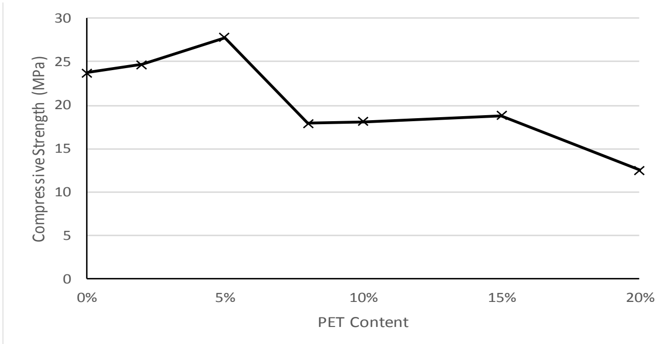

Figure 12 Variation of the compressive strength with PET content

The results of the compressive strength and electrical resistivity tests showed that high ER values correspond to lower compressive strength and to higher PET content (Figure 13). Similar findings were reported by Sadrmomtazi et al. (2015).

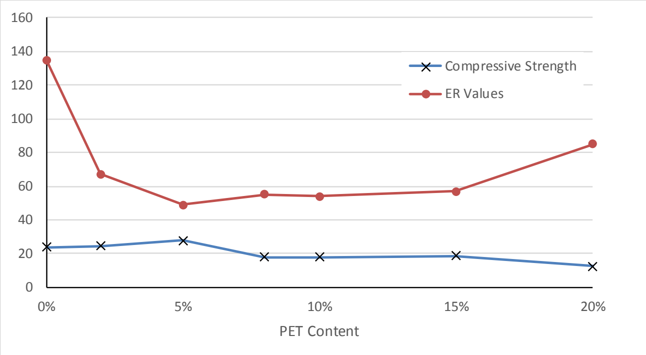

Figure 13 Variation of ER (ohm.m) and Compressive Strength (MPa) with PET content

Conclusions

This study assessed the effects of PET on the physical, mechanical and electrical characteristics of concrete cylinders. It was found that 2D ERT and 1D electrical resistivity testing showed approximately the same trends. ER values decreased as the percentage of PET increased up to 20%. Replacing aggregate with PET had a positive effect on compressive strength up to 5% PET, beyond which a negative effect was observed. It was also found that inclusion of PET increased the probability of corrosion of the concrete mixes.

Based on the findings of this work, it is recommended that additional studies be conducted to: (1) assess the potential of 1D and 2D electrical resistivity testing to characterize concrete mixes with various recycled and waste materials, (2) correlate failure surfaces in concrete cylinders and weak areas identified through 2D tomographies, (3) identify areas susceptible to corrosive actions by means of 3D tomographies performed on concrete cylinders, (4) develop a mathematical model relating mechanical and corrosive properties to 1D and 2D electrical resistivity fields and (5) optimize the average size and shape of the PET waste particles to improve structural performance.

Acknowledgment

The authors would like to thank Rakan Jaber, Paul Yammine, Haitham El Jurdi, and Paolo El Meouchey, for their help in preparing and conducting the laboratory testing and USAID's Partnerships for Enhanced Engagement in Research (PEER) for the funds used to procure the electrical resistivity equipment.

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