Mechanical Properties of Lightweight Concrete Incorporating Recycled Synthetic Wastes

PARVIZ SOROUSHIAN, ABDULRAHMAN ALHOZAIMY, AND ALY I. ELDARWISH

An experimental program was conducted on partial substitution of lightweight aggregates with recycled plastics in lightweight concrete. Bridging cracks in the brittle concrete matrix by soft synthetic inclusions led to the material's enhanced toughness and increased resistance to shrinkage cracking. Plastics also enhanced the impact resistance of lightweight concrete and produced desirable permeability characteristics and acceptable compressive strength-to-unit weight ratios. Because of the desirable performance characteristics of concrete materials incorporating mixed recycled plastics, such materials are expected to have environmental, economic, and technical benefits.

The most widely used construction material is concrete, which is commonly made by mixing portland cement with aggregates and water. Concrete consumption in the United States is close to 2 ton/year for each resident. No other material except water is consumed in such tremendous quantities. There are some key advantages associated with recycling in concrete construction: (*a*) potential development of large-volume markets for waste products, (*b*) reduced need for purification of waste, and (*c*) long-term removal of recycled materials from the waste stream, considering that concrete products typically have a service life exceeding 40 years.

Improvements in some key aspects of concrete performance can make important contributions to developing a more reliable infrastructure. Recycling of plastics in concrete can help overcome problems with the brittleness and relatively high unit weight of concrete. Plastics also can help control shrinkage cracking of concrete. The study presented evaluates recycled plastics as lightweight reinforcing inclusions in concrete.

It is now well known that before application of external load microcracks exist in the transition zone between the mortar matrix and coarse aggregates in concrete (*1*). The number and width of these cracks in concrete would depend, among other factors, on bleeding characteristics, the strength of a transition zone, and the curing history of concrete. Under ordinary curing conditions (whereby a concrete element is subjected to drying shrinkage or thermal strains), differences in dimensional movements and elastic moduli will set up differential strains between the matrix and coarse aggregates, generating microcracks in the transition zone. Under load and environmental effects, the transition zone, microcracks begin to increase in length, width, and number—initially within the transition zone and later into the matrix and, in the case of lightweight aggregates, through the aggregates. The relatively low fracture energies required for propagation of cracks in brittle concrete matrices result in relatively low toughness, impact resistance, and tensile strength for concrete.

In concrete composites containing plastics, the propagating microcracks encounter of with tough, well-bonded plastics relaxes the intensity of stresses at the crack tips, a phenomenon that increases the fracture energy, and thus the toughness and impact resistance, of the composite as well as its resistance to shrinkage cracking. Delayed propagation of microcracks encountering the plastic inclusions would take place mainly within the transition zone instead of through the plastic inclusions [Figure 1 (a)]. Eventually, when increased load levels lead to the interconnection and rapid growth of microcracks, bridging of plastic inclusions across the resulting microcracks [Figure 1 (b)] helps maintain the integrity of the composite at large post-peak deformations and control the crack widths (e.g., under restrained shrinkage movements).

The main objective of this study is to validate these hypotheses regarding microcrack arrest and deflection, and the bridging of cracks by plastic inclusions in concrete—and consequent improvements in toughness and shrinkage crack control. These hypotheses have been validated for lightweight concrete (in terms of toughening effects) and normal-weight concrete (in terms of shrinkage crack control). (*2,3*)

EXPERIMENTAL PROGRAM

An experimental program was designed on the basis of statistical concepts of factorial analysis of variance (2^2 factorial design). The program investigated the following two variables: plastic type (HDPE and "MIXED," as will be defined later) and plastic content. Plastic content was evaluated for two different levels: 20 and 40 percent replacement of fine lightweight aggregate by volume corresponding to 7.5 and 15 percent by total volume of concrete. Control mixtures with no plastics added were also considered.

MATERIALS AND MIX PROPORTIONS

The basic mix ingredients used were Type I portland cement, lightweight coarse aggregate, lightweight fine aggregate, recycled HDPE, water, and air-entraining agent. The lightweight aggregate used in the investigation, Tufflite, is a volcanic rock-based aggregate with a maximum aggregate size of 0.5 in. (12 mm). Specific gravity of lightweight coarse and fine aggregates were 1.2 and 1.5, respectively.

Recycled "MIXED" plastic is a combination of high density polyethylene (HDPE), polystyrene (PS), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephlthalate (PET), and acrylonitrile butadiene styrene (ABS). Table 1 shows the percent-

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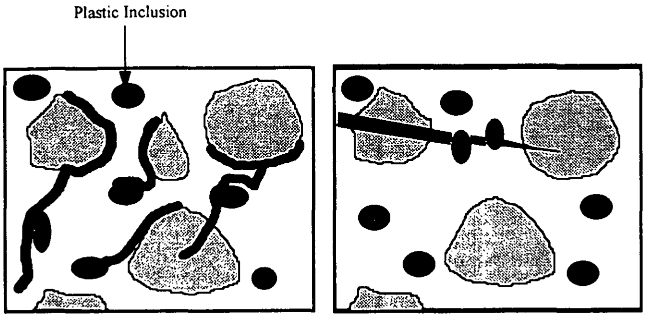
Michigan State University, Department of Civil and Environmental Engineering, A349 Engineering Building, East Lansing, Mich. 48824.



(a) Arrest and Deflection of Microcracks (b) Bridging of Cracks

FIGURE 1 Mechanisms of action of plastic inclusions in concrete.

ages, by weight, of these plastics in municipal solid waste and those used in this investigation.

Recycled HDPE and MIXED plastic particles are irregular (relatively flat) in shape. Specific gravity of different types of plastics ranged from 0.9 to 1.1. HDPE and MIXED plastic have a nominal planar dimension of ⅜ in. (10 mm).

Figure 2 shows the gradation of fine aggregates and plastic-fine aggregate combinations at two replacement levels (20 and 40% replacement of fine aggregate by volume corresponding to 7.5 and 15 percent, respectively, of total volume of concrete).

Different trial mixtures were produced to optimize the cement content, and the fine aggregate to coarse aggregate ratio, to achieve the maximum replacement level of fine aggregates with HDPE or MIXED plastics without adversely influencing fresh mix workability (*2*) The cement content and fine aggregate to coarse aggregate ratio were 750 lb/yd^3 (450 kg/m^3) and 4 (by volume), respectively. It should be noted that a relatively high fine aggregate to coarse aggregate ratio was necessary to achieve the desired workability, compactability, and finishability when part of the lightweight fine aggregate was replaced with HDPE or MIXED plastic. Both the cement content and fine aggregate to coarse aggregate ratio were kept constant in all mixtures. Water content was adjusted to give comparable slumps of 1.5 to 2.0 in. (38 to 51 mm). An air-entraining agent (water-based) was used at 0.06 percent by weight of cement to produce resistance against frost attack. Table 2 presents the optimized mix proportions.

Conventional mixing and curing procedures (ASTM C-192) were used to prepare control mixtures and the plastic-concrete composites. External vibration was found to be suitable for producing concretes incorporating recycled plastics. Optimum vibration time was found to be 25 ± 5 sec at a frequency of 80 Hz. All the specimens (except the drying shrinkage test) were continuously moist-cured [73°F (23°C)] up to the test age of 28 days.

TABLE 1 Types and Percentages of MIXED Plastics by Weight

Plastic Type	MSW*	Used
HDPE	21	31
PP	16	24
PS	16	24
PVC	7	10
PET	4	6
ABS	3	5

*MSW: Municipal Solid Waste

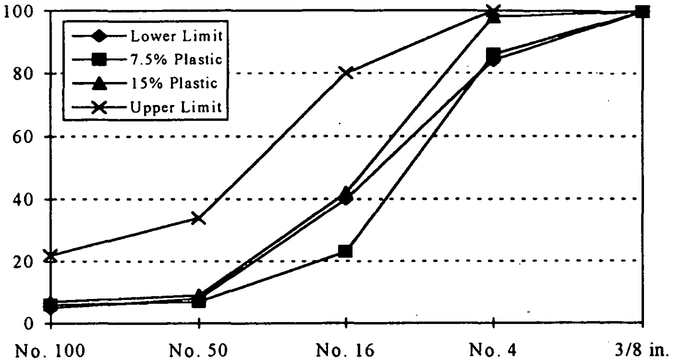


FIGURE 2 Gradation of plastic-fine aggregate combinations.

TEST PROCEDURES

The fresh mix workability was assessed by the slump test (ASTM C-143), and the hardened unit weight was measured following ASTM C-567 procedures.

For hardened materials, flexural strength and toughness, compressive strength, impact resistance, restrained shrinkage cracking characteristics and chloride permeability properties were investigated experimentally to develop an overall understanding of various aspects of material behavior.

The flexural test specimens tested were 4 × 4 × 14 in. (100 × 100 × 350 mm), and the compressive strength test specimens were 3 × 6 in. (75 × 15-mm) cylinders. Flexural and compression tests were conducted following ASTM C-78 (four-point loading) and C-39 procedures. Midspan deflection as well as loads were monitored in flexure tests. The Japanese Concrete Institute specification was followed in calculating flexural toughness, defined as the area underneath the load-deflection curve up to a deflection equal to the span length divided by 150 (*4*). The impact test was conducted following the procedures recommended by the American Concrete Institute (Committee 544). That test measures the amount of impact energy (represented by the number of blows) necessary to start a visible crack in concrete and then continue the opening of crack until failure.

Ring type specimens are used for restrained drying shrinkage test on mortar (*5*). The specimen is cast in two equal layers, leveled by a trowel, and then covered with plastic sheets for 6 hr. Specimens are then exposed to air at approximately 68°F (23°C) and 40 percent relative humidity. Restraint of shrinkage movements by the steel ring inside the specimen creates internal tangential tensile stresses that cause cracking.

Permeability tests were conducted using AASHTO T-277 (Rapid Determination of the Chloride Permeability of Concrete (*6*). That test measures the amount of charge passed through a concrete spec-

TABLE 2 Optimized Mix Proportions lb/yd*

Matrix Comp.	Cement	Coarse Agg.	Fine Agg.	Recycled Plastic	Water	AEA %
Control	750	170	850	-	735	0.06
20% Plastic	750	180	719	120	698	0.06
40% Plastic	750	193	579	258	638	0.06

* 1 lb/yd^3 = 0.594 kg/m^3; AEA = Air Entraining Agent, by weight of cement

imen subjected to permeation of chloride ions at 60 VDC for 6 hr. The total charge passed (in coulombs) is related to chloride ion permeability. The more permeable the concrete, the higher the coulombs. A cylindrical specimen, 4 in. (102 mm) in diameter by 2 in. (51 mm) in thickness, is used for this test.

DISCUSSION OF TEST RESULTS

Hardened Unit Weight

The hardened unit weight test results are presented in Figure 3. The addition of recycled plastics tends to reduce the hardened unit weight that adds value to concrete properties. Reduction in hardened unit weight can be attributed to the fact that the lightweight sand used in this investigation had a higher specific gravity than that of the recycled plastics used.

Flexural Performance

Typical 28-day flexural load-deflection curves for lightweight concrete and plastic concretes incorporating 7.5 and 15 percent plastics—HDPE and MIXED performed similarly—are shown in Figure 4. Figure 5 presents the flexural strength test results, and Figure 6 presents flexural toughness test results.

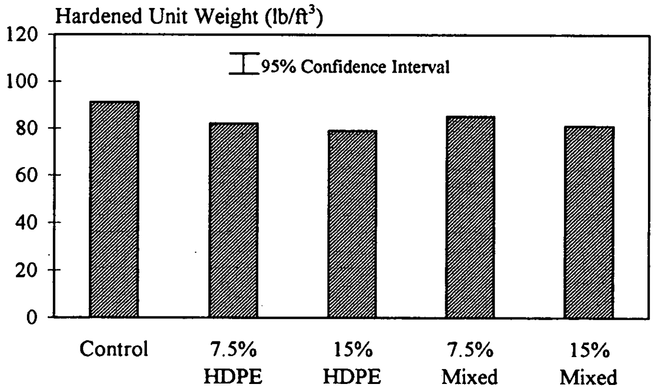


FIGURE 3 Hardened unit weight (means and 95 percent confidence interval).

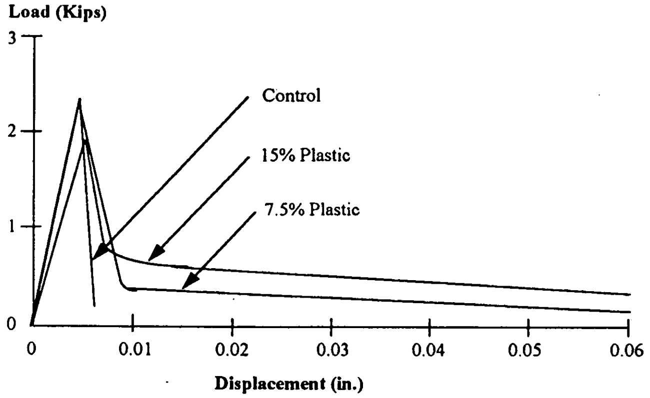


FIGURE 4 Typical flexural load-deflection curves at 28 days.

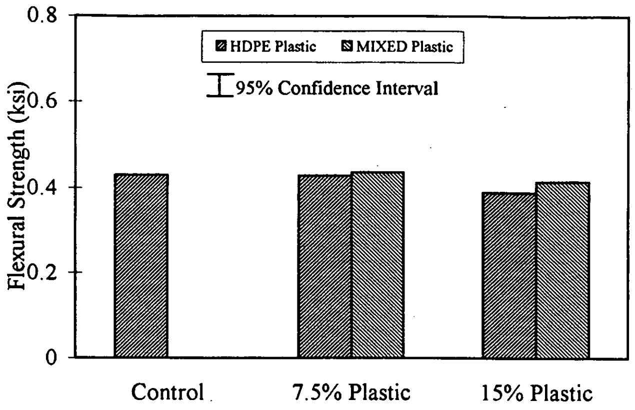


FIGURE 5 Flexural strength test results (means and 95 percent confidence interval).

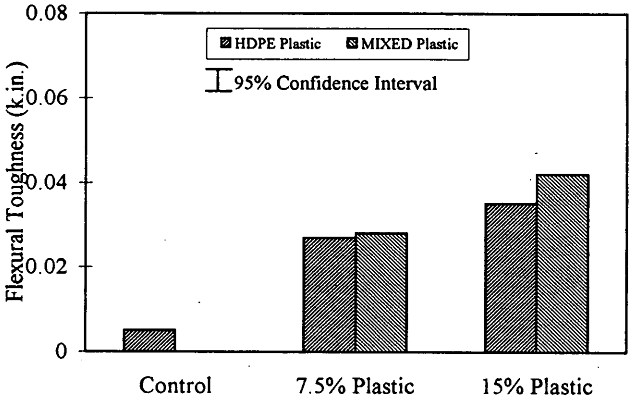


FIGURE 6 Flexural toughness test results (means and 95 percent confidence interval).

For the lightweight concrete mix composition used in this study, the addition of plastics up to a certain level (7.5 percent of total volume) produced a flexural strength comparable to that of the control mixture without plastics. At 15 percent plastic content, however, flexural strength dropped by 6 and 12 percent for MIXED plastic and HDPE, respectively, compared with the control mixture. Two-way analysis of variance and comparison of means of flexural strength test results indicate that, at plastic contents of 7.5 and 15 percent, flexural strength was comparable at 95 percent level of confidence with that of control concrete, except for HDPE with 15 percent plastic content.

Two-way analysis of variance confirmed (95 percent level of confidence) that plastic content influenced flexural toughness. Flexural toughness increased with HDPE and MIXED plastic to 4.5 and 8 times that of the control light lightweight concrete at plastic contents of 7.5 and 15 percent, respectively. That was confirmed statistically (using the separation of means technique between recycled plastics and control) at a 99 percent level of confidence. In general, the positive effects of plastics on flexural toughness reflect their capability to bridge the cracks and mitigate brittle modes of failure in concrete materials by their pull-out resistance across cracks.

Compressive Strength

Figure 7 presents the 28-day compressive strength test results for lightweight concrete. It was confirmed statistically (95 percent level of confidence) that plastics have adverse effects on compressive strength. The situation would be somewhat improved if one considered the compressive strength-to-weight ratio, because plastics also reduce unit weight. A drop in compressive strength with the addition of plastics may be attributed to the relatively low modulus of elasticity of plastics, which would lead to a redistribution of stresses into the more rigid inorganic matrix. It should be noted, however, that limits on load carrying capacity and service life of concrete structures are generally provided by the resistance of concrete of cracking and failure under tensile stress systems. Concrete is fairly strong in compression, and concrete structures rarely fail because of material failure in compression.

Impact Resistance

Figure 8 gives the mean values of the 28-day impact resistance test results for lightweight concrete, presented as the number of blows to first crack and failure. Statistical analysis (comparison of means) indicated, at 95 percent level of confidence, that recycled plastics have a significant positive effect on the impact resistance of concrete beyond the initial crack up to failure.

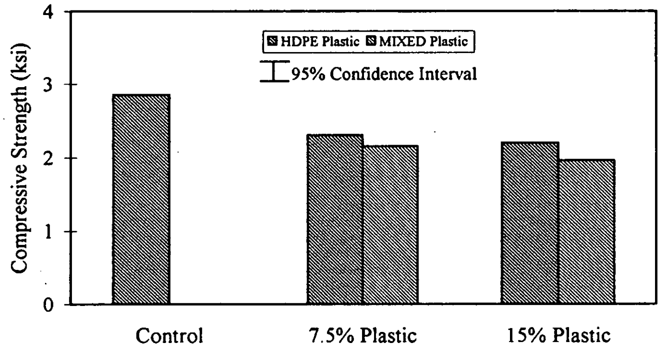


FIGURE 7 Compressive strength test results (means and 95 percent confidence interval).

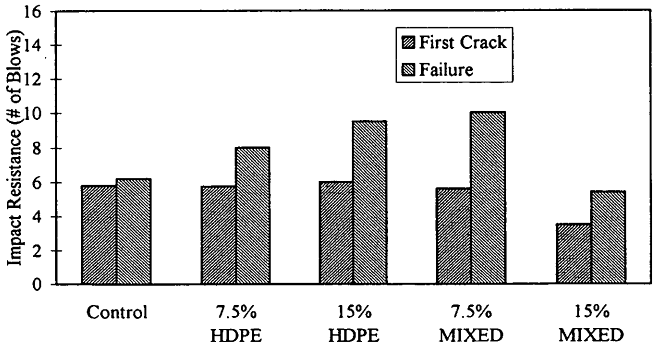


FIGURE 8 Impact resistance test results (means).

Improvements in ultimate impact resistance in the presence of plastics further validate the hypothesis that tough plastic inclusions help to enhance fracture energy and toughness characteristics of concrete materials through bridging across cracks.

Restrained Drying Shrinkage

Figure 9 indicates the maximum crack width versus time in a restrained shrinkage test of lightweight concrete. The addition of recycled plastics to lightweight concrete helps to control the drying shrinkage cracks because recycled plastics (HDPE or MIXED) act as reinforcing inclusions that arrest microcracks and bridge across cracks to restrain their widening.

Permeability

The chloride permeability test results (means and 95 percent confidence intervals) for lightweight concrete and plastic-concrete materials incorporating 20 and 40 percent recycled HDPE or MIXED plastics are presented in Figure 10. Two-way analysis of variance at a 99 percent level of confidence, confirmed that the two variables investigated (replacement level of sand with plastic, and plastic

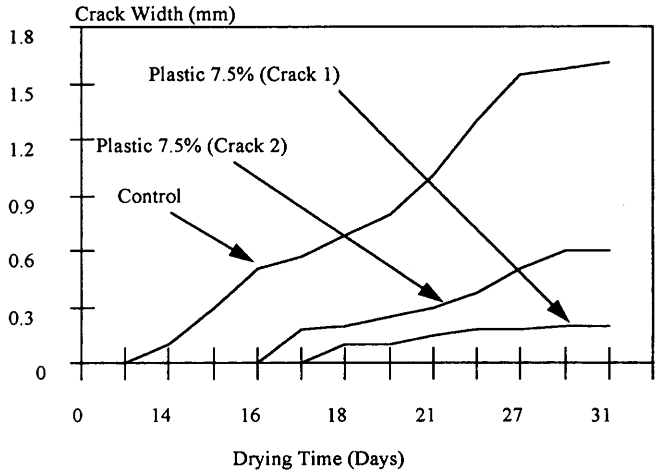


FIGURE 9 Crack width versus drying time.

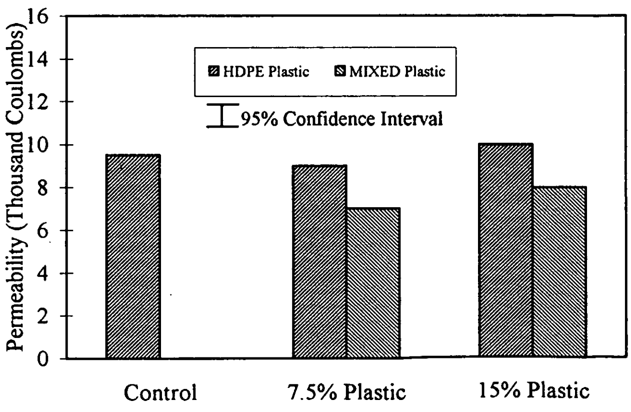


FIGURE 10 Chloride permeability test results (means and 95 percent confidence interval).

type), but not their paired interactions, influenced the permeability of lightweight concrete. Separation of means of the test results confirmed, at a 95 percent level of confidence, that the permeability of control concrete (without plastics) was statistically comparable to that of plastic concrete composites with 20 percent plastic replacement levels when HDPE was used. Increasing the HDPE content to 40 percent led to a slight increase in permeability. However, MIXED plastic at 20 and 40 percent replacement levels reduced permeability by 25 and 17 percent, respectively, when compared to the control (95 percent level of confidence). Hence, plastic concrete presents permeability characteristics comparable or superior to that obtained with conventional lightweight concrete materials.

To understand the effects of plastic on concrete permeability, one should consider that while plastics, as low-permeability inclusions that may reduce microcrack intensity, are expected to reduce permeability, porous or microcracked plastic cement interfaces may cause an increase in permeability. Hence, with improved interface characteristics, one may potentially reduce concrete permeability by adding recycled plastics.

To ensure the environmental safety of recycled plastic-concrete materials, leaching TCLP tests were conducted and it was concluded that the recycled plastic concrete materials are environmentally safe (*3*).

SUMMARY AND CONCLUSIONS

The effects of partial substitution of lightweight aggregate with recycled plastics on concrete properties were investigated. Two plastic types, HDPE and MIXED, and two levels of replacement of fine aggregate (7.5 and 15 percent plastics by total volume of concrete) were used.

The hardened material mechanical properties were assessed through flexure, impact compression, and restrained drying shrinkage tests. Long-term durability characteristics, represented by chloride permeability tests, were evaluated. The following conclusions were derived from analyses of the generated data:

- Addition of recycled plastics to lightweight concrete helps to reduce and control the drying shrinkage cracks.
- Recycled plastics at 7.5 and 15 percent volume fractions gave comparable flexural strengths to that of a control concrete mix. However, flexural toughness was 4.5 and 8 times higher, respectively. The finding was confirmed statistically at a 99 percent level of confidence.
- Compressive strength test results were indicative of the adverse effects of recycled plastics. It should be noted that concrete is fairly strong in compression, and rarely fails because of material failure in compression. Furthermore, because reduction in compressive strength is accompanied by reduction in unit weight, the situation would be somewhat improved if one looked at the compressive strength-to-weight ratio.
- Recycled plastics have a significant and positive effect on the impact resistance of concrete beyond the initial crack up to failure.
- Chloride permeability test results indicate that HDPE's permeability is statistically comparable to that of control concrete. However, MIXED plastic reduced permeability characteristics at 7.5 and 15 percent volume fraction of plastic compared with control concrete.

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