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Lightweight Concrete Containing Recycled Plastic Aggregates

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Abstract. The concrete industry needs millions of tons of aggregate, comprising natural sands and gravels, each year. In recent years there has been an increasing trend towards use of recycled aggregate to save natural resources and to produce lightweight concrete. In this investigation, an attempt was undertaken to produce recycled plastic aggregate (RPA) using waste plastic and red sand as filler. The physical properties of RPA are reported and an experimental investigation of concrete incorporating RPA as coarse aggregates is presented. It was observed that 100% replacement of conventional lightweight aggregate (LWA) with recycled plastic aggregate (RPA) showed about 13% reduction in chloride penetration. Compressive strength was reduced; however, the achieved strength was between 12 and 15 MPa which is useful for non-structural elements such as low side building, cementitious backfill, pavements and others.

Introduction

Reduction of waste produced around the world is a major challenge which society is facing today. Conventional approaches adopted include reduction of waste production and recycling as far as possible of what is inevitably produced. Worldwide plastic production in 1950 was 1.7 Mt. By 2012, this had increased by approximately 170 times to 288 Mt [4]. Polyethylene based products form the largest percentage (about 29%) of total waste plastic [2, 5]. These include low density polyethylene (LDPE), linear low density polyethylene (LLDPE) and high density polyethylene (HDPE). Polyethylene terephthalate (PET) and polypropylene amount to 20% and 18% respectively of global plastic waste [2, 5] and other polymer types represent about 33%. A large quantity of plastic is recycled in various products [1-3], but significant quantities still end up as waste which requires disposal.

One of the potential applications of this waste is in the construction industry, where it has been used in concrete, either in shredded form or combined with other materials, to form a synthetic aggregate. Since plastics have lower density than most natural materials, they can be readily used to form lightweight aggregate which may replace naturally-existing aggregate of similar density. Concrete produced with a conventional lightweight aggregate has been shown to exhibit excessive shrinkage and high water absorption [7]. This is particularly the case with lightweight aggregates (of volcanic origin) available in the Arabian Peninsula. Economic growth in this region has led to high demand for such aggregates in concrete products as they have good insulating properties and hence help to reduce energy costs. Good insulation is important in both hot (as in Saudi Arabia) and cold climates. Local lightweight aggregate used in concrete produced from volcanic rock is associated with problems such as low strength, lack of durability, high mining and hauling costs, excessive drying shrinkage, high water absorption and limited availability [7, 8].

Thus, if an alternative, synthetic, aggregate could be produced using waste materials which can be used to produce lightweight concrete with similar or better insulation properties (compared to concrete produced with local aggregate from volcanic origins) and lesser shrinkage, this will benefit the Gulf region in reducing energy costs. In addition to this it will help to save natural resources. Furthermore, generation of greenhouse gases such as CO² emissions will be reduced as lighter materials may result in lower self-weight of structural elements, leading to possible reductions in consumption of cement [8]. Using waste plastic in construction would lead to reduction in its disposal in landfills and help improve sustainability of natural resources.

A number of researchers have used waste plastic in concrete as a direct replacement for natural aggregates [9-13]. Some researchers [7, 8, 14-18] have undertaken studies on the use of plastic-based aggregate in concrete as a direct full or partial replacement of natural aggregate.

Plastic aggregates such as Plasmatex© and Plasmega© have been produced from shredded mixed plastic waste and secondary aggregates [14, 15]. These aggregates range in size from 5mm to 50 mm [14]. Similarly, synthetic lightweight aggregates (SLA) were produced from a mix of fly ash and plastics such as polystyrene (PS), low density polyethylene (LDPE), high density polyethylene (HDPE), and a mixture of various plastics (MP) [16]. SLA was produced at different fly ash: plastic ratios ranging from 0:100 to 80:20 [16]. Natural aggregate was then replaced with SLA in concrete road pavement. The results of that study showed that at 80% fly ash, the unit weight, slump, compressive strength and split cylinder tensile strength of concretes using SLA were reduced by about 15%, 16%, 43% and 26.4%, respectively, compared to conventional concrete [16,17].

Waste plastic lightweight aggregate (WPLA) was also produced from polyethylene terephthalate (PET) with granulated blast-furnace slag (GBFS) and river sand aggregate [6, 7]. The outcomes revealed that at a replacement level of 75% of WPLA aggregate, the slump of concrete produced increased by 51%, while the density, compressive strength, split cylinder tensile strength, modulus of elasticity and structural efficiency were reduced by 31%, 33%, 43%, 28%, and 23%, respectively, compared to normal concrete [7, 8]. On the other hand, use of LLDPE in aggregate is less investigated compared to other types of plastics from the polyethylene group.

The findings of a study on the effect of using recycled plastic aggregate (RPA) as a total replacement for conventional lightweight coarse aggregates (LWA) in concrete are reported in this paper. This includes findings on the effect of RPA on the compressive strength of concrete and chloride ion penetrability at different w/c ratios.

Experimental Programme

Materials. Locally manufactured ordinary Portland cement was used in this study. The cement had a density of 3150 kg/m³, specific gravity of 3.15, and a fineness of 3500 cm²/gm. Conventional lightweight coarse aggregate (LWA), of volcanic origin, from the western region of Saudi Arabia was used in the experimental work for control mixes. It had a nominal maximum size of 10 mm. Properties of the LWA used in this study are shown in Table 1. The fine aggregate used in this study was a combination of naturally occurring red sand (65%) and crushed sand (35%) to obtain a grading that complied with ASTM C 136. The key material in this investigation was recycled plastic aggregate (RPA) [19]. The production of the aggregate is described in detail elsewhere [19]. It was used to replace local lightweight coarse aggregate in concrete. The physical properties and gradation curve of the RPA aggregate are shown in Fig.1 and Table 1, respectively.

Mixture Proportions. The mix design of the RPA and LWA concrete was developed according to the ACI 211.1. For the mixes containing RPA, the quantity of coarse aggregate was calculated by using the specific gravity of the RPA as a replacement for the specific gravity of the conventional lightweight coarse aggregate. The mixed proportions of all the mixes are shown in Table 2. Four concrete samples were produced using water-to-cement (w/c) ratios of 0.5 and 0.6, and cured for 7, 14 and 28 days according to ASTM C192. For the RPA concrete, the replacement of LWA with RPA was 100%.

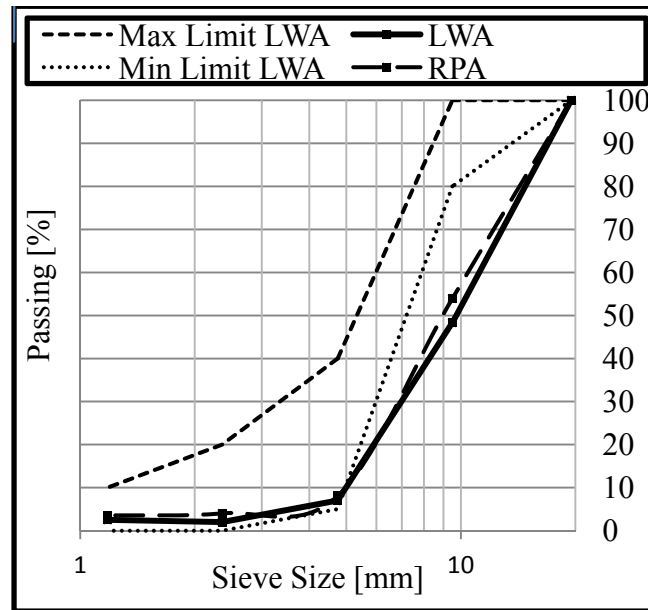


Fig.1. Gradation Curve for LWA and RPA

Table1. Properties of different types of aggregate used in the study

Property	LWA	RPA
Bulk Specific Gravity (OD Basis)	1.41	1.2
Bulk Specific Gravity (SSD Basis)	1.67	1.23
Apparent Specific Gravity	1.41	1.24
Absorption [%]	18.6	2.71
Dry Unit Weight (dense condition) [kg/m^3]	697	600
Voids (dense condition) [%]	50	50
Fineness Modulus	6.5	6.4
Particle Shape/texture	Porous/Rough	Sub angular/Partially rough
Colour	Dark Grey	Brown
Type	Uncrushed	Crushed
Maximum Size [mm]	10	

Table 2.Mix proportions per metre cubed of concrete

Mix designation	W/C ratio	Quantities per [m^3] of concrete				
		Water [kg]	Cement [kg]	Fine Aggregates [kg]	Conventional Lightweight Coarse Aggregates [kg]	Recycled Plastic Aggregates [kg]
LWC0.5	0.5	300	456	909	352	-
RPC0.5	0.5	245	456	902	-	303
LWC0.6	0.6	300	380	972	352	-
RPC0.6	0.6	245	380	965	-	303

Experimental Investigation. The experimental investigation was designed to compare strength and durability properties of the RPA concrete with LWA concrete. Strength was measured using 50mm cubes and durability was assessed in terms of chloride ion penetration. These tests were

conducted in accordance with the ASTM standard procedures and relevant sections are shown in Table 3. Each test was repeated three times and all results were within 95% confidence range. Therefore, the mean values of three results were used to describe behaviour.

Table 3. Properties of concrete and relevant standard used for testing

Property measured	ASTM Standard
Compressive strength (cured for 28 days)	ASTM C579-01
Chloride permeability (cured for 28 days)	ASTM C1202 - 12

Results and Discussion

Compressive Strength. Compressive strengths of concrete made with recycled plastic aggregate and LWA concrete with w/c ratios of 0.5 at 7, 14 and 28 days are shown in Fig.2. The compressive strength of both types of concrete increased with age, i.e. from 7 to 28 days. The percentage increase in compressive strength from 7 to 14 and 14 to 28 days was 16%, 11% and 13%, 12% for LWC0.5 and RPC0.5 respectively. At 28 days, the compressive strength of RPC0.5 was 48% less than that of LWC0.5. The reduction in compressive strength of RPC0.5 may be attributable to the weak bond between the cement mortars and the recycled plastic aggregate particles, as well as the hydrophobic nature of plastic. Other researchers have also noted significant reductions in concrete's compressive strength when plastics were used to replace natural aggregate [3, 7, 8, 16-18].

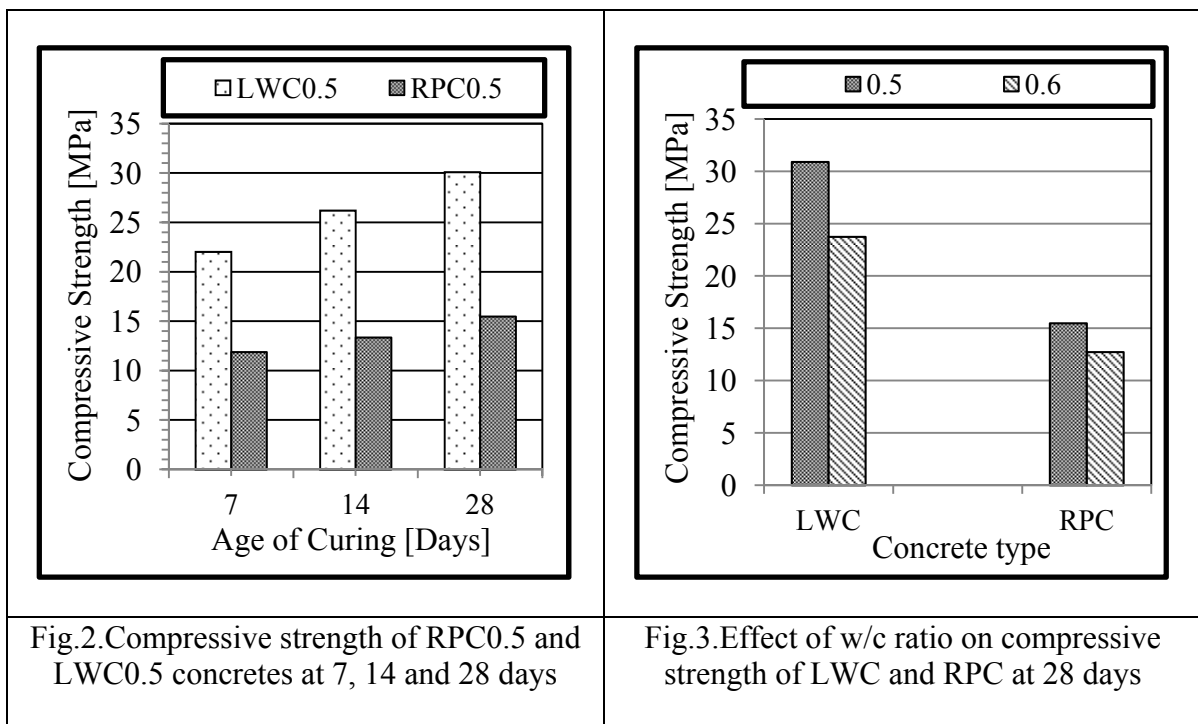


Fig.2. Compressive strength of RPC0.5 and LWC0.5 concretes at 7, 14 and 28 days

Fig.3. Effect of w/c ratio on compressive strength of LWC and RPC at 28 days

The 28 day compression strength of LWA and RPA concretes with w/c ratios of 0.5 and 0.6 are shown in Fig.3. It can be seen that the compressive strength was inversely proportional to the w/c ratio. At a 20% increase in w/c ratio (from 0.5 to 0.6), the compressive strength of RPA and LWA concretes decreased by 17% and 21% respectively. For the same compressive strength, the strength of the recycled plastic aggregate concrete was about half that of the lightweight concrete. This is entirely due to the plastic content of the RPA. It is worth noting that the RPA was about 17% lighter than the LWA available in Saudi Arabia.

Chloride permeability. The effect of w/c ratio and concrete type on chloride ion permeability at 28 days is illustrated in Fig.4. For LWC, the chloride ion permeability decreased to an insignificant

extent, by about 4%, with the increase in w/c ratio from 0.5 to 0.6. Also, the chloride ion permeability of concrete containing plastic aggregate was not affected by the change in w/c ratio. Furthermore, the concrete ion permeability of RPA concretes with 0.5 and 0.6 w/c ratios was 15% and 12% respectively less than the corresponding values for LWA concretes. This is because of the impermeable property of recycled plastic aggregate particles which therefore blocks or distracts the transfer of chloride ions, as agreed by Kou et al. [20]. In contrast with this, research conducted by Bayasi and Zeng [21] concluded that concrete with 19-mm polypropylene fibers had significantly increased concrete permeability.

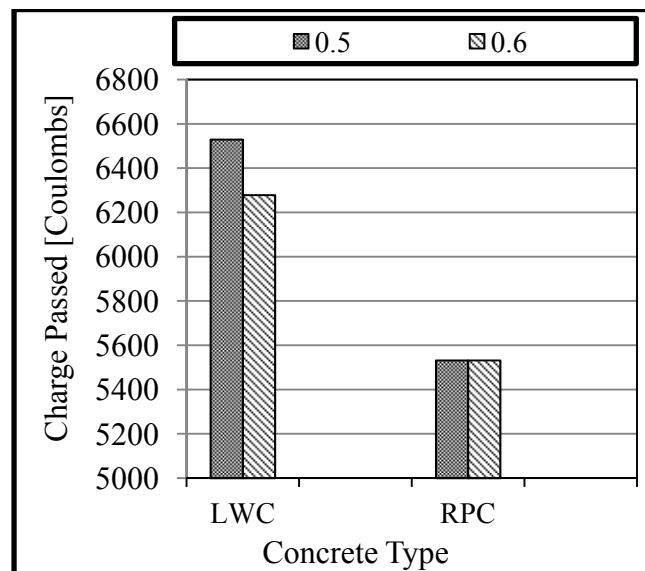


Fig.4. Chloride ion penetrability results for LWC and RPC with w/c ratios of 0.5 and 0.6

The RPA concrete was less sensitive to change in w/c ratio than the control concrete made with lightweight aggregate. In addition to this, the RPA concrete exhibited lesser sensitivity to chloride penetration over the range of w/c ratios examined. Such a material (RPC) could be used in situations where lower strengths are a structural requirement. Such applications could include backfill for trenches, where the strengths should be between 2MPa to 12MPa [22] to enable utilities to be excavated easily. In addition to providing insulation, such materials may be used in low rise housing and in offshore applications where durability can be an exacting requirement.

Conclusions

The results of compressive strength and chloride ion penetration for concrete made with recycled plastic aggregate and lightweight local (to Saudi Arabia) aggregate were investigated and compared. RPA was used to replace 100% coarse fraction of concrete. The study was limited to two w/c ratios (0.5 and 0.6). The conclusions drawn are summarised below.

- At 0.5 w/c ratios, the 28 day compressive strength and chloride permeability of RPA concrete is reduced by 48 and 15% respectively as compared with LWA concrete.
- The concrete made using recycled plastic aggregate (RPA) was a little more durable compared to that made with natural lightweight aggregate.
- It may be possible to use such concrete it in applications which are exposed to severe chemical attack, such as marine structures or in coastal areas. Applications may also include those where low strengths are desirable, such as utility trench backfill. Other applications may include low rise housing.

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