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Engineering Properties of Sustainable Lightweight Concrete Using Waste Polystyrene

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Abstract*— It is well known that the continued extraction of natural aggregates and increasing waste materials not only in the Kurdistan region of Iraq but cross the world is accompanied by serious environmental problems. Therefore, alternative sources of recycled materials are required as substitute for natural aggregates. Due to these issues this paper investigated the results of an experimental study on the effects of waste polystyrene (WP) in concrete. Polystyrene is used as a packaging material or insulating material in construction industry and in other industrial fields. A large quantity of polystyrene is disposed in landfills as a waste. Collecting WP before disposed in landfill sites in crushed and graded form can be used as a lightweight aggregate (LWA) to produce lightweight aggregate concrete (LWAC). In this study the WP was shredded to different sizes. Four concrete mixtures in total with varying WP content ratios of 0, 20, 40 and 60% as partial replacement of natural coarse aggregate by equivalent volume was prepared. The water/cement (W/C) ratio of 0.5 was kept constant for all concrete mixtures. Mechanical and durability properties including compressive strength, water absorption (WA) and density was determined for the various concrete mixtures at the ages of 7 and 28 days of water curing. According to the results obtained, the utilisation of WP in concrete production is possible.

Index Terms— **Compressive strength; Lightweight aggregate concrete; Recycling; Waste polystyrene; Water absorption.**

I. INTRODUCTION

Most of the Municipal Solid Waste (MSW) produced in the Kurdistan region-Iraq is disposed of as landfill or dumped in conveniently located open spaces and often burned and therefore, creating environmental problems and providing no economic benefits. According to the literature, reusing and recycling of waste materials is considered the best environmental solution. One of such waste materials is waste polystyrene (WP). Polystyrene is used as a packaging material or insulating material in construction industry and in other industrial fields cross the world. A large quantity of polystyrene is disposed in landfills or dumped in open spaces as a waste. Collecting WP before disposed in landfill sites in crushed and graded form, can be used as a lightweight aggregate to produce lightweight aggregate concrete (LWAC). The use of LWC can reduce the dead load of structures as well as to reduce the risk of earthquake damages and cross-sectional areas of structural elements. It can also increase the effective usable space for high-rise buildings and increase the span length for bridges [1] – [3]. Costs of transport and handling equipment for pre-cast elements are also reduced by using LWC and, the low heat transfer properties of LWAC provide higher thermal insulation and may improve fire resistance [4]. The main aim of the present study is to investigate the influence of WP based lightweight aggregate (LWA) on the properties of lightweight aggregate concrete (LWAC) and produce a sustainable material for construction industry. The specific objectives of this study are investigating mechanical properties (e.g. compressive strength) and durability properties (e.g. water absorption) of concrete containing different WP replacement levels at different curing times and identify relationship between investigated concrete properties.

II. PREVIOUS WORK

The recent study [5] found that compressive strength values of all waste plastic concrete mixtures tend to decrease below the values for the reference concrete mixtures with increasing the waste plastic ratio at all curing ages. This may be attributed to the decrease in the adhesive strength between the surface of the waste plastic and cement paste. In addition waste plastic is hydrophobic material which may restrict the hydration of cement. There are some techniques for recycling of waste polystyrene. Modifications of plastic waste including polystyrene by heating, by mechanical means, by soaking in water, melting followed by mixing with other materials and other techniques were also done to improve the quality of plastic waste for using as aggregate in concrete [6]. For example, researchers [7] used thermally modified expanded polystyrene (MEPS) foams as lightweight aggregates (LWA) in their investigation. The main aim of thermal treatment technique in their study was to convert the waste polystyrene to a usable product and reduce the amount that requires final disposal in landfills. The modified material was obtained by heat treatment method by keeping waste polystyrene foams in a hot air oven at 130 °C for 15 minutes. Another study, [8] investigated behaviour of lightweight expanded polystyrene concrete containing silica fume and found that the rate of strength development increased and the total water absorption values decreased with increasing in replacement levels of silica fume in concrete. It also was found that the strength of polystyrene concrete marginally increased as polystyrene bead size decreased and increased as the natural coarse aggregate size in concrete increased. The phenomenon was also confirmed by another investigation [9] with ultra-lightweight polystyrene concrete of density ranging from 150 to 300 kg/m^3 made of a foam matrix and polystyrene beads of diameters ranging from 2.5-10 mm. In fact, for the same concrete density, compressive tests results showed an increase of 40% in the compressive strength given by

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2.5-5mm polystyrene beads concrete in comparison with the one given by 5-10mm polystyrene beads concrete. This is in agreement with the results found as in [10], [11]. It seems that most studies reported to date have been essentially related to polystyrene concrete of lower strength. The trend from the previous work on polystyrene concrete is that the compressive strength of the concretes decreased with increasing percentage of polystyrene aggregate, this is due to the polystyrene particles being quite weak. The strength of polystyrene concretes was found to be directly proportional to the concrete density. The strength of polystyrene concrete marginally increased as the aggregate size decreased, and increased as the natural coarse aggregate increased. Some of the previous works have used super plasticisers, silica fume and fly ash to improve the mechanical and durability properties of polystyrene concrete. Additives like these may not be readily available in developing countries [8], [10]. According to the literature, polystyrene is an organic material with a hydrophobic surface, and cement paste is an inorganic material with a strong hydrophobicity. After mixing these two different materials, some problems have occurred such as non-wetting, incompatibility and weak bond force. For solving these problems, some studies have conducted different techniques using different types of chemical materials but these techniques and materials may not be environmentally friendly and readily available in developing countries [7], [10].

III. EXPERIMENTAL METHODOLOGY

A. Materials

The Ordinary Portland Cement (OPC), natural fine aggregate (4mm) and natural coarse aggregate (10mm) was used in concrete mixes. For particle size distribution (sieving) (Fig. 1) test, a representative sample of the aggregates was placed in the oven and dried to a constant weight at a temperature of 110 °C [12]. A novel WP based lightweight aggregate to replace natural coarse aggregate was also used in the concrete mixes.

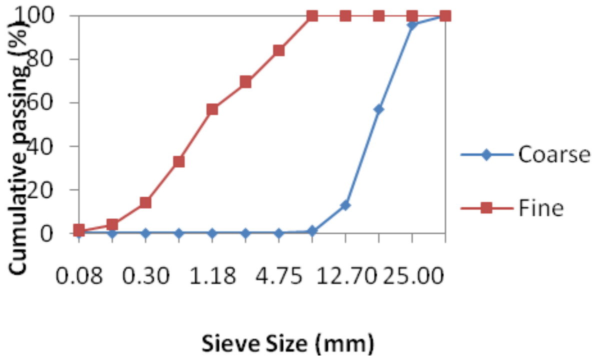

Fig. 1: Particle size distribution of aggregates

B. Concrete mix proportion

A comprehensive summary of the concrete details (ingredients) is presented in Table I. In order to investigate the effect of the novel lightweight aggregate on physical, mechanical and durability properties of concrete, mixtures were prepared in different aggregate replacement levels. Four concrete mixtures in total were used for the present study.

Table I: Details of concrete ingredients

Mix No.	WP (%)	Mixture Constituents (kg/m^3)			
		Cement	Water	NFA	NCA+WP (%)
1	0	329	164	658	1316+0%
2	20	329	164	658	1053+20%
3	40	329	164	658	789+40%
4	60	329	164	658	526+60%

NFA – natural fine aggregate; NCA – natural coarse aggregate; WP – waste polystyrene.

The control mixture had a proportion of 1 (cement): 2 (natural fine aggregate): 4 (natural coarse aggregate). The natural coarse aggregate was replaced in terms of volume due to the nature of WP being a very light-weight material (up to 95% air). The replacement levels of natural coarse aggregate by WP were 0, 20, 40 and 60%. The water to cement ratio (W/C) of 0.5, amount of water, cement and natural fine aggregate was kept constant for all mixtures. Before casting began, the moulds were visually inspected and cleaned thoroughly. Thereafter, A thin layer of oil was applied to the inside surfaces of the moulds for easy de-moulding. The concrete container was cleaned and slightly damped with a wet cloth to avoid any absorption of water by the container. The mixing of materials was done in a specific arrangement, by placing a part of the water with adding the dry aggregates, which was thoroughly mixed for about 2 minutes to get the aggregates wetted with water. Then, the remaining materials (WP and cement) were added to the container and the remaining water was gradually added while the mixing was in progress. The mixing was continued until a mix of uniform consistency was achieved. The slump values comply with [13] was done immediately after mixing for all the concrete mixtures. Standard test specimens have already chosen for investigating the various properties. Specimens were cast in steel moulds. To achieve a fairly uniform lightweight concrete the amount of compaction was limited. After casting, specimens were covered and left in the laboratory for 24 hours. Then, specimens were de-moulded and placed in water for different curing times. Mix preparation is very important when using very lightweight aggregate like WP and enough care was exercised during mixing, pouring and compacting processes.

C. Test procedure

Cubes of 100×100×100mm size were used for the determination of dry density [14]. The cubes were dried until a constant dry mass was attained. The dry density test was carried out on three cubes for each concrete mix and the average was used for analysis purposes. Cubes of 100×100×100mm size were used for the determination of compressive strength at 7 and 28 days. These specimens were cured in normal water until testing. Compressive strength test was carried out using testing machine of 3000 KN capacity at the loading rate of 0.6 MPa/s according to [15]. Compressive strength test was carried out on two cubes from mix combination and the average was used for analysis purposes.

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Specimens of 100×100×100mm size were used for total water absorption test at 28 days. The specimens were cured in normal water until testing. Saturated surface dry cubes were kept in a hot air oven at 80 ºC until a constant dry mass was attained. This is because at temperature range of 100–110 ºC, the polystyrene beads initially shrink and finally evaporate [8]. Specimens were immersed in water and the weight gain was measured at regular intervals until a constant weight is reached. The absorption at the final (total) absorption (at a point when the difference between two consecutive weights at 12-hour interval is almost negligible) was reported to assess the concrete water absorption.

IV. RESULTS AND DISCUSSION

A. Workability

The workability (slump) values for concretes containing varying amounts of WP aggregate are presented in Fig. 2. Slump test measurements were carried out on all four mixtures. Slump test is one of the methods to measure the workability (consistence) of fresh concrete. The slump values are in the range of 10-180mm.

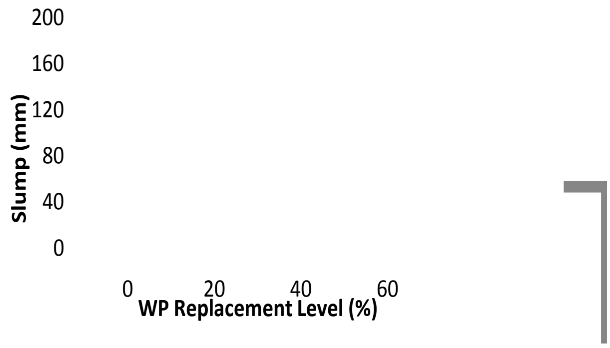

Fig. 2: Slump values of concrete

The workability of the concrete decreased with the increase in WP content. The decrease in concrete workability with higher percentages of WP aggregate may be due to increasing surface area of ingredients used in concrete. Similar to the present study as in [16] reported that when the polystyrene particles content was increased, the fresh concrete mix became rubbery, harsh, and difficult to place and compact.

B. Density

The density of concrete containing varying amounts of WP is presented in Fig. 3. The densities for concretes containing varying amounts of WP were in the range of 1734-2494 kg/m^3. The density of the concretes decreased with the increase in WP replacement. The decrease in density was 11, 17, and 30% for concretes containing 20, 40 and 60% WP, respectively compared to control. The WP aggregate with the density of lower than natural coarse aggregates' in the mixes had a great effect on the concrete density. The density of the concrete depends upon the moisture content, density and grading of the aggregates, mix proportions, cement content, water/binder ratio, chemical and mineral admixtures, method of compaction and curing conditions [17]. The WP concrete can be considered as lightweight concrete depending on WP replacement levels in concrete. Density of concrete is mainly controlled by the volume and density of aggregate and can control many physical properties in lightweight concrete [10].

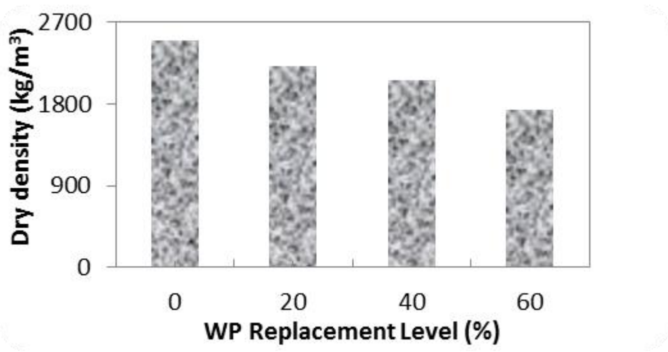

Fig. 3: Density of concrete

Fig. 4 shows the correlation between compressive strength and density of concrete containing varying amounts of WP. An exponential function seems to better describe this correlation:

$$Y = 0.6343e^{0.0015x}, \quad \text{with } R^2 = 0.9903 \qquad (1)$$

The strength of concrete containing varying amounts of WP appears to increase with an increase in concrete density. It is indicating very strong correlation (R^2= 0.9903), where X is the density (kg/m^3) and Y is the compressive strength (MPa).

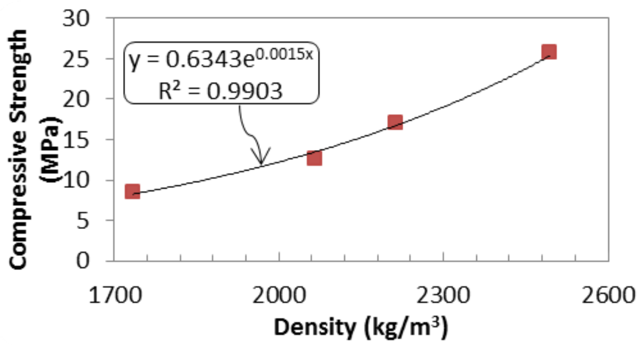

Fig. 4: Correlation between density and compressive strength

C. Compressive Strength

The compressive strength of concretes containing varying amounts of WP aggregate at different curing periods of 7 and 28 days is presented in Fig. 5. The compressive strength values are in the range of 8.50-25.77MPa at 28-day age. Due to the lower strength of WP particles, the incorporation of WP caused a reduction in the compressive strength of concrete depending on the level of replacement with natural coarse aggregate. The compressive strength of the concretes at 28 days age decreased 34, 51 and 67% at WP contents of 20, 40 and 60%, respectively, compared to the control concrete of the same age. Reference [8] shows a 28-day age compressive strength in the range of 10.2-21.4 MPa for concretes containing 21.0-36.4% Polystyrene. However, the 28-day strength for the concrete mix containing 20-40% WP in the present study are in the range of 12.58-17.12MP. According to BS 6073: Part 1 [18], the minimum strength required are

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2.8 MPa for all blocks and 3.5 MPa for facing blocks. Strength requirements for building blocks are most commonly set at 2.5 MPa for filler blocks and 5.0 MPa for load bearing blocks. A minimum strength of 7.5 MPa is required for special purposes and heavy duty bearing blocks as in [18]. Therefore, for a target compressive strength of 7.5 MPa, all concrete mixtures with varying WP aggregate contents (20, 40 and 60%) are suitable to produce all types of blocks including heavy duty bearing blocks. The concrete containing 20% WP can comply with the necessary minimum requirements of [19] and RILEM [20], [21] which requires a mean minimum strength of 17.0 and 15.0 MPa, respectively, for structural lightweight aggregate concrete. Unlike control concrete (0% WP) the failure observed with concrete containing higher amounts of WP was more gradual and compressible under compressive loading, and the specimens were capable of retaining the load after failure without full disintegration.

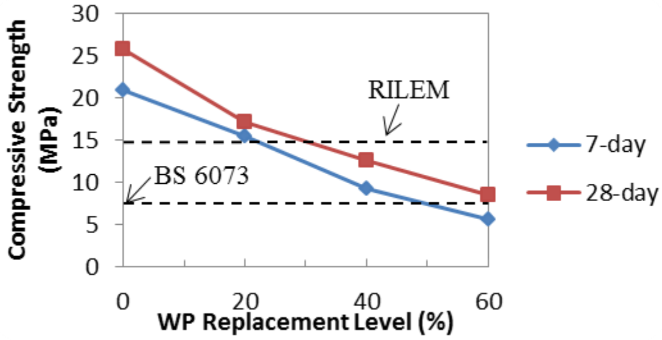

Fig. 5: Compressive strength of concrete containing varying amounts of WP at different curing periods

The strength development of concrete containing different amounts of WP at different curing periods is presented in Fig. 6. In the present study, the compressive strength increases with curing age for all mixes as expected. Control mix (0% WP) gained 81% of 28-day strength in the first 7 days of curing. This strength development for mixes 2 (20% WP), 3 (40% WP) and 4 (60% WP) is 91%, 73% and 66%. The strength development for concrete mixes decreasing with increasing WP content in concrete. The concrete containing 20% WP gained maximum strength compared with other mixtures.

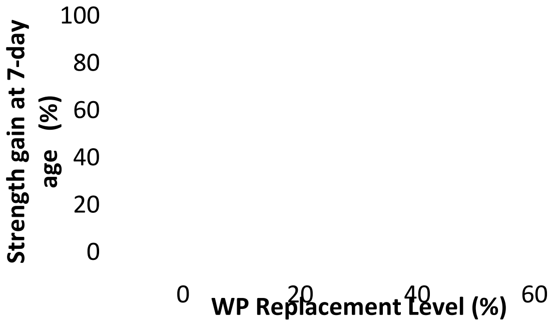

Fig. 6: Strength development of concrete containing varying amounts of WP

C. Water Absorption

The total water absorption of concrete containing different amounts of WP is presented in Fig. 7. At the 28-day age, the total water absorption of concretes is between 4.65-6.06%. The concrete with a higher volume of WP shows higher water absorption. The possibility for higher absorption may be due to the shrinkage of polystyrene particles and increasing porosity in concrete [22]. This can be confirmed from the higher water absorption of low density concretes which have higher volumes of WP. In the investigation conducted by [22], the total water absorption of concrete containing polystyrene was between 6.7-28.8%. In contrast, water absorption for the concretes in the present study made with 20-40% WP is between 4.97-5.27%.

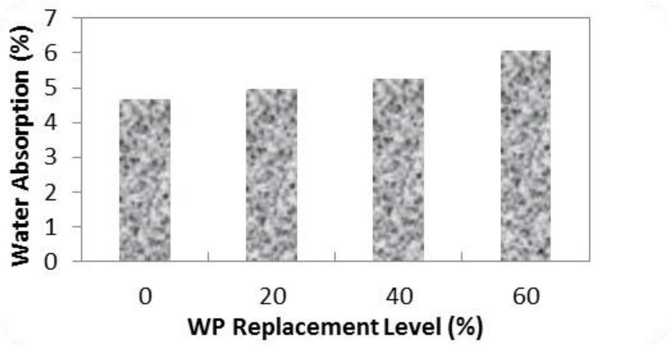

Fig. 7: Water absorption of concrete containing varying amounts of WP

Fig. 8 shows the correlation between compressive strength and total water absorption of concrete containing varying amounts of WP. An exponential function seems to better describe this correlation:

$$Y = 778.27e^{-0.758x}, \quad \text{with } R^2 = 0.9399 \qquad (2)$$

The strength of concrete containing varying amounts of WP appears to decrease with an increase in concrete water absorption. It is indicating strong correlation ($R^2 = 0.9399$), where X is the water absorption (%) and Y is the compressive strength (MPa).

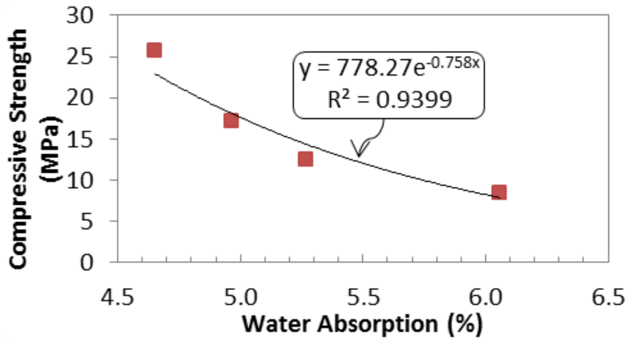

Fig. 8: Correlation between strength and water absorption

V. CONCLUSIONS

Reusing and recycling of waste materials can be the best technique to solve the environmental problems of municipal solid wastes in Kurdistan region. According to the experimental results obtained workability (consistence), compressive strength and density of concrete decrease and

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water absorption increases as waste polystyrene (WP) replacement level in concrete increases. However, with appropriate mix design, the utilisation of WP in concrete production is possible. The main recommendation for further possible work is to investigate the durability properties of concrete incorporating WP e.g. resistance to chemicals or freezing & thaw before this novel lightweight aggregate concrete could be proven OK to use in civil engineering applications.

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