Impact of Elevated Temperature Exposure on Some Properties of Sustainable Mortar with Plastic Bag Waste

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ABSTRACT

The management of solid waste disposal is an important issue worldwide. Currently, eliminating plastic trash is critical. There are numerous recycling facilities around the world, but as plastic is recycled, its strength decreases. Thus, eventually, plastic will become a fill for the soil. Plastic can be used in concrete construction instead of recycling. This study prepared and used Plastic Bag Waste (PBW) as fine aggregate and investigated some of the features of concrete containing diverse contents of PBW as a volumetric replacement part for fine aggregate. The PBW content was 0, 10, 20, and 30%. Concrete properties, such as compressive strength, flexural strength, and direct tensile strength, were investigated at ambient and after exposure to high temperatures of 60, 150, 300, and 400°C. In general, the test results showed that at ambient temperature, the compressive, flexural, and direct tensile strengths decreased as the PBW content increased, and the appropriate percentage of PBW was 10 to 20%. The results also showed that compressive strength increased after exposure to 300°C by 23% on average for specimens with 0, 10, and 20% PBW. It is possible to produce sustainable mortar with acceptable properties before and after exposure to temperatures as high as 300°C, provided the PBW content is at least 10%. This concrete can be used to make various types of boards and paving bricks.

Keywords-plastic bag waste; mortar; fine aggregate; high temperature; strength tests

I. INTRODUCTION

Concrete is the most widely used construction material. The generation of a considerable amount of plastic waste materials due to rapid urbanization is one of the most important problems the world is facing today. Insufficient plastic waste management causes environmental pollution [1]. Recently, the manufacturing industry started reusing recycled plastic artifacts to make various domestic items, including toys, seeding containers, clothes hangers, etc. [2]. Using plastic waste in concrete production is the most environmentally and economically friendly way to reduce the environmental impact of this waste [1].

In Iraq, there is a large amount of plastic waste, which poses a significant hazard to health and the environment. To minimize the problems caused by this waste, it can be used as aggregate, after preparation, by a certain percentage. Since aggregate is a nonrenewable material, it is necessary to maintain it using waste materials. Plastic bottle waste has been used as a sand substitution in composite materials for building applications [3-5]. These studies showed that the rate of strength reduction decreases and slump increases with increasing plastic aggregate content. In [6, 7] the effects of recycling plastic waste as a partial replacement of fine and coarse aggregate on the characteristics of concrete were investigated. In [3], it was shown that using Plastic Bag Waste (PBW) as cut pieces in concrete helps to improve specific properties, such as compressive and tensile strength. Plastic waste is a worldwide problem [8]. As these materials cause several environmental issues, various solutions have been investigated to reduce their effects. According to [9], incorporating waste into concrete has further benefits for the environment and possibly the economy. In [10], the effect of different contents (15, 25, and 45%) of mixed plastic waste as a volume substitute for natural coarse aggregate was investigated on some concrete properties. The increase in plastic aggregate content reduced concrete's compressive strength and dry density. Water absorption increased, whereas a significant improvement in concrete thermal insulation was observed as plastic content increased. In [11], fine aggregate weight fractions in the 5-15% range were replaced by plastic waste, and the results showed that including plastic waste reduced compressive strength and the push-out bond between steel reinforcement and concrete.

Due to several reasons, fire accidents are common in buildings. Therefore, it is necessary to determine the performance of concrete at elevated temperatures [12]. In [13], the influence of elevated temperatures was investigated on the mechanical properties of concrete containing Recycled Tire Rubber (RTR) as a partial replacement for sand with ratios of 0, 6, 12, 18, and 24% by weight. Concrete specimens were exposed to temperatures of 200, 400, and 600°C for one hour. A decrease in linear compressive and tensile strength was observed with increasing temperature and the replacement content of sand with RTR. In [14], a review study was carried out on using plastic waste as aggregate in construction materials, examining the effect of elevated temperatures. In general, limited previous studies concluded that concrete with plastic aggregate had a reduction in compressive and flexural strength after exposure to elevated temperatures.

As information on the influence of high temperatures on the performance of concrete with PBW is very scarce, this study aims to bridge this research gap by evaluating the compressive strength, flexural strength, and direct tensile strength of concrete with different PBW content as a volumetric replacement for fine aggregate, before and after exposure to high temperatures.

II. RESEARCH SIGNIFICANCE

This study focuses on reducing environmental pollution by using PBW in concrete production. This can reduce the high amounts of PBW in the environment that cause severe soil and water pollution and preserve the depletion of natural sand in the environment. The main goal is to investigate the properties of concrete containing different amounts of PBW at ambient temperature and after exposure to high temperatures and to select sustainable concrete with optimal PBW content.

III. EXPERIMENTAL METHOD

A. *Materials*

1) *Cement*

Ordinary Portland cement (CEM I 32.5 R) manufactured by Bazian in Iraq was used. Table I shows its chemical composition and physical properties. The test results illustrate that the cement conforms to Iraqi specifications No.5/2019 [15].

TABLE I. CEMENT CHARACTERISTICS

Chemical analysis		**Physical properties**	**Limits of [15]**
Oxides	**%**		
CaO	60.99	Specific surface area (Blaine method), 3760, (cm^2/gm).	≥ 2800
SiO_2	20.55	Setting time (Vicats method)	
Al_2O_3	4. 61	Initial setting, (hrs: min) 2:37	≥ 45 min.
Fe_2O_3	3.55	Final setting, (hrs: min) 4:27	≥10 hr.
MgO	1.94	Compressive Strength (MPa)	
SO_3	2.65	For 2 days, 23.7	≥ 10.0
Na_2O	0.41	For 28 days, 34.6	≥ 32.5
K_2O	0.21	Soundness (Autoclave method) % 0.4	≤ 0.8
L.O.I	1.82		
I.R.	0.43		
Compound compositions (%)			
C_3S	50.51		
C_2S	21.70		
C_3A	6.28		
C_4AF	10 .49		

2) *Natural Fine Aggregate*

Natural sand of 4.75 mm maximum size was used. It was brought from the AL-Ukaider region, and its classification lies in Zone 1. Table II shows the sieve analysis and the physical properties of this aggregate, which conform to Iraqi Standard No. 45/2019 [16].

TABLE II. GRADING AND PROPERTIES OF NATURAL FINE AGGREGATE

Grading		**Properties**	
Sieve size (mm)	**Passing (%)**		
4.75	100	Material passing sieve 75 µm, %	2
2.36	84	Sulphate content (SO_3), %	0.3
1.18	58.4	Absorption, %	2
0.6	27	Specific gravity	2.7
0.3	7	Bulk density, kg/m_3	1558
0.15	0	Fineness modulus	2.6

TABLE III. RELATIVE CONCENTRATION OF ELEMENTS IN PLASTIC BAGS [17]

Elements	**Relative Abundance (%)**
Ti	0.0587
Al	0.0237
K	0.0123
Si	0.0118
Mg	0.0113
Cl	0.0093
Ca	0.0047
Cu	0.0032
Cr	0.0029
Sr	0.0026
Fe	0.0025
Mn	0.0002
Ag	0.0019
S	0.0014
P	0.0006
Zn	0.0005

3) *Plastic Bag Waste*

Plastic bags were manufactured from Low-Density Polyethylene (LDPE). According to a Wavelength Dispersive X-Ray Fluorescence (WDXRF) analysis of plastic bags, the concentrations of the different elements were observed by [17] as shown in Table III. The plastic bags were collected, washed with water, and crushed into small pieces by a specific plastics crusher. The crushed plastic bags were then screened on standard sieves and prepared to have almost the same grading of fine natural aggregate. Table IV shows the grading and the characteristics of the waste aggregate from plastic bags used.

TABLE IV. GRADING AND PROPERTIES OF PBW

Grading		**Properties**	
Sieve Size (mm)	**Passing (%) Zone 1**		
4.75	96	Fineness Modulus	3.45
2.36	80	Specific Gravity	0.88
1.18	55	Apparent Density, kg/m^3	530
0.6	18		
0.3	6.32		
0.15	0		

Fig. 1. Crushed plastic bags.

4) Water

Water from Baghdad's water supply network (tap water) was used to mix and cure the concrete specimens.

Fig. 2. Specimens of cement mortar.

B. Mixes, Mixing Procedure, and Preparation of Specimens

Cement mortar mixes of 1:3 cement to aggregate by weight, with a cement content of 590 kg/m^3, water-to-cement ratio of 0.67, and with or without 10, 20, and 30% PBW as a volumetric replacement for sand were prepared. All mixes had the same consistency of 100-105%, as determined by a flow test. The mixing process was carried out in a Hobart 0.08 m^3 electrical rotary mixer, according to [18]. Concrete specimens were prepared using cube steel molds of 50 mm to test compressive strength according to [19], and prisms of 40×40×160 mm to determine the rupture modulus (one-point load) according to [20]. In addition, specimens were prepared and tested for direct tensile strength test according to [21], as shown in Figure 2.

C. Curing

After demolding, all specimens were placed immediately in water at a temperature of 23± 2°C for 28 days, including the period in the mold.

D. Exposure of Mortar Specimens to Elevated Temperature

After 28 days of curing, the specimens were removed from the water and left for 24 hours to air dry. The specimens were then placed in an electric furnace and heated to four temperatures, 60, 150, 300, and 400°C. These temperatures were selected according to [22, 23]. After reaching the specified temperature, the specimens were kept at that temperature for one hour before gradually cooled to room temperature and then tested.

IV. RESULTS AND DISCUSSION

A. Effect of Plastic Bag Waste Content on the Mechanical Properties of Mortar at Ambient Temperature

Table V shows the compressive strength results at 28 days for concrete specimens containing various percentages of PBW as a replacement for fine aggregate. The results indicate that the compressive strength decreased as the content of PBW increased. The reduction was 28.4, 33.33, and 36.84% for specimens with 10, 20, and 30% PBW, respectively. In general, previous studies showed that using different types of plastic waste as aggregate in concrete reduced compressive strength [24-28]. Using PBW as fine aggregate in concrete reduces compressive strength due to the reduction in the bond between PBW surfaces and cement paste, causing an increase in the size and number of pores and cavities in concrete [29, 30]. The results in Table V also show that the flexural strength specimens made with PBW at 28 days of age tend to decrease with increasing PBW content. The average decrease was 16.42%. This tendency is attributed to the reduced adhesive strength between the surface of PBW particles and the cement paste. These results agree with the findings of [29]. Most of the PBW aggregate in the concrete does not fail after reaching its full strength, as seen in Figure 3. However, they debond from the cement paste, proving its weak bond with the PBW aggregate. Unlike specimens that do not contain PBW aggregate, specimens with different PBW contents are divided into two parts.

TABLE V. PBW CONTENT AFFECTING THE MECHANICAL PROPERTIES OF MORTAR SPECIMENS

PBW content (%)	**Compressive strength at 28 days**		**Flexural strength at 28 days**		**Direct tensile strength at 28 days**	
	(MPa)	**Variation (%)**	**(MPa)**	**Variation (%)**	**(MPa)**	**Variation (%)**
0	14.25	-	6.19	-	2.01	-
10	10.20	-28.4	5.73	-7.43	2.0	-0.3
20	9.50	-33.33	5.40	-12.76	1.51	-24.88
30	9.0	-36.84	4.39	-29.07	1.14	-43.26

Table V shows the results of the effect of PBW on the direct tensile strength at 28 days. It can be seen that specimens with 10% PBW have a direct tensile strength similar to that without PBW. The reduction for specimens with 20% and 30% PBW was 24.88% and 43.26%, respectively, compared to specimens without PBW. This reduction in tensile strength is due to the low adhesion and bonding strength between the PBW and the other components of the cement mortar. In general, specimens containing plastic aggregate could withstand tensile loads without full deterioration. The collapse was found to be more ductile when the ratio of PBW increased.

B. Influence of Elevated Temperatures on the Mechanical Properties of Mortar with PBW

1) Compressive Strength

Table VI and Figure 3 show the results of the compressive strength of the concrete specimens containing various percentages of PBW after exposure to high temperatures.

TABLE VI. MECHANICAL PROPERTIES OF SPECIMENS AFTER EXPOSURE TO ELEVATED TEMPERATURES

Temperature (°C)	PBW content (%)	Compressive strength at 28 days (MPa)	Flexural strength at 28 days (MPa)	Direct tensile strength at 28 days (MPa)
25	0	14.25	6.19	2.01
	10	10.20	5.73	2.0
	20	9.50	5.40	1.51
	30	9.0	4.39	1.14
60	0	12.57	5.67	1.26
	10	9.53	4.82	1.87
	20	9.90	3.58	1.06
	30	8.0	2.92	0.93
150	0	15.55	7.47	2.39
	10	11.2	6.42	2.78
	20	10.13	3.61	1.61
	30	10.3	1.83	0.90
300	0	17.67	4.31	1.37
	10	12.3	5.25	1.79
	20	11.8	3.34	1.60
	30	4.55	2.56	0.93
400	0	13.45	3.7	0.75
	10	7.45	2.77	1.01
	20	6.55	4.23	Failed before testing
	30	6.40	1.06	Failed before testing

At 60°C, the compressive strength decreased slightly by approximately 11.8, 6.6, and 11.1% for specimens with 0, 10, and 30% PBW, respectively. At the same time, specimens with 20% PBW show a slight increase of approximately 4.2% compared to the corresponding specimens at ambient temperature. This may be because the partial melting of plastic waste particles at this temperature leaves small pores in the microstructure of concrete. After exposure to 150°C, the results show little increase in compressive strength for specimens with and without PBW, with the average increase being 10%. The decrease in the fraction of calcium hydroxide and unhydrated components, which is beneficial to the microstructure of the specimens, is the reason for this slight improvement in compressive strength [24]. The results also show that at 300°C, the compressive strength increased by an average value of 23% with 0, 10, and 20% PBW, while for specimens with 30% PBW, there was a significant reduction in compressive strength of approximately 49.4%. This reduction is probably due to the high content of PBW (30%) that, after melting at high temperatures, leaves the mortar microstructure with a large volume of pores. When the temperature increased to 400°C, the compressive strength of specimens with 10, 20, and 30% PBW decreased sharply, with an average reduction of 29%, while specimens without PBW showed a slight decrease in compressive strength (5.6%). This reduction in strength for all specimens is probably because, as the temperatures increased, most PBW particles deteriorated, causing more voids in the concrete microstructure and a considerable loss in strength [31].

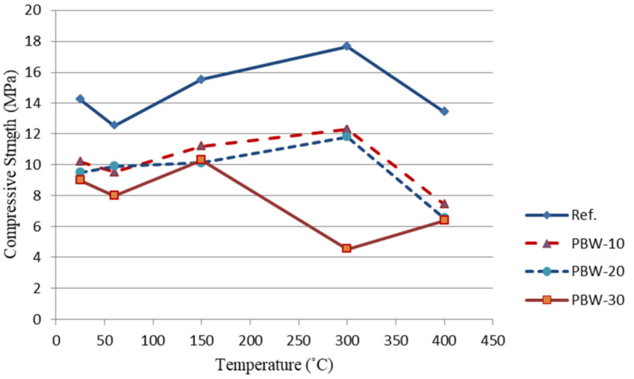

Fig. 3. Relationship between the compressive strength of mortar specimens containing different content of PBW and temperatures.

2) Flexural Strength

Table VI and Figure 4 illustrate the effect of elevated temperatures on the flexural strength of specimens with and without PBW. The results demonstrate that at 60°C, all specimens showed a decrease in flexural strength, and the percentage of reduction increased with the PBW content. Specimens with 0, 10, 20, and 30% PBW showed a reduction in flexural strength of approximately 8.4, 5.9, 33.7, and 33.5%, respectively, related to the corresponding specimens before heating. When the temperature increased to 150°C, flexural strength increased for specimens with 0 and 10% PBW by 20.70% and 12%, respectively. At the same time, the increase in PBW content at 20 and 30% caused a considerable reduction in flexural strength by 33.2 and 58.4%, respectively, compared to those specimens not exposed to elevated temperatures. This reduction in specimens with a high content of PBW is attributed to the large pores that appear in the mortar microstructure after the melting of the PBW particles. The findings also demonstrate that specimens subjected to 300°C and 400°C have lower flexural strength due to their tendency to decompose at higher temperatures due to the loss of water and C-S-H. At the same time, exposure to 400°C demonstrated substantial damage to mortar specimens. This damage is mainly due to the burning of PBW, which increases the porosity of the concrete [32].

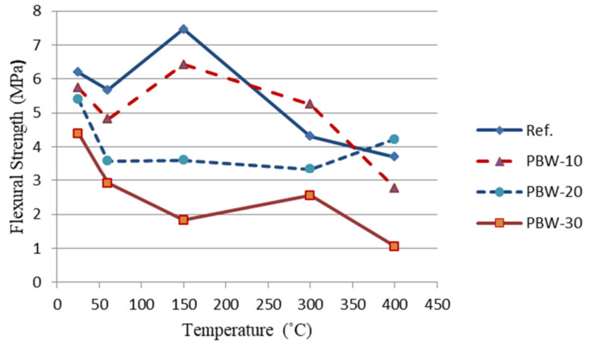

Fig. 4. Relationship between the flexural strength of concrete specimens with different temperatures and PBW content.

3) *Direct Tensile Strength*

Table VI and Figure 5 show the direct tensile strength results for all specimens as a function of temperature. The direct tensile strength of specimens after exposure to 60°C decreased compared to that at ambient temperature. The results also show that at 150°C, the tensile strength of the specimens with 0, 10, and 20% PBW increased by 19.1, 38.7, and 6.6%, respectively, compared to the corresponding specimens, but for specimens with 30% PBW, tensile strength decreased by 20.88%. For temperatures of 300°C and 400°C, direct tensile strength decreased significantly as the content of PBW increased. Specimens with 20 and 30% PBW failed after exposure to 400°C before testing. In general, the loss in tensile strength of the PBW specimens is shown to be greater than that of the specimens without PBW. This is because, at higher temperatures, all types of plastic melt (between 105-250°C [33]), creating more voids in the specimens and causing a more significant loss in tensile strength.

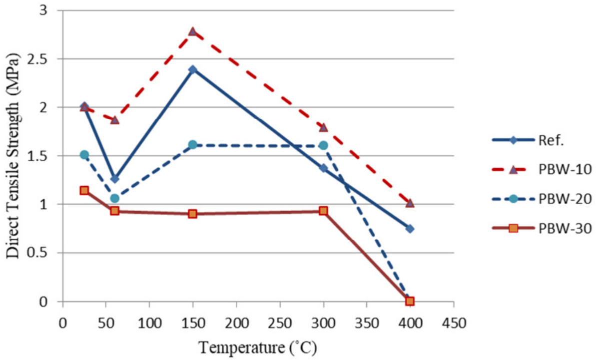

Fig. 5. Relationship of direct tensile strength for concrete specimens with different temperatures and PBW content.

4) *Visual Inspection*

When concrete containing PBW is exposed to elevated temperatures, visual observation provides a first thought about the degree of deterioration of concrete by checking signs caused by plastic melting. Cracking is an observable kind of damage to concrete specimens after exposure to elevated temperatures and has a significant harmful influence on its mechanical and durability characteristics. No cracks appeared in concrete specimens containing PBW aggregate after exposure to different elevated temperatures. However, black pores were shown on the surface of the specimens, especially after exposure to 300 and 400°C. This is due to the melting of plastic waste, as shown in Figure 6. One reason cracks do not occur in the presence of plastic is that the inclusion of PBW increases the ductility of the concrete.

Fig. 6. Black pores in concrete specimens with PBW aggregate after exposure to high temperatures.

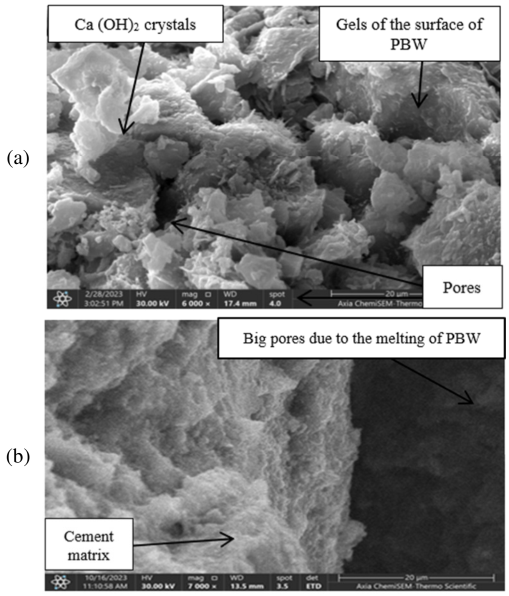

Fig. 7. SEM images for concrete specimens with PBW before and after exposure to 400°C: (a) Before exposure to high temperatures, (b) after exposure to 400°C.

5) *Scanning Electron Microscopy (SEM)*

Figure 7 shows SEM images for concrete specimens with 10% PBW before and after exposure to 400°C. It can be observed that the microstructure is different after exposure to 400°C. There are more pores in the cement matrix and less dense hydration products. The structure of the gel network is broken and disappears. The SEM images show that high temperatures cause changes in cement hydration products and degrade PBW particles in mortar specimens. These images supplement the experimental results that show a significant reduction in the strength of mortar specimens after exposure to 400°C.

V. CONCLUSIONS

From the experimental results, the following conclusions can be drawn:

- PBW in concrete with 10, 20, and 30% as a volumetric replacement for natural sand significantly decreases compressive, flexural, and direct tensile strength at 28 days. The optimal percentage of PBW is 10 and 20%, resulting in a lower decrease in strength than 30% content and gives a mixture with good properties.
- The compressive strength of all mortar specimens after exposure to 60°C decreased slightly, with the average decrease being 7% compared to that at ambient temperature. At 150°C, the specimens showed slightly higher compressive strength.
- The compressive strength of specimens with PBW up to 20% after exposure to 300°C increased by an average value of 23%. For specimens with 30% PBW, there was a significant reduction of approximately 49%. At 400°C, the average decrease for specimens with PBW was 29%, whereas specimens without PBW showed a slight reduction of approximately 5.6% relative to the corresponding specimen at 25°C.
- The flexural strength of all specimens decreased after exposure to 60°C and 300°C, while at 150°C, specimens with 0 and 10% PBW had increased flexural strength by 20.7% and 12%, respectively. In comparison, specimens with 20% and 30% PBW showed a significant reduction of 33.2% and 58.4%, respectively. After exposure to 400°C, there was a substantial increase in specimen damage.
- In general, specimens subjected to 60, 150, 300, and 400°C showed a reduction in direct tensile strength, which increased with the content of PBW.
- SEM images for specimens before and after exposure to high temperatures complemented the experimental results.
- Sustainable concrete with an optimal PBW content of 10% can be produced with acceptable properties before and after exposure to temperatures up to 300°C. This concrete can be used in the production of paving bricks and different types of boards.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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