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Effect of wheat straw ash on mechanical properties of autoclaved mortar

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Abstract

This study investigates the effect of wheat straw ash (WSA) on the mechanical strength of autoclaved mortar. The mechanical properties studied include compressive, tensile, and flexural strengths of mortar. Mortar mixes were prepared using natural silica, wadi (local sand), and crushed limestone fine aggregates at a w/c ratio of 0.6. Mortar specimens were exposed to autoclave for 2.5 h at a pressure of 2 MPa. Three percentages of WSA replacement levels (3.6%, 7.3%, and 10.9%) by weight of sand were utilized in the study. The study showed that the replacement of sand by WSA increases the mechanical strength of autoclaved mortar. Mortar specimens containing limestone aggregate with 10.9% WSA replacement level showed an average increase in compressive, tensile, and flexural strength by 87%, 67%, and 71%, respectively, compared to control mortar specimens. Scanning electron micrographs for autoclaved paste specimens containing 7.3% WSA replacement level revealed a more packed structure compared to control paste specimens. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Mortar; Mechanical properties; SEM; Wheat straw ash; Autoclave

1. Introduction

The use of supplementary cementitious materials, such as fly ash, silica fume, and blastfurnace slag, in concrete construction is widespread. Supplementary cementitious materials may considerably improve the strength and durability of concrete [1–6]. A number of relatively new supplementary cementitious materials, such as rice husk ash, sewage sludge ash, and oil shale ash, have undergone extensive research [7–11]. Recently, wheat straw ash (WSA) was studied by Biricik et al. [12] as a new supplementary cementitious material. A well-burnt and well-ground WSA is very active as a pozzolanic material. Biricik et al. found that (1) wheat straw has 8.6% ash and the silica content of the ash is 73%; and (2) WSA has pozzolanic properties under normal curing conditions. However, Biricik et al. did not investigate the effect of WSA on mechanical properties of concrete under autoclaving curing conditions.

Subjecting concrete to high-pressure steam curing is called autoclaving. Autoclaving is used in the manufacture of sand–lime bricks, lightweight cellular concrete, and small precast concrete products. Autoclaving produces high early-strength concrete, improves the resistance of concrete to sulfate attack and freeze/thaw damage, reduces efflorescence, and reduces drying shrinkage [13–15].

Autoclaving is most effective when supplementary cementitious materials are added to the cement because of the pozzolanic reaction between the silica and calcium hydroxide released during hydration of tricalcium silicate. The pozzolanic reaction leads to the formation of calcium silicate hydrate, which is responsible for the strength of concrete [16,17]. This study focuses on using WSA with cement as partial replacement of sand under autoclaving curing conditions.

2. Experimental program

2.1. Materials

Two types of fine aggregates were used in preparing mortar mixes: crushed limestone, and a mixture of 50% natural silica and 50% wadi (local sand). The physical properties of the aggregates are presented in Table 1. The specific gravity and the absorption of the fine aggregates were determined according to ASTM C128. The gradations

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Table 1
Physical properties of the aggregates used in the study

Aggregate type	Maximum size (mm)	Specific gravity			Absorption (%)	Fineness modulus[a]
		Dry	SSD[b]	Apparent		
Limestone	4.75	2.51	2.59	2.72	3.05	2.76
Silica	1.18	2.60	2.63	2.70	1.50	1.72
Wadi	4.75	2.59	2.65	2.76	2.31	3.51

[a] Fineness modulus is the sum of cumulative retained on sieves (8, 16, 30, 50, 100) divided by 100.
[b] SSD = saturated surface dry.

and fineness moduli of the aggregate were determined according to ASTM C136. The chemical analyses of the aggregates are presented in Table 2.

Wheat straw was obtained from a local store in Irbid, Jordan. Burners at Jordan University of Science and Technology were utilized to incinerate the wheat straw at 650 °C for 20 h. The WSA was collected from the burner and ground for 2 h. The chemical analyses of WSA and Type I cement used in the study are presented in Table 2. Particle size distributions of WSA and Type I cement are presented in Fig. 1. The particle size distributions of WSA and cement were determined in a cement factory. The specific gravity of WSA is 1.97.

2.2. Specimen preparation

The fine aggregates were dried in an oven at 95 °C for 24 h, then cooled for 8 h. The mortar was mixed in a 4730-cm^3 mixing bowl according to ASTM C305 standards. Flow table tests were performed according to ASTM C230. The mortar mix proportions and flow table values are summarized in Table 3. Three percentages of WSA replacement by weight of sand were utilized in mortar mixes: 3.6%, 7.3%, and 10.9%. The mortar was cast in 5-cm cubes, briquettes, and $4 \times 4 \times 16$ cm beams according to ASTM specifications. Three specimens of each mix were cast and tested. Fresh mortar was placed in cubes in two layers; each layer was compacted in 16 strokes. For beams, fresh mortar was also placed in two layers; each layer was compacted in 12 strokes. One layer was used for briquette moulds and pressed by thumbs 12 times. The surface of the mortar was smoothed using a trowel. Specimens were placed in their moulds in a curing room for 24 h. After that, mortar specimens were demoulded and cured in a water tank at 23 °C for 3 days before being exposed to autoclaving. Mortar specimens were allowed to cool down for 24 h before being tested for mechanical strength [18].

Table 2
Chemical analysis of the aggregates, WSA, and Type I cement used in the study

Compound	Aggregate			WSA	Type I cement
	Limestone	Silica	Wadi		
SiO_2	0.98	95.4	80.3	50.7	21.2
CaO	55.5	0.54	5.3	10.6	63.7
Fe_2O_3	0.31	0.96	1.33	0.0	3.1
Al_2O_3	0.31	0.24	0.55	0.48	5.5
MgO	0.25	–	–	2.20	1.5
Na_2O	–	–	0.14	5.41	0.18
SO_3	–	–	–	6.13	2.63
P_2O_5	–	–	–	4.68	0.0
K_2O	–	0.07	0.07	11.4	0.71
Loss on ignition	42.5	0.75	12.2	10	0.96

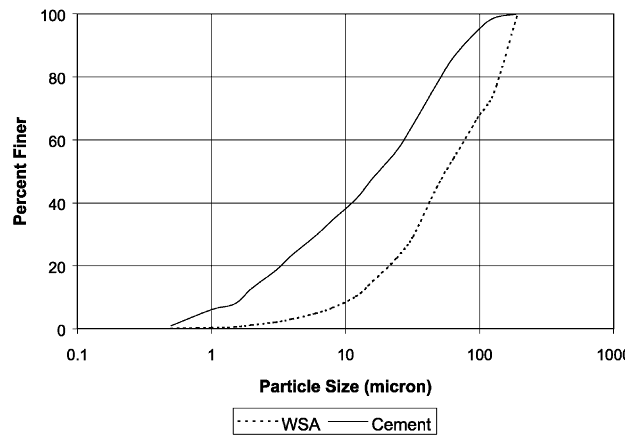

Fig. 1. Particle size distribution for wheat straw ash and Type I Portland cement.

Bulk samples of paste specimens were obtained before and after autoclaving for the scanning electron micrographs (SEM). Before exposing the paste samples to SEM, they underwent a preparation process. The process includes immersing the paste samples in methanol solution. The solution was changed three consecutive times after 24, 48, and 72 h. After that, the paste samples were placed in an oven at 95 °C for 24 h. The paste samples were coated with a thin layer of gold before being scanned by the electron microscope.

3. Results and discussion

Table 2 shows the chemical analysis of the aggregates, WSA, and Type I cement used in the study. Limestone aggregate contains about 55% calcium oxide. Silica and wadi aggregates contain 95% and 80% SiO_2, respectively. Thus, silica–wadi aggregate contains an average of 87.5% silica. Silica constitutes about 51% of the chemical composition of WSA. The presence of silica in WSA is essential for the pozzolanic reaction to occur and consequently to increase the strength of concrete.

The properties of fresh mortar are given in Table 3. The mortar had flow values ranging from 100 to 140. Flow table values decreased with increasing WSA replacement. This may be explained by the fact that the fineness of WSA is more than that of fine aggregate. As the WSA replacement increases, the amount of water necessary to wet the surface of WSA particles increases. Thus, flow table values decrease.

Table 3
Mortar mix proportions for mixes used in the study

Mix number	Cement (g)	WSA (g)	Water (ml)	w/c	Limestone aggregate[a] (g)	Silica–wadi aggregate[a,b] (g)	Flow test values[c]
1	800	0	480	0.6	2200	–	130
2	800	80	480	0.6	2120	–	125
3	800	160	480	0.6	2040	–	121
4	800	240	480	0.6	1960	–	110
5	800	0	480	0.6	–	2200	112
6	800	80	480	0.6	–	2120	109
7	800	160	480	0.6	–	2040	104
8	800	240	480	0.6	–	1960	100

[a] Weight based on saturated surface dry.
[b] A blend of 50% silica and 50% wadi sand.
[c] Average of four readings.

Table 4 shows the initial setting time values for paste specimens containing different levels of WSA replacement. As the percentage of WSA replacement increases, the initial setting time increases. The increase in initial setting time for ash replacement of 3.6%, 7.3%, and 10.9% was 68%, 77%, and 92%, respectively. The initial rate of reaction between WSA and water is slower than that of Portland cement and water. This causes an increase in initial setting time of the blended cement.

The effect of WSA replacement on the compressive, tensile, and flexural strengths is shown in Figs. 2–4, respectively. Except for compressive strength using silica–wadi aggregate, the mechanical properties (compressive, tensile, and flexural) increased steadily and significantly with WSA replacement levels. Mortar specimens containing limestone aggregate at WSA replacement of 3.6%, 7.3%, and 10.9% showed increase in compressive strength by 12%, 75%, and 87%, respectively. Mortar specimens containing the same aggregate type at WSA replacement of 3.6%, 7.3%, and 10.9% showed increase in tensile strength by 11%, 56%, and 67%, respectively. Mortar specimens containing the same aggregate type at WSA replacement of 3.6%, 7.3%, and 10.9% showed increase in flexural strength by 9%, 35%, and 71%, respectively. This result show that blended cement made using WSA increases the mechanical strength of mortar under autoclaving curing conditions. Mortar specimens containing silica–wadi aggregate did not show a significant increase in compressive strength. This behavior may be explained by the fact that silica–wadi aggregate itself has a high silica content (an average of 87.5%) compared to limestone aggregate (about 1% silica). Thus, any WSA replacement will not be significant compared to the high silica content already present in mortar specimens. However, the tensile and flexural strengths seems to be more sensitive to any slight variation in the silica content of mortar specimens subjected to autoclave.

Table 4
Initial setting time for paste specimens containing different WSA replacement levels

WSA replacement (%)	Initial setting time (min)
0	150
10	232
20	245
30	265

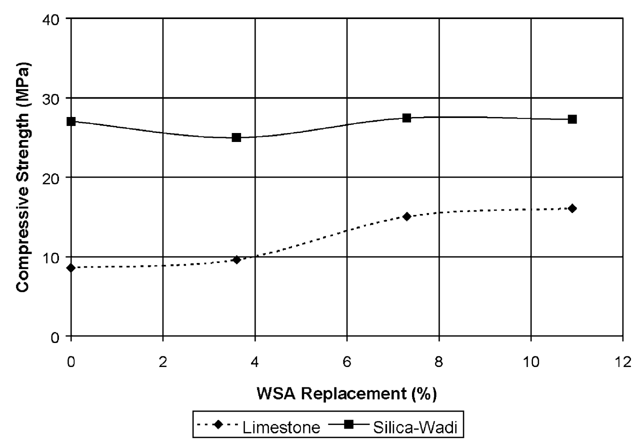

Fig. 2. Compressive strength with WSA replacement for autoclaved mortar specimens using different aggregate types.

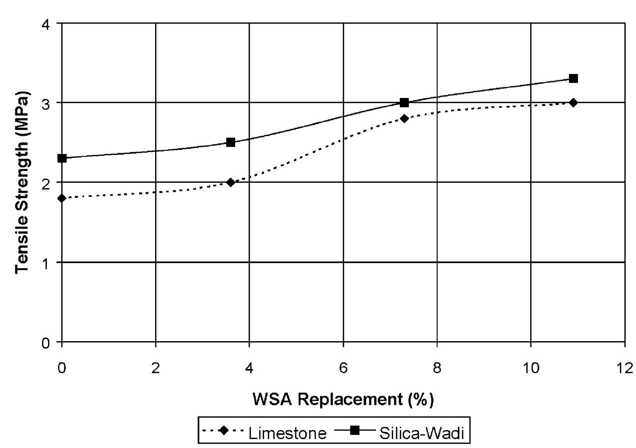

Fig. 3. Tensile strength with WSA replacement for autoclaved mortar specimens using different aggregate types.

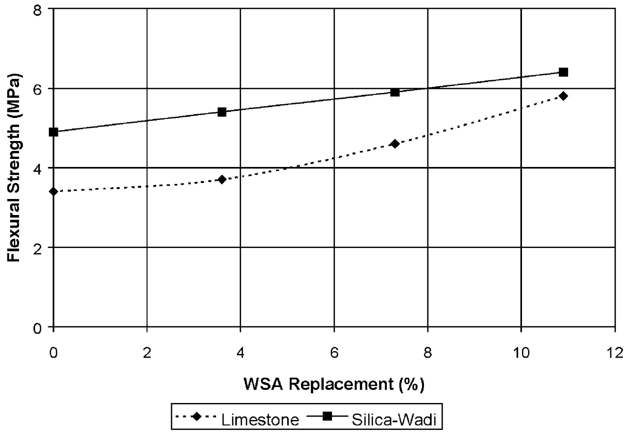

Fig. 4. Flexural strength with WSA replacement for autoclaved mortar specimens using different aggregate types.

SEM at 500 × magnification for control paste specimens examined before and after autoclaving are shown in Figs. 5 and 6, respectively. The micrograph for the control paste specimen examined after autoclaving (Fig. 6) shows more packed formation because of more calcium silicate hydrate compared to that examined before autoclaving (Fig. 5). SEM at 500 × magnification for paste specimens containing 7.3% WSA replacement examined before and after autoclaving are shown in Figs. 7 and 8, respectively. The paste specimen containing 7.3% WSA replacement examined before autoclaving shows more pores between hydration products (Fig. 7). On the other hand, the paste specimen containing 7.3% WSA replacement examined after autoclaving shows more calcium silicate hydrate, thus reducing the porosity of the cement matrix (Fig. 8). The pozzolanic silica reacts with calcium hydroxide and results in the formation of secondary calcium silicate hydrate. This leads to the transformation of large pores into small pores that significantly contribute to a reduction in the porosity and increase in the strength of cement paste.

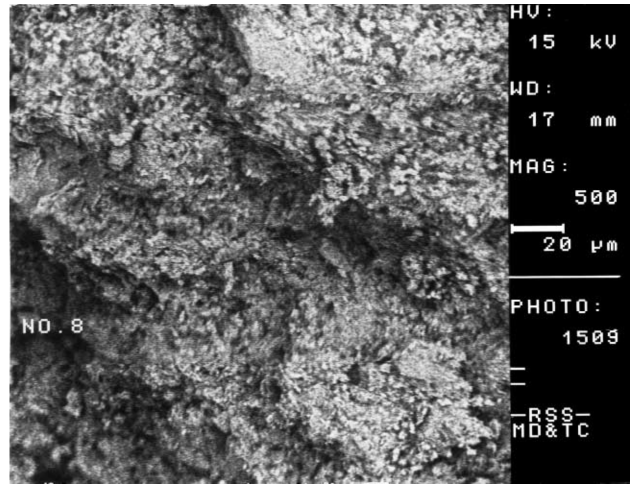

Fig. 6. SEM for control autoclaved paste specimen (500 ×).

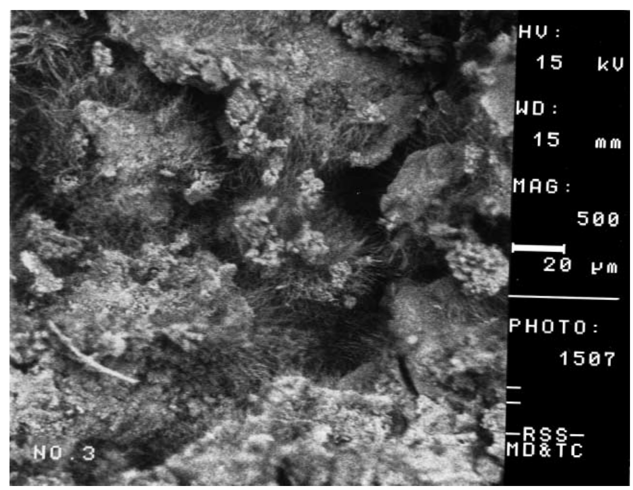

Fig. 7. SEM for paste specimen containing 7.3% WSA replacement level examined before autoclaving (500 ×).

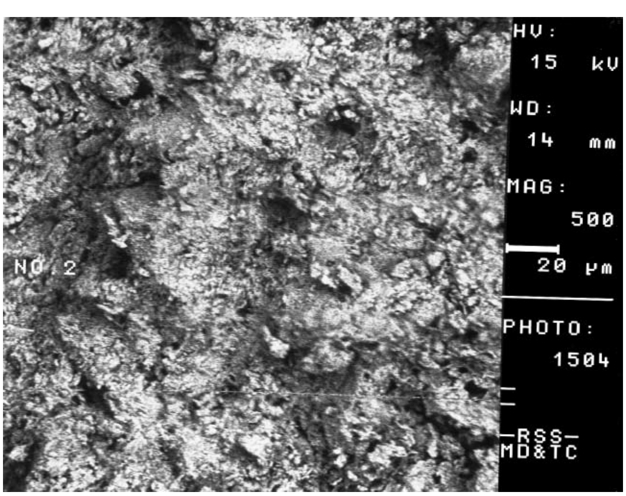

Fig. 5. SEM for control paste specimen examined before autoclaving (500 ×).

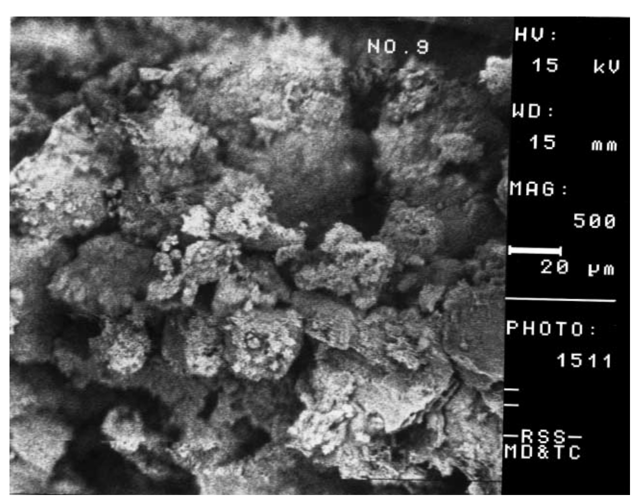

Fig. 8. SEM for autoclaved paste specimen containing 7.3% WSA replacement level (500 ×).

4. Conclusion

WSA was used as partial replacement by weight of sand for mortar specimens exposed to autoclaving. Except for compressive strength when a silica–wadi sand was used, mechanical properties (compressive, tensile, and flexural strength) of mortar specimens increased steadily with WSA replacement levels. SEM for autoclaved paste specimens containing 7.3% WSA replacement revealed more hydration products (calcium silicate hydrate) compared to control paste specimens.

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