

Utilization of Jordanian Bentonite Clay in Mortar and Concrete Mixtures

Ayoup M. Ghrair^{1*}, Adi J. Said², Hussein Al-Kroom³,
Naela Al Daoud², Bassel Hanayneh³, Ahmad Mhanna⁴, and Ahmed Gharaibeh⁵

¹ Department of Water Resources and Environmental Management, Al-Balqa Applied University, Salt 19385, Jordan.

² Foundational Science Research Division, Research for Development Pillar, Royal Scientific Society, Amman 11941, Jordan

³ Department of Civil Engineering, The University of Jordan, Amman 11942, Jordan

⁴ Middle East /North Africa Region at American Concrete Institute, Dubai, United Arab Emirates

⁵ Ministry of Energy and Mineral Resources, P.O Box 140027, Amman 11814, Jordan

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Abstract

The reduction of cement content in mortar and concrete mixtures reduces both the amount of CO₂ in the environment and the cost of production. Therefore, this research utilizes Jordanian bentonite as a pozzolanic material in both mortar and concrete sample mixtures. Three types of Jordanian bentonite samples were added to the mortar and concrete mixtures 1: natural bentonite 2: heated bentonite at 250 °C, 550 °C, and 750 °C, and 3: calcium-bentonite. Then, 21 mortar mixtures were prepared. Bentonite was added to the mortar mixtures in weight proportions of 0% (reference sample), 10%, 20%, 30%, 40%, and 50% by cement weight. On the other hand, 9 concrete mixtures were prepared from natural bentonite, heated bentonite, and ca-bentonite with proportions of 0% (reference sample), 10%, and 20% partial replacement of cement weight. The tested results show that heated bentonite at 750 °C achieved close results to the control sample. Moreover, both natural bentonite and Ca- bentonite reduce concrete shrinkage. Concrete permeability was highly reduced by using bentonite, especially Ca-treated, where permeability was reduced by 60%. Cost and environmental analyses were conducted to evaluate the utilization of bentonite.

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1. Introduction

Cement is known as an essential plastering material in construction in which it is the commonly used binder in a mortar and concrete mixtures. Many researchers have studied the strength of evolving and hydration process of cement along with its production costs [1-5]. Based on the understanding of the rheological behavior of cement, alternative low-CO₂ emission clinker materials were proposed [6, 7]. It is found that belite-rich cement gives promising results in comparison to Ordinary Portland Cement (OPC) as it has good flow properties and stability [8,9]. However, strength development at an early age is relatively slow. Weathered basalt (WB) was deployed in clinker manufacturing to evaluate its performance as an alternative binder material. The results indicate that WB has low silica, SO₃, and chlorine as well as high content of MgO and Fe₂O₃ which gives a better clinker ability and an environmental advantage [10]. Moreover, experimental investigations into the utilization of natural, waste, and by-product industrial materials as partial replacements for cement have been conducted. The investigations of these materials aimed to produce sustainable production at a low cost. For instance, research works on steel slag [11-13], silica fume [14,15], and fly ash [16,17] present very good results in comparison to the control mixtures i.e. concrete mix with 100% OPC.

Because of the aforementioned effort in finding an economical and environmental partial replacement for cement, Bentonite was introduced to the concrete and mortar mixtures [18-21]. Wilbur C. Knight as an absorbent and swelling material proposed the material and it has been mainly used for the development of oil and gas resources as drilling mud [22]. It is a natural pozzolana predominantly composed of montmorillonite. Bentonite is classified into three categories; sodium bentonite, calcium bentonite, and magnesium bentonite. Its influence on the mixtures is based on its chemical composition in which its effects on the strength of concrete and mortar are changeable. Ahmad S. et al. reported that the compressive strength of cement-bentonite concrete mixtures is lower than that of ordinary concrete mixtures [23]. On the other hand, the work of Memon S. et al. shows an increase in compressive strength in the mixtures containing bentonite compared to the control mixtures without bentonite [24]. Nevertheless, there is a consensus on the feasibility of bentonite's contribution to improving the workability and impermeability of mixtures [25, 26].

In most developing countries, like Jordan, natural resources are used in construction leading to a reduction in the cost and improvement of the quality of construction materials. This study is conducted to produce low-cost mortar and concrete by replacing the cement in mortar and concrete

* Corresponding author e-mail: ayoup.ghrair@bau.edu.jo

with local bentonite in various proportions. Incorporating bentonite in mortar and concrete as a substitute for cement can minimize the depletion of natural resources and materials used in cement and solve environmental problems related to its production process. An investigation of the Jordanian natural resource of bentonite was carried out. Three bentonite samples were collected from three different areas in Jordan to evaluate its potential use in mortar and concrete. The locations of the three areas are as follows in Table (1):

Table 1. The explored bentonite locations in Jordan

The areas	Coordinate system in the WGS 84			
	31°	52'	35"	N
Ein Al-Bayda area	36 °	49'	35"	E
	31°	48'	22"	N
Qa' Al-Azraq area	36 °	47'	35"	E
	29 °	26'	58"	N
Al-yamaniah – Aqaba	34 °	58'	26"	E

Samples were taken from different three locations. The Ein Al Bayda bentonite and Q'a Al Azraq bentonite are located in the Azraq area and belonged to the same lithological consequence (Neogene-Quaternary basalt and volcanic tuff). However, Al Yamaniyya bentonite belongs to different lithological consequences. It is found within the Pleistocene sediments close to the shoreline [27]. Comprehensive chemical and mineralogical analyses were done for each sample. In addition, an analysis of the cost and CO_2 emissions of the proposed contribution of bentonite was conducted.

2. Methods & Materials:

An experimental program was carried out to create mortar and concrete mixtures with reduced cement content by using a substitution amount of Jordanian bentonite. The properties of each material in the study were extensively examined to assess their effect on performance in the mixtures. Both the materials and the test procedures are described below.

2.1 Materials

2.1.1 Bentonite:

The bentonite clay was collected from the southern area of Al-Azraq (Qa' Al-Azraq). A comprehensive examination of the material was conducted. The raw bentonite sample was heat-treated at various temperatures 250 °C, 550 °C, and 750 °C utilizing Stackable Electric kilns (Olympic Kilns, Model - 2831HE/240, USA). Afterward, the heated bentonite sample was passed through a 150 µm sieve and then grinded and passed through an 80 µm sieve. Then the produced powder was submicron in size. The median particle size of the grinded sample was 0.51 µm using a laser diffractometer. Bentonite contains negatively charged particles that attract positively charged compounds and trap them in its porous structure. According to the classification scheme of Riddick [28], the stability of the bentonite particles is low at pH = 9.5. The zeta potential is less than 16.6 mV. The electrical conductivity is 79 µS/cm. Figure (1) shows particle size distribution and SEM-image of grinded bentonite. The SEM image shows the needle crystal of Illite.

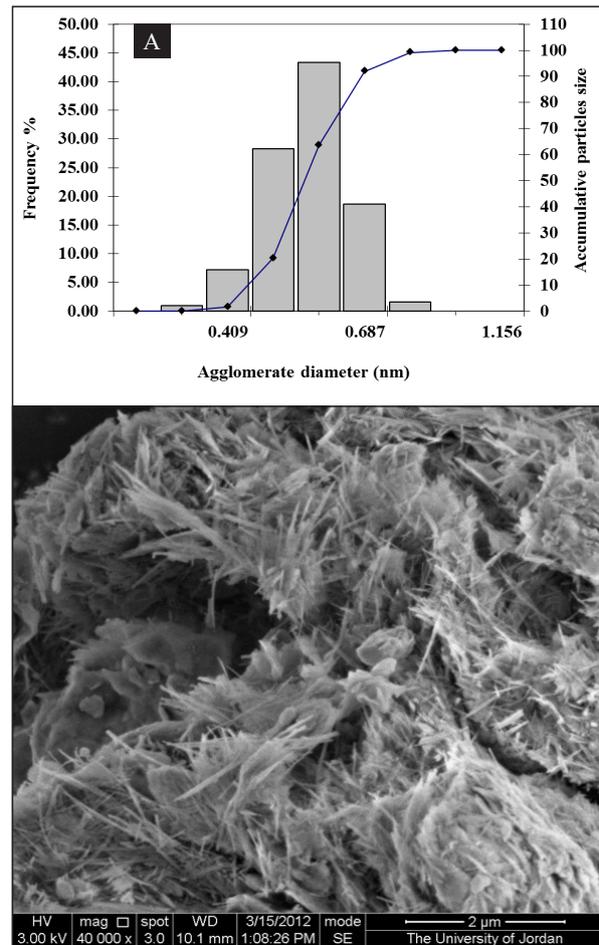


Figure 1. Particles size distribution and SEM-image of grinded bentonite sample. (it was conducted at the University of Jordan)

In addition, the X-ray diffraction (XRD) pattern of natural Jordanian bentonite is given in Figure (2). The spectra indicate that the clay is composed primarily of mixed layers of Illite, Montmorillonite, and Kaolinite. The other peaks are impurities corresponding to quartz. At 550 °C, Kaolinite peaks disappeared. This result is in harmony with the previous literature review. Deer et al [29] reported that Bentonite is a clay rock that consists of minerals mostly of montmorillonite. Moreover, it is found that the Jordanian Bentonite is composed of mixed layers of smectite/illite or Kaolinite with average silica and alumina 28-51 %, and 8.4-15 %, respectively [30]. The chemical composition of natural bentonite is shown in Table (2).

Table 2. Chemical composition of the natural bentonite was conducted by the XRF technique.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	TiO_2	P_2O_5	LOI
49.30	14.50	7.46	2.03	3.63	3.03	0.68	0.80	13.7

Thermal Gravimetric Analysis (TGA) was carried out to determine the sample losses at different temperatures (Isocratic and gradient) of raw Bentonite samples in the open atmosphere condition. The mass of the Bentonite sample used was 5 grams, Max. The heating range was from ambient to 1000°C, at stepwise (Max. Ramp Rate, from Ambient to 104°C the ramp rate was 15°C/min, and from 104°C to 1000°C was 50°C/min). Figure (3) shows the TGA of the air-dried bentonite sample.

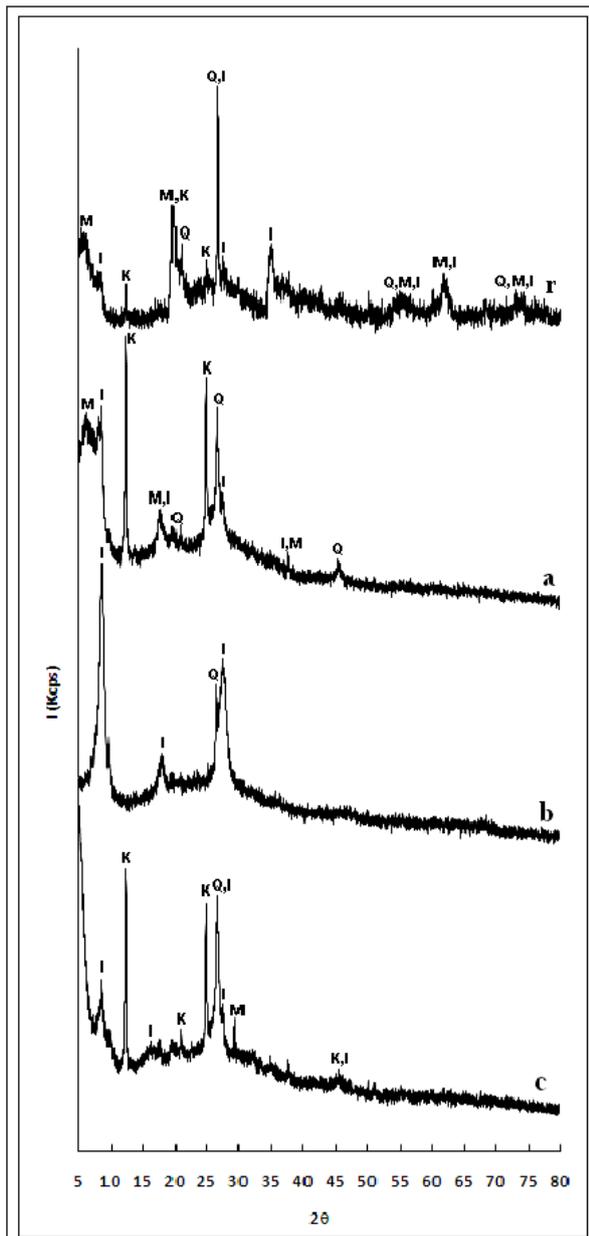


Figure 2. XRD spectra for the bentonite sample (r) randomly powder and oriented crystal distribution [(a) at 105°C, (b) at 550 °C, and (c) with ethylene glycol. (I: Illite, K: Kaolinite, M: Montmorillonite and Q: Quartz). (The XRD test was conducted at the Royal Scientific Society)

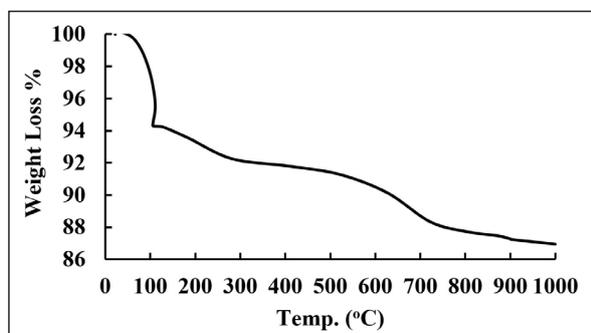


Figure 3. Thermal gravimetric analysis of bentonite (it was conducted at Natural Resources Authority (NRA), Jordan).

The TGA curve of the bentonite sample shows that up to 118 °C, there is a residual humidity (free water) of mass loss characterized by a drop in weight of 6.0%. There is a

significant mass loss until 292°C by 2.0% in the second step. At this step, the loss was characterized by crystalline-bound water (dehydration) and some low-temperature organic volatiles. There is a minor mass loss until 500°C by 0.9%. During this step, the total combustion of any carbonaceous organic compounds almost occurs which mainly derives from plant and animal fossils in the bentonite sample, and partial de-hydroxylation occurs. This is followed by a second significant drop, which ends at 744°C, characterized by a mass loss of 3.1% due to mainly de-hydroxylation and combustion of any residual carbonaceous organic compounds as well as decomposition of the present bentonite sample and minerals such as kaolinite. Finally, a second minor drop, which ends at 1000°C, is characterized by mass loss of 0.7% due to residual de-hydroxylation, calcination, and decomposition of the clays and minerals where the actual clay structure (the hydroxyl groups) is destroyed and decomposition of carbonates with the formation of oxides and carbon dioxide occurs. The most notable metal oxide of all formed by these reactions is calcium oxide (CaO) which is formed from calcium minerals present in clay in the form of calcite ($CaCO_3$). The results are in harmony with the previous literature review [31].

To produce Ca-Bentonite, the exchangeable cations *Na*, *K*, *Ca*, and *Mg* in the raw bentonite were exchanged to *Ca* form following Sarikaya and Yildiz [32]. A composite sample of raw bentonite was crushed and sieved to pass 150 μm to be used to prepare the Ca-bentonite. The raw bentonite sample was treated with 3 grams $CaCl_2$ /100 g bentonite. The excess $CaCl_2$ was washed out with distilled water. Consequently, the obtained Ca-bentonite sample was dried in an oven at 105 °C. The dried sample was crushed and passed through a 150 μm sieve and kept to be used in the concrete mixtures. Finally, 4 grams of Ca-bentonite was taken and washed three times with ethanol until the supernatant liquid electrical conductivity become less than 40 μm . The adsorbed *Ca*-cations in bentonite were replaced by NH_4^+ (Ammonium Acetate solution, 1.0 N). Then, the amount of adsorbed *Ca*-cations was determined.

2.1.2 Cement

Ordinary Portland Cement (Type II) was used in preparing mortar and concrete mixtures. The chemical and physical properties of the cement used are shown in Table (3).

Table 3. The chemical and physical properties of Ordinary Portland Cement (Type II) cement.

Property	Test Result	Limitations	Test Method
% Chloride Content (<i>Cl</i>)	0.037	≤ 0.10	BS EN 196-2 [33]
% Sulfate Content (SO_3)	2.97	≤ 3.5	BS EN 196-2 [33]
Setting Time (min)	180	≥ 60	JS 1470-3 [34]
Expansion (mm)	1.00	≤ 10	JS 1470-3 [34]
Compressive strength at 2 days (MPa)	24.5	≥ 10	JS 1470-3 [34]
Compressive strength at 28 days (MPa)	50.3	$\geq 42.5 \leq 62.5$	JS 1470-1[35]

2.1.3 Coarse and fine aggregate

For concrete mixtures, two sizes of coarse aggregates (coarse and medium-coarse) and two sizes of fine aggregate (medium-fine and fine) were used, while the latter size was used in the preparation of mortar. The physical properties of aggregates are shown in Table (4) while the combined gradations are shown in Figure (4). Curves indicate the upper and lower limits specified in ASTM C 33 [36] for coarse aggregate and fine aggregate. Weight aggregates should meet the requirements of ASTM C 33. These specifications limit the allowable amounts of substances and provide requests for aggregate characteristics.

Table 4. The physical properties of the aggregate.

Aggregate Type	Bulk Specific Gravity (SSD)	Absorption (%)	Fineness Modulus
Coarse Aggregate	2.68	1.0	---
Medium Coarse Aggregate	2.68	1.0	---
Medium Fine Aggregate	2.66	1.4	---
Fine Aggregate	2.64	0.34	2.5

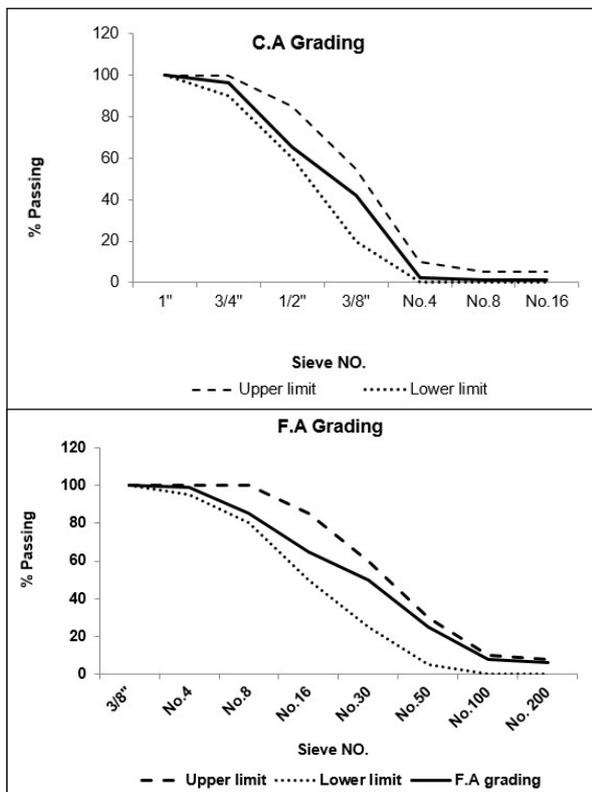


Figure 4. Coarse aggregate (C.A. Grading) and Fine aggregate (F.A. Grading) combined grading curve (

2.1.4 Chemical admixture

For concrete mixtures, a medium-range superplasticizer was used and it was suitable for the components of concrete mixture and greatly improve cement dispersion. The properties of both admixtures are listed in Table (5).

Table 5. The properties of plasticizer/superplasticizer used in the mixtures.

Property	Trowlit P	ADMIX CF 113
Color	Light brown liquid	Brown
Specific Gravity	1.02	1.06
Chloride content	Null	Null
Freezing point	0 °C	--

2.2 Experimental procedure

Twenty-one mixtures of mortar were prepared. The first mix is designated as a control mix where it is free of clay bentonite. The rest of the mixtures were prepared with different proportions of three types of bentonite (natural bentonite, heated bentonite, and Ca-bentonite). The addition of bentonite was introduced as a replacement of 10%, 20%, 30%, 40%, and 50% by the cement quantity. The bentonite was treated with different levels of heat. Three types of heated bentonite were introduced into the mixtures 250 °C, 550 °C, and 750 °C in addition to the natural bentonite. Table (6) shows the proportions of materials of the 21 mortar mixtures where they are considered according to proportion ranges suggested by Jordanian standards [32]. It is shown that the components of the mixtures were kept constant as those in the control one, except water, which was added for each mix to obtain the same workability as the control, mix. During the mortar mix design process, the flow table was used as a workability indicator for the whole mixture, and it was fixed at 70 cm. In this way, it was possible to determine the amount of water needed for each mix.

For each mortar mix, six prisms (40X40X160 mm) and six briquettes (25X25 mm central area) were prepared for sample casting, Figure (5). The samples were prepared to examine the compressive strength, tensile strength, and flexure strength of each mix. The mortar mixtures were performed according to BS EN 196-1 [33]. A standard mixer was used in the mixing process. Afterward, the mortar was filled in the molds and compacted by a Jolting table, and then covered with glass plates and kept in standard conditions (21±2 °C and 50±10% R.H.) to the next day. After 24 hours from casting, samples were taken out from the molds and stored for curing in a water tank under standard temperature (21±2) °C. For each test mix, samples of 6 molds were casted; three of them for the 7 days of age tests and the remaining three for the 28 days of age tests.



a. Compressive and flexural mold



b. Tensile Mold

Figure 5. Molds shapes.

Table 6. Mortar-Bentonite Mixtures Proportions.

Mix Designation	Fine Aggregate (g)	Cement (g)	Water (g)	Bentonite (g)	Type of Bentonite
M1	1350	550	280	0	-
M2	1350	495	320	55	Natural Bentonite
M3	1350	440	360	110	Natural Bentonite
M4	1350	385	400	165	Natural Bentonite
M5	1350	330	440	220	Natural Bentonite
M6	1350	275	480	275	Natural Bentonite
A2	1350	495	320	55	Heated at 250 °C
A3	1350	440	360	110	Heated at 250 °C
A4	1350	385	400	165	Heated at 250 °C
A5	1350	330	440	220	Heated at 250 °C
A6	1350	275	440	275	Heated at 250 °C
B2	1350	495	290	55	Heated at 250 °C
B3	1350	440	320	110	Heated at 250 °C
B4	1350	385	330	165	Heated at 250 °C
B5	1350	330	345	220	Heated at 250 °C
B6	1350	275	360	275	Heated at 250 °C
C2	1350	495	280	55	Heated at 750 °C
C3	1350	440	290	110	Heated at 750 °C
C4	1350	385	320	165	Heated at 750 °C
C5	1350	330	340	220	Heated at 750 °C
C6	1350	275	360	275	Heated at 750 °C

On the other hand, five sets of concrete mixtures were prepared plus the control mix. Each set was developed with two proportions of bentonite, 10%, and 20% by the cement's mass as a partial replacement. One set was mixed with natural bentonite while another one was prepared with Ca-bentonite. The rest of the concrete mixtures were prepared with heated bentonite of 250 °C, 550 °C, and 750 °C, respectively. Table (7) shows the concrete mixture proportions. The mixtures were designed by the Jordanian standard JS 1652 parts 1&2 [34]. For each concrete mix and after the completion of mixing, concrete fresh properties including temperature, slump, density, air content, and setting time respectively were tested. Thereafter, each concrete mix was cast in six

cubes (150X150X150 mm) for compressive strength, three cylinders (150X300 mm) for splitting tensile strength, three prisms (100X100X500 mm) for flexural strength, three prisms (70X70X250 mm) for shrinkage, and three molds (200X200X120 mm) for permeability tests according to EN 12390-8 [40]. Molds were covered with plastic sheets and kept in standard conditions (21±2 °C and 50±10% R.H.) to the next day. After 24 hours from casting, samples were taken out from molds and stored for curing in a water tank at standard temperature (21±2) °C until the testing date. The whole strength tests were performed according to JS 1652 parts 3, 5, and 6 [39].

Table 7. Concrete-Bentonite Mixtures Proportions.

Mix Designation	Type of Bentonite	Coarse Aggregate (kg/m ³)	Fine Aggregate (kg/m ³)	Cement (kg/m ³)	Water (kg/m ³)	Bentonite (kg/m ³)	Superplasticizer (L/100 kg cement)
AC	-	1230	589	315	200	0	0
BC	Natural Bentonite	1230	589	283	200	32	1.
CC	Natural Bentonite	1230	589	252	200	63	1.7
DC	Heated at 250 °C	1230	589	283	200	32	0.4
EC	Heated at 250 °C	1230	589	252	200	63	0.8
FC	Heated at 550 °C	1230	589	283	200	32	0
GC	Heated at 550 °C	1230	589	252	200	63	0.6
HC	Heated at 750 °C	1230	589	283	200	32	0
JC	Heated at 750 °C	1230	589	252	200	63	0.4
KC	Ca-bentonite	1230	589	283	200	32	1.2
LC	Ca-bentonite	1230	589	252	200	63	2

2.3 Statistical analysis

The normality test for the results of all tested hypotheses was conducted for both mortar and concrete mixtures. The

normality test results of all measurements were found to be normally distributed, and therefore, the arithmetic mean and standard deviation were calculated.

3. Results and discussion

3.1 Tests of mortar mixtures

Figure (6) shows the mean value of the compressive strength of the mixtures at 7 days of age compared to the mixtures at 28 days of age which are found to be significantly different at $p < 0.01$. That is consistent with the fact that compressive strength develops with time. In addition, Figure (6) shows the mean value of the compressive strength of the control mix (0 % of bentonite) compared to the mean value of various proportions of bentonite which are found to be significantly different at $p < 0.01$. As it is explained, bentonite was added to the mix in an increment of 10%. Reducing cement content reduces compressive strength. In contrast, compressive strength develops with time. The reduction in strength is referred to as the increase in water content. This interpretation is in line with the finding of Jiang J. et al., whom they indicated that the water content of cement-bentonite mixtures becomes larger as the proportion of bentonite increases [41]. However, the water content does not influence the stability of the mixture. According to the results shown, the mean values of the compressive strength of the mixtures of heated bentonite compared to the natural bentonite mixtures are found to be significantly different at $p < 0.01$ and exhibit relatively higher strength which points out to the efficiency of the heat treatment of bentonite [23].

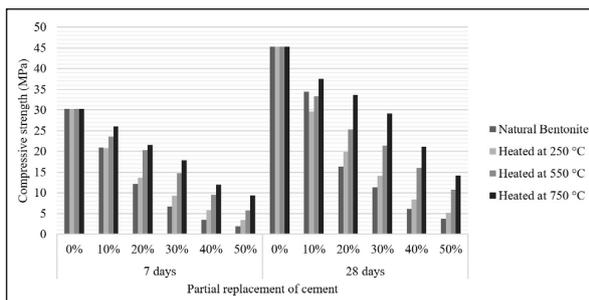


Figure 6. Compressive strength of mortar mixtures at 7 and 28 days.

In general, the results of flexural strength have the same behavior that was observed for the compressive strength of mortar mixtures at 7 and 28 days. Figure (7) shows the mean value of the flexural strength of the mixtures at 7 days of age compared to the mixtures at 28 days of age which are also found to be significantly different at $p < 0.01$. That is consistent with the fact that flexural strength develops with time. Furthermore, Figure (7) shows the mean value of the flexural strength of the control mix (0% of bentonite) compared to the mean value of various proportions of 10% and 20% of heated bentonite at 550 and 750 °C which have not significantly found difference at $p < 0.01$ with values between 87% to 95% of the control mix's flexural strength. These promising outcomes point out the effect of the heat treatment conducted on the material [23]. While the mean values of the flexural strength of the 30%, 40%, and 50% mixtures of natural and heated bentonite at 250 °C compared to the control mix are found to be significantly different at $p < 0.01$, and exhibit relatively higher flexural strength.

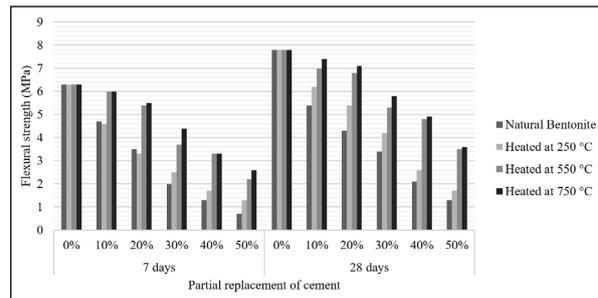


Figure 7. Flexural strength of mortar mixtures at 7 and 28 days

The results of tensile strength have the same behavior observed for the flexural strength of mortar mixtures at 7 and 28 days of age. Figure (8) shows the mean value of the tensile strength of the mixtures at 7 days of age compared to the mixtures at 28 days of age which are also found to be significantly different at $p < 0.01$. And that is consistent with the fact that also the tensile strength develops with time. Furthermore, Figure (8) shows the mean value of the tensile strength of the control mix compared to the mean value of various proportions of 10% and 20% of heated bentonite at 550 and 750 °C which are found to be not significantly different at $p < 0.01$. These promising outcomes point out the effect of the heat treatment conducted on the material [23]. While the mean values of the tensile strength of the 30%, 40%, and 50% mixtures of natural and heated bentonite at 250 °C compared to the control mix are found to be significantly different at $p < 0.01$, and exhibit relatively higher tensile strength.

Herein, it is seen that treated bentonite has better results than natural. The development of the strength of the cement-bentonite mixtures is slower at an early age which is due to the slow gain of strength for the pozzolana materials in general [20]. Nevertheless, the mixtures with 10% and 20% of heated bentonite at 750 °C show development of tensile strength at 28 days by 27 and 32% of their strength at 7 days. In addition, their tensile strengths are 92 and 87% of the tensile strength of the control mixture.

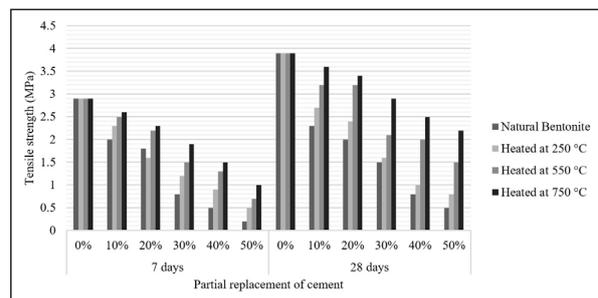


Figure 8. Tensile strength of mortar mixtures at 7 and 28 days

3.2 Tests of concrete mixtures

Results of the tests conducted to find the concrete fresh properties are shown in Table (8) where the mean values were calculated for each test. These results include immediate temperatures at the end of mixing, slump cone, fresh density, air content, and initial setting time. Table (8) includes the testing standard for each test. Temperature results were almost the same for all mixtures due to the standard condition in the lab and fresh densities also were the same. While for slump cone tests, values varied from 3

cm to 18 cm depending on the type and amount of bentonite used. For example, the lowest slump values were obtained for 20% replacement of cement by natural bentonite and *Ca*-bentonite. This is referred to a specific area of bentonite, that is higher than the specific surface area of cement. Thus, the workability of the cement-bentonite mixtures reduces as the bentonite content increases. This finding is in line with the study of [24]. However, the results show that the heat treatment of bentonite can improve workability. This is indicated in the results of mix HC and JC which have heated

bentonite at 750°C. Air content outcomes varied from 1.4% to a maximum of 2.4%, the highest values obtained at 20% replacement of cement with natural and *Ca*-bentonite. These results again point out the advantage of the heat treatment of bentonite, which gives very good results in comparison with the control mix. From the initial setting time, it can be seen that the initial setting time was increased in mixtures containing bentonite and superplasticizer in comparison with the control mix, which is expected out of the known behavior of pozzolana material [14, 20, and 21].

Table 8. Concrete Mixtures Fresh Properties

Mix Designation	Temperature (°C)	Slump (mm)	Fresh Density (kg/m ³)	Air Content (%)	Initial Setting Time (hr)
Standards	ASTM C 1064 [42]	JS 1651-2 [43]	JS 1651-6 [44]	JS 1651-7 [45]	ASTM C 403 [46]
AC	20.3	18	2380	1.5	4:00
BC	20.5	9	2360	2	5:00
CC	20.6	3	2340	2.4	5:30
DC	21.0	15	2380	1.7	4:30
EC	20.5	9	2390	1.6	5:00
FC	20.7	16	2390	1.6	4:30
GC	22.0	12	2380	1.5	5:00
HC	21.8	17	2370	1.6	4:30
JC	21.2	18	2390	1.4	5:00
KC	20.3	12	2390	1.5	5:30
LC	20.9	3	2400	2.3	5:30

As it is mentioned before, the mechanical properties of the mixtures were examined through different experiments. For the compressive strength test, specimens were tested at 7- and 28-days of age, Figure (9). While for flexure and splitting tensile strength tests, specimens were tested at 28 days of age, Figure (10). The mean of the three specimens of each test at each age was calculated.

Figure (9) shows the mean value of the compressive strength of the concrete mixtures at 7 days of age compared to the mixtures at 28 days of age are found to be significantly different at $p < 0.01$. And that is consistent with the fact that compressive strength develops with time. Also, Figure (9) shows the mean value of the concrete compressive strength of the control mix compared to the mean value of 10% and 20% proportions of bentonite are found to be significantly different at $p < 0.01$. Reducing cement content reduces compressive strength. In contrast, compressive strength develops with time. The mean values of the compressive strength of the mixtures with 10% and 20% of heated bentonite and *Ca*-bentonite are compared to the natural bentonite mixtures which are found to be not significantly different at $p < 0.01$. Even though the results show that compressive strength is developed in all mixtures, it is developed for the mix with 10% of heated bentonite at 750°C and *Ca*-bentonite by about 28%. On the other hand, it is almost developed by 25% of the mixture with 20% of heated bentonite at 750°C and *Ca*-bentonite. This is in line with the previous conclusion, that increasing the bentonite affects the development of strength at an early age, which is due to the slow pozzolanic reaction. Thus, it is expected that the compressive strength of the cement-bentonite mixture will increase with time because of the continuous reactions.

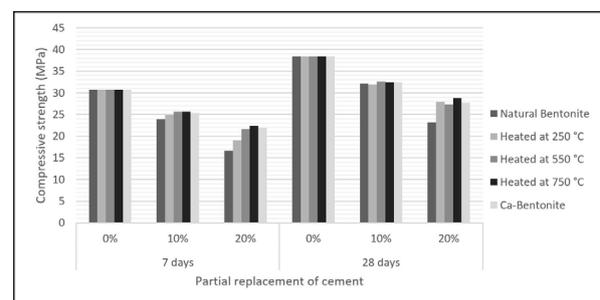


Figure 9. Compressive strength of concrete mixtures at 7 and 28 days.

According to the results shown in Figure (10), the mean value of the 10% and 20% proportions of natural bentonite, heated bentonite, and *Ca*-bentonite concrete flexural strength and splitting tensile strength compared to the mean value of the control mix which is found to be significantly different at $p < 0.01$. There is an increase in the flexural and splitting tensile strength in all tests of the mixtures with the heat-treated bentonite and *Ca*-bentonite. In contradiction, the replacement of natural bentonite reduces the strength compared to the control mixtures. This behavior can be attributed to the structure and the physicochemical properties that could be affected by thermal treatment [47,48]. The flexural strength increased up to 20% with an addition of 10% of heated bentonite at 750°C. On the other hand, the maximum increase of splitting tensile strength is about 25% for the mix with 10% heated bentonite at 750°C in comparison to the control mixture. The findings of these experiments are in line with the conclusion of Xianggyang Man et al. [49].

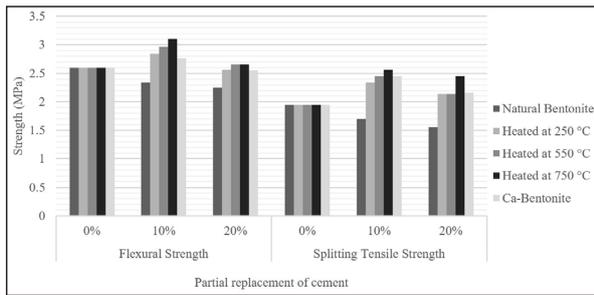


Figure 10. Flexural and splitting tensile strengths of concrete mixtures at 28 days

Figure (11) shows the results of the shrinkage and water permeability tests of concrete mixtures at 28 days of the age of the 10% and 20% proportions of natural bentonite, heated bentonite, and *Ca*-bentonite and the control mix. The mean values of the 10% and 20% proportions of natural bentonite, heated bentonite, and *Ca*-bentonite maintain shrinkage and impermeability compared to the mean value of the control mix which is found to be significantly different at $p < 0.01$. The concrete shrinkage in all cement-bentonite mixtures is reduced especially for the mixtures with natural and *Ca*-bentonite. The recorded shrinkage of the control mixture at 28 days is 296- μ strain, whereas it drops to 226 and 206 μ strain for the mixture of 10% and 20% of the *Ca*-bentonite, respectively. However, the shrinkage of the heat-treated bentonite at 750 °C with replacement of 10% and 20% is 287

and 267 μ strain, respectively. The behavior of the heat-treated bentonite can be explained by the thermal gravimetric analysis, Figure (3). It is indicated that the weight losses of bentonite at 250 °C, 550 °C, and 750 °C are 92.6%, 91.2%, and 88.1%, respectively. Thus, the free water of the bentonite is reduced by increasing the heating of the bentonite and so the shrinkage increases. Nevertheless, the TGA tests and the mechanical experiments of the cement-bentonite mixtures point to the stability and durability of the heated bentonite at 750 °C. Salman Afzal et al. [50] examined the effect of the partial replacement of cement by bentonite on autogenous shrinkage. The findings of their work are in high agreement with the outcomes of the experiment that was attained in this study. They concluded that the presence of bentonite enhances the relative humidity and then improves concrete shrinkage.

The results of the permeability tests show an improvement where the maximum reduction is noticed in the mixture of 20% of the *Ca*-bentonite (24.4 mm). These results describe the characteristics of bentonite, which is known as a filling material. In addition, that improvement in impermeability is attributed to the chemical composition of the used bentonite, which is mainly composed of SiO_2 and Al_2O_3 (63.8%). That chemical characteristic helps increase the rate of the hydration process, and thus refine the pores, which lead to enhancing the impermeability [25, 26].

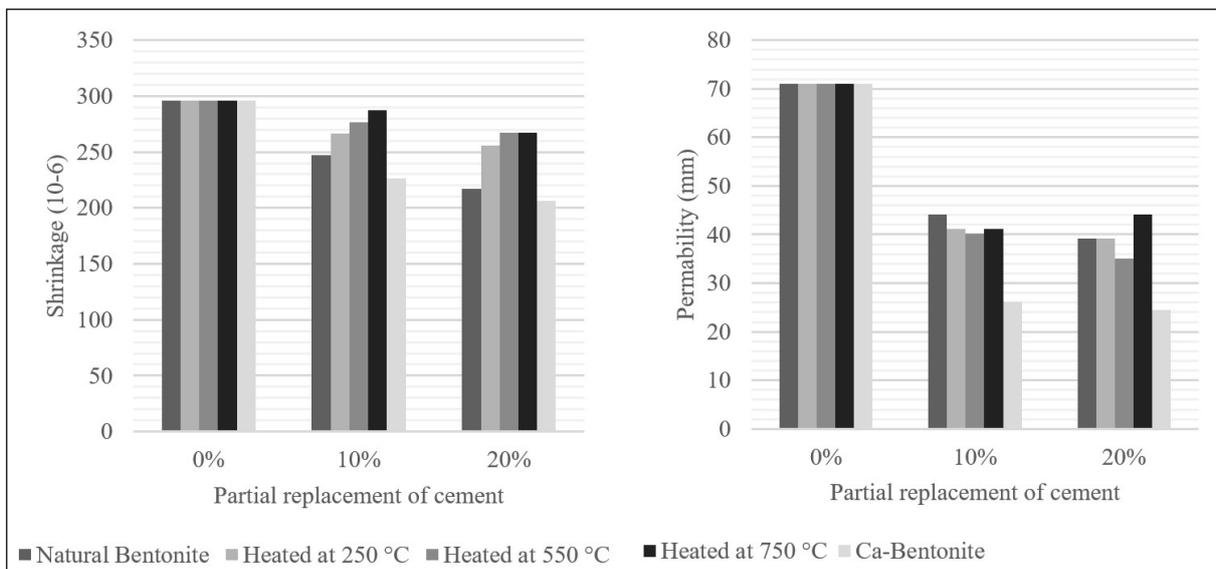


Figure 11. Shrinkage and permeability of concrete mixtures at 28 days

4. Cost analysis

The manufacturing of cement involves the sintering of blended ingredients (limestone, sand, and clay) at 1480 °C in a rotary kiln. The high temperature needed for the production process makes it an energy-intensive process. The production of one ton of cement requires 5-6 GJ of energy from fuel. This amount of energy is obtained from the burning of 175 m³ of natural gas, 263 m³ of LPG, or 6 tons of heavy fuel

oil. In addition, the process requires 100-200 KW/ton of electricity for the motors that derive the rotary kiln and mills. On the other hand, calcination of bentonite requires firing at 550 °C, hence replacing part of the cement with bentonite in any proportion will lead to a great reduction in fuel and electricity consumption. Tables (9 and 10) show the effects of replacing the cement with bentonite. The calculations are based on data obtained from a cement factory, in Amman.

Table 9. Shows the effect of replacing cement with bentonite up to 50% on the consumption of heavy fuel oil and consumption of electricity.

	The Mixtures		Energy consumption		Energy reduction	
	Cement %	Bentonite %	HFO ton	Electricity KW	Fuel	Electricity
Case 1	100	0	6	130	-	-
Case 2	90	10	5.68	123	5%	5%
Case 3	80	20	5.36	116	11%	11%
Case 4	70	30	5.04	109	16%	16%
Case 5	60	40	4.72	102	21%	22%
Case 6	50	50	4.4	95	27%	27%

Table 10. Shows the effect of using bentonite as a substitute for part of the cement on liquid propane gas (LPG) consumption.

	The Mixtures		Energy consumption		Energy reduction	
	Cement %	Bentonite %	Fuel LPG	Electricity KW	Fuel	Electricity
Case 1	100	0	263	130	-	-
Case 2	90	10	249.7	123	5%	5%
Case 3	80	20	236.4	116	10%	11%
Case 4	70	30	223.1	109	15%	16%
Case 5	60	40	209.8	102	20%	22%
Case 6	50	50	196.5	95	25%	27%

It is evident from the data shown in Tables (9 and 10) that replacing cement with bentonite reduces the consumption of heavy fuel oil by 5% to 27%, and the LPG by 5% to 25% depending on the percentage quantity of bentonite. The percentage reduction in electrical power follows the same trend. The reduction in fuel quantity (whether it is heavy fuel oil, LPG, or any other fossil fuel) with a reduction in electric power consumption has a great reflection on the total cost of cement.

In addition, cement manufacturing releases CO_2 in the atmosphere both directly when calcium carbonate is heated, producing lime and carbon dioxide [51], and indirectly through the use of energy. The cement industry produces about 5% of global man-made CO_2 emissions of which 50% is from the chemical process and 40% from burning fuel [52]. The amount of CO_2 emitted by the cement industry is nearly 900 kg of CO_2 for every 1000 kg of cement produced [53]. In comparison with Ordinary Portland Cement (OPC), heat-treated bentonite at 550 °C produces only 16% CO_2 from burning fuel instead of 40%. The heating of bentonite does not produce any CO_2 by itself. Therefore, the total amount of CO_2 emitted by 1000 kg of bentonite produced at 550 °C is 144 kg, and at 750 °C is 193 kg. Heat-treated bentonite partially applies for replacing cement in concrete mixtures to reduce CO_2 . It also has consumed a lower energy requirement in production compared to OPC cement.

5. Conclusion

The following conclusions can be drawn from the experimental results obtained: Bentonite addition decreased mortar strength in comparison with the control mix without bentonite due to the increase in water need, but it still can be used for producing low-strength products with lower cost.

The mortar mixtures containing heated bentonite at 750 °C achieved good results close to those results achieved by OPC alone. The bentonite particles seem to act as a pore-reducing or filling material.

For concrete mixtures, natural and *Ca*-treated bentonite increase fresh concrete viscosity and as a result increase its cohesion and consistency. This property can be very useful in the field of self-compaction concrete instead of viscosity modifier admixtures where this is mandatory. Using natural bentonite instead of a viscosity modifier can reduce production costs.

Both flexural and compressive strength was increased by 20% and 25% respectively for most of the bentonite-concrete mixtures. These results can be used for producing products where these properties are more critical.

Both natural and *Ca*-treated bentonite reduce concrete shrinkage at an early age due to its expansion nature. *Ca*-bentonite behavior was slightly better than natural bentonite at the early ages of concrete.

Concrete permeability was highly reduced by using bentonite especially *Ca* treated where permeability was reduced by 60%. This is an excellent indication for using this material in producing more durable concrete structures or concrete components such as curbstone, concrete pipes, or even tiles and bricks.

In conclusion, Jordanian clay bentonite has the potential to become an alternative for producing more durable concrete structures or concrete components such as curbstone, concrete pipes, or even tiles and bricks. Furthermore, bentonite particles seem to act as a pore-reducing or filling material. Consequently, it decreases concrete permeability. More investigations shall be conducted on dry mortar products and applications using treated bentonite like cement plaster, grout, and repair mortar.

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