Performance of Jordanian Masonry Cement for Construction Purposes

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ABSTRACT

Laboratory tests were conducted to evaluate the performance of a newly produced Jordanian masonry cement by Jordan Cement Factories Company (Lafarge), and to identify the optimum mortar mixes best suited to different masonry applications. Tests conducted include air content, water retention and workability in the fresh state, compressive, flexural and tensile strengths, and capillary water absorption in the hardened state. Test results indicated that masonry mortar mixtures proposed in this investigation met the European and American standard requirements for water retention and air content. The use of hydrated lime in these mixtures resulted in reducing the compressive and flexural strengths without enhancing the workability. The strength test results also indicated that masonry mortars, prepared at an aggregate to cement ratio equal to or less than 4 on loose volume basis, can be successfully used for different masonry applications in Jordan.

KEYWORDS: Masonry cement, Mortar, Plastering bricks, Joints.

INTRODUCTION

Masonry cements are being produced around the world with significant replacements of cement by pozzolanic matter (natural pozzolan, slag, silica fume, fly ash or metakaolin), lime or both (Lanas et al., 2004; Fortes Revilla et al., 2006; Lanas et al., 2006; Lanas and Alvares, 2003; Gleize et al., 2003). Therefore, cement pastes or mortars made with such cements would have higher initial and final setting times, better workability, high resistance to water penetration and a more natural color than those made with conventional cements. Moreover, the replacement of cement by additives at high percentages (reaching as high as 50%) has two advantages: (a) reducing the quantities of calcinated cement required for producing a certain quantity of masonry cement, and thus the accompanying quantities of carbon dioxide and harmful dust emitted; and (b) reducing the production cost significantly. The masonry cements produced in different countries have varying properties because of the difference in the type and content of additive used, chemical composition of the cement clinker, and specific surface of cement (ASTM, 2005; VDZ, 2003-2004). Therefore, mix proportions recommended by working codes for mortars with Type I ordinary cement are subjected to modification whenever a new masonry cement is to be used. Recently, the Jordan Cement Manufacturing Company (Lafarge) has been involved in the process of producing local masonry cement (MC 22.5X) using natural Jordanian pozzolan at a replacement level of 45% of cement and about 1.6% of gypsum, on weight basis. The lack of information and specifications related to this type of cement necessitates the need for exploring its potential applications in the construction industry sector.

The increasing use of cement-based mortars for the restoration of historic buildings and structures justifies

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the research on these materials. Masonry mortar can be defined as a mixture of Portland cement, hydrated lime and sand with water. Masonry mortar functions include: bonding units of masonry, distributing loads, absorbing deformations and sealing joints. To permit effective use, mortars should be workable and cohesive in the fresh state in order to bed bricks and blocks or render and plaster surfaces with minimal efforts. The durability and the resistance against water penetration are best provided by a strong mortar, whereas movement tolerance is best provided by a weak mortar which cracks readily if movement occurs; the mortar must not be stronger than the units it is bonding.

Table 1. Details of testing program for mortars with masonry cement.

Number	Proportion (C: L: A)	Tests in Fresh State				Tests in Hardened State			
		AC	WR	W	PA	CS	FS	WAC	AS
1	1: 0: 2	•	•	•	•	•	•	•	
2	1: 0 :2.5	•	•	•	•	•	•	•	
3	1: 0: 3	•	•	•	•	•	•	•	•
4	1: 0: 3.5	•	•	•	•	•	•	•	•
5	1: 0: 4	•	•	•	•	•	•	•	•
6	1: 0: 4.5	•	•	•	•	•	•	•	•
7	1: 0: 5	•	•	•	•	•	•	•	
8	1: 0: 6	•	•	•	•	•	•	•	
9	1:0.25:3	•	•	•	•	•	•	•	•
10	1:0.5:3.5	•	•	•	•	•	•	•	
11	1:0.75:4	•	•	•	•	•	•	•	
12	1:1:4.5	•	•	•	•	•	•		
13	1:1.25:5	•	•	•	•	•	•		
14	1:1.5:6	•	•	•	•	•	•		

• : Masonry cement; based on bulk loose volume; AG: Aggregate Gradation; AC: Air Content; WR: Water Retention; W: Workability; PA: Plastering Area; CS: Compressive Strength; FS: Flexural Strength; WAC: Water Absorption Coefficient; AS: Adhesive Tensile Strength.

Masonry mortar mixtures are usually prepared using either ordinary cement or masonry cement without and with additives such as hydrated lime or special plasticizers. These help improving the relatively low strength and workability of mortars. The European (EN 413-1) and American (ASTM C270) standards classify four types of masonry mortars according to their use, (I, II, III, IV) and (M, S, N, O), respectively (ASTM, 2005; EN, 1994). Because of their relatively high bond and resistance to water penetration in their hardened state, type (II or S) is recommended for external use, whereas types (III or N) and (IV or O) are recommended for internal use. It should be indicated that masonry mortars exhibit high shrinkage, often over 2000 x 10^{-6}, yet this is of little consequence especially when correctly used in small thicknesses.

The main objectives of this study were to evaluate the performance of a newly produced Jordanian masonry cement, and to identify the optimum mortar mixes, best suited to different masonry applications. Tests conducted include air content, water retention and workability in the fresh state, modulus of rupture, compressive strength, capillary water absorption, and adhesive tensile strength in the hardened state.

Table 2: Chemical composition of cement clinker, natural pozzolan, and masonry cement.

Oxide	Clinker (%)	NP (%)	Masonry Cement MC22.5X (%)
Si_2O	20.5	37.22	26.4
CaO	64.3	12.00	46.0
Fe_2O_3	3.5	10.17	6.6
Al_2O_3	5.2	12.42	7.3
MgO	4.3	8.12	6.4
SO_3	1.00	0.25	2.15
K_2O	0.7	2.07	0.85
IR[1]	0.12	--	
LOI[2]	5.5	12.7	4.4
SSB (CM^2/GM)			5370

1: Insoluble Residue; 2: Loss on Ignition; NP: Natural Pozzolan.
SSB: Blain Specific Surface.

Table 3: Loose unit weight for different ingredients of mortars.

Material	Masonry cement (kg/m^3)	Hydrated lime (kg/m^3)	Limestone aggregate (kg/m^3)
LUW	1035	487	1468

LUW: Loose Unit Weight.

Table 4: Proportions of mortars prepared using masonry cement and aggregates.

Mix	(C:AG)[1]		(C:AG)[2]		C (g)	AG (g)	W (g)	PN (mm)	FT (%)
MC-1	1	2	1	2.8	400	1135	284	35	260
MC-2	1	2.5	1	3.5	400	1418	336	35	260
MC-3	1	3	1	4.3	400	1702	392	33	270
MC-4	1	3.5	1	5.0	400	1986	420	32	260
MC-5	1	4	1	5.7	400	2269	480	33	260
MC-6	1	4.5	1	6.4	400	2553	520	33	270
MC-7	1	5	1	7.1	400	2837	582	34	260
MC-8	1	6	1	8.5	400	3404	696	36	270

C: Cement; AG: Aggregate; W: Water; PN: Penetration;
FT: Flow Table reading;1: on bulk loose volume basis; 2: on mass basis.

Table 5: Proportions of mortars prepared using masonry cement, lime and aggregate.

Mix	C	L	AG[1]	C	L	AG[2]	C (g)	AG (g)	L (g)	W (g)	PN (mm)	FT (%)
MCL-3	1	0.25	3	1	0.12	4.3	400	1702	47	438	37	260
MCL-4	1	0.5	3.5	1	0.24	5.0	400	1986	94	454	36	260
MCL-5	1	0.75	4	1	0.35	5.7	400	2269	141	432	37	250
MCL-6	1	1.0	4.5	1	0.47	6.4	400	2553	188	417	34	250
MCL-7	1	1.25	5	1	0.59	7.1	400	2837	235	287	35	240
MCL-8	1	1.5	6	1	0.71	8.5	400	3404	282	294	33	240

C: Cement; AG: Aggregate; L: Lime; W: Water; PN: Penetration; FT: Flow Table reading;
1: bulk loose volume basis; 2: based on mass ratios.

Table 6: Results of different tests performed on mortar with masonry cement.

		Tests in Fresh State				Tests in Hardened State			
Mix	**(C: L: A)**	**AC (%)**	**WR (%)**	**W**	**PA[1] (m^2/bag)**	**CS (MPa)**	**RM (MPa)**	**WAC ($kg/m^2.min^{0.5}$)**	**AS (MPa)**
MC-1	1: 0: 2*	3.3	94	Excellent	3.9	19.23	6.45	0.92	N.M.
MC-2	1: 0 :2.5	3.8	94	Excellent	4.4	15.21	5.39	1.21	N.M.
MC-3	1: 0: 3	4.5	93	Excellent	5.4	11.39	4.38	1.54	N.M.
MC-4	1: 0: 3.5	4.9	93	Very Good	5.6	10.26	4.08	1.6	0.87≤
MC-5	1: 0: 4	5.9	93	Good	6.3	8.42	3.30	1.69	0.67≤
MC-6	1: 0: 4.5	7.5	93	Good	7.8	7.11	2.78	1.83	0.59≤
MC-7	1: 0: 5	7.4	93	FAIR	8.3	5.71	2.41	1.9	0.47≤
MC-8	1: 0: 6	7.6	93	FAIR	9.4	4.31	2.13	2.22	N.M.
MCL-3	1:0.25:3	4.6	93	Excellent	6.1	9.17	3.89	1.2	0.90
MCL-4	1:0.5:3.5	5.1	93	Excellent	7.2	6.78	3.14	1.61	N.M.
MCL-5	1:0.75:4	5.4	93	Very Good	7.8	5.5	2.52	1.85	N.M.
MCL-6	1:1:4.5	7.3	94	Good	8.7	4.71	2.08	N.M	N.M.
MCL-7	1:1.25:5	6.8	94	FAIR	9.6	3.67	1.77	N.M	N.M.
MCL-8	1:1.5:6	7.3	94	FAIR	10.4	2.8	1.41	N.M	N.M.

*: Based on bulk loose volume; 1:for standard thickness of 25 mm; AC: Air Content; WR: Water Retention; W: Workability; PA: Plastering Area; CS: Compressive Strength; RM: Rupture Modulus (Flexural Strength); WAC: Water Absorption Coefficient; AS: Adhesive Tensile Strength.

MATERIALS AND TEST PROCEDURES

Materials

The materials used in this study consist of :

Masonry Cement (MC): supplied by the Jordanian Manufacturing Company (Lafarge). It is a mixture of natural pozzolan (Type F), cement clinker and gypsum. To compensate for the relatively high replacement percentage of natural pozzolan at 45 (by wt), the mixture was ground finer to achieve relatively a fineness of about 550 m^2/kg. The chemical composition of the natural pozzolan, cement clinker and masonry cement, as provided by the manufacturer, are presented in Table 2.

Limestone Aggregate: Crushed limestone fine aggregate was used in preparing mortars for general masonry works and plastering. The gradation of the aggregate used in this study was performed in the laboratory and compared with the Jordanian standard specification limits (JSS) as shown in Fig. 1.

Hydrated Lime: The lime used in preparing the mortar was purchased in powdered and hydrated form from the local market.

Tap Water: impurities free water was used in the mixing process.

The loose unit weight for the aggregate, cement and lime were obtained and listed in Table 3.

Based on these values, the weight ratios between mortar ingredients were computed.

2.2 Testing Procedure

A series of laboratory tests were conducted in order to evaluate the performance of the cement produced in the fresh and hardened states following European standards (EN). Mortar mixtures for tests in fresh and hardened states were prepared according to test method EN 196-1, (EN, 1995). The water was placed first in the mechanical mixer, and then the cement was added and mixed, before the sand was placed and mixed with the cement paste. The proportions for the mortar mixtures proposed in this study are listed in Tables 4 and 5.

Tests in the Fresh State

Determination of water content: the water content corresponding to normal consistency was determined following the penetration test method EN 413-2, (EN, 1994). The normal consistency was defined at a penetration (PN) of 32±3 mm. Corresponding Flow Table values (FT) were also determined according to test method EN 1015-3, (EN, 1999). The penetration and flow values for the mixtures proposed in this investigation are presented in Tables 4 and 5.

Determination of air content: the Air Content (AC) of the mortar is determined from the reduction in volume which occurs when the air is expelled by a liquid. The tests were performed according to test method EN 413-2, (En, 1994). The air content was determined for all mortar mixtures as shown in Table 6.

Determination of water retention: the Water Retention (WR) of the mortar is the mass of water retained (in the mortar) after suction treatment and is expressed as a percentage by mass of its original content. The tests were conducted according to test method EN 413-2, (EN, 1994). The water retention values of the mixes investigated are listed in Table 6.

Workability: Workability is the ease with which masonry mortars can be spread to bed concrete bricks and building stones, and plaster or render concrete surfaces. There is no single test followed in determining the workability of mortar. Usually the person's own judgment is the best measure in this regard. Therefore the degree of Workability (W) of the mortar mixtures proposed in this study was subjectively evaluated and reported in Table 6 as either being excellent, very good, good, fair or not good.

Estimation of plastering area: the Plastering Area (PA) for various mixtures was measured as follows: Certain quantity of each mixture was spread above concrete blocks of 150 x 550 mm^2 area at a thickness of 25mm and their areas were measured. Knowing the amount of cement used in each mixture, the plastering area per 50 kg of cement (one cement bag) was computed. The plastering areas for the mixtures investigated are listed in Table 6.

Table 7: Limits set on compressive strength, air content, water retention and capillary water absorption.

Test	Load Bricks Laying	Non-Load Bricks Laying	Stone Laying	Plastering & Rendering
CS (MPa)	5.2: ASTM 6.5: JSS	2.4: ASTM 2.5: JSS	6.5: JSS* 7.5: ENS*	2.5:ENS1 5: ENS2
AC (%)	14, max: ASTM	14, max: ASTM	6, max: ENS*	6, max: ENS*
WR (%)	75, min: ENS	75, min: ENS	75, min: ENS	75, min: ENS
CWA ($kg/m^2.min^{0.5}$)	0.4, max: ENS	0.40,max: ENS	0.20,max:ENS	0.20,max:ENS

CS: Compressive Strength (MPa); *: No specific values are available; AC: Air Content; Plastering;
2: Rendering; WR: Water Retention; JSS: Jordanian Standard Specifications; ENS: European Standards;
CWA: Capillary Water Absorption; ASTM: American Standards for Testing Materials.

Table 8: Physical properties of the masonry cement performed by the Royal Scientific Society (RSS).

Property	Result	Standard European Specification BS EN 413-1/04	
		Test Method	Specification Requirements
Initial Setting Time (min)	250	EN 196-3/05	60 ≤….
Final Setting Time (min)	330	EN 196-3/05	---------
Fineness (retained on sieve 90μm) (%)	7.5	EN 196-6/05	…..≤ 10
Water Content for Normal Consistency (%)	25.4	EN 196-3/05	---------
Expansion (Lechatelier) (mm)	1.5	EN 196-3/05	…..≤ 10
Compressive Strength (MPa)	14.4 at 7 days	EN 196 1/05	10 ≤…
	27.6 at 28 days		22.5≤… ≤42.5
Cement Fineness (cm^2/gram)	5400		3500 ≤….

Tests in the Hardened State

Determination of water absorption coefficient: the Water Absorption Coefficient (WAC) due to capillary action of hardened mortars was determined using (40x40x160 mm) prisms and filter papers. The WAC was computed following EN 1015-18, (EN, 2002). Standard test procedures are presented in Table 6 for certain mortar mixtures.

Determination of flexural strength: Flexural strength of mortars was determined using (40x40x160 mm) prisms which were tested at the age of 3, 7 and 28 days using a flexural test machine. The preparation of the mortar mixes, curing and testing of the specimens were performed following EN 196-1 standards (EN, 1995). The flexural strength of the proposed mortar mixtures is listed as a modulus of rupture (RM), as shown in Table 6.

Determination of compressive strength: The compressive strength of the mortar mixtures was determined at 3, 7 and 28 days using portions of the prismatic specimens made and broken in the flexure test shown above following EN 196-1 standards (EN, 1995).

The Compressive Strength (CS) of the proposed mortar mixtures is listed in Table 6.

Determination of adhesion tensile strength: the adhesion strength of hardened mortars used for rendering and plastering on concrete substrates was determined according to EN test method 1015-12, (EN, 2000). Layers of certain mortar mixtures were attached to substrates of matured concrete blocks (150x50x550 mm), and then cured for 28 days before the 10 mm- layers were pulled off the surface of the concrete blocks to determine bond strength.

RESULTS AND DISCUSSION

Results of tests on various mortars in fresh and hardened states are listed in Table 6. Compressive and flexural strength variation with aggregate to cement ratio as well as curing period for different mixtures are presented graphically in Figs. 2-4. The mixtures prepared were given letter-number designations. Letters MC refer to masonry cement and letter L refers to hydrated lime. These letters are followed by integers from (1 to 8) which refer to aggregate to cement ratios of (2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5 and 6), respectively. For example, MCL3 refers to a mortar mixture made with masonry cement and lime, at an aggregate-to-cement ratio of 3.

In the following sections the test results are analyzed to determine optimum mixing proportions for different applications of masonry mortar based on the requirements of Jordanian, American and European specifications, summarized in Table 7 (ASTM, 2005; EN, 1994; General Technical Specifications for Buildings, 1996).

Fresh Properties of Masonry Mortars

Air Content

The results of Table 6 show that the air content measurements for mortars made with masonry cement varied between 3.3 to 5.9 % for mixtures MC-1 through MC-5 and MCL-3 through MCL-8, and between 6.8 and 7.6% for mixtures MC-6 through MC-8 and MCL-6 through MCL-8, respectively. It should be noted that increasing the proportion of the volume of aggregates in these mixtures caused a considerable increase in air content which remained within the ranges of air contents specified by European standards and ACI code, as shown in Table 7. It can be concluded that all mortar mixtures meet the requirements for bricks laying at 14%, whereas only MC-1 through MC-5, MCL-3 through MCL-5 mixtures satisfy the requirements for mortars to be used in stone laying, plastering and rendering.

Water Retention

The water retention test measures the ability of mortars to maintain water; and thus be workable enough to be handled, used and gain satisfactory strength with minimal curing. The results presented in Table 7 indicate that all mortar mixtures attained water retention values greater than 75% (the lowest limit put on mortars for different masonry applications) given by the standards shown in Table 7.

Workability

The workability test results presented in Table 7 indicate that good workability of the mortar mixtures developed in this study can be achieved by keeping the proportion of the volume of aggregates with respect to masonry cement less than or equal to 4. It can also be observed that the incorporation of lime had limited contribution to improving the workability of relatively rich mixtures and negative impact on the workability of lean mortar mixtures; as an additional effort was needed to spread these mortars over concrete surfaces.

Plastering Area

The test results presented in Table 6 showed an increase of about 2.4 times in plastering areas per bag of cement corresponding to an increase of 3 times in the proportion of the volume of fine aggregates to masonry cement within the same mixtures. The test results shown in Table 6 also indicated that the use of lime increased the plastering area per bag of cement. The mortar mixtures containing hydrated lime achieved an increase of about 12% in plastering areas compared to mixtures without lime.

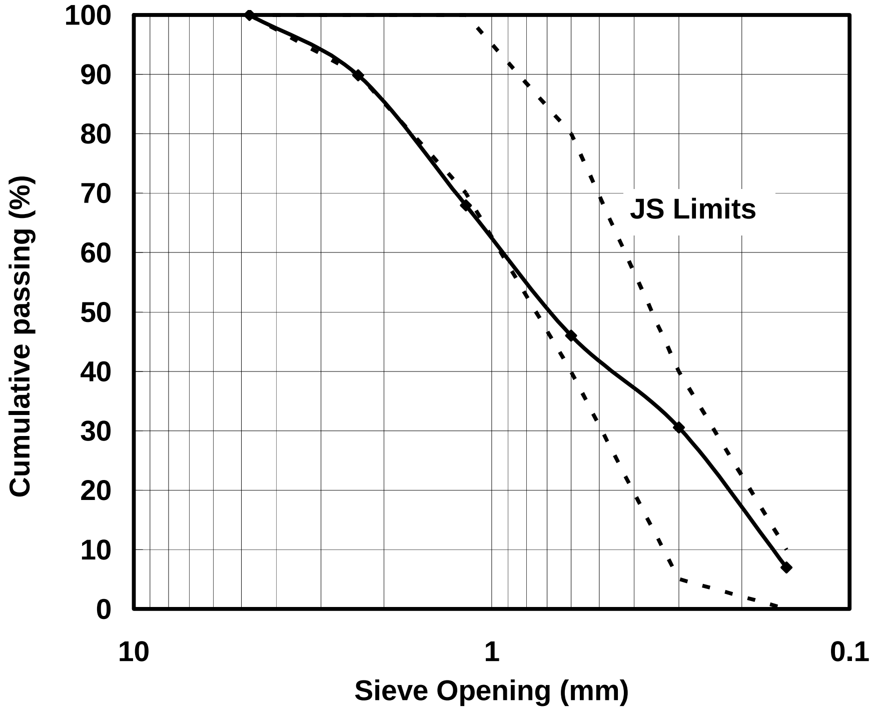

Fig. (1): Gradation of fine aggregates used in general masonry works.

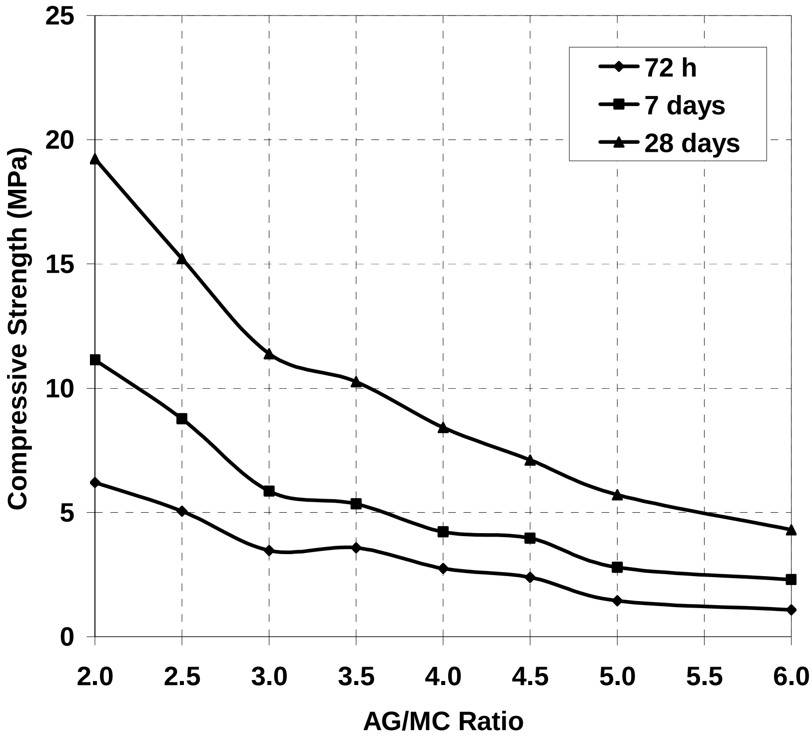

Fig. (2): Compressive strength versus ratio of aggregate to masonry cement at 3, 7 and 28 days.

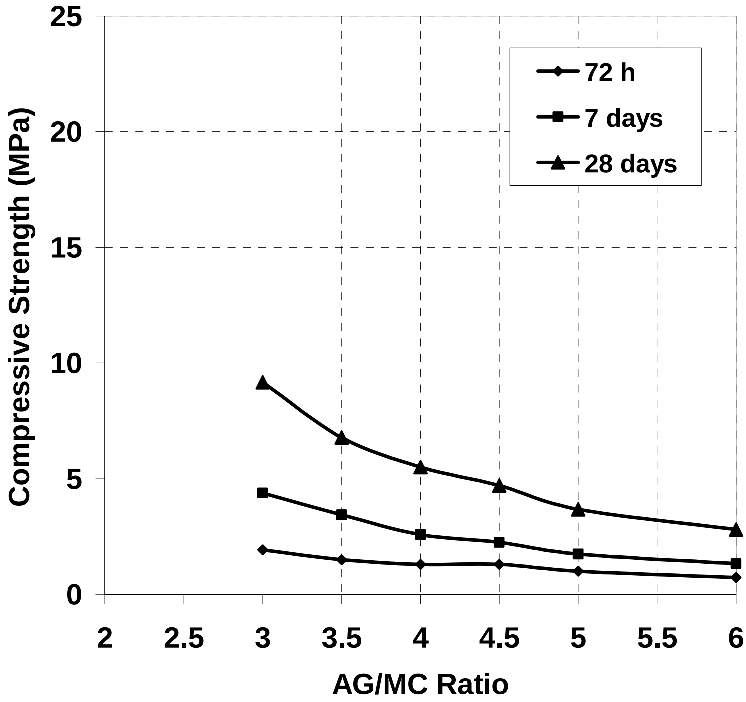

Fig. (3): Compressive strength versus ratio of aggregate to masonry cement at 3, 7 and 28 days (with lime).

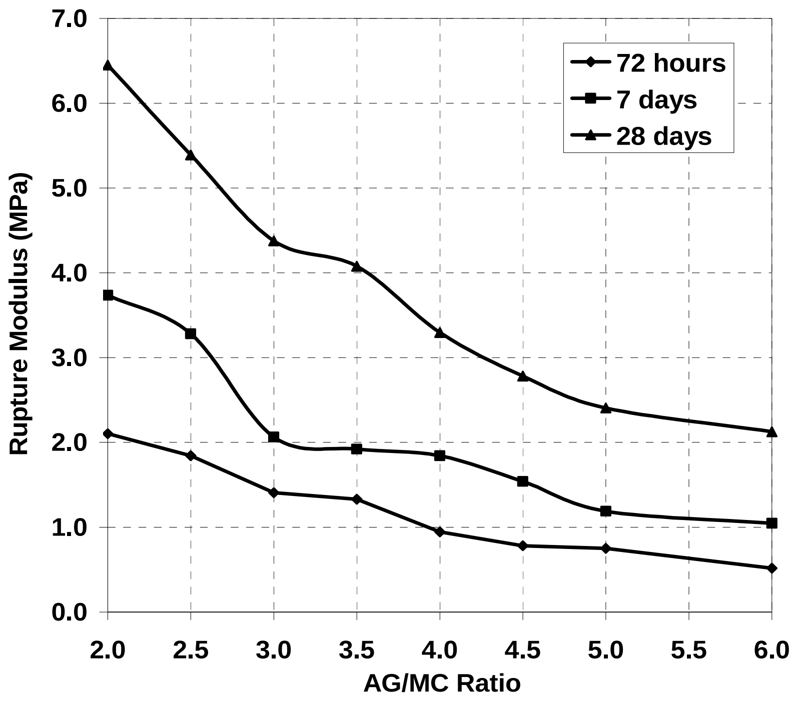

Fig. (4): Rupture modulus versus ratio of aggregate to masonry cement at 3, 7 and 28 days.

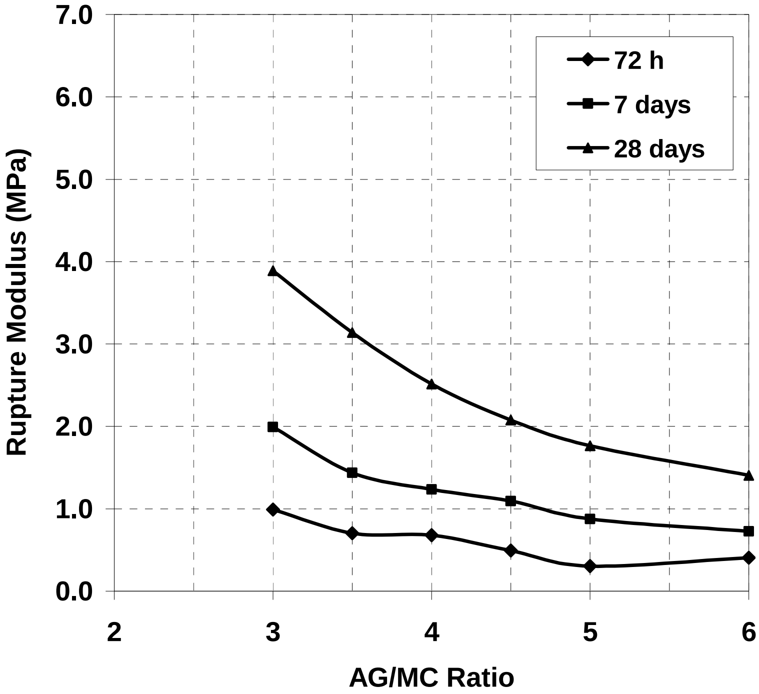

Fig. (5): Rupture modulus versus ratio of aggregate A to masonry cement at 3, 7 and 28 days (with lime).

Hardened Properties of Masonry Mortars

Compressive Strength

The compressive strength was determined for all mortar mixtures proposed in this study. The test results listed in Table 6 and shown in Figs. 2 and 3 can be used to decide the compliance of masonry mortar with existing standards and to aid in the selection of a certain mortar mixture for a specific application. It can be observed that masonry mortars made with an aggregate to cement ratio equal to or less than 4 met the European Standards and ASTM requirements shown in Table 7. The test results also showed that increasing the aggregate to cement ratio within the mortar mixtures caused a significant decrease in the compressive strength at different curing ages. The incorporation of lime in the mortar mixture had a negative effect on the compressive strength as seen from Fig. 3. The seven to twenty eight-day compressive strength ratio averaged about 53% and 48% for mixtures without and with lime, respectively.

Flexural Strength

The flexural strength of mortar controls its ability to resist cracking. The flexural strength test results of the mortar mixtures are presented in terms of rupture modulus as shown in Table 6 and Figs. 4 and 5. It can be observed that the rupture modulus values of masonry mortars reported in this investigation compare well with test results available in the literature for ordinary cement mortar (Erodogdu and Kurbetci, 2005). It can also be observed that increasing the aggregate to cement ratio within the mixtures caused a significant reduction in rupture modulus at different curing ages. The incorporation of lime in the mixtures caused a considerable decrease in rupture modulus values as seen from Fig. 5. The seven to twenty eight-day rupture modulus ratios averaged about 53% and 50% for mixtures without and with lime, respectively.

Adhesive Tensile Strength

The adhesive strength measures the ability of masonry mortar to bond masonry units together. The results of adhesive tensile strength of masonry mortars showed that for the majority of specimens tested the cast mortar layer detached from the concrete substrate, which means that the values reported in Table 6 underestimated the adhesive tensile strength. It can be seen from the Table that masonry mortars proposed in this investigation achieved an adhesion tensile strength of less than 1 MPa. Assuming that the minimum acceptable adhesive strength is 0.50 MPa, one can easily conclude that mixtures MC-4 through MC-6 as well as MCL-3 would meet the requirements for adhesive strength.

Water Absorption Coefficient

The Water Absorption Coefficient (WAC) test was carried out on selective mortar mixtures, which satisfied strength requirements for different masonry applications. The results listed in Table 6 indicated that all mixtures violated the limitation put on the water absorption coefficient of mortars used in different applications by the EN standards. The relatively high absorption values are related to the high porosity of the fine aggregates used; in excess of 3%. It should be mentioned that the WAC is a requirement by ES, and ACI for acceptance of masonry cement and not so for determining appropriate proportions of mortar mixtures. In this study, the WAC is used for comparative purposes. As can be noticed from Table 6, the use of lime had contributed to reducing the WAC value for mortars at an aggregate ratio equal to or less than 4, yet had limited effect on the WAC value for leaner mixtures.

COMPLIANCE OF MASONRY CEMENT WITH JORDANIAN STANDARDS

A further evaluation of the performance of the newly produced masonry cement was conducted at the building research center of the Royal Scientific Society. The test report obtained indicated the compliance of the produced cement with the existing Jordanian standards shown in Table 8. Therefore, the produced cement has officially achieved the Jordanian Accreditation System (JAS) for use in the construction industry sector.

CONCLUSIONS

Based on the complete experimental data and brief discussion already presented, the following conclusions could be stated:

1. The newly produced masonry cement can be successfully used for different masonry applications such as plastering, rendering and bonding masonry units without violating American, European or Jordanian specification standards.
2. The strength test results indicated that the mortar mixtures prepared at an aggregate to masonry cement ratio equal to 4 or less (on loose volume basis) seem to provide an optimum performance and can be recommended for different applications in Jordan.
3. Most of the mortar mixtures that were prepared at an aggregate to masonry cement ratios in the range of 2 to 6 (on loose volume basis) met the European and ASTM requirements for air content and water retention.
4. The use of lime in masonry mortars resulted in lower compressive strength and rupture modulus as compared to those without lime, without enhancing the workability. Hence, it is recommended not to use lime with masonry cement in producing masonry mortars.
5. The adhesive tensile strength results indicated that for general plastering works mortar mixtures with masonry cement must be prepared at an aggregate to cement ratios of 4 or less (on loose volume basis).

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