Case Studies in Construction Materials 11 (2019) e00295

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Case study

Interior plastering of Ottoman bath buildings

Emre İpekci*, Elif Uğurlu Sağın, Hasan Böke

Department of Architectural Restoration, Faculty of Architecture, İzmir Institute of Technology, 35430, İzmir, Turkey

ARTICLE INFO

Article history:
Received 10 September 2019
Accepted 17 October 2019

Keywords:
Çinili Bath
Architect Sinan
Plaster
Brick
Hydraulicity
Self-healing

ABSTRACT

Ottoman baths were peculiar buildings with their function in community life, architectural characteristics and material use. Their interior spaces were exposed to high humidity and temperatures that made the building structure vulnerable to physical, chemical, physicochemical and biological degradations. Plasters used on the interior wall surfaces were the most important agents to protect the structure from deterioration and provide durability. This study aims to exhibit the plaster characteristics of Çinili Bath in İstanbul which was an outstanding example of Ottoman baths and built by Great Architect Sinan. Basic physical properties, raw material compositions, mineralogical, microstructural and hydraulic properties of original brick-lime plasters called as horasan (khorasan) plasters used on the walls were determined by XRF, XRD, SEM-EDS and TGA. Multilayered plaster application together with the use of glazed tiles were observed on the wall surfaces of all interior spaces. The plasters were produced from pure lime and pozzolanic crushed brick or tile aggregates and hydraulic because of the pozzolanic properties of aggregates. They are stiff, compact and durable in hot and humid conditions of bath buildings due to their self-healing properties and the formation of calcium silicate hydrates and calcium aluminate hydrates at the lime-brick interfaces and in the pores of the pozzolanic brick aggregates by the reaction of lime. Characteristics of brick aggregates were compared with the construction bricks used in the building. Their chemical and mineralogical compositions revealed that the aggregates had not been produced from construction bricks. All the results indicated that brick-lime plasters were the most suitable materials for bath buildings to protect the structure from the effect of water.

1. Introduction

Plasters and renders are important parts of historic buildings that provide surface protection to the structural system of buildings against water and moisture penetration, salt crystallization, wetting-drying and freezing-thawing cycles and biological growths. They also support fire resistance, show high resistance against impact damages, modify sound absorption and improve thermal and sound insulation. In addition to these functions, they also provide an aesthetic finishing and a regular, smooth surface proper to painting or decoration which can be easily repaired [1,2].

Lime had been one of the most common raw materials used in plaster manufacturing since ancient times. Lime plasters which had been produced by using lime as binding material and aggregates of different origins can be classified according to their hydraulic properties as non-hydraulic and hydraulic. Non-hydraulic plasters were produced by using non-hydraulic

---

* Corresponding author.
E-mail addresses: emreipekci@iyte.edu.tr (E. İpekci), elifugurlu@iyte.edu.tr (E. Uğurlu Sağın), hasanboke@iyte.edu.tr (H. Böke).

https://doi.org/10.1016/j.cscm.2019.e00295

lime with inert aggregates, whereas hydraulic ones were consisted of either hydraulic lime with inert aggregates or non-hydraulic lime with natural or artificial pozzolans (crushed bricks or roof tiles).

Plasters made by mixing of lime and crushed bricks were the essential materials of the historic aqueducts, bridges and bath buildings due to their hydraulicity and durability. The use of these plasters can be regarded an ancient tradition dating back to 3000 BCE [3]. They were used as wall plastering, floor covering and as mortars in the arches, foundations and cisterns in Greek and the following civilizations [3–5]. These plasters had different names according to the region and the period they had been used like “Cocciopesto” in Roman [6], “Surkhi” in India [7], “Homra” in Arabic countries and “Horasan (Khorasan)” in Turkey [8]. In the Ottoman period, the most widespread use of horasan plasters was in the bath buildings [9,10].

The raw materials of crushed brick aggregates are obtained by heating the natural raw material sources containing clay minerals between 450 and 800 °C. Between these temperature intervals, the crystal structures of the clays are converted to the pozzolanic amorphous materials [11]. Pozzolanic amorphous materials are mainly aluminosilicates that react with lime to produce calcium silicate hydrate and/or calcium aluminate hydrate. These products give the hydraulic character to the mortars and plasters [10,12,13]. Type and purity of clays, heating temperature, particle size distribution and specific surface area of the amorphous substances affect the formations of calcium silicate hydrate and tetracalcium aluminate hydrate [5].

In the recent studies, raw material compositions, physical, mineralogical and microstructural characteristics of crushed brick-lime mortars and plasters (horasan) used in some historic buildings such as in Rhodes, Crete, İstanbul (Hagia Sofia) and cathedrals in Kiev, Israel [14–16], Archaeological Roman site of Troia in Portugal [17], Ancient cities of Aigai (Manisa) and Nysa (Aydın) [18], historical town of Mertola [19], some Ottoman bath buildings [9,10], water channel of hydraulic structures of Augusta Emerita (Mérida, Spain) [20], Roman, proto-Byzantine and Medieval mortars collected from Kyme (Turkey) [21], Lucknow monuments (18th century) [22] were determined. The results of the studies indicated that the crushed brick aggregates-lime mortars have 1/4 to 1/2 in volume binder/aggregate ratios. The binders were found as calcite because of the carbonated lime and as calcium silicate hydrates and calcium aluminate hydrates due to hydraulic reaction of lime with the pozzolanic crushed brick aggregates.

In this study, characteristics of original lime plasters (horasan) used on the walls of Çinili Bath which is one of the most remarkable Ottoman architectural monuments designed by Great Architect Sinan in İstanbul were determined by XRF, XRD, SEM-EDS and TGA analysis. The Bath was very famous with the İznik glazed tiles (çini) covering the interior wall surfaces. The aim of this study was to understand the use of the horasan plasters and to define the necessary characteristics of the new compatible plasters which will be used in the restoration works of the Bath without damaging its historical, architectural and aesthetic values.

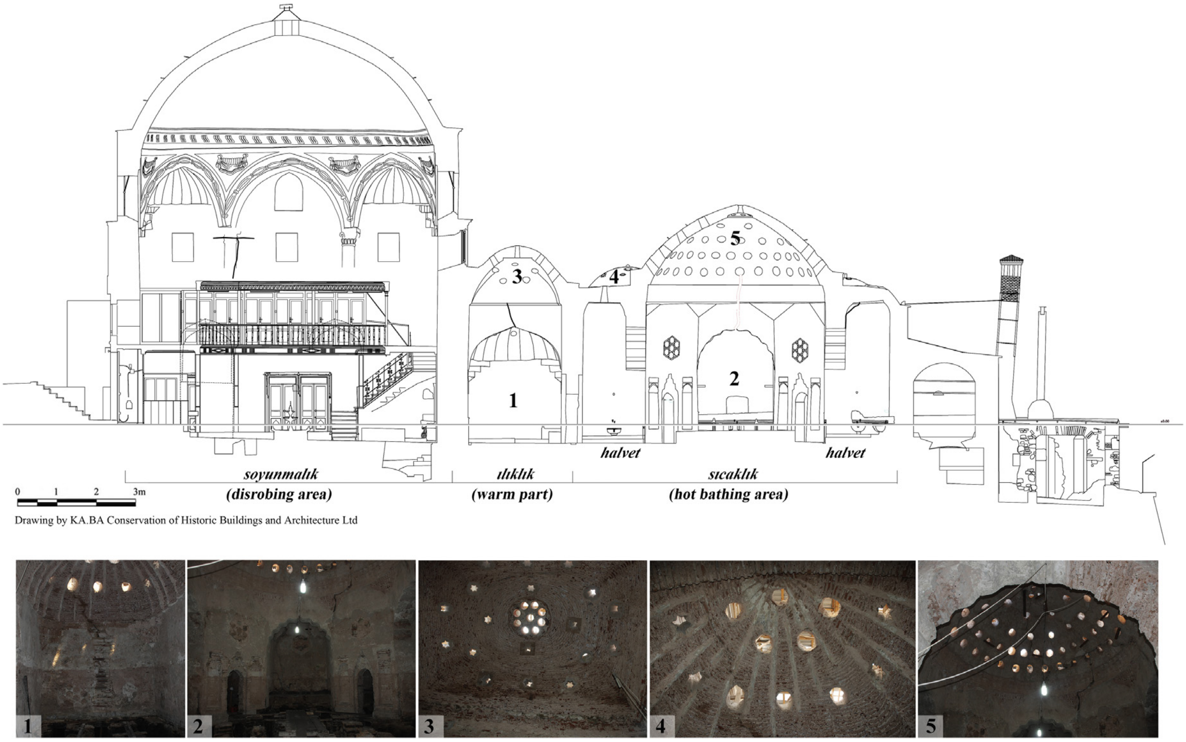
2. Çinili Bath and experimental studies on its plasters

Sinan who lived in the 16th century was the most famous Ottoman architect and engineer and regarded as the symbol of the classical Ottoman period that was contemporary to the Italian Renaissance. His famous Selimiye Mosque and its Social Complex in Edirne (Turkey) [23] and Mehmed Paša Sokolović Bridge in Višegrad (Bosnia and Herzegovina) [24] was selected for the UNESCO World Heritage list since they were both evaluated as “the apogee of the Ottoman Empire” and also “a masterpiece of the human creative genius” and “a major stage in the history of civil engineering and bridge architecture”. Apart from these, he designed dozens of monumental buildings like mosques, madrasas, baths, khans, tombs and bridges in different regions under Ottoman rule. Çinili Bath is one of the most outstanding Ottoman bath buildings (1540–1546) designed by Great Architect Sinan in İstanbul (Fig. 1). It was built as a typical double bath consisting of women’s and men’s parts with soyunmalık (disrobing area), ılıklık (warm part), sıcaklık (hot bathing area) and halvet (private hot cells) spaces (Fig. 1). The name of the Bath (“Çinili” means “with çini”) comes from the glazed tiles (çini) used on the interior surfaces of its walls. The Bath is of great importance since it had been one of the outstanding works of Great Architect Sinan, had historical, architectural and aesthetic values and had survived substantially with its original material characteristics. Glazed tiles which were rarely found in Ottoman period bath buildings also contributed for the architectural, aesthetic and rarity values of the building.

2.1. Sampling

On the interior wall surfaces of the bath, multilayered plaster application that was distinguished as lower level and upper level plasters due to their layers, colors and traces of glazed tiles was observed (Fig. 2). The lower level plasters on the wall surfaces are extended to 1.5 m height from the floor surfaces of the bath whereas the upper level plasters are extended along the wall surfaces from 1.5 m height. The lower levels of wall surfaces were covered with two horasan plaster layers and glazed tiles (Fig. 2). Glazed tiles were attached to wall surface by adhesives and joint mortars were used between the tiles [25]. In the present situation of the Bath, the glazed tiles had been removed from the walls, but their traces are still visible (Fig. 2). The upper levels were covered with one horasan plaster and one or two lime plaster layers.

In this study, 6 horasan plasters used on the walls of the bath were collected. In addition to these samples, 3 construction bricks were collected to make comparison with chemical and mineralogical properties with the brick aggregates used in the plasters. Also, 1 glazed tile adhesive and 1 joint mortar samples were collected to understand the tile application technique (Fig. 3, Table 1).



Drawing by KA.BA Conservation of Historic Buildings and Architecture Ltd

Fig. 1. Section and photos of the Çinili Bath showing the spaces.

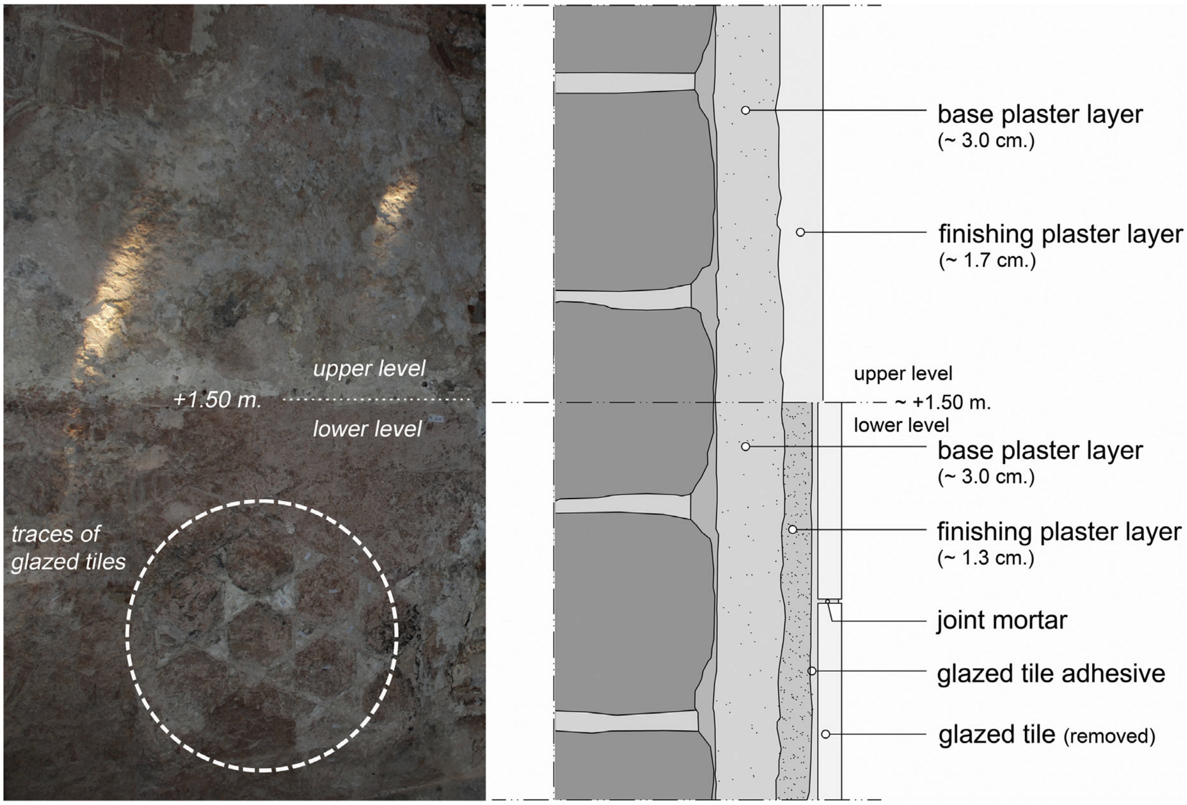


Fig. 2. Plaster layers of interior spaces.

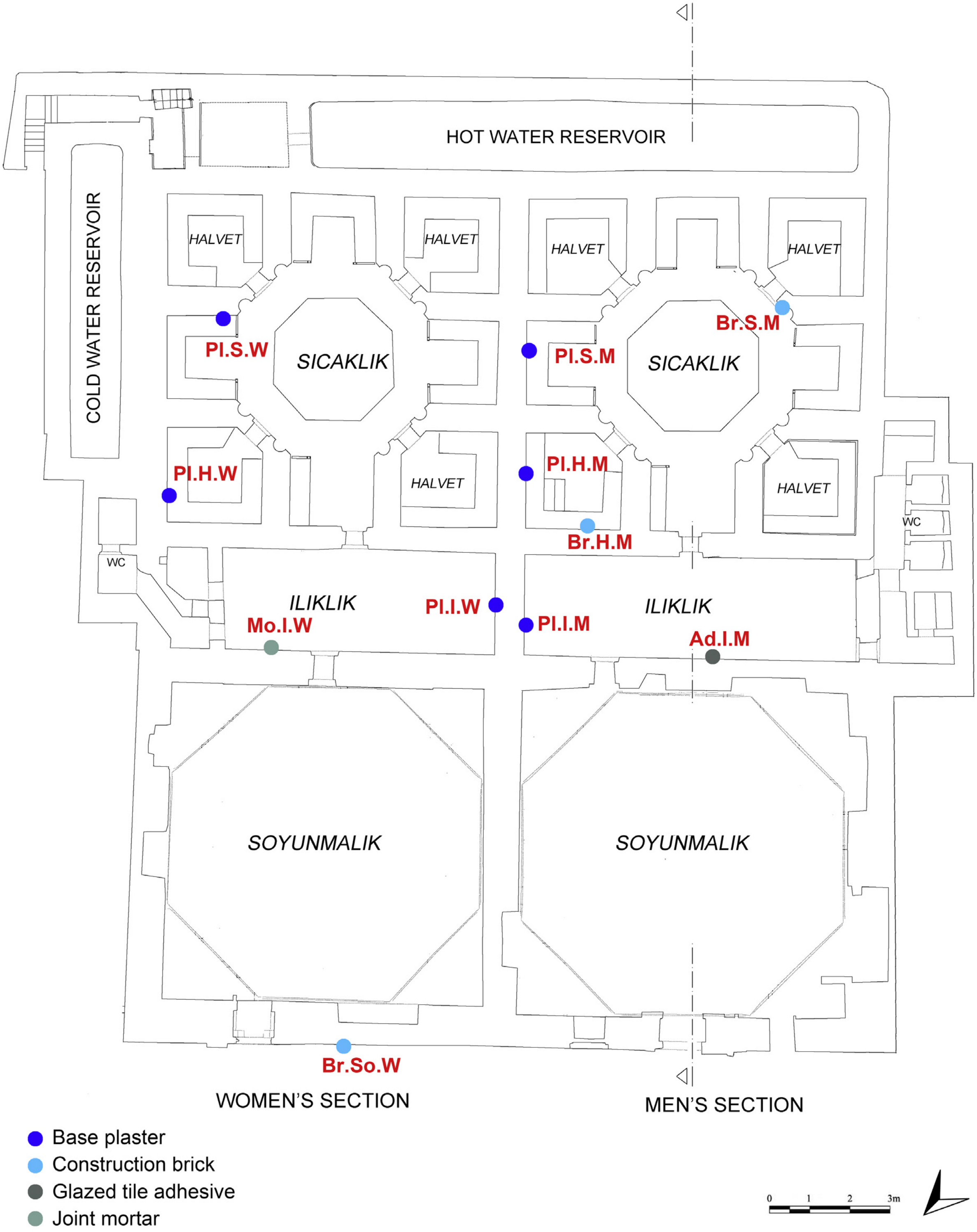


Fig. 3. Plan of the Çinili Bath showing where the samples were collected.

Table 1
Samples of the Çinili Bath.

Sample	Definition
Pl.I.W	Base plaster from *Ilıklık* wall of women's section
Pl.S.W	Base plaster from *Sıcaklık* wall of women's section
Pl.H.W	Base plaster from *Halvet* wall of women's section
Pl.I.M	Base plaster from *Ilıklık* wall of men's section
Pl.S.M	Base plaster from *Sıcaklık* wall of men's section
Pl.H.M	Base plaster from *Halvet* wall of men's section
Br.So.W	Construction brick from *Soyunmalık* wall of women's section
Br.H.M	Construction brick from *Halvet* wall of men's section
Br.H.Ni.M	Construction brick from niche part of *Halvet* room of men's section
Ad.I.M	Glazed tile adhesive from *Ilıklık* wall of men's section
Mo.I.W	Joint mortar from *Ilıklık* wall of women's section

Pl: Plaster, Br: Brick, Ad: Glazed Tile Adhesive, Mo: Joint Mortar, I: *Ilıklık* space, S: *Sıcaklık* space, H: *Halvet* space, So: *Soyunmalık* space, Ni: Niche, W: Women's section, M: Men's section.

Table 2
Raw material, mineralogical and chemical compositions.

Sample	Raw Material Compositions	Mineralogical Composition	Chemical Compositions %								Hydraulicity CO_2 /H_2O
	Lime/Aggregate		CaO	MgO	SiO2	Al2O3	FeO	Na2O	K2O	SO3	
Pl.I.W	2/3	Calcite, Quartz, Albite	57,6	1,3	30,2	7,4	2,1	–	0,2	1,1	3,65
Pl.S.W	1/1	Calcite, Quartz	46,6	3,4	32,4	10,1	3,4	0,5	1,5	1,9	3,49
Pl.H.W	3/2	Calcite, Quartz	38,7	2,5	25,4	7,2	2,6	–	0,3	3,5	3,11
Pl.I.M	2/3	Calcite, Quartz, Albite	44,3	1,9	36	10,2	3,4	0,5	1,2	2,1	1,59
Pl.S.M	1/1	Calcite, Quartz, Albite	44,7	2,2	35,8	10	3,9	0,2	0,5	2,4	2,79
Pl.H.M	5/4	Calcite, Quartz	41,7	1,2	48,1	6,5	1,1	0,2	0,7	0,2	4,2

Pl: Plaster, I: *Ilıklık* space, S: *Sıcaklık* space, H: *Halvet* space, So: *Soyunmalık* space, Ni: Niche, W: Women's section, M: Men's section.

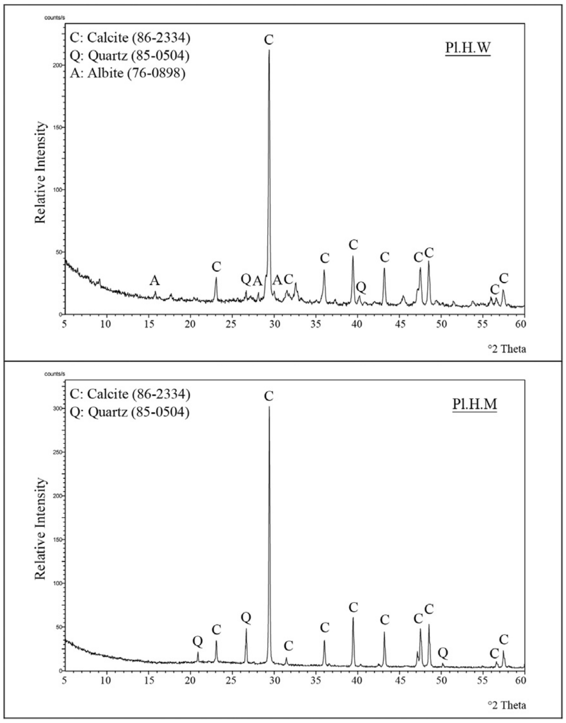


Fig. 4. XRD patterns of horasan plasters.

2.2. Analysis of the samples

In this study, basic physical properties, raw material compositions, chemical and mineralogical compositions, microstructural properties and hydraulic properties of the plasters were indicated. Basic physical properties (bulk density and porosity) were determined by standard test methods [26]. Lime to aggregates ratios and particle size distribution of aggregates of plaster samples were determined by dissolving of the carbonated lime in dilute hydrochloric acid, followed by filtering, washing, drying and sieving the aggregates.

Mineralogical compositions of fine plaster matrices, construction bricks and crushed brick aggregates were determined by X-ray Diffraction (XRD) analysis using a Philips X-Pert Pro X-ray Diffractometer (CuK_α radiation in the 5–70° range). Chemical compositions of fine plasters and their microstructural characteristics were identified by Philips XL 30-SFEG Scanning Electron Microscope (SEM) equipped with X-Ray Energy Dispersive System (EDS). Hydraulic properties of plasters were established by determining the weight loss due to chemically bound water of hydraulic products between 200 and 600 °C, and the weight loss due to the carbon dioxide content of the carbonated lime between 600 and 900 °C by thermogravimetric analysis (Shimadzu TGA-21) [27].

Elemental compositions of construction bricks and brick aggregates were determined by X-ray fluorescence spectroscopy (XRF). XRF analyses were conducted by a Spectro IQ II on melt tablets of powdered samples $< 53\ \mu m$ diluted with lithium tetraborat.

Pozzolanic activities of the powdered brick samples (less than 53 μm) were determined by measuring the differences in electrical conductivities (mS/cm) before and after the addition of samples into saturated calcium hydroxide solution [28].

3. Results and discussion

Results of the experimental studies are given and discussed as basic physical properties of plasters, chemical and mineralogical compositions of plasters, brick aggregates and construction bricks, pozzolanic properties of bricks and hydraulic properties of plasters.

3.1. General characteristics of plasters

Basic physical properties of horasan plasters were described by density (gr/cm^3) and porosity values (%). All plasters used in the bath are low dense and high porous materials. Their density and porosity values were between 1.1–1.6 g/cm^3 and 29–56 % by volume, respectively.

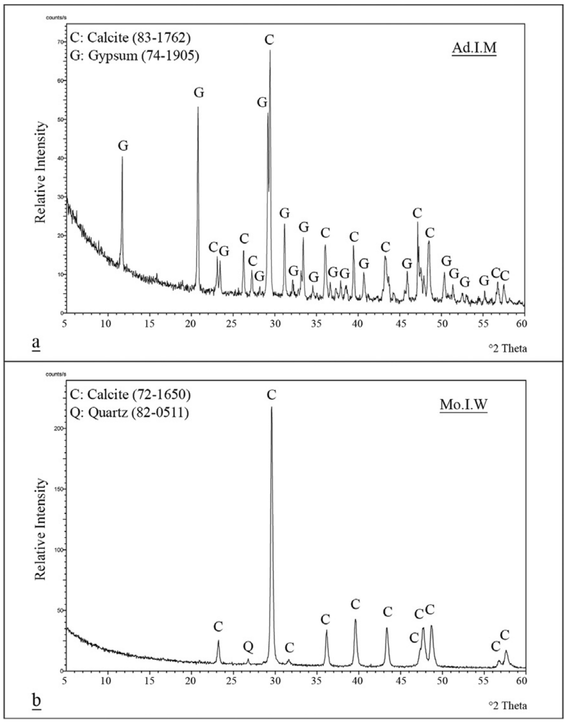


Fig. 5. XRD patterns of glazed tile adhesive (a) and joint mortar (b).

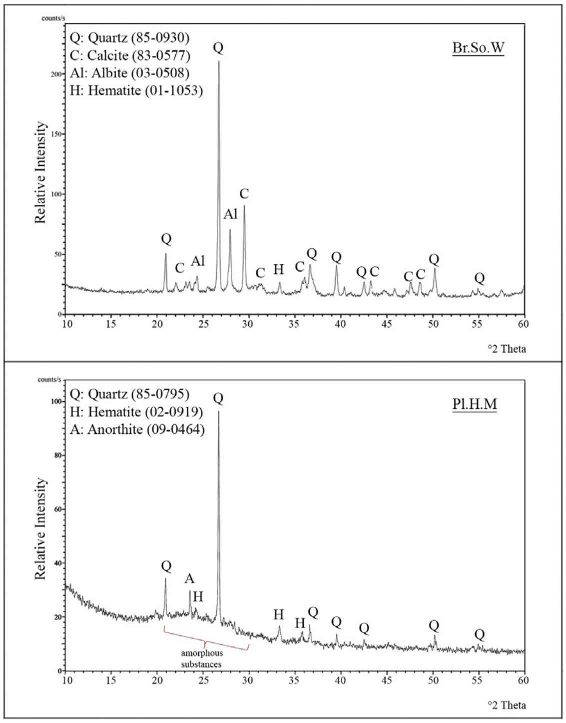


Fig. 6. XRD patterns of construction bricks and brick aggregates.

Raw material compositions were defined by lime-aggregate ratios and particle size distribution of aggregates. Lime-aggregate ratios of horasan plasters of the bath varied between 1/2–3/2 by weight (Table 2). Particle size distribution of crushed brick aggregates which had particle sizes 500 μm. constituted the major fraction of the total aggregates. The results revealed that raw material compositions of horasan plasters did not differ according to the space they had been used.

Quantitative chemical analysis carried out by SEM-EDS indicated that they were consisted of high amounts of CaO, SiO_2, Al_2O_3 and low amounts of FeO, MgO, SO_3, K_2O and Na_2O (Table 2). Presence of mainly CaO was resulted from carbonated lime and SiO_2 and Al_2O_3 were resulted from brick powders. SO_3 detected in all horasan plaster in the amounts ranged between 0.55–3.55 % may show the use of small amount of gypsum addition in the lime binder to provide quick setting of lime plaster (Table 2).

Mineralogical compositions of horasan plasters of Çinili bath determined by XRD revealed that all horasan plasters used were composed of calcite (C:$CaCO_3$), quartz (Q:SiO_2) and albite (A:($Na(AlSi_3O_8)$)) (Fig. 4).

3.2. General characteristics of glazed tile adhesives and joint mortars

XRD analysis clearly indicated that glazed tile adhesive applied on horasan plasters and joint mortar between the tiles had different compositions. XRD patterns of glazed tile adhesive showed that they were mainly composed of gypsum (Fig. 5a).

Table 3
Oxide compositions (%) and pozzolanic activities of construction bricks and brick aggregates.

Sample	Major Oxides (%)									Pozzolanic Activity (mS/cm)
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	
Pl.I.W	86,34	6,096	4,105	0,972	0,5889	< 0,11	0,267	1,017	0,3041	3,70
Pl.S.W	90,43	4,367	2,532	0,851	0,3771	< 0,11	0,027	0,9306	0,2866	5,60
Pl.H.W	91,72	3,041	2,918	0,394	0,3984	< 0,11	< 0,0012	1,067	0,2578	4,50
Pl.I.M	89,6	4,772	2,901	0,512	0,376	< 0,11	0,169	1,155	0,2779	4,80
Pl.S.M	85,97	6,748	4,244	0,974	0,4424	< 0,11	0,156	0,978	0,3089	5,10
Pl.H.M	88,53	5,695	3,256	0,657	0,2681	< 0,11	0,088	1,033	0,2994	5,80
Br.So.W	62,67	19,72	6,98	2,762	2,22	2,44	1,63	0,9448	0,3772	0,30
Br.H.M	50,26	18,23	6,41	7,169	12,24	2,46	1,736	0,7036	0,3701	1,10
Br.H.Ni.M	61,55	20,87	7,359	2,848	2,185	1,97	1,464	1,101	0,3604	0,60

Pl: Plaster, Br: Brick, I: *Ilıklık* space, S: *Sıcaklık* space, H: *Halvet* space, So: *Soyunmalık* space, Ni: Niche, W: Women’s section, M: Men’s section.

Minor calcite peaks observed on their patterns may because of the impurities originated from sampling. On the other hand, joint mortars were mainly consisted of calcite and quartz (Fig. 5b). The reason of the gypsum free composition of joint mortars which were exposed to water more than glazed tile adhesives could be explained by avoiding the water-soluble character of gypsum.

3.3. General characteristics of construction bricks and brick aggregates

Recent researches revealed that historic bricks were mainly composed of quartz, feldspar, muscovite, amorphous silica, alumina and hematite which provides red color for the bricks [29–31]. The chemical composition of the historic bricks consisted of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), potassium oxide (K_2O), sodium (Na_2O), calcium (CaO) and magnesium (MgO) oxides. Silica and alumina constitute the major oxides of historic bricks were found in the ranges of 53–61 % and 22–32 %, respectively from the 12th to 18th centuries [32,29].

In this study, construction bricks of the Bath were found to be composed of mainly quartz (SiO_2), potassium feldspar ($KAl_2Si_2O_5(OH)_4$), sodium feldspars ($NaAlSi_3O_8$), biotite ($KMg_3AlSi_3O_{10}(OH)_2$) and hematite (Fig. 6). In addition to these minerals, brick aggregates contained more amorphous substances indicated by a diffuse band between 20°and 30°2θ on the XRD patterns (Fig. 6). Amorphous substances could be originated from the higher amounts of heated clay minerals or addition of natural amorphous minerals into the fine brick aggregates [10]. Minerals indicating high firing temperatures during manufacturing like mullite and cristobalite [33] were not observed on the XRD patterns. This reveals that both brick aggregates and construction bricks were manufactured at temperatures not exceeding 950−1000 °C. Also, the presence of hematite mineral shows that the firing temperatures were around 850 °C.

XRF results revealed that construction bricks were composed of mainly SiO_2 (50.26–62.67 %) and Al_2O_3 (18.23–20.87 %); moderate amounts of Fe_2O_3(6.41–7.36 %); lower amounts of MgO (2.76–7.17 %), CaO (2.19–12.24 %), Na_2O (1.97–2.46 %) and K_2O (1.46–1.74 %); very low amounts of TiO_2 (0.70–1.10 %) and P_2O_5 (0.36-0.38 %) (Table 3).

Results of the major oxide compositions of construction bricks of Çinili Bath were similar to the chemical composition of historical bricks from 12th to 18th centuries [34,30,31]. But then, brick aggregates of plasters had higher SiO_2 (85.97–91.72 %),

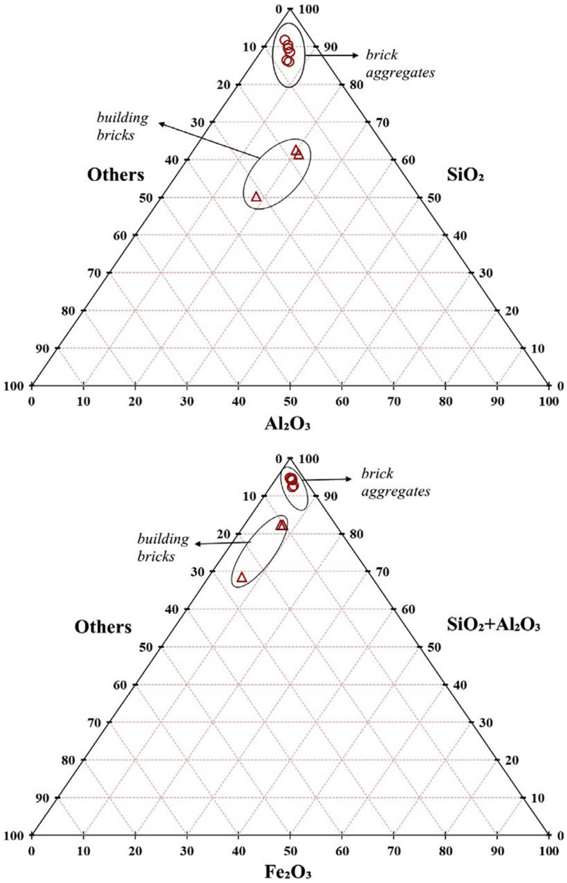
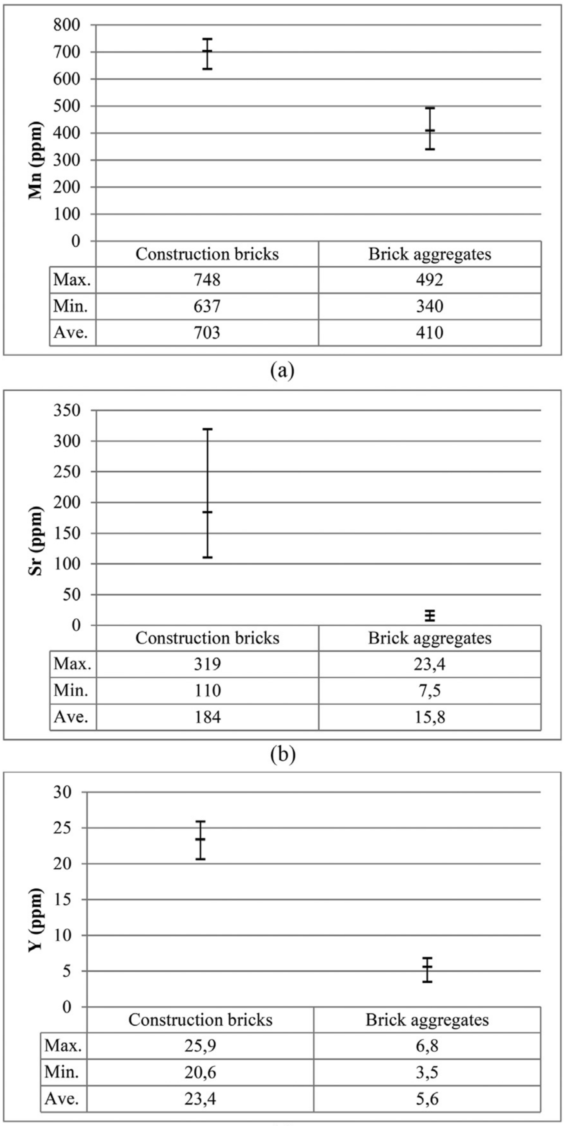


Fig. 7. Ternary diagrams SiO_2-Al_2O_3-others and SiO_2+Al_2O_3-Fe_2O_3-others.

lower Al_2O_3 (3.04–6.75 %), MgO (0.39-0.97 %) and CaO (0.27-0.59 %) content compared to construction bricks. Major oxide compositions were used to generate ternary diagrams depending on SiO_2-Al_2O_3-other major oxides and (SiO_2+Al_2O_3)-Fe_2O_3-other major oxides in order to exhibit the differences between construction bricks and brick aggregates in a statistical way. Both diagrams revealed that distinctive groups can be established depending on the major oxide compositions (Fig. 7).

Trace elements compositions are generally considered as an important determinant of the provenance of raw materials from which bricks are produced [35]. Trace elements compositions determined by XRF revealed that Mn, Sr, Y and Ba concentrations (ppm) of construction bricks and brick aggregates are significantly different from each other (Fig. 8, Table 4). The differences in major oxide and trace elements compositions may be interpreted as the indicator of the conscious selection of different raw material sources during the manufacturing of construction bricks and brick aggregates.

The pozzolanic activities of construction bricks and brick aggregates were determined by following the reaction between lime and brick powders by electrical conductivity measurements. The differences more than 2 mS/cm before and after the reaction revealed highly energetic pozzolanicity [28]. Electrical conductivity differences of brick aggregates were found between 3.70–5.80 mS/cm, whereas the differences were found between 0.30–1.10 mS/cm in construction bricks (Table 3). These results exhibit that brick aggregates used in plasters can be regarded as energetic pozzolans while construction bricks do not possess pozzolanic properties.



	Construction bricks	Brick aggregates
Max.	748	492
Min.	637	340
Ave.	703	410

(a)

	Construction bricks	Brick aggregates
Max.	319	23,4
Min.	110	7,5
Ave.	184	15,8

(b)

	Construction bricks	Brick aggregates
Max.	25,9	6,8
Min.	20,6	3,5
Ave.	23,4	5,6

(c)

Fig. 8. Mn (a), Sr (b), Y (c) contents of construction bricks and brick aggregates.

Table 4
Traces (ppm) of construction bricks and brick aggregates.

Sample	Traces (ppm)																	
	S	Cl	Cr	V	Mn	Ni	Cu	Zn	Ge	Se	Br	Sr	Y	Nb	Mo	Te	Ba	Pb
Pl.I.W	80,2	1309	111	<5,1	423	36	319	<1,0	<0,3	19,3	<1,0	20,5	6,8	11,2	3,7	<7,1	<106	7,6
Pl.S.W	93,6	284,2	121	<5,1	352	36	337	29,9	<1,7	19,7	6,2	15,2	3,5	9,8	3,5	<7,1	74	<2,0
Pl.H.W	85,5	376,6	41,7	<5,1	399	36	397	14,5	26	9,5	4,6	7,5	6,4	11,5	6,1	<7,1	8,1	<2,0
Pl.I.M	43,8	629,1	66,1	<5,1	451	<9,6	425	18,9	26	25,6	8,3	23,4	5,8	17,5	<10	<7,1	<8,1	<2,0
Pl.S.M	37,2	348,7	76	<5,1	492	<2,0	220	36,2	<1,0	6,9	<1,0	16,6	6,4	7,3	2,6	<104	<8,1	<2,0
Pl.H.M	87,3	298,5	66,1	<26	340	<8,6	259	32,1	<1,0	9,5	2	11,7	4,6	6,3	<10	111	<8,1	<2,0
Br.So.W	45,1	93,7	125	65,7	637	<12	446	46,5	<1,0	19,6	<1,0	124	23,8	7,2	<10	<7,1	285	<2,0
Br.H.M	157	208,9	189	22,9	748	216	634	49,1	<1,0	18	6,8	319	25,9	7,9	<10	<72	521	<2,0
Br.H.Ni.M	52,2	201,4	81,6	99,9	723	<12	492	28,8	<1,0	18,8	8,8	110	20,6	8,6	<10	<7,1	238	<2,0

Pl: Plaster, Br: Brick, I: *Ilıklık* space, S: *Sıcaklık* space, H: *Halvet* space, So: *Soyunmalık* space, Ni: Niche, W: Women's section, M: Men's section.

The mineralogical and chemical compositions, and pozzolanic activity analysis results indicated that the bricks used in plasters were not identical to bricks used in building construction. These results indicate that the pozzolanic bricks were intentionally manufactured and chosen for hydraulic lime plasters used in the bath buildings.

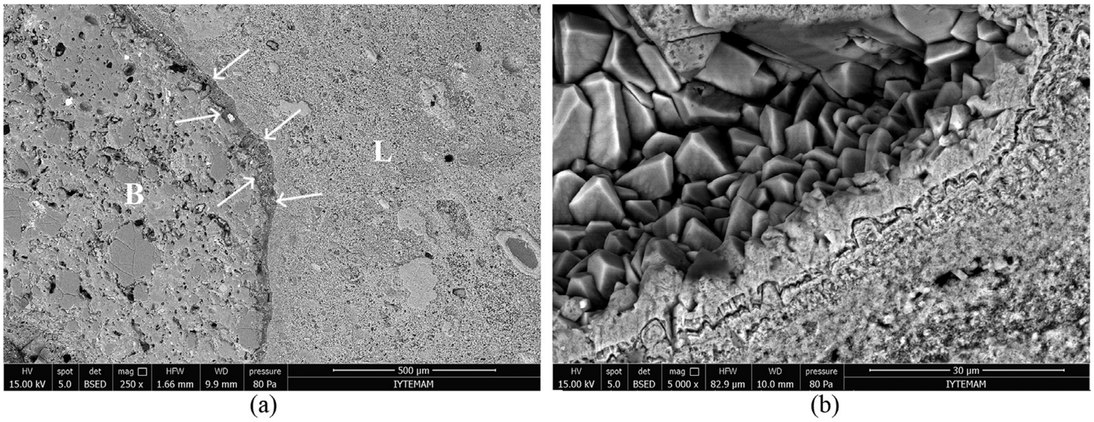
3.4. Microstructural properties of plasters

Microstructural properties of horasan plasters of Çinili Bath were examined by SEM-EDS. SEM analyses indicated that crushed brick aggregates and lime were well adhered to each other. This strong adhesion revealed that a very well mixing had been carried out during preparation of horasan plasters and also the reaction between brick aggregates and lime. Brick-lime interfaces were rich in calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) formations by the result of this reaction (Fig. 9). CSH and CAH formations provide hydraulic properties to horasan plasters.

SEM analysis also showed that microcracks in the plasters and pores of the bricks aggregates were filled with calcite crystals by the dissolution and precipitation reactions of carbonated lime in the humid and hot conditions of the bath [9]. This process, called self- healing, heal the micro cracks and fissures and enhance the durability of plasters.

3.5. Hydraulic properties of plasters

Hydraulic properties of the horasan plasters related to the pozzolanicity of the brick aggregates were determined by using thermogravimetric analysis (TGA). For this purpose, the percentage of weight losses between 200–600 °C due to loss of chemically bound water (H_2O) of hydraulic components and 600–900 °C due to the release of CO_2 during decomposition of $CaCO_3$ were calculated. If the ratio of CO_2/chemically bound water of plasters is between 1 and 10, plasters could be accepted as hydraulic [27]. Investigated plasters had CO_2 content between 3,56-17,03 %, and chemically bound water content between 0,98-7,44 %. According to these results, their CO_2/H_2O ratios were found between 1.59–4.20 which indicated that all horasan plasters of Çinili bath were hydraulic (Fig. 10). Hydraulic properties of horasan plasters can be attributed to the use of pozzolanic aggregates.



(a) (b)

Fig. 9. BSE images of brick(B)-lime(L) interface of horasan plaster (a) and the precipitated calcite crystals in the pores of the brick aggregates (b).

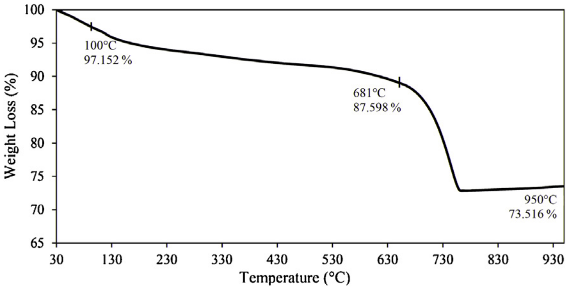


Fig. 10. TGA curves of hydraulic plasters.

4. Conclusions

Çinili Bath designed by the Great Architect Sinan is one of the most remarkable Ottoman bath buildings in İstanbul which survived by preserving its original material characteristics. Ottoman baths had a hot and humid inner climate which caused great difficulty to control and maintain the material degradation caused by water. This difficulty had been overcomed for hundreds of years by using horasan plasters which had self-healing characteristics that eliminated the need for renewal. Also, multilayered plaster application was observed on the wall surfaces of all interior spaces which was distinguished as lower level and upper level plasters. Lower level plasters were consisted of two horasan plaster layers and glazed tiles; whereas upper level plasters were consisted of one horasan plaster layer and one or two fine lime plaster layers. Multilayered plaster application together with the use of glazed tiles is a rare example for Ottoman period bath buildings.

All base horasan plasters have similar physical, mineralogical, chemical and microstructural properties. They are of low density and high porosity. Horasan plasters were produced from pure lime and pozzolanic crushed brick aggregates. They were hydraulic due to the use of highly energetic pozzolanic crushed bricks. They are durable and stable materials in moist, humid and hot conditions of the bath buildings due to their self-healing properties and the formation of calcium silicate hydrate and calcium aluminate hydrate that are formed at the surfaces and in the pores of the brick aggregates by the reaction of lime. Glazed tiles were attached to wall surface by gypsum based adhesives. Despite the use of gypsum, glazed tiles and lime joint mortars between the tiles prevented direct water penetration to glazed tile adhesives. New materials that will be used during the conservation of Çinili Bath should be compatible with the original material characteristics determined by this study.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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.

Acknowledgements

The authors thank Cengiz Kabaoğlu (KA.BA Conservation of Historic Buildings and Architecture Ltd) for sharing the measured drawings of Çinili Bath. Their special thanks are for Burçin Altınsay Özgüner (Conservation Architect) and Yavuz Suyolcu (Project Manager) for their help during field survey. They also thank İzmir Institute of Technology, Centre for Materials Research for XRF, XRD, SEM-EDS and TGA analyses.

References

[1] I.H. Seeley, Building Technology, 5th ed., The Macmillan Press Ltd., Basingstoke, Hampshire, 1995.
[2] A. Watts, Modern Construction Handbook, Springer, New York, 2001.
[3] A. Moropoulou, A. Bakolas, S. Anagnostopoulou, Composite materials in ancient structures, Cem. Concr. Compos. 27 (2005) 295–300.
[4] G. Baronio, L. Binda, N. Lombardini, The role of brick pebbles and dust in conglomerates based on hydrated lime and crushed bricks, Constr. Build. Mater. 11 (1997) 33–40.
[5] G. Matias, P. Faria, I. Torres, Lime mortars with heat treated clays and ceramic waste: a review, Construct. Build. Mater. 73 (2014) 125–136.
[6] R. Bugini, A. Salvatori, G. Capannesi, A.F. Sedda, C. D'Agostini, C.F. Giuliani, Investigation of the characteristics and properties of 'cocciopesto' from the ancient Roman period, Proceedings of the international UNESCO-RILEM congress, ed. M.J. Thiel, Paris, France, (1993), pp. 386-393.
[7] R. Spence, Lime and surkhi manufacture in India, Appro. Technol. 1 (1974) 6–8.
[8] F.M. Lea, Investigations on pozzolanas, Build Res. Technol. Paper 27 (1940) 1–63.
[9] E. Uğurlu, H. Böke, The use of brick–lime plasters and their relevance to climatic conditions of historic bath buildings, Constr. Build. Mater. 23 (2009) 2442–2450.

[10] H. Böke, S. Akkurt, B. İpekoğlu, E. Uğurlu, Characteristics of brick used as aggregates in the historic brick-lime mortars and plasters, Cem. Concr. Res. 36/6 (2006) 1115–1122.

[11] C. He, B. Osbaeck, E. Makavicky, Pozzolanic reactions of six principal clay minerals: activation, reactivity assessments and technological effects, Cem. Concr. Res. 25 (8) (1995) 1691–1702.

[12] W. Prince, G. Castanier, J.L. Giafferi, Similarity between alkali – aggregate reaction and the natural alteration of rocks, Cem. Concr. Res. 31 (2001) 271–276.

[13] A. Moropoulou, G. Çakmak, A. Biscontin, E. Bakolas, E. Zendri, Advanced Byzantine cement based composites resisting earthquake stresses: the crushed brick-lime mortars of Justinian's Hagia Sophia, Constr. Build. Mater. 16 (2002) 543–555.

[14] A. Moropoulou, A. Bakolas, B. Bisbikou, Characterization of ancient byzantine and later historic mortars by thermal and X-ray diffraction techniques, Thermomica Acta. 269/270 (1995) 779–795.

[15] P. Maravelaki-Kalaitzaki, A. Bakolas, A. Moropoulou, Physico-chemical study of Cretan ancient mortars, Cem. Concr. Res. 33 (2003) 651–668.

[16] A. Moropoulou, A.S. Çakmak, N. Lohvyn, Earthquake resistant construction techniques and materials on byzantine monuments in Kiev, Soil Dyn. Earthq. Eng. 19 (2000) 603–615.

[17] A. Santos Silva, M. Paiva, J. Ricardo, M. Salta, A.M. Monteiro, A.E. Candeias, Characterisation of roman mortars from the archaeological site of Tróia (Portugal), Mater. Sci. Forum 514-516 (2006) 1643–1647.

[18] E. Uğurlu, Characterization of Horasan Plasters from Some Ottoman Baths in İzmir M.SC. Thesis, İzmir Institute of Technology, İzmir, Turkey, 2005.

[19] A. Santos Silva, J. Ricardo, M. Salta, P. Adriano, J. Mirão, A.E. Candeias, Characterization of Roman mortars from the historical town of Mértola in Heritage, in: R. Fort (Ed.), International Conference on Heritage, Weathering and Conservation, Taylor & Francis, London, 2006, pp. 85–90.

[20] M.D. Robador, J.L. Perez-Rodriguez, A. Duran, Hydraulic structures of the roman mithraeum house in Augusta Emerita, spain, J. Archaeol. Sci. 37 (2010) 2426–2432.

[21] D. Miriello, A. Bloise, G.M. Crisci, C. Apollaro, A. La Marca, Characterisation of archaeological mortars and plasters from kyme (Turkey), J. Archaeol. Sci. 38 (2011) 794–804.

[22] D.C. Rai, S. Dhanapal, Mineralogical and mechanical properties of masonry and mortars of the Lucknow monuments circa the 18th century, Int. J. Archit. Herit. 9 (2015) 300–309.

[23] UNESCO 2011, Selimiye Mosque and its Social Complex, (2019) . (Accessed June 25, 2019) https://whc.unesco.org/en/list/1260.

[24] UNESCO 2007, Mehmed Paša Sokolović Bridge in Višegrad, (2019) . (Accessed June 25, 2019) https://whc.unesco.org/en/list/1366.

[25] E. İpekci, Plaster Characteristics of Çinili Hamam Built by Mimar Sinan in İstanbul, M.Sc. Thesis., İzmir Institute of Technology, İzmir, Turkey, 2016.

[26] RILEM Commission 25 PEM, Tests defining the structure, Mater. Constr. 13 (75) (1980) 177–181.

[27] A. Bakolas, G. Biscontin, A. Moropoulou, E. Zendri, Characterization of structural byzantine mortars by thermogravimetric analysis, Thermochim. Acta 321 (1-2) (1998) 151–160.

[28] M.P. Luxan, F. Madruga, J. Saavedra, Rapid evaluation of pozzolanic activity of natural products of conductivity measurement, Cem. Concr. Res. 19 (1989) 63–68.

[29] F.M. Fernandes, P.B. Lourenço, F. Castro, Ancient Clay bricks: manufacture and properties, in: M.B. Dan, R. Přikryl, Á. Török (Eds.), Materials, Technologies and Practice in Historic Heritage Structures, Springer, Dordrecht, 2010, pp. 29–48.

[30] E. Uğurlu Sağın, H. Böke, Characteristics of bricks used in the domes of some historic bath buildings, J. Cult. Herit. 14 (S) (2013) 73–76.

[31] M. Stefanidou, I. Papayianni, V. Pachta, Analysis and characterization of Roman and Byzantine fired bricks from Greece, Mater. Struct. 48 (2015) 2251–2260.

[32] F.M. Fernandes, Evaluation of Two Novel NDT Techniques: Microdrilling of Clay Bricks and Ground Penetrating Radar in Masonry, PhD Thesis, University of Minho, Guimarães, 2006.

[33] L. Sujeong, Y.J. Kim, H.S. Moon, Phase transformation sequence from kaolinite to mullite investigated by an energy-fıltering transmission electron, J. Am. Ceram. Soc. 10 (1999) 2841–2848.

[34] P. Cardiano, S. Ioppolo, C. Stefano, A. Pettignano, S. Sergi, P. Piraino, Study and characterization of the ancient bricks of Monastery of San Filippo di Fragalà in Frazzanò (Sicily), Anal. Chim. Acta 519 (1) (2004) 103–111.

[35] H. Mommsen, Provenance determination of pottery by trace element analysis: problems, solutions and applications, J. Radioanal. Nucl. Chem. 247 (3) (2001) 657–662.