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Earthquakes and Monuments - The Role of Materials in the Earthquake Protection of Monuments

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ABSTRACT: There are several monuments worldwide that through the years they presented an excellent behavior under earthquake, such as the Hagia Sophia in Istanbul, and the church of St.Michael in Kiev. A thorough study in the structural materials used revealed that they presented a similar nature and production technology (p.ex. lime mortars with crushed brick in the masonry joints) that resulted to similar physicochemical and mechanical characteristics (low values of elastic modulus, high compressive and tensile strength). In this way, the materials contributed to the earthquake resistance of monuments. Therefore, in order to design restoration and conservation materials that will assure the earthquake protection of monuments along with the compatibility to the authentic units, it is indispensable to decode the historic materials technology and to redesign them through a reverse engineering approach.

1 INTRODUCTION

The study of the behaviour of historic buildings that have suffered from earthquakes and presented an excellent behavior can become a valuable tool for the understanding of earthquake resistant construction techniques and materials. More specifically, characteristic monuments of Byzantine era that presented a great durability in time and an excellent behavior under earthquake stresses are the Hagia Sophia in Istanbul, and the church of St. Michael in Kiev (Cakmak et al (1996), Moropoulou et al (1997), Moropoulou et al (2000a)). A thorough study in the structural materials revealed that they presented a similar nature and production technology. The study of these buildings could become a valuable tool for the decoding of construction techniques and materials and therefore the reproduction of materials with analogous behavior that could be used for the restoration interventions on structures of Byzantine era.

Regarding the masonry structure type of these two monuments, the structural materials were bricks and the mortar joint was about 1-1.5 times the brick thickness, up to 4-5 cm. Furthermore the mortars used presented a binder of hydraulic nature. The aggregates were coarse and composed by a mixture of ceramic fragments and sand. Especially, in the case of Hagia Sophia, the aggregates dimensions are in the range of 0-16mm and this is the reason that this kind of mortar is considered as concrete. Regarding their physicochemical and mechanical characteristics they both exhibited a high tensile strength, a low value of elasticity modulus, low values of density, high value of hydraulicity (Cakmak, et al (1996), Moropoulou et al (1997), Moropoulou et al (2000a), Moropoulou et al (2000b)).

The main goal of this research is the design, production and evaluation of concrete for restoration interventions of monuments thick joints brickwork masonries of Byzantine era that simulate the historic concrete, regarding the physico-chemical and mechanical data.

2 MATERIALS AND TECHNIQUES

2.1 Materials

Traditional types of materials were used for the concrete production in order to assure the physico-chemical compatibility to authentic materials. Lime powder ($Ca(OH)_2$: 89 %, $CaCO_3$: 5 %, CaO Hellas) and natural hydraulic lime (NHL3.5-Z according to CEN EN 459-1) were used as binding materials along with cement (I/45, TITAN Cement Industry) for comparative reasons.

The pozzolanic additions used were either earth of Milos (EM) – a natural pozzolan derived by the island of Milos in Greece or metakaolin, an artificial high reactive pozzolanic addition (Moropoulou et al 2004) (Metastar 501 of IMERYS Minerals L.t.d). Table 1 reports the chemical composition, the physical properties of materials used for concrete preparation. In addition, the percentage of total and reactive silica (EN 197-1, EN 196-2) for the two pozzolanic additions is presented along with the values of specific surface area, measured by the adsorption of nitrogen method, according to Brunauer-Emmett-Teller (BET) method.

The grain size distribution of the pozzolanic additions is determined by laser CILAS 715 method. Metakaolin is the finest pozzolanic addition with cumulative passing percentage at 64 μm up to 100 % and at 16 μm up to 95.6 %. On the other hand, Earth of Milos presents more coarse grain size distribution with a cumulative passing percentage at 64 μm up to 88.1 %.

The aggregates used consist of a mixture of sand (calcitic and quartz origin) and ceramic fragments. The former has already been detected in historic mortars samples resulted to the production of lightweight, low- modulus of elasticity materials, due to its lower bulk density in respect to the sand aggregates (Livingston et al 1992).

Table 1 : Physico-chemical characteristics of materials used for the concrete preparation.

MT	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	K_2O (%)	Na_2O (%)	SO_3 (%)	LOI (%)	Tot. SiO_2 (%)	React. SiO_2 (%)	S.S.A. (m^2/g)
MK	51.70	40.60	0.64	0.71	0.96	2.00	0.31	0.11	1.19	54.19	44.59	13.83
EM	69.66	12.21	2.34	2.01	0.70	3.28	0.62	-	7.35	70.15	52.89	4.34
L	0.17	0.18	0.07	70.06	2.35	-	-	0.77	25.60	-	-	-

MT: Material, MK: Metakaolin, EM: Earth of Milos, L: Hydrated Lime, LOI: Loss of ignition, Tot. SiO_2: total silica percentage, React. SiO_2: reactive silica percentage, S.S.A.: Specific Surface Area

In order to achieve an analogous grain size distribution to Hagia Sophia historic one 4 types of aggregates were mixed:

- Sand of quartz origin with the following fractions of grain size (0.063-0.5 mm, 0.5-1 mm, 1-2 mm, 3-6 mm)
- Sand of calcitic origin with a grain size fraction of 2-4 mm.
- Coarse calcitic gravel with a grain size fraction of 2-16 mm.
- Ceramic Fragments disposed in two grain size fractions (0-8, 2-16 mm)

Fig. 1 presents the grain size distribution of aggregates mixes compared to the Hagia Sofia historic concrete.

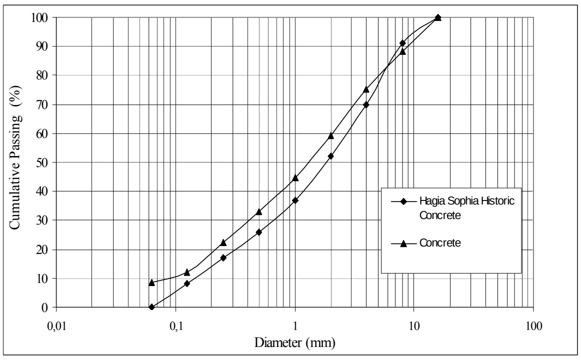

Figure 1 : Grain size distribution of aggregates compared to the Hagia Sofia Historic Concrete.

Table 2 states the materials mixing proportions as percentage per weight (%, p.w.) for the concrete preparation. The amount of water that was added in the syntheses was determined through the criteria of slump cone test. The acceptable value of slump was determined as lower than 40 mm, according to EN 12350-2 (Testing Fresh Mortar – Part 2: Slump Test). In that way, the amount of water was the minimum that could be added and the syntheses presented almost the same consistency.

Once the concrete was prepared, it was molded in moulds of 10x10x50cm, using a vibrator table with the intention of accomplishing a sufficient compaction. Then, they were stored in a moist curing chamber of relative humidity RH > 95 % and temperature T = 20±2 °C for 7 days in the case of concrete 3-9 and 14 days in the case of concrete 1-2. Afterwards, they were de-moulded and stored in a chamber of standard conditions (RH = 50±1 %, T = 20±2 °C) till the testing day.

Table 2 : Mixing Design of Concrete - Materials mixing proportions as percentage per weight (%, p.w.)

	Code	L	EM	MK	C	NHL	Aggregates (%.p.w.)		
							Gr	*Snd*	*CF*
1	EM2.Gr.S.	10	20				7	63	
2	EM2.CF.S.	10	20					35	35
3	MK1.Gr.S.	15		15			7	63	
4	MK1.CF.S.	15		15				35	35
5	MK1.CF.	15		15				35	35
6	MK05.CF.S.	20		10				35	35
7	LCem.CF.S.	15			15			35	35
8	NHL.CF.S.					30		35	35
9	MK2.5.CF.S.	27,5		2,5				35	35

L: Hydrated Lime, EM: Earth of Milos, MK: Metakaolin, C: Cement, NHL: Natural Hydraulic Lime, Gr: Gravel, Snd: Sand, CF: Ceramic Fragment

2.2 *Techniques*

The concrete mechanical and chemical characteristics were evaluated using the following techniques:

- Flexural strength, using prisms of 10 × 10 × 50 cm according to ASTM C 78-00 (Triscan 100, max load: 100 KN, load rate: 0.05 mm/min) at the time of 1, 3, 6 and 12 months
- Compressive strength tests using portions of beams broken in flexure according to ASTM C 116 (Form – Test Type: 110/300, max load: 300 KN load rate: 0.2 MPa/s) at the time of 1, 3, 6 and 12 months
- Compressive strength tests using cylinders (height: 30 cm, diameter: 15 cm) according to ASTM C 116-99 (Impact CTE 19, maximum load: 2000 KN, load rate: 1 KN/s) at the time of 12 months
- Ultrasonic technique (CNS Farnell-Pundit 6, transducers frequency: 54 KHz) for the estimation of ultrasonic velocity propagation through concrete and the dynamic modulus of elasticity (Ed) at the time of 1, 3, 6 and 12 months.

3 RESULTS

In general, all the concrete syntheses present a uniform distribution of the aggregates in the whole concrete mass and a good homogeneity in binder matrix (Photo 1-3). Furthermore, it could be noticed that a better adhesion of the binder matrix to the aggregates is occurred in the case of ceramic aggregates than to the gravels/sand aggregates.

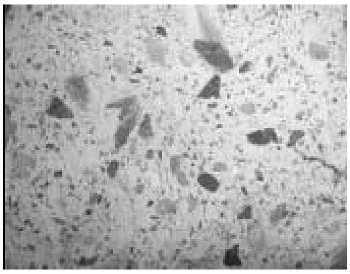

Photo 1 : Concrete 3

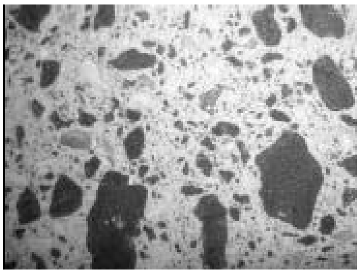

Photo 2 : Concrete 4

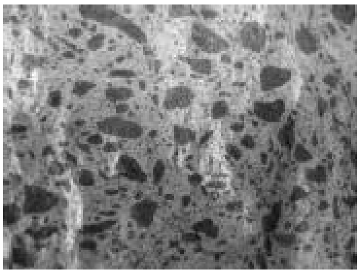

Photo 3 : Concrete 5

Table 3 present the apparent density values for the concrete in 12 months of curing time. The minimum value is reported for concrete synthesis 5 (~1,56 g/cm^3) where only ceramic fragments are used. On the other hand the maximum value is stated for concrete syntheses 1 (~1,95 g/cm^3) where the aggregates of sand and gravel are used as aggregates. Furthermore, concrete syn theses 9 exhibits low value of apparent density (~1,63 g/cm^3), fact that could be attributed to the use of a high percentage of hydrated lime and the use of ceramic fragments up to 50% in the total fraction of aggregates.

Table 3 : Physico-mechanical characteristics of concrete at 12 months of curing time.

Code Concrete	1	2	3	4	5	6	7	8	9
dapp. (g/cm^3)	1,95	1,74	1,87	1,77	1,56	1,69	1,83	1,85	1,62
SD	0,04	0,02	0,02	0,01	0,01	0,03	0,04	0,03	0,01

Fig. 2 and 3 report the flexural and compressive strength data for concrete at the time of 1,3, 6 and 12 months of curing. Regarding the effect of binder nature to concrete mechanical strength it could be noticed that in the case of using EM as a pozzolanic addition, the concrete presents low values of compressive strength (6,2 and 5,8 MPa for the syntheses 1 and 2, respectively at 12 months of curing time) and flexural strength (0,44-0,54 MPa). This fact could be attributed to the low reactivity of this pozzolanic addition regarding the $Ca(OH)_2$ consumption. Moreover, in the case of EM concrete the maximum value of compressive strength is gained by the time of 6 months whereas the flexural strength increases till 12 months of curing time.

On the other hand, MK concrete exhibit a wide range of compressive strength (8,4-26,5 MPa) and flexural strength (1,42-2,82 MPa) values at 12 months of curing time, fact that could become a valuable tool for the design of restoration concrete, taking into account each time the historic structure' s specific characteristics.

MK concrete syntheses (3-6) present high values of mechanical strength. By the time of 3 το 6 months MK concrete present the maximum value of mechanical strength while beyond this period it is decreased.

By the time of 1 month these mortars gain the 90-100 % of the final compressive strength and the 79-100 % of the final flexural strength and therefore it could be used as a pozzolanic addition for restoration mortars/concrete production in order to ameliorate the early strength of hydrated lime mortars.

Comparing the concrete syntheses 3, 6 and 9 as far as the 3, 4 and 5, it could be figured that by increasing the lime percentage and the ceramic fragments percentage, the mechanical strength is reduced.

Almost all MK concrete syntheses (concrete 3, 4, 5, 6) present too high values of compressive strength compared to the one of traditional handmade bricks of brickwork masonry. Regarding the mechanical compatibility, only concrete 9 presents a sufficient value of compressive and flexural strength at 12 months of curing.

Furthermore, some results could be drawn regarding the two different pozzolanic additions that are tested. From the obtained mechanical strength results, it could be said that metakaolin presents a much higher reactivity in reacting with lime compared to the natural pozzolanic addtion.

This fact resulted to a total increase on the compressive the flexural strength up to 400% and it could be attributed to the metakaolin fine grain size distribution, chemical composition and high specific surface area.

Concrete produced by mixing hydrated lime and cement (Concrete 7) exhibit an increase in compressive strength values till the time of 12 months whereas a decrease in flexural strength is observed from 6 to 12 months. Regarding the mechanical behavior of hydraulic lime concrete, it is observed that the strength is increased till the 12 months of curing time. Though, both syntheses present too high values of mechanical strength regarding the strength of traditional structural materials.

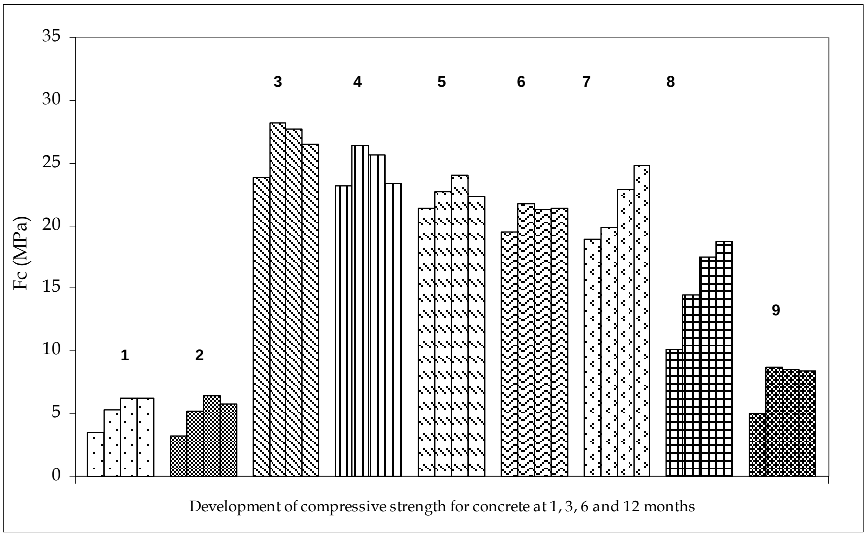

Figure 2 : Compressive strength for concrete at the time of 1,3, 6 and 12 months of curing.

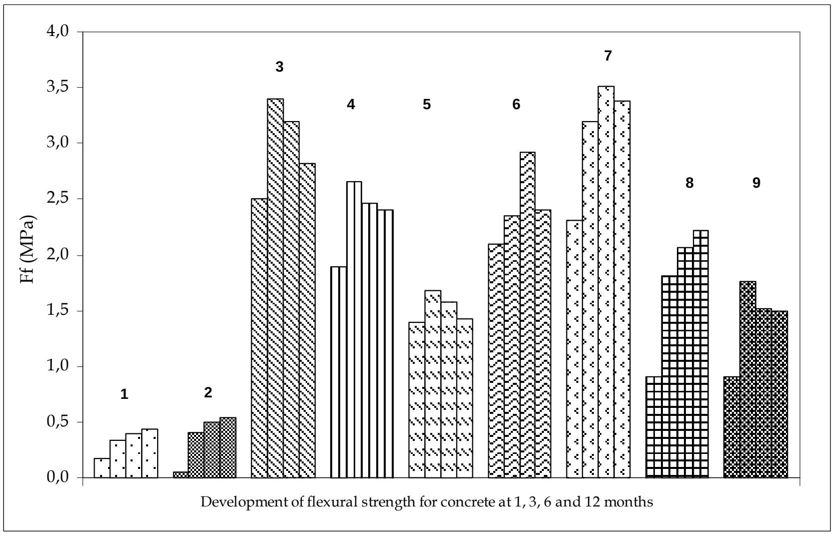

Figure 3 : Flexural strength for concrete at the time of 1,3, 6 and 12 months of curing.

Fig. 4 presents the data of static and dynamic (estimated by ultrasonic method) modulus of elasticity for concrete. In general, it could be said that the modulus of elasticity values are in accordance with the mechanical strength ones, meaning that concrete with high mechanical strength present, also, high values of modulus of elasticity.

Regarding the static modulus of elasticity, it could be observed that concrete produced by earth of milos present low values of static modulus of elasticity ($E_{st.}$: 337-570 MPa) while the metakaolin concrete exhibit much higher values (1950-5650 MPa).

In addition, it could be discerned that by using ceramic fragments as aggregates instead of conventional aggregates, the value of modulus of elasticity is decreased. Though, syntheses 5 where the aggregates were all ceramic fragments exhibit a decrease in $E_{st.}$ value up to 50 % compared with synthesis 4 where the ceramic fragments comprise the 50 % of the total percentage of aggregates used.

Furthermore, by using hydrated lime in a higher proportion in concrete the static modulus of elasticity is decreased. Synthesis 4 exhibits value of static modulus of elasticity up to 4190 MPa while syntheses 6 equal to 2419 MPa. Finally, concrete prepared by natural hydraulic lime or by mixing hydrated lime with a low percentage of metakaolin presents the lowest value of static modulus of elasticity (E_{st}. ~824 MPa).

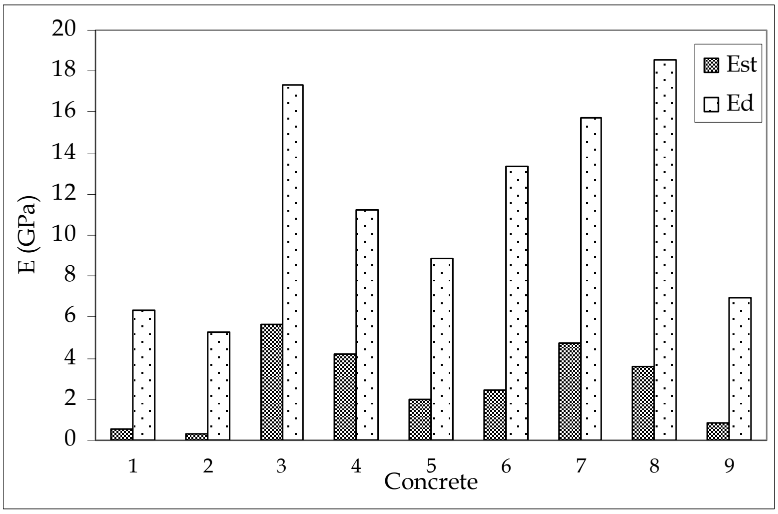

Figure 4 : Static and dynamic modulus of elasticity for concrete at 12 months of curing time.

Regarding the dynamic modulus of elasticity, the maximum value is reported for natural hydraulic lime concrete while high values are reported for syntheses 3 and 7. On the contrary, the lowest values are reported for concrete of earth of milos and concrete syntheses 9 (7539 MPa).

Comparing, the data of static modulus of elasticity with the dynamic one, it could be observed that the data differ very much, though, they present similar trend. The ratio of Ed/Est. varies in the range 3-16, while these data seem to be close as the ultrasonic propagation velocity increases. Fig. 5 present the correlation between the static and dynamic modulus of elasticity.

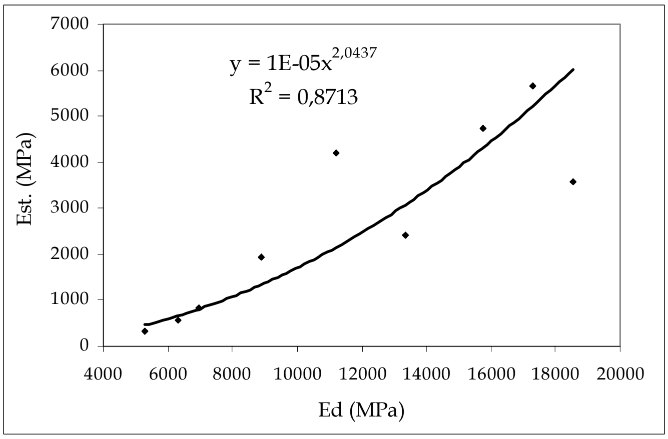

Figure 5 : Dynamic modulus of elasticity versus static modulus of elasticity.

4 CONCLUSIONS

From the obtained results the following conclusive remarks can be point out:

- The natural pozzolanic addition-earth of milos presents low reactivity regarding the $Ca(OH)_2$ consumption resulted to low values of final mechanical strength and mechanical strength acquisition.
- The artificial pozzolanic addition-metakaolin presents high reactivity regarding the $Ca(OH)_2$ consumption due to its physicochemical and mineralogical characteristics. Therefore, it could be used as a pozzolanic addition (in small percentages) in hydrated lime restoration mortars in order to ameliorate the early strength of lime mortars.
- Concrete prepared by mixing lime/metakaolin/ceramic fragment/sand:27.5/2.5/35/35 (p.w.%), present sufficient mechanical strength (F_c: 8.4 MPa, F_f: 1.50 MPa and Est.: 824 MPa), in 12 months of curing time, assuring in that way the mechanical compatibility with the traditional structural materials of Byzantine structures.
- Concrete produced by natural hydraulic lime or lime/cement in mixing ratio (p.w.):1/1 or by mixing lime and metakaolin in ratio 1/1 or 2/1 (p.w.) present too high values of mechanical strength, fact that could provoke a mechanical incompatibility problem in historic brickwork masonries.
- By increasing the hydrated lime percentage in the mixture and the percentage of ceramic fragments in the total fraction of aggregates, a decrease in compressive and flexural strength, dynamic and static modulus of elasticity and apparent density occurs.
- The ratio of Ed/Est varies in the range 3-16, while these data seem to be close as the compressive strength increases.

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