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PHYSICAL PROPERTIES FOR THE CHARACTERIZATION OF WATERLOGGED ARCHAEOLOGICAL WOODS OF EIGHT YENİKAPI SHIPWRECKS FROM BYZANTINE PERIOD

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ABSTRACT

37 shipwrecks, constituting the biggest medieval shipwrecks collection in the world, which are dated from 5th to 11th centuries AD, were uncovered by salvage excavations conducted in Yenikapı, Istanbul. In this study, 160 wood samples taken from eight shipwrecks (YK 13, YK 16, YK 18, YK 21, YK 22, YK 25, YK 29 and YK 35) were analyzed for determining degradation degree of the woods. For this purpose, physical property analyses such as maximum water content, basic density, and loss of wood substance, and SEM-EDS were conducted. In order to examine the relationship between the degradation degree of the woods and wood species, samples were taken from different shipwrecks considering wood species. The wood samples were determined as 9 different species of wood (oak, pine, elm, cedar, cypress, ash, fir, plane and chestnut). Maximum water content values of the samples ranged between 148% and 1044%. With the evaluation of the highly degraded wood samples group, especially plane wood samples were found in this group.

KEYWORDS: Yenikapı shipwrecks, waterlogged wood, physical property of wood, maximum water content, basic density, loss of wood substance.

1. INTRODUCTION

In the Yenikapı Excavations, 37 shipwrecks are considered as the world's largest medieval shipwreck collection and provide information about Byzantine Period ship building technology. Istanbul Archaeological Museums conducted a joint project with Istanbul University (total 31 shipwrecks) continuing conservation studies on the shipwrecks (Kocabaş, 2008; Kocabaş, 2012; yenikapibatiklari.com). Department of Conservation of Marine Archaeological Objects was founded in 2008 at Istanbul University, and the laboratories of the department have carried out conservation and restoration works of Yenikapı Shipwrecks. The shipwrecks have been lifted and transported to the laboratories of the department between 2006 and 2013. In the laboratories, documentation, desalination, removing of iron compounds, physical-chemical analyses and conservation works are carried out by IU Yenikapı Shipwrecks Project Team. Analyses were carried out on woods during the conservation process for the conservation of wood with proper methods. The woods of the shipwrecks, which were found during the excavation, were in the waterlogged state. The waterlogged wood means that the entire pore space of the wood filled with water (Grattan, 1987). Water exists in two different forms in waterlogged wood. In the first form, water molecules are bound to the molecules, which are formed the frame of the wood, directly with hydrogen bond. The loss of the first form of the water causes shrinkage on the wood. Therefore, if waterlogged wood is allowed to dry in an uncontrolled environment, it may collapse, shrink or degrade, irreversibly. The structure of the second form of the water is like the one in bulk liquid water (Grattan, 1987; Schniewind, 1989; Christensen, et al, 2006).

In this study, samples from YK 13, 16, 18, 21, 22, 25, 29 and 35 were analyzed. YK 13 is one of the galleys uncovered at Yenikapı and dated to AD 690–890 by radiocarbon analyses. YK 16, which is thought to be a galley, and it is dated to AD 720–890 by radiocarbon analyses. YK 18 is a merchantman, and it is dated to the 10th century based on stratigraphy only. YK 21 is a merchantman, which is thought to be dated to 9th–10th centuries. YK 22 is the largest merchantman of the Yenikapı shipwrecks. Radiocarbon analyses carried out by the Oxford Radiocarbon Accelerator Unit (ORAU) at Oxford University, indicate a date in the range of AD 430–606. YK 25 is thought to be a galley and it is dated to the 10th century by its stratigraphic context. YK 29 is thought to be as a merchantman dated to 8–9th century based on its stratigraphy. YK 35 is a merchantman and it is dated to 5th century AD (Figure 1) (Kocabaş, 2010; Kocabaş, 2015a; Kocabaş, 2015b). With dating the shipwrecks, information about the construction techniques and wood species used in different periods can be obtained. In addition, the relationship between the degree of degradation of wood and age can be investigated. The wood used for Yenikapı ships changed from earlier time to the later time. During 5th – 8th centuries, generally softwoods were preferred. On the other side, during 9th – 11th century's elm, oak, chestnut species had been used for ship building (Akkemik and Kocabaş, 2013; Akkemik and Kocabaş, 2014: 325).

Physical and chemical properties of the wood are degraded during burial but also wood can be preserved for a very long time in an anaerobic environment (in the event of a rapid and complete burial). The degradation of waterlogged wood evolves by the loss of the carbohydrate components within the fibrillary texture, from the lumen towards the middle lamella, while the lignin almost unchanged unless some oxidative modification (Capretti et al, 2008: 856). Hydrolysis processes deteriorate the wood slowly but also biological factors also effect the deterioration of the wood (Passialis, 1997). For instance, woods of the YK 13 were heavily degraded by microorganisms, such as soft-rot fungi and erosional bacteria (Köse and Taylor, 2013; Wada, et al, 2014; Safa et al., 2018). In addition, biological deterioration of the wood may start before it buried under soil or water (Passialis, 1997).

The degradation degree of the waterlogged wood varies depending on the age of the wood, wood species, intended use of the wood, the ambient conditions under which it is buried and the time it spends under these conditions (Hedges, 1990: 111-140). The determination of physical and chemical changes of waterlogged wood is important for understanding the degradation process of wood and deciding the conservation method of the waterlogged wood (Florian, 1990).

The simplest indicators of the condition of waterlogged wood are pin test, measuring of water content and basic density and also other techniques that require access to specific equipment such as FTIR (Fourier-transform infrared spectroscopy), Sibert drill, X-radiography, SEM (Scanning electron microscopy) and NMR (Nuclear magnetic resonance) can be used (English Heritage, 2015:27; Grattan, 2000: 665).

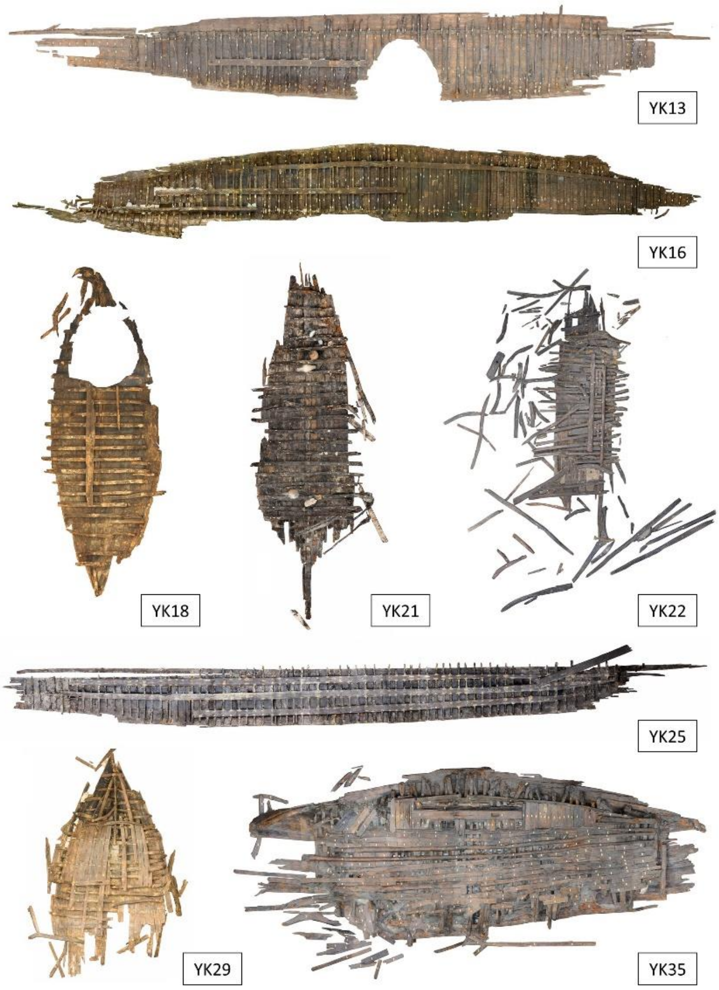


Figure 1. Photos of the shipwrecks (IU Yenikapı Shipwrecks Project Archive).

During burial under water or wet land, water enters the porous of the material such as wood, the apparent density of the water increases due to sorption in the cell wall (Jensen and Gregory, 2006: 552). Therefore, there is a correlation between the water content of the wood and the degradation of the wood. In order to maintain an accomplished conservation process of waterlogged woods, it is important to know the degradation degree of the waterlogged wood. Maximum water content and basic density are often used as the determiner of solid wood loss (Passialis, 1998). For determining the maximum water content of waterlogged wood, the wood sample is weighed firstly when it is wet and then weighed again after oven dried. With these measurements, the water content of the wood can be calculated (English Heritage, 2015:28). Evaluation of degradation degree of waterlogged wood is most often based on the physical properties of the wood, related to its mass and volume because of the simplicity of these techniques (Babinski et al, 2014: 372). On the other hand, comparing the physical properties of waterlogged without considering the properties of the wood species is very important. The durability of the wood varies according to species of wood as well as the environment in which it is buried. Therefore, the loss of wood substance, which is calculated based on properties of fresh wood, should be considered (Babinski et al, 2014).

Degraded waterlogged wood is altered morphologically, chemically and physically. Therefore, it must be taken care in drying process against any irreversible damage (Capretti et al, 2008: 858) Physical parameters such as maximum water content and basic density of the wood give an indication of the tendency of an artefact to collapse during conservation. Based on these, a conservation method and an impregnation chemical with appropriate physical and chemical properties, such as Polyethylene Glycol (PEG) with a suitable molecular weight, can be chosen. (Jensen and Gregory, 2006; Christensen, et al, 2006). For conservation of waterlogged wood, preventing directly water evaporation from the wood is very important to avoid the collapse of the wood because of the surface tension of water. For instance, the woods which have 100- 300% MWC values can be treated with mixture of PEG 400 and 2000, the woods which have 300- 400% MWC values can be treated with PEG 2000, the woods which have 400-600% MWC values can be treated with PEG 3350, and also the woods with higher 600% MWC values can be treated with PEG 4000. After PEG impregnation followed by vacuum freeze drying may provide an optimum result (Kılıç and Kılıç, 2019). Because water transitions directly from the solid phase to the gas phase in pre-impregnation of PEG by the vacuum freeze drying method (Christensen, et al, 2006).

The aim of this study is to make a comparison of the degradation degree of waterlogged archaeological evaluated based on its wood species, maximum water content, basic density and loss of wood substance.

2. MATERIAL AND METHODS

All wood samples were kept waterlogged prior to use in this study. During the desalination process, woods of the Yenikapı shipwrecks are kept in 50-ton tanks. The study was done on 160 samples of 8 shipwrecks. All of the samples were taken from the woods, which are kept in desalination tanks. As many samples as possible were taken considering the species of wood used in the construction of the shipwrecks to the extent permitted by physical conditions of the desalination tanks.

2.1. Wood Species

Species identification is very important for comparison of the status of degradation of wood and its species. The durability of fresh wood varies according to species of wood. Heartwoods are mostly more durable than softwoods. In addition, the durability of wood varies in ground contact, above ground contact, in water and within marine sediments (Björdal and Gregory, 2012: 55). Species identification of the samples was carried out by Prof. Dr. Ünal Akkemik, Istanbul University Cerrahpaşa's Faculty of Forestry. There are many wood species, which has different physical and chemical properties (Björdal and Gregory, 2012: 51). Nine species of wood were identified to be represented-namely, oak, pine, elm, cedar, cypress, ash, fir, plane and chestnut. Detailed information on the woods species of the samples is presented in Table 1.

Table 1. The genera and possible species of the samples (Akkemik and Kocabaş, 2014: 320).

Genera identified	Their potential species
Pine (*Pinus* L.)	Black pine (*Pinus nigra* Arn), Calabrian pine (*Pinus brutia* Ten.), Stone pine (*Pinus pinea* L.)
Cypress (*Cupressus* L.)	Mediterranean cypress (*Cupressus sempervirens* L.)
Cedar (*Cedrus* L.)	Taurus cedar (*Cedrus libani* A.Rich.)
Fir (*Abies* L.)	Caucasian fir (*Abies nordmanniana*) / Taurus fir (*Abies cilicica*)
Oak (*Quercus* L.)	White oaks (*Quercus petraea, Q.robur, Q.frainetto, Q.infectoria.*) Red oaks (*Quercus cerris, Q.ithaburensis subsp.macrolepis*) Evergreen oaks (*Quercus ilex, Q.coccifera*)
Chestnut (*Castanea* L.)	Spanish chestnut (*Castanea sativa* L.)
Plane (*Platanus* L.)	Oriental plane (*Platanus orientalis* L.)
Elm (*Ulmus* L.)	Field elm (*Ulmus minor*) / Mauntain elm (*Ulmus glabra*) / European white elm (*Ulmus laevis*)
Ash (*Fraxinus* L.)	Common ash (*Fraxinus excelsior*) / Narrow-leaved ash (*Frax-inus angustifolia*) / Manna ash (*Fraxinus ornus*)

2.2. Determination of physical properties of wood

Before starting the conservation of waterlogged, it is important to determine its state of preservation. Non-destructive and destructive methods such as the maximum water content and the basic density are used for determining the physical parameters of waterlogged wood (Jensen and Gregory, 2006). Moreover, imaging methods such as SEM also provide information about the physical degradation of wood. Figure 2 shows highly degraded and relatively well-preserved surface areas of a sample taken from YK 16.

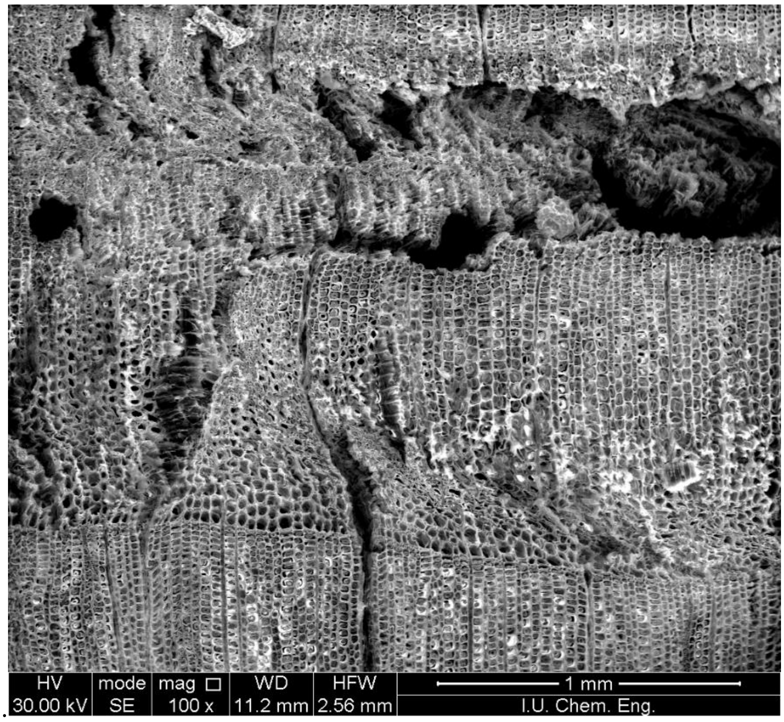
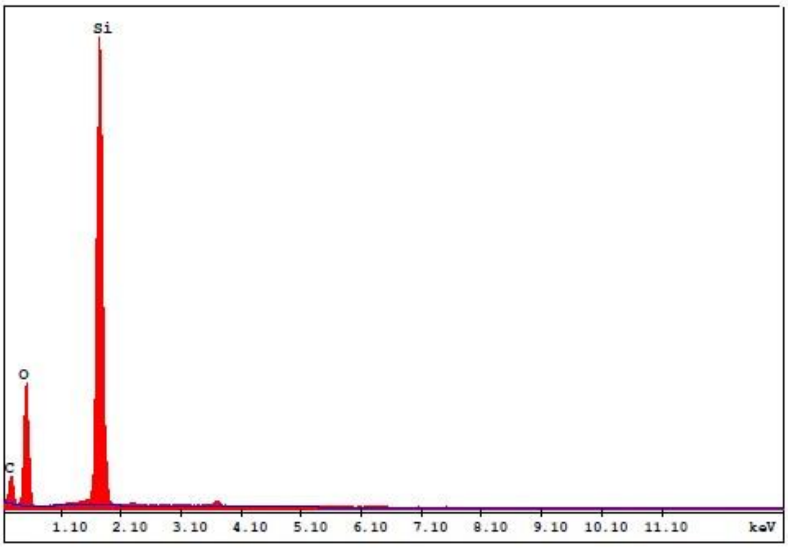


Figure 2. SEM image of YK 16-SK2-1 sample (100×).

Before the measurement, the dirt on the surface of the samples was cleaned because the contaminations could effect the calculations. For instance, sand and soil particles accumulated on the surfaces of woods can cause measurement errors. The presence of them was also determined by SEM-EDX analysis (Figure 3).



EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : Default

Element	Wt %	At %	K-Ratio	Z	A	F
C K	23.35	33.53	0.0345	1.0230	0.1444	1.0004
O K	41.78	45.05	0.0899	1.0086	0.2133	1.0005
SiK	34.87	21.42	0.2567	0.9734	0.7564	1.0000
Total	100.00	100.00				

Element	Net Inte.	Bkgd Inte.	Inte. Error	P/B
C K	49.17	10.20	2.11	4.82
O K	323.40	8.09	0.71	39.98
SiK	1624.25	15.75	0.31	103.16

Figure 3. The presence of Si determined by SEM-EDX.

In addition, calcium tunnels were formed while *Teredo navalis* (one of the biological organisms damaging the woods under water) bored the woods, was also determined by SEM-EDX analysis (Figure 4-5).

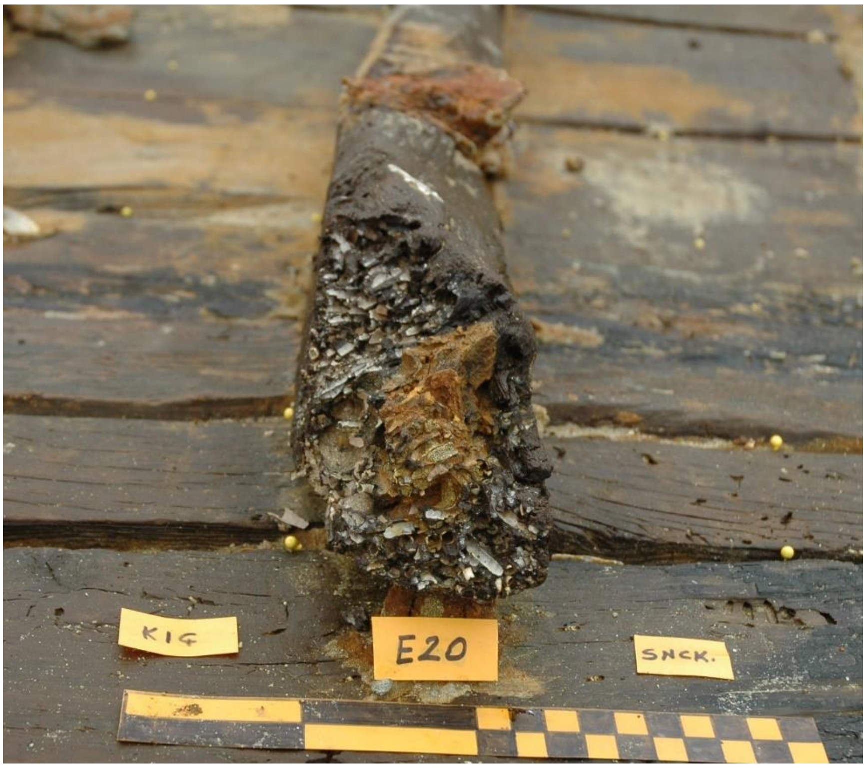
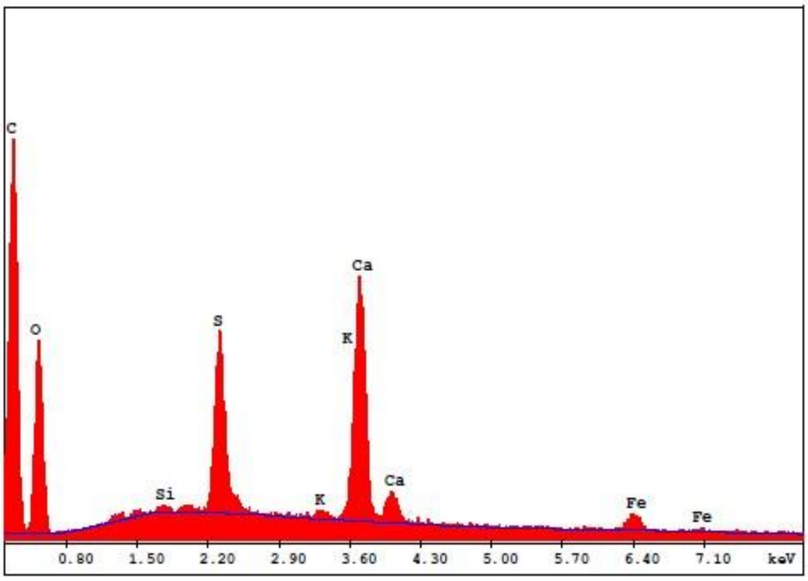


Figure 4. A wooden element of the shipwrecks bored by Teredo navalis (IU Yenikapı Shipwrecks Project Archive).



EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : Default

Element	Wt %	At %	K-Ratio	Z	A	F
C K	51.21	62.63	0.1847	1.0140	0.3556	1.0003
O K	34.76	31.92	0.0503	0.9998	0.1447	1.0001
SiK	0.18	0.10	0.0012	0.9651	0.7021	1.0053
S K	4.36	2.00	0.0387	0.9593	0.9189	1.0074
K K	0.25	0.09	0.0023	0.9108	1.0007	1.0307
CaK	8.07	2.96	0.0769	0.9322	1.0200	1.0014
FeK	1.18	0.31	0.0104	0.8641	1.0197	1.0000
Total	100.00	100.00				

Figure 5. The presence of Ca determined by SEM-EDX.

In the first stage of the experiment, the waterlogged samples were divided into smaller pieces but not less than 1 g and waterlogged samples weighed in air. In the second stage of the experiment, the wet density of the samples was measured by weighed in water. For measurement of the wet density of samples, the sample was measured on the tip of a needle when all of its pores are full of water. Finally, samples were oven-dried until the water inside them were completely removed and weighed again. An analytical balance with an accuracy up to 0.0001 g was used for weighing (Kılıç and Kılıç, 2018; Kılıç, 2018). Usually, in order to determine the degradation degree of waterlogged wood, its maximum water content and basic density are considered. Comparing the physical properties of archaeological wood may be misleading because of the lack of information on the properties of the wood before its degradation. Therefore, the loss of wood substance values should be considered. Loss of wood substance calculated in relation to the average basic density of fresh wood (Babinski et al, 2014). The average basic density values of fresh woods are presented in Table 2.

Table 2. The average basic density values of fresh woods (Babinski et al, 2014; Rauf and Raza, 2012; Taşcıoğlu et al, 2014).

Species	Average basic density of fresh wood (g/cm^3)
Oak	0,58
Ash	0,57
Elm	0,57
Pine	0,42
Cypress	0,51
Cedar	0,42
Fir	0,46
Plane	0,66
Chestnut	0,56

The degree of wood degradation was presented based on maximum water content (MWC), basic density (BD) and loss of wood substance (LWS) were calculated according to the following formulas:

$MWC = 100 \times (m_w - m_d) / m_d$

$BD = m_d / V_w$

$LWS = 100 \times (BD_f - BD_a) / BD_f$

where

MWC: maximum water content (%),

BD: basic density (g/cm^3),

LWS= loss of wood substance (%),

m_w: mass of waterlogged sample (g),

m_d: mass of oven-dry sample (g),

V_w: volume of waterlogged sample (cm^3),

BD_f: basic density of fresh wood (g/cm^3),

BD_a: basic density of archaeological wood (g/cm^3) (Babinski, et al., 2014).

In this study, maximum water content, basic density, and loss of wood substance values of 160 samples were calculated with the above formulas.

3. RESULTS AND DISCUSSION

The results of identification of the wood species together with physical properties such as maximum water content, basic density, and loss of wood substance of the woods are presented in Table 3. 13 samples (12 pine samples and 1 plane sample) from YK 13, 17 samples (7 elm sample, 5 plane sample, 3 pine and 2 fir sample) from YK 16, 15 samples (all of them are oak) from YK 18, 36 samples (35 oak samples and 1 chestnut sample) from YK 21, 27 samples (16 oak samples, 10 cypress samples and 1 ash sample) from YK 22, 15 samples (5 plane sample, 4 pine sample, 3 cedar sample, 2 fir sample and 1 elm sample) from YK 25, 17 samples (8 cypress samples, 6 pine samples, 2 elm samples and 1 ash sample) from YK 29 and 21 samples from (10 cypress samples, 5 pine samples, 2 oak samples, 2 elm samples and 1 cedar sample) from YK 35 were studied (Akkemik, 2015) . Degree of the degradation of the wood samples is shown by the physical characteristics such as MWC and basic density, and loss of wood substance.

Table 3. Physical properties of wood samples with wood species identifications.

Sample	MWC (%)	BD (g/cm^3)	LWS (%)	Species
YK 13				
İB1-1	554	0,16	62,8	Pine (*Pinus L.*)
İB1-2	653	0,14	65,9	Pine (*Pinus L.*)
İÇT2	583	0,16	61,4	Pine (*Pinus L.*)
İK1-2	400	0,23	44,4	Pine (*Pinus L.*)
İK1-3	512	0,17	59,1	Pine (*Pinus L.*)
İK2-1	552	0,16	62,1	Pine (*Pinus L.*)
İK2-2	404	0,22	48,2	Pine (*Pinus L.*)
İK3	390	0,26	38,9	Pine (*Pinus L.*)

İK4-2	357	0,25	41,6	Pine (*Pinus L.)*
İK4-5	600	0,15	64,1	Pine (*Pinus L.)*
İK5-1	575	0,16	62,8	Pine (*Pinus L.)*
Om2	728	0,13	79,6	Plane *(Platanus L.)*
SB1-2	444	0,21	51,2	Pine (*Pinus L.)*
YK 16				
E2	831	0,11	82,9	Plane *(Platanus L.)*
E47a	1044	0,09	86,6	Plane *(Platanus L.)*
E47b	940	0,10	84,2	Plane *(Platanus L.)*
E74	600	0,17	70,5	Elm *(Ulmus L.)*
E103-S1	686	0,13	76,4	Elm *(Ulmus L.)*
E115	776	0,12	82,4	Plane *(Platanus L.)*
E118	727	0,12	81,2	Plane *(Platanus L.)*
E122	650	0,15	74,5	Elm *(Ulmus L.)*
E130	867	0,11	80,1	Elm *(Ulmus L.)*
E134a	554	0,16	71,5	Elm *(Ulmus L.)*
E134b	475	0,20	64,9	Elm *(Ulmus L.)*
İB1-2	643	0,14	66,0	Pine (*Pinus L.)*
İçK1	477	0,18	60,0	Fir *(Abies L.)*
İK1	521	0,17	59,9	Pine (*Pinus L.)*
S-E27	552	0,17	70,8	Elm *(Ulmus L.)*
SK2-1	519	0,19	55,3	Pine (*Pinus L.)*
SK7-1	336	0,25	45,7	Fir *(Abies L.)*
YK 18				
E2	444	0,23	59,7	Oak (*Quercus L.)*
E3	600	0,18	69,8	Oak (*Quercus L.)*
E7*	43	0,72	-24,1	Oak (*Quercus L.)*
E9a	563	0,15	74,0	Oak (*Quercus L.)*
E9b	368	0,28	52,5	Oak (*Quercus L.)*
E11	660	0,15	74,1	Oak (*Quercus L.)*
E12	606	0,23	60,2	Oak (*Quercus L.)*
E16	429	0,23	60,4	Oak (*Quercus L.)*
E19-İ2	533	0,17	69,9	Oak (*Quercus L.)*
İK7-4	559	0,17	70,4	Oak (*Quercus L.)*
İK8-3	486	0,22	62,3	Oak (*Quercus L.)*
İK8-6	279	0,42	26,9	Oak (*Quercus L.)*
SB2	368	0,27	53,2	Oak (*Quercus L.)*
SK3-2	316	0,34	41,3	Oak (*Quercus L.)*
SK4-2	518	0,22	61,4	Oak (*Quercus L.)*
YK 21				
E1	600	0,15	73,4	Oak (*Quercus L.)*
E5	708	0,13	77,4	Oak (*Quercus L.)*
E6	560	0,16	71,7	Chestnut (*Castanea L.)*
E9	596	0,16	72,7	Oak (*Quercus L.)*
E10	478	0,21	62,9	Oak (*Quercus L.)*
E13	361	0,28	51,0	Oak (*Quercus L.)*
E14	641	0,14	75,6	Oak (*Quercus L.)*
E16	588	0,15	74,1	Oak (*Quercus L.)*
E18	365	0,24	59,3	Oak (*Quercus L.)*
E20*	93	0,65	-11,2	Oak (*Quercus L.)*
İK1-1	517	0,19	67,7	Oak (*Quercus L.)*
İK1-2	527	0,17	69,9	Oak (*Quercus L.)*
İK2-2	496	0,19	66,9	Oak (*Quercus L.)*
İK3-1	444	0,24	59,1	Oak (*Quercus L.)*
İK3-2	535	0,21	63,7	Oak (*Quercus L.)*
İK4-2	287	0,30	49,1	Oak (*Quercus L.)*
İK6-1	403	0,22	62,3	Oak (*Quercus L.)*
İK6-2	638	0,15	74,0	Oak (*Quercus L.)*
İK6-3	429	0,21	64,6	Oak (*Quercus L.)*
İK6-5	577	0,15	73,9	Oak (*Quercus L.)*
İK6-5	453	0,19	66,4	Oak (*Quercus L.)*
İK7-1	665	0,14	75,7	Oak (*Quercus L.)*
İK8	614	0,15	74,9	Oak (*Quercus L.)*
İK9-1	427	0,21	64,6	Oak (*Quercus L.)*
İK9-2	679	0,15	73,8	Oak (*Quercus L.)*
OM1	326	0,33	43,5	Oak (*Quercus L.)*

SK1-1	287	0,29	50,1	Oak (*Quercus L.)*
SK1-2	389	0,26	54,4	Oak (*Quercus L.)*
SK1-3	538	0,17	71,3	Oak (*Quercus L.)*
SK2-2	586	0,15	74,0	Oak (*Quercus L.)*
SK3-1	525	0,17	70,0	Oak (*Quercus L.)*
SK3-2	440	0,20	66,0	Oak (*Quercus L.)*
SK4-2	293	0,32	45,1	Oak (*Quercus L.)*
SK6-3	555	0,16	72,2	Oak (*Quercus L.)*
SK7-1a	631	0,22	61,7	Oak (*Quercus L.)*
SK7-1b	633	0,15	74,9	Oak (*Quercus L.)*
YK 22				
E12a	608	0,15	74,6	Oak (*Quercus L.)*
E12b	336	0,25	56,9	Oak (*Quercus L.)*
E14	600	0,17	71,3	Oak (*Quercus L.)*
E15	567	0,16	72,6	Oak (*Quercus L.)*
E16	614	0,15	74,9	Oak (*Quercus L.)*
SK1	329	0,26	49,8	Cypress (*Cupressus L.)*
SK12-1	364	0,23	54,2	Cypress (*Cupressus L.)*
SK15-2	337	0,25	51,9	Cypress (*Cupressus L.)*
SK2	199	0,36	29,8	Cypress (*Cupressus L.)*
SK3	148	0,43	15,7	Cypress (*Cupressus L.)*
SK4	268	0,29	42,7	Cypress (*Cupressus L.)*
SK5-2	340	0,25	51,9	Cypress (*Cupressus L.)*
SK6-1	339	0,25	51,3	Cypress (*Cupressus L.)*
TP1	519	0,17	70,5	Oak (*Quercus L.)*
TP22	555	0,16	72,2	Oak (*Quercus L.)*
TP23	671	0,14	76,3	Oak (*Quercus L.)*
TP25	540	0,17	71,1	Oak (*Quercus L.)*
TP41	686	0,13	77,1	Oak (*Quercus L.)*
YBO E36	346	0,25	57,7	Oak (*Quercus L.)*
YBO E42	457	0,19	67,1	Oak (*Quercus L.)*
YBO E5	494	0,18	68,7	Ash (*Fraxinus L.)*
YBO E7	505	0,17	71,3	Oak (*Quercus L.)*
YBO E54	544	0,16	72,1	Oak (*Quercus L.)*
YBO E81	237	0,33	42,4	Oak (*Quercus L.)*
YBO E83	672	0,14	76,6	Oak (*Quercus L.)*
YBO K22	232	0,33	35,6	Cypress (*Cupressus L.)*
YBO K3	250	0,32	37,6	Cypress (*Cupressus L.)*
YK 25				
E6	423	0,23	59,5	Elm (*Ulmus L.)*
E7	730	0,14	79,5	Plane (*Platanus L.)*
E8	888	0,11	83,8	Plane (*Platanus L.)*
E14	700	0,13	80,1	Plane (*Platanus L.)*
E19	879	0,11	83,4	Plane (*Platanus L.)*
E35	836	0,12	81,3	Plane (*Platanus L.)*
İB1-2	600	0,15	64,1	Pine (*Pinus L.)*
İçK2.1	534	0,30	35,0	Fir (*Abies L.)*
İçK3	611	0,15	67,9	Fir (*Abies L.)*
İK2-1	225	0,36	13,4	Cedar (*Cedrus L.)*
İK2-3	232	0,39	7,7	Cedar (*Cedrus L.)*
İK3-3	565	0,17	60,3	Cedar (*Cedrus L.)*
İK4-2	494	0,18	56,7	Pine (*Pinus L.)*
İK5-1a	552	0,17	60,6	Pine (*Pinus L.)*
İK5-1b	419	0,21	49,6	Pine (*Pinus L.)*
YK 29				
F1	630	0,15	65,3	Pine (*Pinus L.)*
F12	390	0,24	43,4	Pine (*Pinus L.)*
F13	603	0,15	64,7	Pine (*Pinus L.)*
İ-E13	519	0,18	68,8	Ash (*Fraxinus L.)*
İF7	484	0,18	57,2	Pine (*Pinus L.)*
İK1a	174	0,42	17,5	Cypress (*Cupressus L.)*
İK1b*	55	0,74	-45,2	Cypress (*Cupressus L.)*
İK4-2	274	0,30	42,0	Cypress (*Cupressus L.)*
İK8-2	279	0,30	41,2	Cypress (*Cupressus L.)*
İK10	342	0,24	52,5	Cypress (*Cupressus L.)*
İK13-2	351	0,24	53,6	Cypress (*Cupressus L.)*

Om1	400	0,23	46,3	Pine (*Pinus L.)*
S-E7a*	171	0,41	28,7	Elm (*Ulmus L.)*
S-E7b	395	0,22	61,4	Elm (*Ulmus L.)*
S-E11	447	0,20	53,2	Pine (*Pinus L.)*
SK4-2	303	0,27	47,2	Cypress (*Cupressus L.)*
SK9	350	0,24	53,1	Cypress (*Cupressus L.)*
YK 35				
E17-S1a	650	0,14	75,4	Oak (*Quercus L.)*
E17-S1b	438	0,22	62,2	Oak (*Quercus L.)*
E19-S1	478	0,18	56,2	Pine (*Pinus L.)*
E34	697	0,13	76,7	Elm (*Ulmus L.)*
F12-9	340	0,25	40,5	Pine (*Pinus L.)*
F14-4	447	0,19	54,0	Cedar (*Cedrus L.)*
F9-2	400	0,21	49,0	Pine (*Pinus L.)*
İçK1-1	378	0,22	46,5	Pine (*Pinus L.)*
İçK6	345	0,24	53,4	Cypress (*Cupressus L.)*
İçK7	188	0,39	22,6	Cypress (*Cupressus L.)*
İçK9-3	307	0,25	50,1	Cypress (*Cupressus L.)*
İK1-3	230	0,34	33,8	Cypress (*Cupressus L.)*
SÇT2-2	200	0,38	24,8	Cypress (*Cupressus L.)*
SÇT3	357	0,24	53,7	Cypress (*Cupressus L.)*
S-E41	520	0,17	69,8	Elm (*Ulmus L.)*
SK12-3	297	0,27	47,6	Cypress (*Cupressus L.)*
SK22	305	0,26	48,1	Cypress (*Cupressus L.)*
SK2-2*	75	0,74	-45,9	Cypress (*Cupressus L.)*
SK6	158	0,45	11,8	Cypress (*Cupressus L.)*
TP1	383	0,23	45,1	Pine (*Pinus L.)*

Key to symbols
E, YBO E, S-E, İ-E: Frame
F,İF: Ceiling
İÇK: Stringer
İÇT, SÇT: Wale
İK,SK, YBO K: Plank
OM: Keel
TP: Unidentified
** Samples were taken from near the iron corrosion products*

Firstly, the results of the shipwrecks were examined separately. MWC value of a sample (plane sample) which was taken from the keel of YK 13 was 728% and it is the highest value for the shipwreck. Maximum water content in pine woods from YK 13 ranged between 357% and 653% and high values of MWC were shown. The pine wood samples of YK 13, evaluated according to the high values of MWC, may be recognized as highly degraded.

MWC value of a sample (plane sample) which was taken from a frame of YK 16 was 1044% and maximum water content in plane wood from YK 16 was generally higher than other samples of the shipwrecks. Maximum water content in elm wood ranged between 475% and 867%, according to these values, the woods were recognized highly degraded. Maximum water content in pine wood ranged between 519% and 643%. Maximum water content in fir wood ranged between 336% and 477% according to these values, the woods were recognized less degraded than the others. Two different samples were taken from the same frame of the shipwreck and the MWC values were found very similar thus, results were verifiable.

MWC value of the sample of YK 18, which are oak wood, ranged between 279% and 660%, according to these values, most of the woods of the shipwreck recognized highly degraded. On the other hand, there were also samples with less degree of degradation. In order to reveal the misleading effect of inorganic compounds on the results, samples were taken from near the iron corrosion products, which accumulate in the wood (Figure 6).

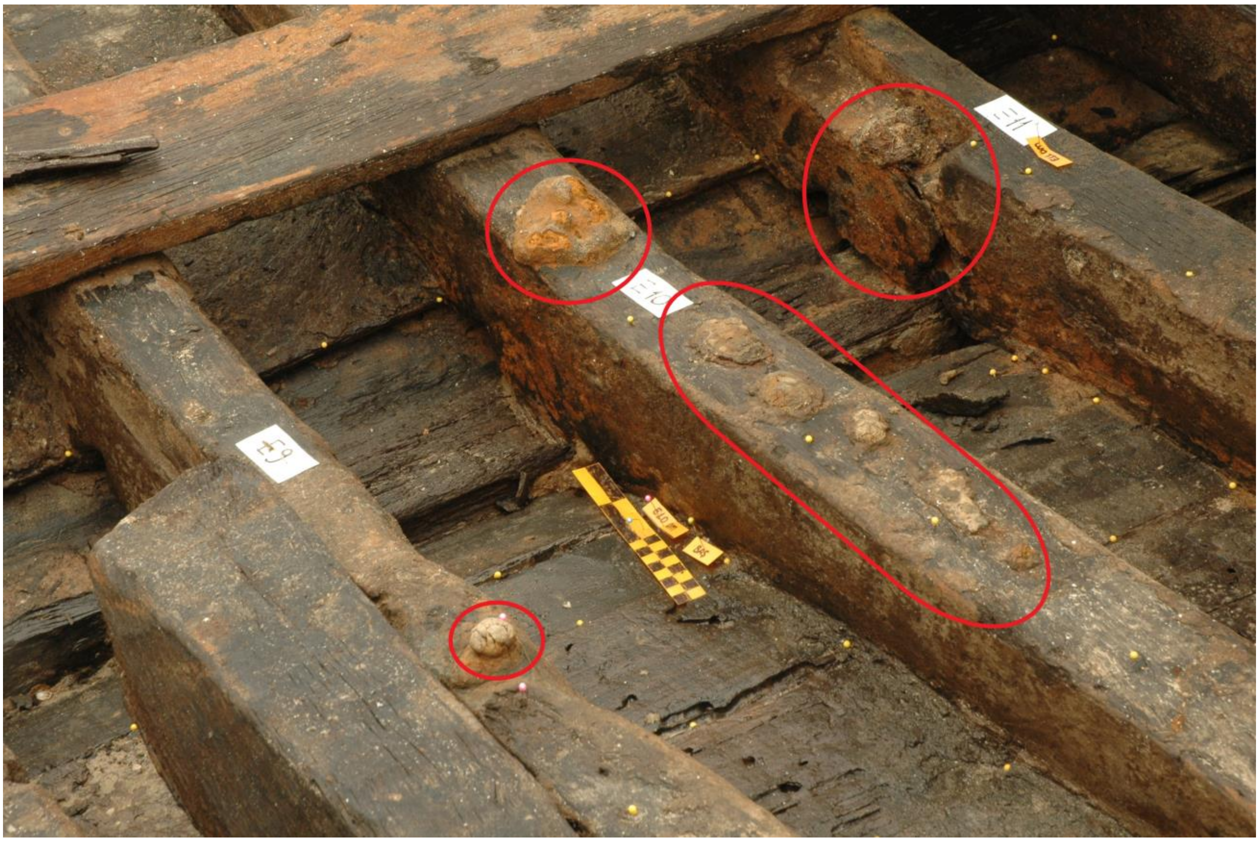


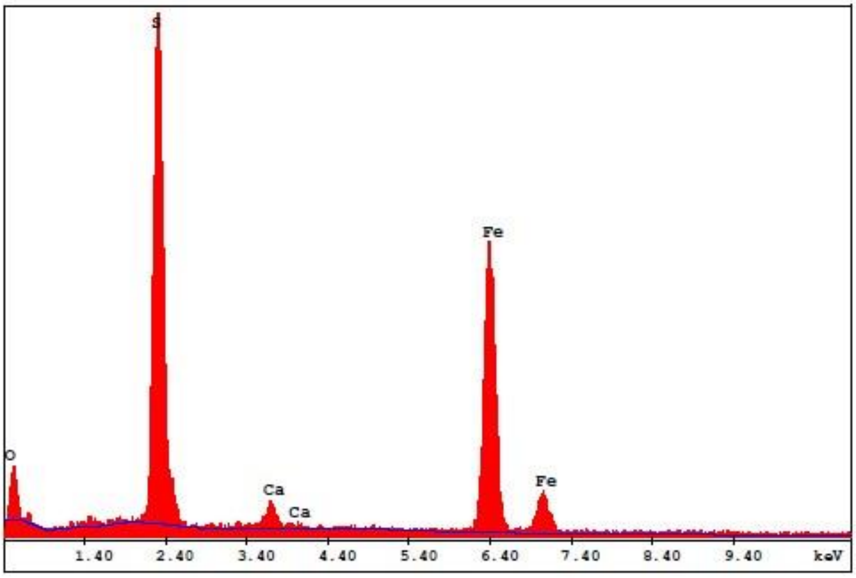
Figure 6. Iron corrosion part in the woods of a Yenikapı Shipwreck (IU Yenikapı Shipwrecks Project Archive).

The presence of iron corrosion product in the samples can be easily detected by eye, as well as it was detected by SEM-EDX analysis (Figure 7) (Eriksen, et al, 2014). The MWC of the sample was 43% and it appears that this value is very low when compared to other samples. The reason of this incorrect result was due to the porous structure of the wood that has been filled with iron corrosion products. Therefore drying process did not change the weight of the sample significantly.

Only one of the sample taken from YK 21 is chestnut tree and the MWC of it was 560%. The rest of the samples are oak wood and MWC values ranged between 287% and 708% while most of the samples had MWC values around 400% and above, according to these values, most of the woods of the shipwreck recognized highly degraded. As in YK 16, two different samples were taken from the same frame of the shipwreck and the MWC values were found very similar thus, results were verifiable again. MWC of the sample taken from near the iron corrosion products was 33% and it appears that this value is very low when compared to other samples as in the sample from YK 18.

Only one ash wood sample were taken from YK 22 and the MWC of it was 494%. 10 cypress wood samples were taken from the wrecks and some of them were degraded while others were well-preserved. One of the cypress wood sample shows the best state of preservation. Most of the samples taken from the shipwrecks are oak wood and were highly degraded. Maximum water content in oak woods from YK 22 ranged between 505% and 686%. The oak wood samples of YK 22, evaluated according to the high values of MWC, may be recognized as highly degraded. To compare different part/layer of the wood, two samples were taken from a frame of YK 22. First one was taken from outer zone of the wood and the other was taken 7 cm inside towards core. MWC of the first sample was 336% and the other one was 608%. It is shown that the outer part of the wood was degraded more.

MWC value of the sample of YK 25 which are plane wood ranged between 700% and 888%, so according to these values, plane woods of the shipwreck recognized as highly degraded. Moreover, MWC value of pine wood ranged between 419% and 600%, so according to these values, pine woods of the shipwreck recognized as highly degraded. Maximum water content in fir woods from the shipwreck was 534% and 611% and these values show that woods were highly degraded. Only one elm sample was taken and its MWC value was 423%. One of the cedar wood sample of the shipwreck had high MWC value while MWC values of two of the cedar sample were 225% and 232%. The best preserved samples were these.



EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : Default

Element	Wt %	At %	K-Ratio	Z	A	F
O K	12.45	27.43	0.0268	1.0832	0.1983	1.0020
S K	35.78	39.34	0.2556	1.0376	0.6851	1.0051
CaK	2.17	1.91	0.0176	1.0253	0.7706	1.0264
FeK	49.60	31.32	0.4533	0.9426	0.9694	1.0000
Total	100.00	100.00				

Element	Net Inte.	Bkgd Inte.	Inte. Error	P/B
O K	10.44	3.63	4.78	2.88
S K	160.36	4.30	0.96	37.26
CaK	8.83	3.56	5.36	2.48
FeK	128.65	2.01	1.06	63.97

Figure 7. The presence of iron products determined by SEM-EDX.

MWC value of the sample of YK 29 which are pine wood ranged between 390% and 630% and the most degraded sample of the wreck is pine wood. One ash sample was taken from the shipwrecks and its MWC value was 519%. Some of the cypress samples of the shipwreck were degraded while others were less degraded or well-preserved. MWC of the sample taken from near the iron corrosion products was 171% and it appears that this value is very low when compared to other sample taken from the same frame of the shipwreck. In addition, MWC of the sample taken from near the iron corrosion products was 55% and it appears that this value is very low as in other examples.

In YK 35, elm and oak woods samples had the highest degradation level. MWC value of the other elm sample was 520%. MWC values of the samples of the shipwreck, which are pine wood, ranged between 340% and 478%. To compare different part/layer of the wood, two samples were taken from a frame of YK 35 as in YK 22. First one was taken from outer zone of the wood and the other was taken 7 cm inside towards core. MWC of the first sample was 438% and the other one was 650%. It is shown that the outer part of the wood was degraded more heavily. The cedar sample had 447% MWC value. Most of the samples of the shipwreck are cypress and MWC values of them ranged between 158% and 357%, according to these values, these samples were recognized as well-preserved. MWC of the sample taken from near the iron corrosion products was 75% and it appears that this value is very low when compared to other samples taken from the shipwreck.

With examining all the MWC and basic density values of the samples, an inverse proportion between MWC and basic density in general was determined. Basic density of highly degraded samples was lower, and basic density of well-preserved samples was higher. Detailed information on the relation between MWC and basic density with woods species of the samples are presented in Figure 8.

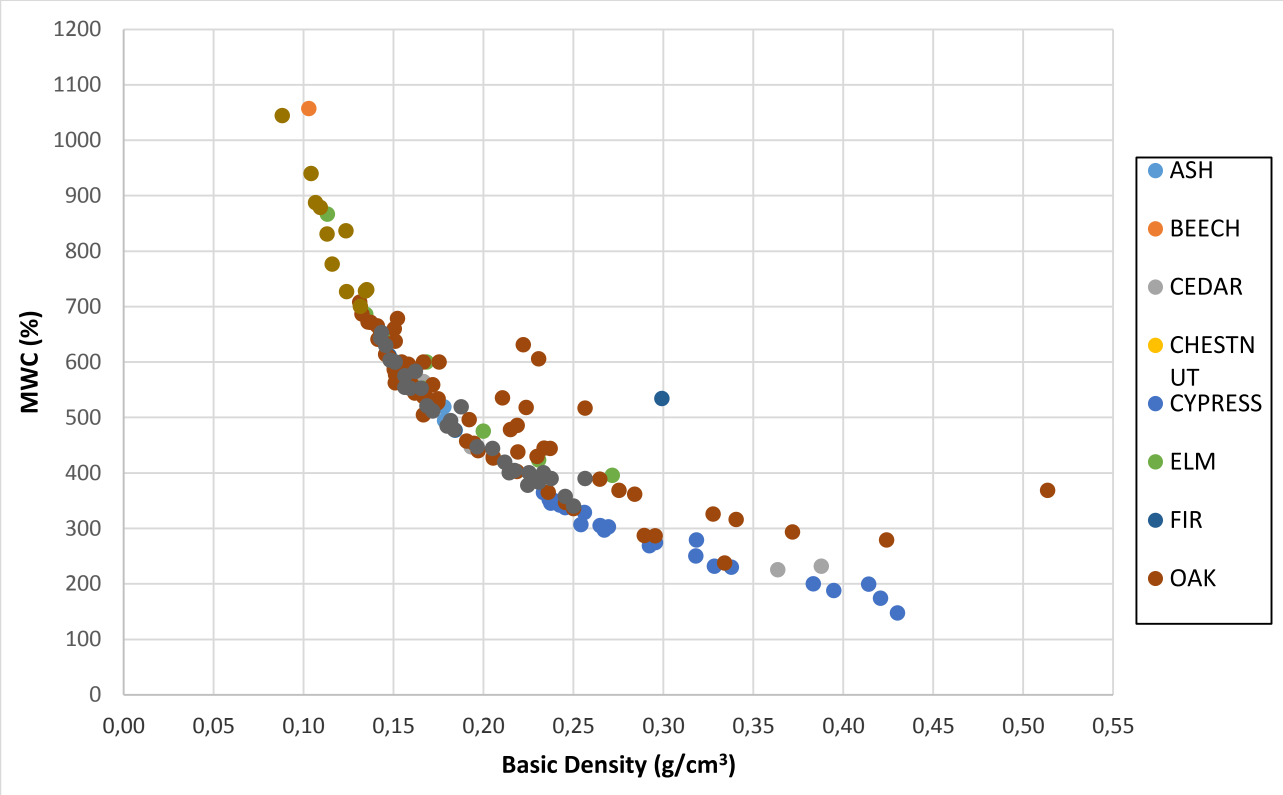


Figure 8. Detailed information on the relation between MWC and density with woods species of the samples.

With the aim of comparing the degradation degree of various species of wood, the degree of degradation was presented as loss of wood substance, calculated in relation to the average basic density of fresh wood. For instance, two samples were taken from YK 16 which had similar MWC value, and one of them is elm wood and the other one is pine wood. When comparing the loss of wood substance values of the samples, the value of elm wood samples was higher than pine wood samples because of the difference between densities of fresh woods.

With the evaluation of the results obtained from 160 samples together; MWC values of the samples ranged between 148% and 1044%. The samples taken from near the iron corrosion products were not included in this evaluation. The highest MWC value belonged to a plane wood sample, and the lowest value belonged to a cypress wood sample. With the evaluation of the highly degraded wood samples group, plane wood samples were found especially in this group. MWC values of the samples which are plane wood ranged between 700% and 1044%. In addition, wooden elements of the shipwrecks which are plane wood could not be lifted with hand and needed epoxy supporter to lift and carry them during the excavation (Figure 9).

Only one of the sample taken from YK 21 is chestnut tree and the MWC of it was 560%. The rest of the samples are oak wood and MWC values ranged between 287% and 708% while most of the samples had MWC values around 400% and above, according to these values, most of the woods of the shipwreck recognized highly degraded. As in YK 16, two different samples were taken from the same frame of the shipwreck and the MWC values were found very similar thus, results were verifiable again. MWC of the sample taken from near the iron corrosion products was 33% and it appears that this value is very low when compared to other samples as in the sample from YK 18.

Only one ash wood sample were taken from YK 22 and the MWC of it was 494%. 10 cypress wood samples were taken from the wrecks and some of them were degraded while others were well-preserved. One of the cypress wood sample shows the best state of preservation. Most of the samples taken from the shipwrecks are oak wood and were highly degraded. Maximum water content in oak woods from YK 22 ranged between 505% and 686%. The oak wood samples of YK 22, evaluated according to the high values of MWC, may be recognized as highly degraded. To compare different part/layer of the wood, two samples were taken from a frame of YK 22. First one was taken from outer zone of the wood and the other was taken 7 cm inside towards core. MWC of the first sample was 336% and the other one was 608%. It is shown that the outer part of the wood was degraded more.

MWC value of the sample of YK 25 which are plane wood ranged between 700% and 888%, so according to these values, plane woods of the shipwreck recognized as highly degraded. Moreover, MWC value of pine wood ranged between 419% and 600%, so according to these values, pine woods of the shipwreck recognized as highly degraded. Maximum water content in fir woods from the shipwreck was 534% and 611% and these values show that woods were highly degraded. Only one elm sample was taken and its MWC value was 423%. One of the cedar wood sample of the shipwreck had high MWC value while MWC values of two of the cedar sample were 225% and 232%. The best preserved samples were these.

Figure 9. A wood lifted with an epoxy supporter during the excavation (IU Yenikapı Shipwrecks Project Archive).

MWC values of the samples which are elm wood ranged between 395% and 867%, according to these values, elm woods of the shipwrecks were recognized as highly degraded. Oak wood samples, which is largely present in the samples, had MWC values between 237% and 708%. Some of the oak wood samples were highly degraded while others were well-preserved. Pine wood samples, the second largest group in the samples, had MWC values between 340% and 653%. Some of the pine wood samples were highly degraded while others were well-preserved as in oak wood samples. MWC values of the samples which are fir wood ranged between 336% and 611%, according to these values, some of the fir wood samples were highly degraded while others were relatively well-preserved. MWC values of the samples which are ash wood ranged between 494% and 519%, according to these values, ash wood samples were highly degraded. MWC values of the samples which are cedar wood ranged between 225% and 565%, according to these values, some of the cedar wood samples were highly degraded while others were well-preserved. MWC values of the samples which are cypress wood ranged between 148% and 364%, according to these values, some of the cypress wood samples were degraded while others were well-preserved

4. CONCLUSION

In this study, results of physical properties analyses such as maximum water content, basic density, and loss of wood substance were used to determine the degradation degree of the waterlogged wood samples. Firstly, samples from each shipwreck were examined individually, and then all samples were examined together to provide a general database on degradation degree of the waterlogged woods of eight shipwrecks. As a result, MWC values of the samples (except samples taken from near the iron corrosion products) ranged between 148% and 1044%. A plane wood sample had the highest MWC, and the lowest value belonged to a cypress wood sample. Plane wood samples were found especially in highly degraded woods group. This result has been predicted since most of the wooden elements used for the construction of the ships, which are plane wood, were lifted from the excavation site by epoxy support due to their softness. Although visual examinations can provide a foresight about the state of preservation of the wood, the classification of the woods according to the degradation degree of the wood can be made with the analyses performed within the scope of this study. In addition, determination of the physical degradation of waterlogged wood is very important for the conservation of the wood. In this study, the deterioration degree of the woods of the eight Yenikapı shipwrecks was determined and the data may be used in order to determine the conservation method and the property of the conservation chemical which used for the selected method.

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