ANNEXES

Annex A: Summary tables

The following annex presents a series of tables that summarize all the information obtained during the research on old and new handmade clay bricks. Table A.1 presents the information gathered during the literature survey. Table A.2, Table A.3 and Table A.4 present the results obtained from the tests carried out with the old clay bricks collected from the six Portuguese monuments that were the object of laboratory tests in this research work. The partial results obtained with the new handmade clay bricks are presented in Table A.5.

Table A.1 – Properties of old clay bricks obtained from the literature survey.

Date	Description	Location	Dimensions	Compressive strength	Tensile strength	Elastic modulous	Bulk weight	Water absorption	Porosity	Suction	References
(century)		(Town, Country)	(cm×cm×cm)	(MPa)	(MPa)	(GPa)	(kg/m^3)	(%)	(%)	(g/cm^2/min)	
1-5th	Bricks from buildings and structures from the Byzantine Period			9.2-18.0	2.6-10.8		1400-1900		15 to 35		Papayianni and Stefanidou (2000)
			(35-48)×(24-30)×(4-6)								Radivojevic (2000)
3-4th	Church of S. Lorenzo	Milan, Italy		12.5-27.5			1550-1750	14.5-17.5			Baronio and Binda (1985)
							1784				Baronio *et al.* (1985)
				34.5							Baronio and Binda (1986)
6th	Church of Hagia Sophia	Istambul, Turkey	37.5×37.5×5				1600-2000		26-30 (red) 40-55 (beige)		Livingston (1993)
8-13th	Bell Tower of the Cathedral of Cremona	Cremona, Italy	(24-28)×(10-12)×(5.5-7)	8.0-12.4 (red) 9.4-25.4 (brown)	0.1-1.6 (red) 2.2-2.6 (brown)	1-2.2 (red) 1.7-4.4 (brown)		24.9 20.1			Binda *et al.* (2000)
9-10th	Church Sta Maria Rossa	Milan, Italy					1600	18-19	21-35		Maierhofer *et al.* (1998)
11-13th	Vaults of Our Lady Monastery	Magdeburg, Germany		13.1-14.1							Marzahn *et al.* (2004)
12th	Church of San Gervásio and San Protasio	Santervás de Campos, Spain	(33-32)×(16-15)×(3.5)								Carrió and Olea (1998)
	Church of San Pedro	Alcazarén, Spain	38×18×3.5 38×(16.5-17)×4								Carrió and Olea (1998)
12-13th	Medieval brick masonry walls	Toledo, Spain					1600	19	32.5	0.18	López-Arce *et al.* (2003)
13th	Church of San Miguel Arcángel	San Miguel, Spain	30×13×4								Carrió and Olea (1998)
	Church of Assunção	Almenara de Adaja, Spain	26×13×4; 28×17×4.5 29×14×4								Carrió and Olea (1998)
	Church of San Andrés	Olmedo, Spain	35×17×(3-3.5) (?)×18×3.5								Carrió and Olea (1998)
	Church of San Miguel	Olmedo, Spain	30×19×4								Carrió and Olea (1998)
	Church Sta Maria Rossa	Milan, Italy					1600-1830	12-24	21-35		Maierhofer *et al.* (1998)
13-14th	Bricks from houses	Toledo, Spain					1510	22	43.1	0.08	López-Arce *et al.* (2003)
13-17th	Exterior Wall	Siena, Italy		27.9		5.8					Barbi *et al.* (2002)
14th	Church of San Boal	Pozaldez, Spain	28×18×3.5								Carrió and Olea (1998)
	Church of San Andrés	Olmedo, Spain	35×16×3.5								Carrió and Olea (1998)
	Tower of the Church of Assunção	Móstoles, Spain	27×(?)×(3.5-4)								Carrió and Olea (1998)
	Church of San Miguel	Olmedo, Spain	28×19×3.5								Carrió and Olea (1998)
15th	Tower of Lujanes	Madrid, Spain	30×13×4								Carrió and Olea (1998)
	Tower of San Ginés	Madrid, Spain	30×(?)×(3-4)								
	Episcopal palace	Pienza, Italy		26.9	7.3						Barbi *et al.* (2002)
				21.7-51.4	11.6-18.6						Bati and Ranocchiai (1994)
	Exterior Wall	Colle Val d'Else, Italy		19.9	4.1						Barbi *et al.* (2002)
				30.0							Bati and Ranocchiai (1994)
15-16th	Church of Sta Maria Incoronata	Milan, Italy		12.5-27.5			1550-1750	14.5-17.5			Baronio and Binda (1985)
16th	Hospital de las Cinco Llagas	Seville, Spain	28.3×13.7×4.7	14.3-32.9				11-21	0.11-0.23		Barrios *et al.* (2000)
	Bishop's residence	Pienza, Italy					1550				Bati and Ranocchiai (1994)
	Library wall of the Monastery of Monte Oliveto Maggiore	Siena, Italy		31.1	6.3						Barbi *et al.* (2002)
16-17th	Bell Tower of the Cathedral of Monza	Monza, Italy		4.0-12.0							Binda *et al.* (2000)
17th	Tower of the Church in Agustín de Lara's square	Madrid, Spain	28×21×6								Carrió and Olea (1998)
	Church of San Juan Bautista	Atanquines, Spain	(29-30)×(13-14)×(3.5-4) (?)×(14-15)×(3.5-4) (?)×(18-19)×(3.5-4)								Carrió and Olea (1998)
	Vaults of the Monastery of Salzedas	Salzedas, Portugal		5.2	7.3		1560	19			Lourenço *et al.* (2000)
	House bricks	North America	22.2×10.8×6								
17-18th	Cloister of the Church of S. Eustorgio	Milan, Italy		12.5-27.5			1550-1750	14.5-17.5			Baronio and Binda (1985)
18th	Church of San Miguel Arcángel	Spain	(?)×(17-18)×3.5								Carrió and Olea (1998)
	Church of San Juan Bautista	Ataquines, Spain	(32-33)×(13-14)×3.5								Carrió and Olea (1998)
	Cloister of the Monastery of Salzedas	Salzedas, Portugal	22×12.2×4								Lourenço *et al.* (2000)
	Lazzaretto	Ancona, Italy	18.5		4.2						Barbi *et al.* (2002)
18-19th	Centenary chimney from ceramic industry	Basque country, Spain		20.8						0.2	Jimenez *et al.* (2000)
19th	"Pombalino" buildings	Lisbon, Portugal	22×11×7								

Table A.2 – Properties of old clay bricks obtained through experimental work. Part 1/3.

Date	Brick specimen	Location	Dimensions	Bulk weight	Water absorption	Porosity	Suction	Compressive strength	Drilling resistance	Chemical properties												
										SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
(century)		(Town)	(cm×cm×cm)	(kg/m^3)	(%)	(%)	(g/cm^2/min)	(N/mm^2)	(N/mm^2)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
	OU01		13.5×8.5×(3.5-4)	1782	22.72	34.11		13.78	8.52	59.79	26.07	7.22	3.78	0.57	0.92	0.22	1.19	819	306	93	209	1061
	OU02		13.5×13.5×4	1697	22.68	35.58		1.86	2.38	62.14	23.51	6.71	3.41	0.60	0.96	0.59	1.86	903	334	66	219	745
	OU03		12.5×9×4	1755	17.54	28.96		9.11	3.22	54.32	25.83	12.33	3.62	0.48	1.04	0.41	1.79	685	250	73	190	616
	OU04		14×8.5×4.2	1785	17.58	28.55		7.63	2.90	51.51	26.46	14.45	3.51	0.65	1.05	0.22	1.96	534	237	70	197	859
17th	OU05	Outeiro (Bragança)	15×13.2×4.5	1712	24.04	36.62		7.26	4.99	61.13	23.66	7.30	3.54	0.80	0.97	0.46	1.91	822	309	58	199	1011
	OU06		14×8.5×4	1747	17.10	28.58		8.48	2.44	54.06	25.14	13.67	3.54	0.49	1.01	0.51	1.41	613	231	74	179	556
	OU07		14.2×8.8×4	1751	18.21	29.81		8.65	3.94	52.89	25.56	14.00	3.79	0.55	1.06	0.43	1.53	735	248	69	189	695
	OU08		15.5×8.5×4.2					6.50		46.14	26.08	21.01	3.78	0.21	1.02	0.16	1.44	535	230	65	180	623
	OU09		14×12.5×3	1741	32.32	43.16			3.96	59.01	26.76	6.78	4.01	0.47	1.20	0.39	1.14	883	328	120	239	978
	OU10		20×14×4.5	1706	19.51	32.03		6.30	4.40	61.34	23.62	10.70	2.16	0.12	1.24	0.09	0.58	451	373	61	151	436
	PO01		14×12×3.3	1752	15.98	27.14		7.32	3.22	55.64	25.78	9.48	5.01	0.63	1.28	0.23	1.73	952	347	164	281	405
	PO02		17.5×13.4×3	1714	15.72	27.41		7.14	2.44	58.04	25.06	8.16	4.52	0.53	1.28	0.47	1.73	930	280	162	247	504
	PO03		16.5×12×3	1844	14.61	24.20		11.34	7.87	55.43	25.06	10.54	5.11	0.53	1.42	0.21	1.47	952	409	61	349	511
	PO04		15.5×11.3×3	1777	9.55	17.93			10.12	59.13	22.13	9.13	5.49	0.63	1.36	0.62	1.27	1034	389	185	295	443
	PO05		23×12×3.5	1760	7.65	15.06		16.81	20.52	59.52	22.62	8.38	5.60	0.65	1.24	0.51	1.23	1070	428	70	346	472
	PO06		12×11×3.2	1731	16.56	28.16		6.70	3.69	56.49	25.63	9.04	4.84	0.57	1.23	0.22	1.76	887	333	175	282	407
	PO07		13×12×(3.5-4)	1739	15.22	26.37		7.07	2.61	61.34	24.18	6.22	4.47	0.45	1.11	0.24	1.75	943	516	204	302	420
	PO08		12.5×12.2×3.8	1723	15.46	26.92		7.85	5.98	54.65	27.48	9.02	4.62	0.54	1.22	0.46	1.84	785	289	140	265	381
	PO09		19×12×(3.4-3.9)	1731	14.98	26.19			7.57	58.46	23.13	9.05	5.43	0.71	1.33	0.30	1.35	938	464	76	380	535
	PO10		17×12.2×(3-3.4)	1693	21.20	34.11		8.26	3.89	53.77	27.38	9.86	4.32	0.46	1.26	0.94	1.82	871	291	169	257	374
	PO11		23.5×12×(3-3.8)	1786	5.85	11.73		22.27	27.89	59.88	21.98	8.99	5.56	0.69	1.30	0.20	1.16	1005	436	56	354	477
	PO12		14×10.2×(3-3.1)	1779	7.90	15.29		14.30	16.87	58.93	22.35	9.67	5.54	0.58	1.30	0.18	1.21	1083	393	191	314	432
	PO13		14×12.5×3.8	1690	21.31	34.30		8.87	3.09	53.60	27.52	10.02	4.55	0.44	1.43	0.29	1.95	894	330	67	323	452
	PO14		17.5×11×3.8	1739	13.86	24.60		6.74	5.08	55.63	24.91	10.08	5.31	0.56	1.37	0.21	1.70	977	379	168	327	442
	PO15		(10-13)×12.2×3	1775	20.04	31.45		10.90	4.19	51.60	29.48	10.71	4.02	0.45	1.31	0.29	1.95	906	240	128	261	363
	PO16		15×13×(2.5-3)	1760	20.34	32.03			1.61	57.75	28.43	5.22	4.25	1.15	1.12	0.35	1.51	820	495	146	298	402
12-16th	PO17	Pombeiro (Felgueiras)	16.5×11.5×(4-4.5)	1708	19.28	31.74		6.07	3.86	57.58	30.42	4.60	4.21	0.24	1.33	0.14	1.22	1200	397	271	355	398
	PO18		16.5×12×5	1817	24.73	35.48		2.33	0.52	54.81	29.11	7.84	4.59	0.24	1.06	0.09	2.07	698	315	55	274	551
	PO19		(8-12)×11.5×3.3	1681	21.03	34.17		6.38	1.78	53.15	28.44	9.39	4.57	0.40	1.25	0.59	2.03	828	268	164	255	352
	PO20		16×11.5×2.7	1786	7.78	15.02			18.15	58.37	21.30	10.06	5.58	0.63	1.39	1.48	0.94	1068	444	185	330	526
	PO21		16×14×3.5	1768	13.71	24.00			7.67	61.07	24.03	7.02	4.56	0.48	1.05	0.16	1.41	837	480	174	328	441
	PO22		(24.5-19)×12.5×3	1739	13.37	23.93		13.74	8.22	59.48	25.52	7.01	4.21	0.47	1.28	0.09	1.70	1016	449	168	309	473
	PO23		18×12.2×3	1762	10.33	19.28		10.97	7.40	59.26	22.68	9.09	5.43	0.55	1.32	0.19	1.24	942	452	73	352	519
	PO24		15×11×3	1763	15.91	26.88		10.65	6.79	56.79	26.21	8.72	4.37	0.57	1.24	0.27	1.64	782	267	106	237	474
	PO25		(15-19.5)×12.5×3.5	1744	12.63	22.83		9.13	5.43	64.95	19.96	6.57	5.12	0.40	1.38	0.19	1.14	1141	643	250	364	535
	PO26		24×12.3×(3.4-3.8)	1769	7.87	15.32		19.69	21.00	59.15	22.22	9.48	5.62	0.63	1.30	0.23	1.14	928	414	185	316	449
	PO27		4.5-18×12×5.5	1821	24.08	34.82		2.01	0.54	58.25	26.05	7.82	4.43	0.42	1.03	0.16	1.67	731	209	49	233	448
	PO28		12×(6-9.5)×5.5	1823	26.01	36.55			0.46	57.33	25.88	8.35	4.76	0.40	1.18	0.18	1.75	673	288	0	281	554
	PO29		8×5×5.5	1794	24.86	35.96		2.00		58.85	26.28	7.14	4.27	0.40	1.01	0.14	1.76	650	182	59	208	400
	PO30		15×11.5×5	1732	19.24	31.28		3.16	1.36	58.81	23.51	6.65	6.45	0.94	1.12	0.56	1.44	2694	443	346	366	1304
	PO31		20×11.8×3.5	1739	13.07	23.52		12.18	7.27	58.47	24.06	7.81	4.92	0.41	1.41	1.16	1.46	1097	575	206	359	614
	PO32		(10-18)×11×3	1776	15.26	25.88		6.25	2.52	54.38	24.35	9.88	5.34	0.63	1.29	2.20	1.69	1016	352	211	300	403
	PO33		14×12.5×3.5	1696	16.72	28.94		8.59	3.61	53.13	26.46	9.80	5.26	0.41	1.57	1.50	1.57	1215	581	121	212	883
	PO34		12.3×11×3.7	1723	14.53	25.72		7.29	3.88	61.02	24.63	6.26	4.39	0.42	1.34	0.27	1.42	974	550	211	304	523
	TI01		16.8×8.8×(3-3.1)	1740	12.00	22.01		9.67	3.96	60.62	22.64	7.79	5.39	0.55	1.22	0.38	1.16	1099	373	211	311	452
	TI02	Mire de Tibães (Braga)	19.5×12.9×4.5	1676	16.86	29.48		10.79	10.10	52.35	32.48	5.34	4.64	0.64	1.15	2.27	0.97	666	396	6	397	355
17th	TI03		19×18.5×4.5	1709	22.99	35.66				52.70	31.60	8.18	3.97	0.50	1.13	0.50	1.25	674	312	77	217	467
	TI04		20.5×18.5×4.5	1716	23.08	35.62		2.61	1.39	53.55	30.28	7.98	4.34	0.52	1.30	0.56	1.26	813	504	15	280	550
	TI05		19.5×19×(4.5-5)	1737	20.84	32.95		4.41	2.36	54.94	27.35	9.07	4.72	0.44	1.19	0.82	1.24	843	424	139	282	526

Table A.3 – Properties of old clay bricks obtained through experimental work. Part 2/3.

Date	Brick specimen	Location	Dimensions	Bulk weight	Water absorption	Porosity	Suction	Compressive strength	Drilling resistance	Chemical properties												
										SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
(century)		(Town)	(cm×cm×cm)	(kg/m^3)	(%)	(%)	($g/cm^2/min$)	(N/mm^2)	(N/mm^2)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
	TI06		28×19×4.2	1711	21.30	33.89			15.45	51.32	30.86	8.77	4.17	0.54	1.17	1.62	1.35	657	308	104	242	571
	TI07		22×19×4	1753	21.17	33.02		4.27	1.47	52.10	30.89	8.79	4.35	0.36	1.33	0.62	1.31	947	502	14	298	711
	TI08		19×17×3.5	1723	22.61	35.01		4.32	1.47	49.76	33.11	9.37	4.14	0.33	1.32	0.26	1.49	832	355	114	252	674
	TI09		19×13×4.5	1712	21.55	34.12			0.98	51.11	31.81	8.36	4.22	0.58	1.15	1.19	1.39	741	313	94	221	476
	TI10		22.5×12×3.3	1730	15.64	27.04		12.93	8.24	53.12	28.17	9.49	4.21	0.57	1.25	1.24	1.76	979	339	98	246	403
	TI11		12.5×9.5×3.5	1726	18.68	30.76		5.39	1.77	48.44	31.40	10.10	4.65	0.65	1.30	1.32	1.94	850	299	180	301	395
	TI12		19×13.7×3.5	1728	17.67	29.55		10.76	5.00	53.03	32.63	5.82	3.81	0.81	1.12	1.59	1.04	506	451	93	272	288
	TI13		16×10.2×3.4	1750	15.50	26.57		6.95	2.91	52.04	29.22	7.81	5.09	1.03	1.35	1.72	1.51	1111	442	215	284	342
	TI14		17.5×10×3	1732	12.68	23.09			3.69	57.18	25.74	8.20	5.20	0.65	1.19	0.27	1.34	1007	337	164	301	450
	TI15		15.5×12×3.8	1795	17.46	28.28		5.49	2.10	52.76	27.78	10.23	4.35	0.59	1.14	1.37	1.61	813	206	34	211	412
	TI16		(16-21.5)×12.5×3	1776	11.95	21.48		10.68	9.19	54.84	24.81	10.10	5.33	0.67	1.40	1.05	1.54	1135	424	172	352	440
	TI17		23×12×(3.7-4.2)	1768	21.97	33.60		4.46	1.10	56.89	26.91	8.69	4.05	0.29	1.18	0.24	1.58	760	327	0	227	407
	TI18		24.7×12.7×3.5	1744	16.58	27.99		8.13	6.54	52.71	28.53	8.51	4.62	0.61	1.49	1.15	2.10	1118	549	214	362	478
17th	TI19	Mire de Tibães (Braga)	19×17×3.7	1712	23.77	36.36		3.32	1.53	57.99	29.43	5.32	3.86	0.33	1.19	0.27	1.38	883	521	132	264	448
	TI20		19×18.5×(4-4.5)	1722	24.32	36.71				54.49	29.14	7.90	4.30	0.42	1.23	0.89	1.42	797	497	12	260	518
	TI21		19×18.5×3.7	1752	20.13	31.93		4.58	1.82	50.86	30.50	9.71	4.76	0.44	1.30	0.85	1.33	1021	409	150	292	591
	TI22		25×12.5×2.5	1766	13.80	24.14			1.49	52.62	28.32	8.44	5.32	0.71	1.44	1.08	1.80	1123	558	148	375	539
	TI23		21×15.7×3	1741	12.83	23.16		9.01	8.88	59.11	22.63	9.12	4.54	0.48	1.28	1.66	0.94	1029	356	199	268	494
	TI24		18.5×16.5×4.8	1713	23.03	35.63		2.46	0.86	59.03	28.53	5.08	3.97	0.28	1.20	0.34	1.31	910	526	170	272	590
	TI25		23×13×4	1723	17.71	29.69		15.89	11.41	52.71	32.38	6.56	4.28	0.61	1.16	0.94	1.18	524	422	98	422	391
	TI26		19×18×(4-4.2)	1788	16.65	27.43		6.63	2.38	57.47	27.07	7.53	4.33	0.46	1.14	0.69	1.13	816	360	115	252	420
	TI27		17.5×13.5×(2.9-3.3)	1764	15.93	26.89			5.79	57.02	31.67	4.88	3.59	0.26	1.20	0.16	0.98	706	801	140	313	358
	TI28		(15-17)×13×2.9	1739	15.18	26.32			2.11	52.33	30.39	7.47	4.71	0.61	1.22	1.15	1.90	946	316	229	290	369
	TI29		(23.5-27.5)×18.5×4.5	1751	18.56	30.19		4.99	1.65	50.70	31.77	9.11	3.99	0.52	1.22	0.98	1.52	823	275	142	236	492
	TI30		39.5×18.5×4.5	1722	22.36	34.78		3.86	1.33	49.89	30.67	9.67	4.51	0.62	1.39	1.51	1.52	838	476	17	281	619
	TI31		19.5×18×(3-4)	1732	22.64	34.89		2.03	1.39	53.87	29.82	8.98	3.94	0.36	1.19	0.27	1.39	691	311	109	226	457
	TI32		19.5×18×(3-4)	1773	23.22	34.75				53.53	30.92	8.08	3.94	0.40	1.15	0.28	1.52	727	314	101	216	491
	TA01		20×15.5×3	1711	21.24	33.83				50.38	33.28	10.46	2.88	0.63	0.84	0.20	1.22	366	66	22	189	464
	TA02		11×8×2.5	1717	19.70	32.06			7.63	51.28	31.99	9.84	3.89	1.19	0.67	0.11	0.89	347	170	1	320	441
	TA03		13×12.5×3	1711	17.60	29.75			7.82	52.25	33.56	7.84	3.69	1.16	0.49	0.11	0.81	267	47	43	261	309
	TA04		11×10.5×2.5	1742	19.58	31.49			4.13	52.22	32.69	8.68	3.52	1.28	0.55	0.10	0.87	319	40	48	228	295
	TA05		15×15×2.8	1768	18.50	29.87			4.36	55.41	32.80	6.18	3.38	0.82	0.55	0.03	0.74	290	157	43	280	270
	TA06		11×8×2.5	1731	18.36	30.30			6.55	55.47	29.09	9.01	3.64	1.27	0.58	0.10	0.75	332	71	27	228	265
	TA07		19×15×2.8	1720	21.49	33.93			4.13	49.45	33.62	10.26	4.16	0.83	0.60	0.14	0.80	576	160	0	332	385
	TA08		15×12.5×2.5	1756	13.48	23.84			8.65	51.66	27.45	13.15	3.76	0.59	1.02	0.51	1.73	528	73	47	154	510
	TA09		11×8.5×4	1750	19.36	31.12		7.31	2.51	59.57	23.00	10.20	3.08	1.06	0.83	1.04	1.09	464	116	111	134	514
	TA10		18.5×11.5×4	1800	10.93	19.74		16.43	9.07	56.77	22.38	12.29	3.90	0.86	1.07	1.26	1.31	307	228	68	162	775
12-17th	TA11	S. João de Tarouca (Tarouca)	13×12.5×4	1730	18.26	30.21		7.76	3.92	51.16	31.56	10.94	2.88	0.56	0.93	0.18	1.64	426	221	51	207	587
	TA12		23×12.5×3.8	1727	19.20	31.33		8.46	10.56	49.83	31.64	12.71	2.73	0.36	1.01	0.18	1.37	520	258	70	227	585
	TA13		22×12.5×3.5	1791	12.46	22.00		12.60	11.76	57.63	23.79	11.13	3.11	0.92	0.98	0.89	1.37	528	271	151	170	641
	TA14		15×11.5×(3.5-4)	1733	18.77	30.74				50.02	28.02	14.00	4.07	0.59	1.03	0.52	1.63	538	74	58	156	531
	TA15		13×12.5×4						6.33	50.95	31.09	11.57	3.10	0.66	0.91	0.26	1.31	467	191	0	206	570
	TA16		11×8.5×4	1716	19.89	32.28		7.19	2.69	53.23	26.34	12.87	3.60	0.40	1.07	0.47	1.83	580	245	79	190	655
	TA17		12×9×4	1720	20.26	32.61		7.66	4.83	49.40	28.10	14.41	4.06	0.52	1.07	0.61	1.68	594	81	58	155	556
	TA18		10×8.5×4	1726	19.76	31.96		8.33	2.44	56.47	24.73	11.18	3.33	1.02	0.92	0.82	1.35	527	134	109	141	887
	TA19		12.5×8.5×4	1763	19.54	31.11		17.25		53.46	26.83	12.49	3.71	0.66	0.82	0.22	1.64	453	192	76	198	612
	TA20		11×8.5×4	1763	20.44	32.08		3.75	2.55	58.26	27.36	7.94	4.03	0.87	0.39	0.17	0.87	335	121	81	235	376
	TA21		12×11.5×4	1780	15.11	25.64		8.24	3.68	52.34	27.73	12.31	3.83	0.65	0.92	0.26	1.80	574	75	64	173	743
	TA22		(14-17)×8×4.2	1791	10.38	19.04		5.44	9.89	61.50	22.98	8.49	4.56	0.17	1.03	0.16	0.82	1495	354	226	256	451

Table A.4 – Properties of old clay bricks obtained through experimental work. Part 3/3.

Date	Brick specimen	Location	Dimensions	Bulk weight	Water absorption	Porosity	Suction	Compressive strength	Drilling resistance	Chemical properties												
										SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
(century)		(Town)	(cm×cm×cm)	(kg/m^3)	(%)	(%)	(g/cm^2/min)	(N/mm^2)	(N/mm^2)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
12-17th	TA23	S. João de Tarouca (Tarouca)	9×8.5×4.5					10.26		51.88	27.71	12.24	3.95	0.63	1.03	0.39	2.02	582	72	45	150	598
	TA24		16×8.2×4	1821	15.96	26.14		7.80	5.53	55.84	26.08	11.06	3.66	0.72	0.75	0.20	1.52	508	174	56	203	572
	TA25		12×8.7×4.5	1737	18.97	30.90		8.56	3.00	52.21	27.15	12.94	3.79	0.55	0.94	0.62	1.65	563	75	57	148	503
	TA26		12×8.5×3.9					5.55	5.56	47.62	26.46	17.96	4.38	0.44	1.06	0.34	1.57	629	163	0	203	668
	TA27		14×8.3×4.2	1761	14.19	24.72		5.03	3.19	55.55	25.99	10.69	4.46	0.27	1.27	0.16	1.32	1588	357	217	259	468
	TA28		12.5×8.5×4.5	1706	20.89	33.55		9.41	3.47	60.62	22.64	7.79	5.39	0.55	1.22	0.38	1.16	1099	373	211	311	452
18-19th	TO01	Tomar	26×13.5×(3.4-3.6)	1634	17.16	30.66		16.92	6.55	58.60	24.10	7.98	4.08	0.39	0.75	1.88	2.12	454	82	43	159	295
	TO02		27×13×(3.3-3.4)	1799	7.77	14.89		32.66	22.71	62.96	21.46	6.11	3.10	0.30	0.70	3.72	1.57	352	90	27	129	217
	TO03		26×12.2×(3.8-4.1)	1681	15.17	27.25		20.01	12.24	63.38	22.14	6.99	3.27	0.29	0.76	1.05	2.01	485	87	34	130	385
	TO04		26×13.5×(3.3-3.6)	1694	16.10	28.21		26.16	15.02	58.25	22.94	7.49	3.95	0.48	0.68	4.00	2.09	536	86	34	153	276
	TO05		26×14×(3.0-3.6)	1625	16.21	29.65		14.69	5.86	60.46	23.74	6.97	4.00	0.45	0.65	1.58	2.05	387	72	30	162	306
	TO06		18×13×(3.6-3.8)	1650	15.39	28.10		19.73		61.93	20.06	6.40	5.91	0.58	0.87	2.08	2.06	368	136	29	119	384
	TO07		13×12.5×(3.2-3.4)	1667	16.62	29.34		19.09	28.50	60.07	20.45	6.67	3.20	0.36	0.91	5.97	2.26	387	137	34	128	373
	TO08		14×12.5×(3.5-4.2)	1615	15.79	29.31		17.38	17.61	56.62	17.61	5.55	2.85	0.29	0.74	13.39	2.83	403	162	56	134	468
	TO09		14×13×(2.9-3.4)	1647	14.16	26.50		38.22	31.44	62.31	19.96	6.66	2.80	0.64	0.91	4.24	2.38	394	137	43	118	312
	TO10		18×12.5×(2.6-3.5)	1651	15.81	28.63		21.86	13.41	61.12	21.55	7.15	3.22	0.43	0.86	3.11	2.46	414	138	48	130	289
	TO11		16×12.5×(3.1-3.6)	1641	12.92	24.85		27.69	23.98	61.72	19.85	6.78	3.10	0.48	0.83	4.79	2.35	366	121	46	124	292
	TO12		16×13×(3.4-3.6)	1650	16.49	29.50		18.76	11.14	59.22	23.88	7.54	3.91	0.40	0.72	2.12	2.11	511	76	37	155	264
	TO13		11×13×(3.4-3.6)	1557	17.29	32.58		20.13	7.17	58.37	24.32	7.88	4.07	0.44	0.73	1.91	2.20	372	63	42	154	295
	TO14		14×12.5×(2.9-3.5)	1628	13.83	26.40		24.64	25.99	63.68	19.21	7.36	3.00	0.39	0.89	2.73	2.65	359	142	25	136	260
	TO15		14×12×(4.8-5.2)	1703	12.69	23.52		11.77	4.61	64.84	20.04	6.48	2.79	0.44	0.84	2.83	1.60	345	208	66	138	559
	TO16		26×13.5×(3.4-3.6)	1662	17.11	30.05		19.29	8.68	59.28	23.83	7.24	3.99	0.51	0.67	2.27	2.10	433	78	41	161	266
18-19th	SA01	Salzedas (Tarouca)	25.7×12.5×3	1852	18.68	28.87		12.05	3.16	55.62	31.25	2.94	5.78	3.20	0.15	0.26	0.70	290	42	73	304	195
	SA02		25×12.5×3	1798	16.75	27.39		12.88	3.74	55.72	29.72	4.22	6.23	2.11	0.30	0.78	0.80	337	126	0	401	356
	SA03		24.7×12.5×3.2	1791	15.34	25.78		22.21	30.02	53.16	35.52	2.51	4.65	2.13	0.12	1.03	0.79	292	15	97	266	203
	SA04		24.5×12.3×3	1788	16.08	26.73		20.40	9.86	57.47	32.27	2.13	4.61	2.19	0.13	0.48	0.61	313	93	116	336	252
	SA05		25×12.5×3	1793	16.85	27.59		16.74	7.31	54.75	31.24	4.38	5.49	2.23	0.33	0.68	0.80	369	71	98	260	307
	SA06		24.9×12.5×3	1784	17.88	28.92	0.18	17.12	6.99	57.44	31.91	2.15	4.82	2.07	0.15	0.75	0.60	264	102	101	361	255
	SA07		25.2×12.5×3	1790	19.67	30.83		10.50	13.08	56.13	32.00	3.47	4.59	1.56	0.29	0.89	0.94	382	136	120	327	243
	SA08		25×12.8×3.2	1787	19.47	30.66		13.51	6.71	57.34	30.45	3.32	5.24	2.14	0.28	0.29	0.82	349	123	90	343	280
	SA09		25×12.3×3	1863	14.40	23.71		25.91	20.92	55.93	29.61	3.25	6.45	3.25	0.17	0.60	0.63	352	60	90	325	258
	SA10		25×12.7×3.2	1776	20.61	32.04		10.59	6.45	54.15	32.83	4.73	4.94	1.43	0.38	0.44	0.99	408	133	0	380	385
	SA11		25.5×12.5×3	1790	18.95	30.04		12.22	2.55	52.72	34.92	3.14	4.91	1.90	0.11	1.23	0.95	404	39	158	314	243
	SA12		29.2×15.8×4.2	1745	19.93	30.99	0.15	10.11	4.89	55.25	33.83	2.18	5.11	1.60	0.12	0.98	0.81	380	88	171	359	229
	SA13		30.1×16×4.2	1785	15.36	25.88	0.12	12.42	3.82	52.90	26.91	9.20	4.08	1.22	1.09	2.12	2.26	750	283	240	206	632
	SA14		31.5×15.5×3.8	1756	12.91	23.07	0.07	8.62	4.47	54.29	26.53	7.82	4.28	1.52	1.13	2.24	1.96	738	352	256	265	660
	SA15		29.7×15.8×4	1754	18.26	29.82	0.09	11.22	15.55	52.67	31.32	6.30	5.53	1.29	0.56	1.05	1.13	501	174	121	332	376
	SA16		24.2×12.2×3.1	1827	11.88	20.79	0.18	15.56	9.70	55.32	32.88	2.88	5.14	2.40	0.14	0.52	0.61	356	29	78	271	244
	SA17		25.3×12.5×3	1844	16.45	26.44	0.27	16.94		54.85	31.39	3.23	5.74	2.95	0.17	0.81	0.76	374	64	83	328	236
	SA18		25×12.7×3	1779	20.13	31.49	0.14	13.17	7.74	52.47	36.08	2.91	4.78	1.62	0.12	1.24	0.69	208	41	94	289	247
	SA19		25.4×12.8×3.2	1802	19.22	30.16	0.17	11.55	3.14	56.80	28.40	3.82	6.98	2.40	0.26	0.53	0.72	0	113	0	400	505
	SA20		25×12.6×3.3	1776	19.10	30.42		15.64	10.21	54.31	31.49	4.00	5.44	2.86	0.22	0.67	0.90	278	57	140	283	295
	SA21		25.5×12.5×3.3	1798	19.76	31.63	0.08	10.25	10.29	54.98	32.59	3.81	4.73	1.44	0.32	1.07	0.92	350	141	148	398	311
	SA22		25.4×12.5×3.2	1774	19.84	31.25	0.14	12.95	5.67	54.00	36.27	2.37	4.30	1.50	0.15	0.63	0.67	223	98	102	353	264
	SA23		25.5×12.5×3.2	1796	19.47	30.52		11.97	10.24	54.05	34.03	4.37	4.10	1.49	0.38	0.41	1.05	384	159	110	315	313
	SA24		25.2×12.7×3.2	1855	18.51	28.65	0.28	11.82	4.58	52.31	36.22	2.74	4.62	1.81	0.12	1.36	0.74	218	23	91	267	210
	SA25		25×12.4×2.7	1866	13.44	22.46		26.40	12.20	56.36	29.44	3.52	6.12	3.12	0.24	0.40	0.73	0	94	0	404	351
	SA26		25×12.5×3.2	1786	18.05	29.08		14.62	5.73	53.40	34.53	3.45	5.17	2.10	0.20	0.25	0.82	249	33	51	269	236
	SA27		24.9×12.5×3	1855	16.98	26.92		14.88	18.11	44.91	34.79	13.01	4.46	0.82	0.75	0.09	1.03	760	65	52	254	356

Table A.5 – Properties of new handmade clay bricks obtained through experimental work.

Date	Brick specimen	Location	Dimensions	Bulk weight	Water absorption	Porosity	Suction	Compressive strength	Drilling resistance	Chemical properties												
										SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
(century)		(Town)	(cm×cm×cm)	(kg/m^3)	(%)	(%)	(g/cm^2/min)	(N/mm^2)	(N/mm^2)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
	GA01		20×10×6	1734	11.08	20.74				69.12	18.37	4.75	4.14	0.70	1.09	0.52	1.13	508	272	76	151	757
	GA02		20×10×6	1732	10.84	20.42				68.53	18.32	5.04	4.05	0.74	1.24	0.62	1.23	500	306	73	160	1151
	GA06		20×10×6	1738	11.21	20.89		9.46	0.73													
	GA07		20×10×6	1725	11.01	20.76		7.68														
	GA09		20×10×6	1734	10.92	20.50		8.27	0.80													
	GA10		20×10×6	1725	11.04	20.80		9.71	0.60													
	GA12		20×10×6	1726	11.06	20.83		8.52														
	GA15		20×10×6	1738	11.03	20.63		9.16	0.56													
	GA17		20×10×6	1731	10.72	20.24		9.02	0.98													
	GA20		20×10×6	1736	11.13	20.79				67.50	18.46	5.61	4.21	0.90	1.29	0.62	1.23	531	303	79	173	723
	GA29		20×10×6	1732	10.96	20.58		10.50	0.93													
	GA30		20×10×6	1726	10.77	20.39		8.46	0.61													
21th	GA34	Galveias	25×14×6	1741	10.70	20.10	0.12	11.68	1.15													
	GA37		25×14×6	1786	11.97	21.39	0.18	8.74	0.56													
	GA49		25×14×6	1732	10.62	20.09	0.18	8.98	0.48													
	GA60		25×14×6	1735	10.97	20.57	0.14	9.76	0.62													
	GA63		25×14×6	1736	10.63	20.04	0.18	8.21	0.58													
	GA65		25×14×6	1735	11.66	21.58	0.19	9.40	0.65													
	GA79		30×15×4	1731	11.40	21.26				64.71	19.87	6.49	4.34	0.66	1.50	0.71	1.51	589	349	97	171	940
	GA83		30×15×4	1727	11.86	21.98			0.95													
	GA87		30×15×4	1730	10.63	20.12			0.70													
	GA92		30×15×4	1724	11.30	21.20			0.68													
	GA97		30×15×4	1734	11.32	21.10			1.16													
	GA99		30×15×4	1718	10.04	19.37			1.00													
	PC01		30×15×6	1751	11.25	20.79		6.14	0.57	55.52	20.21	9.21	3.40	2.01	1.11	4.06	4.26	443	193	248	104	1173
	PC02		30×15×6	1749	11.22	20.76		6.37	0.63	52.97	19.60	11.40	3.90	1.49	1.33	4.40	4.65	579	257	303	140	1407
	PC03		30×15×6	1751	11.27	20.80		3.98	0.21													
	PC04		30×15×6	1753	11.44	21.03	0.12	4.28	0.27													
	PC05		30×15×6	1745	11.17	20.74		6.31	0.36													
	PC06		30×15×6	1766	10.83	19.98	0.17	6.25	0.28													
	PC07		30×15×6	1755	11.05	20.45		6.63	0.45													
	PC08		30×15×6	1750	10.64	19.89		7.18	0.44													
	PC09		30×15×6	1758	10.96	20.27	0.20	7.62	0.30													
	PC10	S. Pedro	30×15×6	1754	11.16	20.61		5.31	0.38													
21th	PC11	doCorval	30×15×6	1740	10.69	20.10		5.32	0.46													
	PC12		30×15×6	1765	11.01	20.26	0.17	6.99	0.36													
	PC13		30×15×6	1764	10.72	19.85		6.13	0.53													
	PC14		30×15×6	1769	10.72	19.78		6.19	0.43													
	PC15		30×15×6	1749	10.96	20.38		5.02														
	PC18		30×15×4	1745	9.98	18.94			0.97	52.74	18.96	11.84	3.74	1.45	1.35	5.30	4.34	546	278	307	127	1544
	PC21		30×15×4	1763	10.67	19.78			0.66													
	PC32		30×15×4	1748	11.21	20.76			0.78													
	PC34		30×15×4	1745	11.53	21.27			0.64													
	PC42		30×15×4	1757	10.07	18.94			0.91													
	PC55		25×10×5	1755	10.60	19.77				53.99	19.61	10.46	3.49	1.71	1.20	4.73	4.58	458	210	242	107	1349

Annex B: Methodology for the treatment of chemical data from clay samples

The following annex provides a short description of the analytical methodology used for the chemical analysis of clay bricks used in this research work and the statistical procedure that result in the grouping of samples and the estimation of the origin of raw clay. The reader is referred to Castro *et al.* (1997) and Castro (1998a; 1998b; 1999) for further details about this subject.

B.1. General description of the methodology

The determination of the chemical composition of archaeological and ethnographical samples and clay products is a matter of interest for researchers in many ways. In one way, it helps determining the durability of clay bricks and their susceptibility to modern pollution. On the other way, it allows to estimate, with further calculations, the provenance of the raw clay, which permits to understand commercialisation circuits, technical aspects of production, etc. Such calculations are based in the following assumptions:

- The chemical composition of ceramic fragments is strongly related to the chemical composition of raw clay;
- Considering that the commerce of raw materials at long distance is rare, it is acceptable to consider that the chemical composition of ceramic fragments are a good indicator of the raw material's provenance;
- It is essential to know the chemical composition patterns of raw clays and ethnographic ceramic production centres from perfectly known origins. All the collected data is reported in a database.

Thus, the comparison of the chemical composition of a ceramic, or clay, fragment with the typical chemical composition of a known production centre allows to determine, through appropriate procedures and statistical calculations, the probability of this fragment to come from that particular production centre. These procedures are illustrated in Figure B.1 (Castro *et al.*, 1997). Although this analytical methodology had been mostly applied in ethnographical and archaeological ceramics, the study of old and new handmade clay bricks (construction material) followed the same methodology.

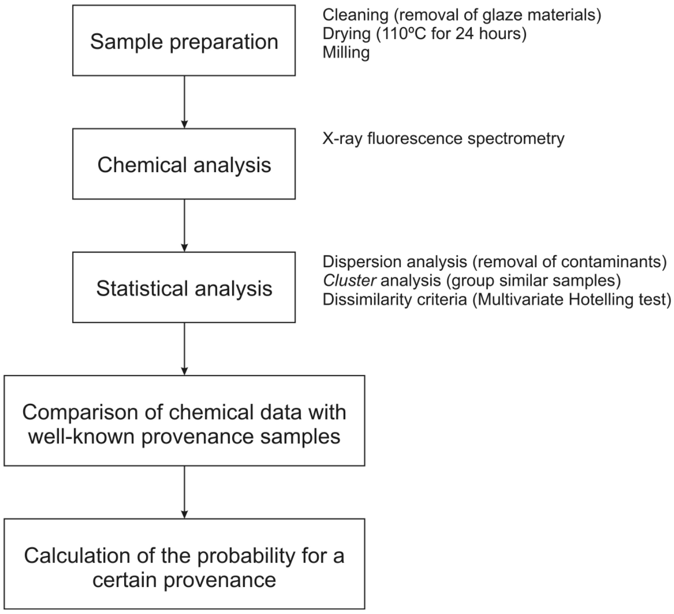


Figure B.1 – Flowchart showing the method to perform chemical and statistical analysis on antique ceramic wares and clay samples and to estimate their provenance.

The first step consists in the preparation of the sample. This is a very important step that consists in a series of procedures to guarantee uniform analysis conditions and to avoid contaminations by elements present in glass coatings. In the case of old bricks, possible contaminations are caused by lime mortars. Thus, the procedures taken to minimise the effect of the presence of glass coatings in ceramic fragments are followed in the case of lime mortars in the chemical composition of clay bricks. Clays are dried at 110 ºC during 24 hours to remove moisture. Afterwards, the samples are milled and pressed in 4.0 ± 0.2 mm plastic discs.

Next, the chemical analysis is carried out by X-ray fluorescence spectrometry with the following analysing crystals: LiF220, Pe, Ge, PX1 and TLAP, which allow measuring elements with an atomic number inferior to 11. The equipment is calibrated with clay type certified reference materials (C.R.M.) and with internal standards produced by the addition of certain pure substances to the C.R.M.s. The elements analysed are: Na (sodium), Mg (magnesium), Al (aluminium), Si (silicon), P (phosphorus), K (potassium), Ca (calcium), Ti (titanium), Mn (manganese), Fe (iron), Sr (strontium), Rb (rubidium), Zr (Zirconium) and Ba (barium).

Prior to the statistical analysis itself, some of the elements that are generally considered as contaminants are discarded from the analysis. These elements are: Na (sodium) and P (phosphorus). Sodium appears generally when contamination due to culinary use exist and phosphorus may derive from contamination with organic animal materials. Thus, the statistical analysis is commonly performed with the following elements: SiO_2, Al_2O_3, MgO, CaO, Fe_2O_3, TiO_2, K_2O, Mn, Ba, Rb, Sr, Zr. Next, all elements are transformed on a new weight 100 % basis. This eliminates differences on loss on ignition values due to different types of clay materials, different firing conditions, different residual moisture contents and different organic matter contents. It eliminates also the eventual effect that different degrees of contamination of the samples would have on the results. Afterwards, all chemical composition values are transformed in reduced variables using, for that effect, the Equation B.1, where C_i represents the content of the element *i* in the sample, $\overline{C_i}$ is the content of the element *i* in all the samples considered and σ_i is the corresponding standard deviation.

$$Z_i = \frac{\left(C_i - \overline{C_i}\right)}{\sigma_i} \tag{B.1}$$

This procedure allows to reduce the sensitivity of the analysis relatively to the different proportions of the chemical elements in the chemical composition, allowing to consider all the chemical elements equally important in the statistical analysis. Thus, variations in the major constituents (silica and alumina) will be considered as strongly as in minor elements (manganese, strontium, titanium, zirconium, etc.).

Afterwards, the samples are grouped by chemical similarity using *cluster* analysis. This is especially important in the case of having large amounts of data. The clustering method employed is the *nearest neighbour method* applied to the Euclidean distances between samples, or between groups of chemically similar samples, and carried out using specialized statistical software packages (SPSS, NCSS, Origin, etc.). The Euclidian distance between two chemical compositions allows to verify how close two chemical compositions are similar or distinct. In order to confirm that a particular chemical composition belongs to a specific cluster (with a certain probability), the dissimilarity between compositions is evaluated through the multivariate Hotelling's T^2 test (analysis of the variance). If the probability of the two clusters tested being different is superior to 95 %, then the clusters are accepted. Otherwise, they are merged into a larger group. Finally, additional discriminant analysis can be done to evidence the main components responsible for the differentiation between the clusters.

After forming an adequate number of clusters with the ceramic fragments and clay products under investigation, they are compared with the chemical composition patterns from known provenance that are present in the database with the same methodology. If the Hotelling's T^2

test is close to zero, the two clusters are very similar and there is a high probability that the source of the two tested clusters is the same.

B.2. Results for old clay bricks

Table B.1 – Groups formed with the bricks from Outeiro.

Outeiro 1													
Specimens	OU03, OU04, OU06, OU07												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	53.19	25.75	13.61	3.62	0.54	1.04	0.39	1.68	642	241	71	189	681
Std dev.	1.28	0.55	0.91	0.13	0.08	0.02	0.12	0.25	87	9	2	7	131
Outeiro 2													
Specimens	OU01, OU02, OU09												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	60.31	25.45	6.90	3.73	0.54	1.02	0.40	1.40	868	323	93	223	928
Std dev.	1.63	1.71	0.28	0.30	0.07	0.15	0.18	0.40	44	15	27	15	164

Table B.2 – Groups formed with the bricks from Pombeiro.

Pombeiro 1													
Specimens	PO18, PO24, PO27, PO28, PO29												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	57.21	26.71	7.97	4.48	0.41	1.10	0.16	1.78	707	252	54	247	485
Std dev.	1.56	1.35	0.60	0.19	0.12	0.10	0.07	0.17	52	55	38	31	66
Pombeiro 2													
Specimens	PO08, PO10, PO13, PO15, PO19, PO33												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	53.32	27.79	9.80	4.56	0.45	1.34	0.68	1.86	917	333	131	262	468
Std dev.	1.01	1.04	0.58	0.41	0.05	0.14	0.47	0.16	153	125	37	35	207
Pombeiro 3													
Specimens	PO01, PO02, PO03, PO04, PO05, PO06, PO07, PO09, PO11, PO12, PO14, PO16, PO21, PO22, PO23, PO26, PO31, PO34												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	58.59	24.13	8.37	5.01	0.59	1.28	0.32	1.46	966	433	149	319	471
Std dev.	1.83	1.69	1.48	0.51	0.17	0.10	0.25	0.22	77	75	55	33	56

Table B.3 – Groups formed with the bricks from Tarouca.

Tarouca 1													
Specimens	TA09, TA10, TA13, TA18												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	57.61	23.47	11.20	3.36	0.96	0.95	1.00	1.28	457	187	110	152	705
Std dev.	1.40	1.02	0.86	0.38	0.09	0.10	0.20	0.13	104	75	34	17	162
Tarouca 2													
Specimens	TA08, TA14, TA16, TA17, TA19, TA21, TA23, TA24, TA25, TA26												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	51.77	27.19	13.34	3.88	0.58	0.97	0.41	1.71	555	123	54	173	595
Std dev.	2.31	0.73	1.87	0.24	0.10	0.11	0.16	0.14	50	65	22	23	77
Tarouca 3													
Specimens	TA01, TA11, TA12, TA15												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	50.58	31.89	11.42	2.90	0.55	0.92	0.21	1.39	445	184	36	207	551
Std dev.	0.60	0.96	0.97	0.15	0.13	0.07	0.04	0.18	65	83	31	16	59
Tarouca 4													
Specimens	TA02, TA03, TA04, TA05, TA07												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	52.12	32.93	8.56	3.73	1.05	0.57	0.10	0.82	360	115	27	284	340
Std dev.	2.16	0.68	1.64	0.31	0.22	0.07	0.04	0.06	125	65	24	43	71

Table B.4 – Groups formed with the bricks from Tibães.

Tibães 1													
Specimens	TI02, TI03, TI04, TI05, TI06, TI07, TI08, TI09, TI10, TI11, TI12, TI15, TI20, TI21, TI25, TI26, TI29, TI30, TI31, TI32												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	52.43	30.53	8.45	4.28	0.52	1.22	0.99	1.38	778	374	86	270	490
Std dev.	2.05	1.80	1.34	0.27	0.12	0.08	0.53	0.23	134	85	52	56	108
Tibães 2													
Specimens	TI13, TI18, TI22, TI28												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	52.43	29.11	8.06	4.93	0.74	1.38	1.28	1.83	1074	466	201	328	432
Std dev.	0.31	0.93	0.50	0.33	0.20	0.12	0.30	0.25	85	113	36	47	92
Tibães 3													
Specimens	TI19, TI24, TI27												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	58.01	29.88	5.09	3.81	0.29	1.20	0.26	1.23	833	616	147	283	465
Std dev.	1.00	1.62	0.22	0.19	0.04	0.01	0.09	0.21	110	160	20	27	117

Table B.5 – Groups formed with the bricks from Tomar.

Tomar													
Specimens	TO01, TO02, TO03, TO04, TO05, TO06, TO07, TO08, TO09, TO10, TO11, TO12, TO13, TO14, TO15, TO16												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	60.80	21.40	6.94	3.57	0.44	0.79	3.72	2.23	411	117	40	139	338
Std dev.	2.34	2.10	0.59	0.83	0.10	0.09	3.09	0.30	59	42	11	15	88

Table B.6 – Groups formed with the bricks from Salzedas.

Salzedas													
Specimens	SA01, SA02, SA03, SA04, SA05, SA06, SA07, SA08, SA09, SA10, SA11, SA12, SA15, SA16, SA17, SA18, SA19, SA20, SA21, SA22, SA23, SA24, SA25, SA26												
Element	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	CaO	MgO	Ba	Zr	Sr	Rb	Mn
Average	54.88	32.51	3.41	5.23	2.12	0.22	0.72	0.80	303	86	89	329	283
Std dev.	1.60	2.27	0.96	0.71	0.60	0.11	0.33	0.14	116	46	49	47	71

Table B.7 – Non-grouped brick specimens.

Specimens	OU05, OU08, OU10, PO17, PO20, PO25, PO30, PO32, TA06, TA20, TA22, TA27, TI01, TI14, TI16, TI17, TI23, SA13, SA14, SA27

Annex C: Basic signal pos-processing of GPR data

The following annex provides a short description of the basic signal processing techniques in use in this research work during the processing of 2D radargrams. The objective is to explain the reader with the most important terms and techniques used in this research wok. Signal pos-processing addresses the fundamental manipulations and enhancements applied to GPR data in order to make it more acceptable for initial interpretation and data evaluation. Figure C.1 gives an overview of the most important pos-processing steps. Additional insight in this topic can be found in Annan (1999b), Conyers (2004) and Daniels (2004).

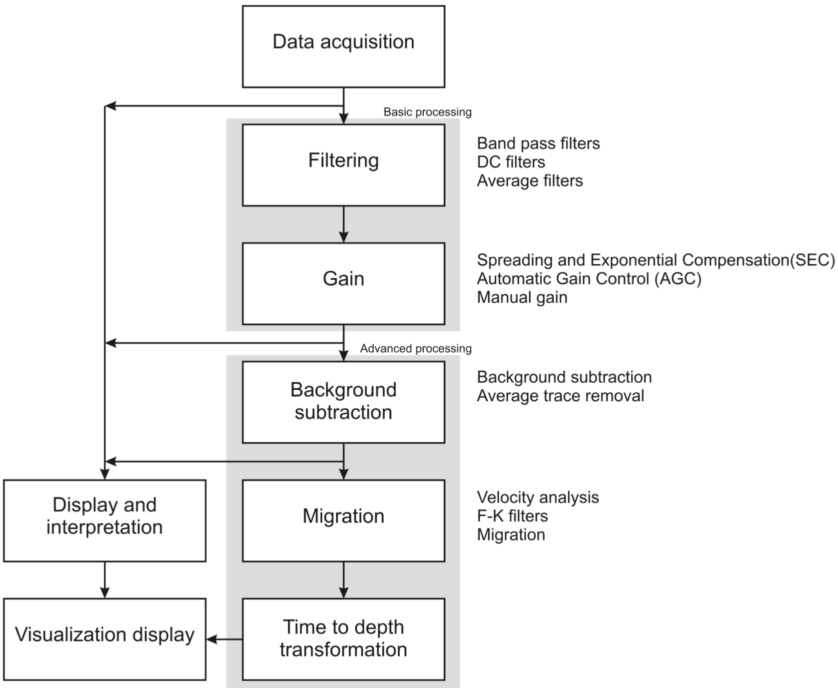
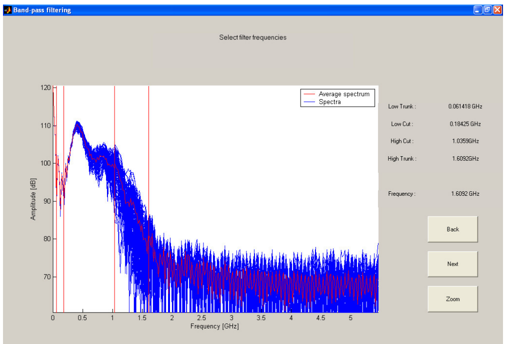


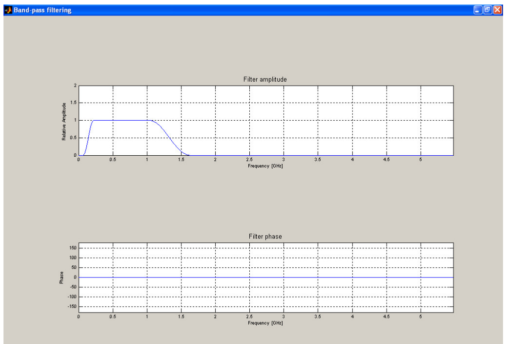
Figure C.1 – General overview of GPR pos-processing data flow. After Annan (1999b).

The first steps include the initial data compilation and general editing requirements of data. The following steps are constituted by the processing of the data acquired during the survey. Although the techniques described hereafter are rather usual in GPR processing software, their application or implementation can differ greatly. Thus, the description will be focussed in the application GPR2D, developed by Prof. Luigi Zanzi (Polytechnic of Milan).

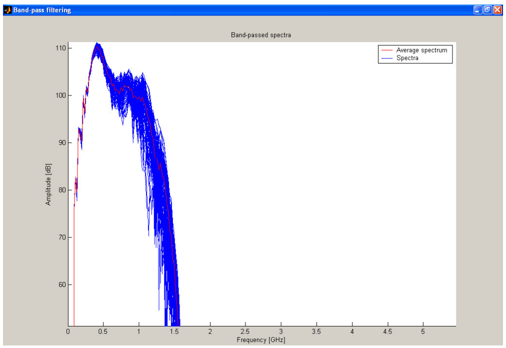
The initial filtering processing step is usually constituted by temporal filtering with the aim of removing very low frequency components and the DC component from the data, as well as unwanted frequencies from the traces. In GPR2D, this step is carried out by applying to the data a band pass filter in the frequency domain, as illustrated in Figure C.2. Additionally, the band pass filter improves the Signal to Noise Ration (SNR) by removing the out band noise components. A zero-phase band pass filter is designed in the frequency domain with the amplitude according to the lower and upper truncation and cut frequencies entered previously by the user The Figure C.3 shows the radargrams before and after applying band pass filtering. Additional averaging filters offer powerful data “clean-up” filters for noise spikes, and can be applied in both time and space domain.



(a)

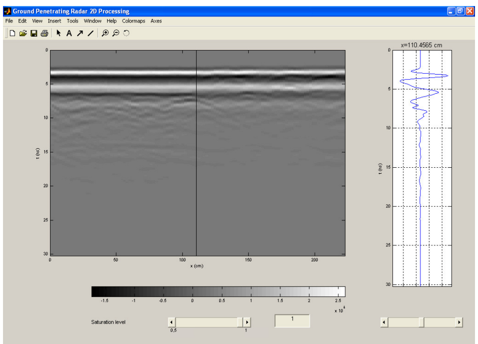


(b)

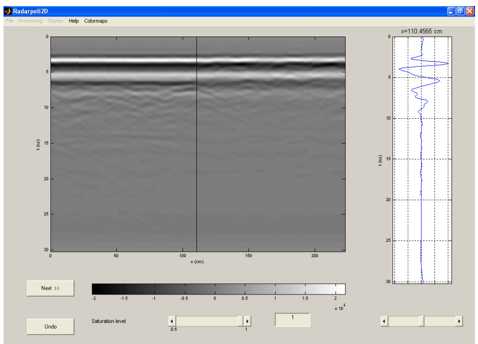


(a)

Figure C.2 – Applying a band pass filter in frequency domain. (a) Low-truncation, low-cut, high-cut and high-truncation frequencies. (b) Zero-phase band-pass filter. (c) Final filtered frequency spectrum.



(a)



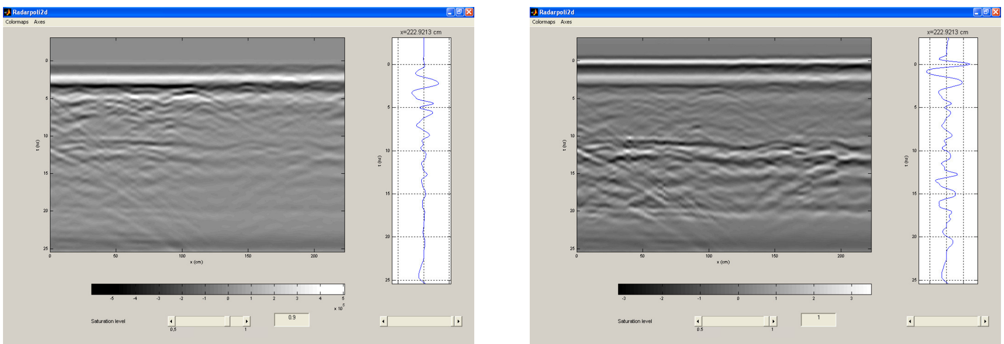
(b)

Figure C.3 – Examples of radargrams showing the effect of a band pass filter. (a) Before and (b) after applying the filter. Note the position of the horizontal axis.

Then, the next step is usually to select a time gain for the data set in order to compensate the attenuation of the signal as it penetrates into the soil. Generally, the main issue that apply here is whether or not one wants to maintain some sort of amplitude fidelity or whether one only wants to display all of the signals in the data. In the first case, physical phenomenon based systematic gains attempt to emulate the variation of signal amplitude (loss of energy) as it propagates in the ground such as spherical and exponential compensation gain filter. SEC amplifies each sample along the time window using an exponential expression to compensate the geometrical spreading attenuation of the electromagnetic signal, and given by

$$v.t.e^{\alpha.v.t} \tag{C.1}$$

where v represents the radiowave's velocity of propagation (cm/ns), t the time (ns) and α the attenuation coefficient (dB/m). In the second case, when showing all the information is more important than amplitude fidelity, a continuously adaptive gain such as AGC (Automatic Gain Control) is used. This filter tries to adjust the gain of each trace by equalizing the mean amplitudes observed in a sliding time window. Figure C.4 illustrates two examples of the previous radargram (Figure C.3b), one after applying SEC and the second one after an AGC.



(a) (b)

Figure C.4 – Radargrams showing the effect of (a) SEC (v = 12 cm/ns and α = 0.02 dB/m) and AGC gain (10 ns window) filter.

More advanced data processing addresses the type of processing that require a certain amount of operator experience to be applied and which generally results in data that is significantly different from the raw input information. Some examples of advanced signal processing techniques included in the GPR2D package are: background subtraction and F-K filtering. The most important advantage of these processing techniques is that they focus in making weaker signals visible and enhance specific components of the data, among others.

The most common in GPR processing, and the only one used successfully within this research work, was background subtraction. The background subtraction works generally by removing the direct wave and its reverberations (antenna ringing). This operation is performed by subtracting the average trace after time and amplitude corrections. Background subtraction enhances diffractions and dip events while removing all horizontal events. Figure C.5 illustrates the application of the background subtraction (original radargram in Figure C.3b).

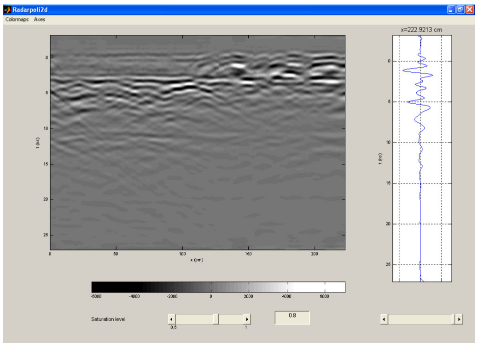


Figure C.2 – Applying the background subtraction.

Great care must be taken when using background subtraction due to the frequent creation of artefacts in areas where there are no responses from the ground giving rise to inaccurate interpretations. This technique should also be avoided in cases where horizontal events represent the objective of the acquisitions.