The use of finely ground pumice pozzolan in GFRC composites

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Abstract

This paper includes the historical use of pumice pozzolan, results of an accelerated age test performed by Washington University on GFRC composites containing a range of UltraPozz pumice pozzolan and test results from a 2012 study by the University of Utah on concrete samples containing UltraPozz pozzolan. The results shown in this paper include pozzolanic effect, hydration, workability, durability, chemical and physical characteristics.

PART ONE – HISTORY

Introduction

ASTM C-1560 tests were completed in December, 2012 by Washington University and in early 2013 Nippon Electric Glass America became the exclusive distributor of UltraPozz pumice pozzolan in North America. Throughout this paper I use the term pozzolana (latin- pulvis puteolanus) which can only be used for pozzolan originating from volcanic pumice or volcanic ash. The term pozzolan refers to materials having no specific origin.

Replacing Portland cement with pozzolana and other pozzolans in concrete and glass fiber reinforced concrete not only reduces the emission of greenhouse gasses into the atmosphere, particularly carbon dioxide, but improves the durability of the finished products by combining with free lime.

Early Use

According to ancient scripts pozzolanas were used in the Eastern Mediterranean since 500-400 BC. Although pioneered by the ancient Greeks, it was the Romans that eventually developed the potential of lime-pozzolana pastes as the binder phase in Roman concrete for buildings and underwater construction.

Vitruvius, noted Roman architect (circa 20 BC) mentions mixtures of two part pozzolana to one part lime. Ancient Roman texts show concrete consisting of pozzolana, lime and fist sized rock. The Roman port at Cosa was built of lime-pozzolana concrete that was cured in sea water. The three piers are still visible today, with the underwater portion generally in excellent condition after more than 2,100 years of weathering.

***Figure A**. The Pantheon, Rome*

The Pantheon (Figure A), called the Temple of the Gods, is one of the greatest engineering wonders of the Roman Empire. Built by Agrippa and restored by Emperor Hadrian (AD 138), the Pantheon held the world record for the largest dome diameter (43.2 meters) for almost 1,800 years. The dome and the 6 meter thick walls supporting the Pantheon dome are cast solid concrete made of lime-pozzolana cement. Roman pozzolana are composed mostly of volcanic tuff.

Santorin earth of Greece, Bacoli pozzolana of Italy and Shirasu pozzolana of Japan are examples of pozzolanic materials that derive their lime reactivity characteristics mainly from unaltered aluminosilicate glass. The Roman pozzolana in Italy, used in the construction of the Pantheon, and the German trass of Rheinland and Bavaria are typical volcanic tuffs that are a product of hydrothermal alteration of volcanic glass. When ground to a fine particle size these tuffs show considerable reactivity with lime and develop cementitious characteristics similar to pozzolana containing volcanic glass. As a rule, small amounts of non-reactive crystalline minerals are embedded in the glassy matrix. Quartz and anorthite in Shirasu pozzolana. Leucite, feldspar and augite in Bacoli pozzolana. Quartz and feldspar in Santorin Earth.

Knowing the chemistry and placement of ancient Roman concrete will help us understand how the Romans around the time of Christ were able to construct such elaborate, ageless structures in concrete. Before the time of Christ, people of the Middle East made balls for their fortifications and homes by pounding moist clay between forms, called pise work. To protect the clay from erosion, the ancients discovered that a moist coating of thin, white, burnt limestone would chemically combine with the gases in the air to give a hard protective shield. We can only guess that the event of discovering concrete occurred some 200 years before Christ when a lime coating was applied to a wall made of pozzolan volcanic ash near the town of Pozzouli in Italy. A reaction took place between the silica and small amounts of alumina and iron oxide in the volcanic ash and the layer of lime (calcium hydroxide) applied to the wall. Later, they found that mixing a small amount of volcanic ash in a fine powder with the moist lime made a thicker coat, but it also produced a durable product that could be submerged in water; something the plaster product of wet lime and sand could not match.

Common plaster is made with wet lime and plain sand. This sand has crystalline atomic structure whereby the silica is so condensed there are no atomic holes in the molecular network to allow the calcium hydroxide molecule from the lime to enter and react. The opposite is true with wet lime- pozzolana concrete. The pozzolana has an amorphous silica atomic structure with many holes in the molecular network. When mixing the wet lime with pozzolana, the calcium hydroxide enters the atomic holes to make a concrete gel which expands, bonding pieces of rock together. The fine powder condition of the pozzolana provides a large surface area to enhance the chemical reaction.

According to the writings of Roman architect Vitruvius, the Romans mixed their components (wet lime and volcanic ash) in a mortar box with very little water to give a nearly dry composition; carried it to the job site in baskets placing it over a previously prepared layer of rock pieces; and then proceeded to pound the mortar into the rock layer using special tamping tools. Close packing of the molecular structure by tamping reduced the need of excess water, which is a source of voids and weakness. But also close packing produces more bonding gel than might be normally expected.

Mineralogical Composition

ASTM C 618 classifies pumice as a Class N pozzolan, raw or calcined natural pozzolan, if it meets specific physical and chemical requirements. Class N pozzolan should have a minimum of + + content of 70%. As shown in the chart below all pozzolans noted fit the description of Class N with the exception of the Handelage calcined clay.

Table A. *% of Oxides in Natural Pozzolans*

Pozzolan				CaO	MgO		
Volcanic Glasses							
Bacoli (Italy)	53.1	18.2	4.3	9.0	1.2	3.1	7.6
Santorin Earth (Greece)	65.1	14.5	5.5	3.0	1.1	2.6	3.9
Shirasu (Japan)	69.3	14.6	1.0	2.6	0.7	3.0	2.4
UltraPozz (USA)	69.8	11.2	1.0	1.0	0.3	2.3	4.8
Volcanic Tuffs							
Segni-Latium (Italy)	45.5	19.6	9.9	9.3	4.5	0.9	6.4
Rheinisch Trass (Germany)	52.1	18.3	5.8	4.9	1.2	1.5	5.1
Bavarian Trass (Germany)	62.4	16.5	4.4	3.4	0.9	1.9	2.1
Higashi-Matusyma (Japan)	71.8	11.5	1.1	1.1	0.5	1.5	2.6
Diantomites							
Diatomaceous Earth (California)	86.0	2.3	1.8	-	0.6	0.4	-
Calcined Clays							
Handelage (Germany)	42.2	16.1	7.0	21.8	1.9	0.3	1.0

PART TWO – TESTING

Glass fiber reinforced concrete, GFRC, loses strength and ductility due to interaction of calcium hydroxide with AR glass fiber bundles. The durability of GFRC is normally determined by accelerated aging. Test panels are first submerged in hot water for varying lengths of time. The panels are then tested in four-point bending according to ASTM C947-03. Durability of GFRC can be improved by additives that reduce the alkalinity of the concrete. The purpose of the test program reported here is to determine the change in durability of GFRC due to the addition of different amounts of UltraPozz pumice pozzolan.

The objective of the test program reported here was to compare the durability of three different modified GFRC matrices with a control mix without pozzolan.

Four GFRC boards were prepared, each having a different amount of additive as given in Table 1. Board thicknesses varied from approximately 0.6 in. to 0.8 in.

Table 1. *Test Boards*

Board	Pozzolan	Cement	Sand	Polyplex Polymer	Water	NEG AR roving	SCC admix
1	0	79 4 lb	84 lb	10 lb	26 lb	11 lb	2 oz
2	14.1 lb.(15%)	79.9 lb	84 lb	10 lb	27 lb	11 lb	2 oz
3	14.1 lb.(15%)	75.2 lb	84 lb	10 lb	28 lb	11 lb	2 oz
4	23.5 lb.(25%)	70.5 lb	84 lb	10 lb	29.5 lb	11 lb	2 oz

The Boards were cut into test samples that were 2 in. wide by 12 in. long. The boards were placed in hot water tanks and aged for varying durations according to ASTM C1560-03. The samples were placed in the tanks on plastic racks approximately 0.5 inches apart. The samples from each board were kept in a separate water tank. The water temperature was maintained at 50 degrees centigrade. At various times, six boards were removed from the tanks and tested in four point bending with a span of 10 in. according to ASTM C947-03 as shown in Figure 1. The cross-head deflection speed was 0.1 inches per minute. Three of the boards from each group of six were tested with the form side up and three were tested with the form side down.

Test Results

The results of the tests are summarized in Table 2 for each test performed. The first three results for each test group of six were tested form side up and the remaining three were tested form side down. The thickness given is the average of three thickness measurements taken at the fracture plane. Figures 2 through 5 are plots of averaged results versus days aged at . Each test value in the plot represents the average of 6 tests. The results presented in the plots are in order, the modulus of rupture, the proportional limit, the stress ratio and the strain ratio.

The natural weathering equivalence at C (F) in water for 1 day would be 101 days (3.5 months) weather in the United Kingdom.[7]

Figure 1. *Test setup*

Table 2. *Test Results*

Days aged	%	Yield lbs	Disp. In.	Peak lbs	Disp. In.	Thick in.	PEL psi	PEL Strain	MOR psi	MOR strain	MOR/ PEL	MOR STR./ PEL STR.
0	0	143.5	0.048	250.1	0.336	0.635	1779	0.0001431	3101	0.001002	1.74	7.00
		141.5	0.036	254	0.248	0.663	1610	0.0001121	2889	0.000772	1.80	6.89
		157.5	0.03	281.7	0.229	0.675	1728	0.0000951	3091	0.000726	1.79	7.63
		166.4	0.03	248.9	0.219	0.676	1821	0.0000952	2723	0.000695	1.50	7.30
		159.7	0.033	253.8	0.24	0.681	1722	0.0001055	2736	0.000767	1.59	7.27
		184.7	0.033	300.6	0.244	0.707	1848	0.0001095	3007	0.000810	1.63	7.39
	15	101.5	0.026	128.5	0.077	0.641	1235	0.0000782	1564	0.000232	1.27	2.96
		71.7	0.022	86.8	0.063	0.589	1033	0.0000608	1251	0.000174	1.21	2.86
		111.7	0.026	168.1	0.138	0.572	1707	0.0000698	2569	0.000371	1.50	5.31
		140.3	0.035	219.3	0.211	0.617	1843	0.0001014	2880	0.000611	1.56	6.03
		105.1	0.032	168.7	0.195	0.61	1412	0.0000916	2267	0.000558	1.61	6.09
		108.7	0.028	159.5	0.134	0.616	1432	0.0000810	2102	0.000388	1.47	4.79
	20	158	0.024	217.5	0.112	0.671	1755	0.0000756	2415	0.000353	1.38	4.67
		144.6	0.024	213.5	0.119	0.665	1635	0.0000749	2414	0.000372	1.48	4.96
		134.7	0.024	194.4	0.134	0.651	1589	0.0000734	2294	0.000410	1.44	5.58
		128	0.02	216.9	0.108	0.663	1456	0.0000623	2467	0.000336	1.69	5.40
		160.2	0.029	227	0.101	0.66	1839	0.0000899	2606	0.000313	1.42	3.48
		156	0.027	211	0.109	0.662	1780	0.0000839	2407	0.000339	1.35	4.04
	25	165.1	0.028	267.5	0.198	0.716	1610	0.0000941	2609	0.000666	1.62	7.07
		187.6	0.029	295.1	0.187	0.718	1820	0.0000978	2862	0.000630	1.57	6.45
		187.2	0.026	303.7	0.18	0.73	1756	0.0000891	2850	0.000617	1.62	6.92
		195.7	0.027	320.7	0.172	0.755	1717	0.0000957	2813	0.000610	1.64	6.37
		156.1	0.026	224.1	0.164	0.673	1723	0.0000822	2474	0.000518	1.44	6.31
		181.5	0.025	274.5	0.167	0.702	1842	0.0000824	2785	0.000550	1.51	6.68

Table 2 continued

Days aged	%	Yield lbs	Disp. In.	Peak lbs	Disp. In.	Thick in.	PEL psi	PEL Strain	MOR psi	MOR strain	MOR/ PEL	MOR STR./ PEL STR.
10	0	102	0.024	180.4	0.201	0.572	1559	0.0000645	2757	0.000540	1.77	8.38
		122	0.023	216	0.15	0.634	1518	0.0000685	2687	0.000446	1.77	6.52
		152	0.025	268	0.15	0.676	1663	0.0000793	2932	0.000476	1.76	6.00
		216	0.021	338	0.133	0.798	1696	0.0000787	2654	0.000498	1.56	6.33
		211	0.022	328	0.128	0.766	1798	0.0000791	2795	0.000460	1.55	5.82
		183	0.024	300	0.145	0.704	1846	0.0000793	3027	0.000479	1.64	6.04
	15	116	0.021	142	0.068	0.626	1480	0.0000617	1812	0.000200	1.22	3.24
		109	0.024	153	0.103	0.648	1298	0.0000730	1822	0.000313	1.40	4.29
		117	0.023	148	0.076	0.658	1351	0.0000711	1709	0.000235	1.26	3.30
		140	0.027	214	0.114	0.653	1642	0.0000828	2509	0.000349	1.53	4.22
		142	0.024	172	0.068	0.693	1478	0.0000781	1791	0.000221	1.21	2.83
		138	0.026	187	0.104	0.69	1449	0.0000842	1964	0.000337	1.36	4.00
	20	86	0.019	175	0.101	0.585	1256	0.0000522	2557	0.000277	2.03	5.32
		135	0.026	234	0.161	0.636	1669	0.0000776	2892	0.000481	1.73	6.19
		116	0.022	177	0.104	0.675	1273	0.0000697	1942	0.000330	1.53	4.73
		146	0.024	258	0.126	0.677	1593	0.0000763	2815	0.000400	1.77	5.25
		132	0.019	228	0.092	0.656	1534	0.0000585	2649	0.000283	1.73	4.84
		142	0.024	200	0.093	0.661	1625	0.0000745	2289	0.000289	1.41	3.88
	25	228	0.026	400	0.137	0.801	1777	0.0000978	3117	0.000515	1.75	5.27
		268	0.019	491	0.124	0.886	1707	0.0000790	3127	0.000516	1.83	6.53
		271	0.018	474	0.103	0.962	1464	0.0000813	2561	0.000465	1.75	5.72
		317	0.022	531	0.116	0.962	1713	0.0000994	2869	0.000524	1.68	5.27
		172	0.024	297	0.136	0.658	1986	0.0000741	3430	0.000420	1.73	5.67
		273	0.021	479	0.13	0.862	1837	0.0000850	3223	0.000526	1.75	6.19

Table 2 continued

Days aged	%	Yield lbs	Disp. In.	Peak lbs	Disp. In.	Thick in.	PEL psi	PEL Strain	MOR psi	MOR strain	MOR/ PEL	MOR STR./ PEL STR.
20	0	119	0.027	194	0.16	0.575	1800	0.0000729	2934	0.000432	1.63	5.93
		110	0.025	210	0.105	0.664	1247	0.0000779	2382	0.000327	1.91	4.20
		128	0.016	186	0.056	0.677	1396	0.0000509	2029	0.000178	1.45	3.50
		133	0.02	176	0.065	0.636	1644	0.0000597	2176	0.000194	1.32	3.25
		121	0.017	150	0.048	0.634	1505	0.0000506	1866	0.000143	1.24	2.82
		131	0.022	194	0.101	0.627	1666	0.0000648	2467	0.000297	1.48	4.59
	15	53	0.006	149	0.042	0.647	633	0.0000182	1780	0.000128	2.81	7.00
		120	0.024	172	0.055	0.626	1531	0.0000705	2195	0.000162	1.43	2.29
		140	0.025	222	0.125	0.63	1764	0.0000739	2797	0.000370	1.59	5.00
		116	0.022	122	0.04	0.584	1701	0.0000603	1789	0.000110	1.05	1.82
		107	0.024	150	0.103	0.62	1392	0.0000699	1951	0.000300	1.40	4.29
		140	0.03	210	0.123	0.611	1875	0.0000861	2813	0.000353	1.50	4.10
	20	142	0.024	233	0.117	0.656	1650	0.0000739	2707	0.000360	1.64	4.88
		75	0.022	169	0.105	0.619	979	0.0000639	2205	0.000305	2.25	4.77
		123	0.02	270	0.109	0.725	1170	0.0000681	2568	0.000371	2.20	5.45
		101	0.024	160	0.114	0.628	1280	0.0000708	2028	0.000336	1.58	4.75
		102	0.024	155	0.124	0.6	1417	0.0000676	2153	0.000349	1.52	5.17
		99	0.027	140	0.103	0.576	1492	0.0000730	2110	0.000279	1.41	3.81
	25	175	0.017	354	0.075	0.788	1409	0.0000629	2850	0.000277	2.02	4.41
		196	0.027	295	0.119	0.745	1766	0.0000944	2658	0.000416	1.51	4.41
		220	0.019	302	0.059	0.776	1827	0.0000692	2508	0.000215	1.37	3.11
		167	0.032	251	0.131	0.71	1656	0.0001067	2490	0.000437	1.50	4.09
		275	0.021	393	0.079	0.843	1935	0.0000831	2765	0.000313	1.43	3.76
		272	0.021	365	0.064	0.847	1896	0.0000835	2544	0.000254	1.34	3.05

Table 2 continued

Days aged	%	Yield lbs	Disp. In.	Peak lbs	Disp. In.	Thick in.	PEL psi	PEL Strain	MOR psi	MOR strain	MOR/ PEL	MOR STR./ PEL STR.
30	0	126	0.02	192	0.056	0.587	1828	0.0000551	2786	0.000154	1.52	2.80
		139	0.021	193	0.064	0.638	1707	0.0000629	2371	0.000192	1.39	3.05
		105	0.023	167	0.106	0.579	1566	0.0000625	2491	0.000288	1.59	4.61
		190	0.02	235	0.053	0.712	1874	0.0000669	2318	0.000177	1.24	2.65
		90	0.02	165	0.066	0.507	1751	0.0000476	3210	0.000157	1.83	3.30
		123	0.019	159	0.055	0.625	1574	0.0000558	2035	0.000161	1.29	2.89
	15	129	0.034	175	0.085	0.615	1705	0.0000982	2313	0.000245	1.36	2.50
		45	0.008	131	0.024	0.642	546	0.0000241	1589	0.000072	2.91	3.00
		144	0.032	181	0.07	0.638	1769	0.0000958	2223	0.000210	1.26	2.19
		137	0.022	137	0.022	0.642	1662	0.0000663	1662	0.000066	1.00	1.00
		162	0.024	162	0.024	0.664	1837	0.0000748	1837	0.000075	1.00	1.00
		165	0.026	208	0.067	0.65	1953	0.0000793	2462	0.000204	1.26	2.58
	20	116	0.021	190	0.096	0.632	1452	0.0000623	2378	0.000285	1.64	4.57
		150	0.022	195	0.055	0.618	1964	0.0000638	2553	0.000160	1.30	2.50
		140	0.025	178	0.063	0.612	1869	0.0000718	2376	0.000181	1.27	2.52
		129	0.02	184	0.158	0.636	1595	0.0000597	2274	0.000472	1.43	7.90
		137	0.024	206	0.067	0.653	1606	0.0000736	2416	0.000205	1.50	2.79
		121	0.027	196	0.146	0.598	1692	0.0000758	2740	0.000410	1.62	5.41
	25	126	0.026	210	0.144	0.566	1967	0.0000691	3278	0.000383	1.67	5.54
		226	0.022	305	0.087	0.743	2047	0.0000767	2762	0.000303	1.35	3.95
		271	0.023	366	0.095	0.751	2402	0.0000811	3245	0.000335	1.35	4.13
		260	0.022	356	0.075	0.749	2317	0.0000774	3173	0.000264	1.37	3.41
		246	0.024	344	0.093	0.764	2107	0.0000861	2947	0.000334	1.40	3.88
		153	0.02	258	0.086	0.668	1714	0.0000627	2891	0.000270	1.69	4.30

Table 2 continued

Days aged	%	Yield lbs	Disp. In.	Peak lbs	Disp. In.	Thick in.	PEL psi	PEL Strain	MOR psi	MOR strain	MOR/ PEL	MOR STR./ PEL STR.
40	0	140	0.017	205	0.037	0.699	1433	0.0000558	2098	0.000121	1.46	2.18
		144	0.02	185	0.056	0.634	1791	0.0000595	2301	0.000167	1.28	2.80
		165	0.018	207	0.046	0.693	1718	0.0000586	2155	0.000150	1.25	2.56
		157	0.02	271	0.095	0.69	1649	0.0000648	2846	0.000308	1.73	4.75
		168	0.018	201	0.035	0.675	1844	0.0000570	2206	0.000111	1.20	1.94
		140	0.015	208	0.042	0.685	1492	0.0000482	2216	0.000135	1.49	2.80
	15	123	0.022	135	0.025	0.636	1520	0.0000657	1669	0.000075	1.10	1.14
		124	0.022	128	0.025	0.619	1618	0.0000639	1670	0.000073	1.03	1.14
		152	0.021	164	0.024	0.621	1971	0.0000612	2126	0.000070	1.08	1.14
		193	0.028	260	0.082	0.68	2087	0.0000894	2811	0.000262	1.35	2.93
		162	0.027	230	0.079	0.636	2002	0.0000806	2843	0.000236	1.42	2.93
		109	0.024	159	0.06	0.596	1534	0.0000672	2238	0.000168	1.46	2.50
	20	157	0.022	202	0.06	0.656	1824	0.0000678	2347	0.000185	1.29	2.73
		178	0.023	196	0.048	0.66	2043	0.0000713	2250	0.000149	1.10	2.09
		166	0.022	190	0.044	0.638	2039	0.0000659	2334	0.000132	1.14	2.00
		169	0.026	204	0.06	0.682	1817	0.0000832	2193	0.000192	1.21	2.31
		185	0.023	243	0.072	0.698	1899	0.0000754	2494	0.000236	1.31	3.13
		161	0.022	212	0.066	0.69	1691	0.0000713	2226	0.000214	1.32	3.00
	25	230	0.018	359	0.067	0.795	1820	0.0000672	2840	0.000250	1.56	3.72
		144	0.022	206	0.094	0.589	2075	0.0000608	2969	0.000260	1.43	4.27
		167	0.019	276	0.085	0.707	1671	0.0000631	2761	0.000282	1.65	4.47
		268	0.02	359	0.048	0.817	2008	0.0000767	2689	0.000184	1.34	2.40
		158	0.018	236	0.06	0.691	1655	0.0000584	2471	0.000195	1.49	3.33
		221	0.019	302	0.05	0.781	1812	0.0000697	2476	0.000183	1.37	2.63

Table 2 continued

Days aged	%	Yield lbs	Disp. In.	Peak lbs	Disp. In.	Thick in.	PEL psi	PEL Strain	MOR psi	MOR strain	MOR/ PEL	MOR STR./ PEL STR.
50	0	166	0.018	203	0.042	0.723	1588	0.0000611	1942	0.000143	1.22	2.33
		127	0.012	198	0.037	0.727	1201	0.0000410	1873	0.000126	1.56	3.08
		145	0.019	192	0.046	0.712	1430	0.0000635	1894	0.000154	1.32	2.42
		120	0.015	183	0.059	0.674	1321	0.0000475	2014	0.000187	1.53	3.93
		144	0.021	195	0.052	0.696	1486	0.0000686	2013	0.000170	1.35	2.48
		121	0.015	193	0.035	0.725	1151	0.0000511	1836	0.000119	1.60	2.33
	15	121	0.019	132	0.029	0.673	1336	0.0000600	1457	0.000092	1.09	1.53
		131	0.019	190	0.05	0.656	1522	0.0000585	2208	0.000154	1.45	2.63
		123	0.02	133	0.03	0.75	1093	0.0000704	1182	0.000106	1.08	1.50
		119	0.023	169	0.057	0.624	1528	0.0000674	2170	0.000167	1.42	2.48
		108	0.021	151	0.053	0.594	1530	0.0000586	2140	0.000148	1.40	2.52
		110	0.019	152	0.045	0.604	1508	0.0000539	2083	0.000128	1.38	2.37
	20	140	0.021	197	0.066	0.662	1597	0.0000653	2248	0.000205	1.41	3.14
		130	0.019	197	0.068	0.618	1702	0.0000551	2579	0.000197	1.52	3.58
		132	0.022	169	0.045	0.646	1582	0.0000667	2025	0.000136	1.28	2.05
		141	0.019	227	0.081	0.722	1352	0.0000644	2177	0.000275	1.61	4.26
		133	0.017	176	0.047	0.648	1584	0.0000517	2096	0.000143	1.32	2.76
		132	0.016	210	0.047	0.719	1277	0.0000540	2031	0.000159	1.59	2.94
	25	174	0.021	248	0.052	0.7	1776	0.0000690	2531	0.000171	1.43	2.48
		266	0.017	363	0.05	0.853	1828	0.0000681	2494	0.000200	1.36	2.94
		177	0.018	232	0.056	0.72	1707	0.0000608	2238	0.000189	1.31	3.11
		154	0.021	199	0.053	0.648	1834	0.0000639	2370	0.000161	1.29	2.52
		180	0.018	220	0.038	0.706	1806	0.0000597	2207	0.000126	1.22	2.11
		184	0.02	255	0.056	0.704	1856	0.0000661	2573	0.000185	1.39	2.80

Table 2 continued

Days aged	%	Yield lbs	Disp. In.	Peak lbs	Disp. In.	Thick in.	PEL psi	PEL Strain	MOR psi	MOR strain	MOR/ PEL	MOR STR./ PEL STR.
60	0	138	0.018	187	0.037	0.645	1659	0.0000545	2247	0.000112	1.36	2.06
		205	0.015	306	0.037	0.815	1543	0.0000574	2303	0.000142	1.49	2.47
		258	0.018	333	0.036	0.855	1765	0.0000723	2278	0.000145	1.29	2.00
		145	0.017	187	0.033	0.668	1625	0.0000533	2095	0.000103	1.29	1.94
		192	0.017	233	0.03	0.73	1801	0.0000583	2186	0.000103	1.21	1.76
		191	0.017	224	0.027	0.771	1607	0.0000615	1884	0.000098	1.17	1.59
	15	134	0.021	134	0.021	0.611	1795	0.0000602	1795	0.000060	1.00	1.00
		127	0.023	147	0.029	0.617	1668	0.0000666	1931	0.000084	1.16	1.26
		108	0.021	126	0.041	0.601	1495	0.0000593	1744	0.000116	1.17	1.95
		112	0.018	166	0.044	0.655	1305	0.0000554	1935	0.000135	1.48	2.44
		128	0.021	180	0.048	0.663	1456	0.0000654	2047	0.000149	1.41	2.29
		122	0.024	179	0.066	0.652	1435	0.0000735	2105	0.000202	1.47	2.75
	20	152	0.016	232	0.042	0.709	1512	0.0000533	2308	0.000140	1.53	2.63
		128	0.019	174	0.033	0.741	1166	0.0000661	1584	0.000115	1.36	1.74
		108	0.015	161	0.041	0.703	1093	0.0000495	1629	0.000135	1.49	2.73
		126	0.015	197	0.04	0.768	1068	0.0000541	1670	0.000144	1.56	2.67
		85	0.011	206	0.078	0.67	947	0.0000346	2294	0.000245	2.42	7.09
		75	0.012	215	0.078	0.688	792	0.0000388	2271	0.000252	2.87	6.50
	25	190	0.014	356	0.048	0.872	1249	0.0000573	2341	0.000197	1.87	3.43
		214	0.02	327	0.071	0.817	1603	0.0000767	2449	0.000272	1.53	3.55
		231	0.017	319	0.042	0.83	1677	0.0000662	2315	0.000164	1.38	2.47
		113	0.024	190	0.092	0.612	1509	0.0000690	2536	0.000264	1.68	3.83
		185	0.02	285	0.061	0.792	1475	0.0000744	2272	0.000227	1.54	3.05
		229	0.016	411	0.065	0.826	1678	0.0000620	3012	0.000252	1.79	4.06

Table 2 continued

Days aged	%	Yield lbs	Disp. In.	Peak lbs	Disp. In.	Thick in.	PEL psi	PEL Strain	MOR psi	MOR strain	MOR/ PEL	MOR STR./ PEL STR.
70	0	111	0.018	155	0.038	0.618	1453	0.0000522	2029	0.000110	1.40	2.11
		97	0.018	162	0.07	0.6	1347	0.0000507	2250	0.000197	1.67	3.89
		110	0.018	165	0.055	0.641	1339	0.0000542	2008	0.000166	1.50	3.06
		99	0.022	107	0.03	0.562	1567	0.0000580	1694	0.000079	1.08	1.36
		145	0.012	284	0.041	0.798	1138	0.0000450	2230	0.000154	1.96	3.42
		164	0.014	249	0.037	0.766	1398	0.0000503	2122	0.000133	1.52	2.64
	15	110	0.021	129	0.033	0.599	1533	0.0000591	1798	0.000093	1.17	1.57
		98	0.019	133	0.058	0.575	1482	0.0000513	2011	0.000157	1.36	3.05
		77	0.015	130	0.025	0.616	1015	0.0000434	1713	0.000072	1.69	1.67
		142	0.024	174	0.043	0.661	1625	0.0000745	1991	0.000133	1.23	1.79
		124	0.02	165	0.04	0.629	1567	0.0000591	2085	0.000118	1.33	2.00
		145	0.025	200	0.054	0.666	1635	0.0000782	2255	0.000169	1.38	2.16
	20	135	0.025	154	0.034	0.658	1559	0.0000772	1778	0.000105	1.14	1.36
		247	0.02	372	0.073	0.815	1859	0.0000765	2800	0.000279	1.51	3.65
		157	0.02	184	0.039	0.694	1630	0.0000652	1910	0.000127	1.17	1.95
		155	0.021	201	0.058	0.678	1686	0.0000668	2186	0.000185	1.30	2.76
		146	0.02	215	0.045	0.695	1511	0.0000653	2226	0.000147	1.47	2.25
		180	0.019	235	0.04	0.73	1689	0.0000651	2205	0.000137	1.31	2.11
	25	286	0.019	382	0.045	0.843	2012	0.0000752	2688	0.000178	1.34	2.37
		207	0.021	287	0.056	0.722	1985	0.0000712	2753	0.000190	1.39	2.67
		201	0.017	260	0.046	0.7	2051	0.0000559	2653	0.000151	1.29	2.71
		272	0.019	319	0.037	0.795	2152	0.0000709	2524	0.000138	1.17	1.95
		234	0.02	323	0.058	0.804	1810	0.0000755	2498	0.000219	1.38	2.90
		200	0.019	247	0.043	0.631	2512	0.0000563	3102	0.000127	1.24	2.26

Table 2 continued

Days aged	%	Yield lbs	Disp. In.	Peak lbs	Disp. In.	Thick in.	PEL psi	PEL Strain	MOR psi	MOR strain	MOR/ PEL	MOR STR./ PEL STR.
80	0	177	0.018	248	0.041	0.712	1746	0.0000602	2446	0.000137	1.40	2.28
		187	0.02	219	0.036	0.652	2199	0.0000612	2576	0.000110	1.17	1.80
		182	0.019	240	0.038	0.697	1873	0.0000622	2470	0.000124	1.32	2.00
		163	0.021	188	0.031	0.633	2034	0.0000624	2346	0.000092	1.15	1.48
		171	0.017	239	0.032	0.713	1682	0.0000569	2351	0.000107	1.40	1.88
		196	0.019	220	0.03	0.745	1766	0.0000665	1982	0.000105	1.12	1.58
	15	79	0.024	119	0.078	0.546	1325	0.0000615	1996	0.000200	1.51	3.25
		147	0.021	147	0.021	0.666	1657	0.0000657	1657	0.000066	1.00	1.00
		131	0.02	143	0.027	0.684	1400	0.0000642	1528	0.000087	1.09	1.35
		165	0.023	221	0.046	0.687	1748	0.0000742	2341	0.000148	1.34	2.00
		148	0.019	249	0.052	0.682	1591	0.0000608	2677	0.000166	1.68	2.74
		104	0.022	194	0.086	0.603	1430	0.0000623	2668	0.000243	1.87	3.91
	20											
	25	201	0.017	361	0.056	0.83	1459	0.0000662	2620	0.000218	1.80	3.29
		204	0.021	307	0.063	0.791	1630	0.0000780	2453	0.000234	1.50	3.00
		206	0.021	362	0.071	0.814	1554	0.0000803	2732	0.000271	1.76	3.38
		152	0.021	287	0.091	0.699	1555	0.0000689	2937	0.000299	1.89	4.33
		224	0.018	358	0.069	0.793	1781	0.0000670	2846	0.000257	1.60	3.83
		174	0.018	315	0.068	0.753	1534	0.0000636	2778	0.000240	1.81	3.78

Table 2 continued

Days aged	%	Yield lbs	Disp. In.	Peak lbs	Disp. In.	Thick in.	PEL psi	PEL Strain	MOR psi	MOR strain	MOR/ PEL	MOR STR./ PEL STR.
90	0	158	0.018	226	0.059	0.675	1734	0.0000570	2480	0.000187	1.43	3.28
		167	0.02	234	0.063	0.685	1780	0.0000643	2493	0.000203	1.40	3.15
		167	0.018	230	0.063	0.701	1699	0.0000592	2340	0.000207	1.38	3.50
		112	0.018	158	0.032	0.621	1452	0.0000525	2049	0.000093	1.41	1.78
		149	0.018	198	0.047	0.626	1901	0.0000529	2526	0.000138	1.33	2.61
		139	0.019	192	0.056	0.645	1671	0.0000575	2308	0.000170	1.38	2.95
	15	96	0.022	129	0.065	0.571	1472	0.0000590	1978	0.000174	1.34	2.95
		73	0.025	97	0.053	0.565	1143	0.0000663	1519	0.000141	1.33	2.12
		75	0.021	111	0.066	0.567	1166	0.0000559	1726	0.000176	1.48	3.14
		139	0.027	195	0.069	0.607	1886	0.0000769	2646	0.000197	1.40	2.56
		112	0.022	151	0.049	0.624	1438	0.0000645	1939	0.000144	1.35	2.23
		130	0.024	152	0.041	0.611	1741	0.0000688	2036	0.000118	1.17	1.71
	20	157	0.022	216	0.059	0.687	1663	0.0000710	2288	0.000190	1.38	2.68
		179	0.018	196	0.027	0.716	1746	0.0000605	1912	0.000091	1.09	1.50
		181	0.022	246	0.064	0.687	1917	0.0000710	2606	0.000206	1.36	2.91
		158	0.02	237	0.067	0.666	1781	0.0000625	2672	0.000209	1.50	3.35
		194	0.018	233	0.03	0.698	1991	0.0000590	2391	0.000098	1.20	1.67
		155	0.021	257	0.088	0.644	1869	0.0000635	3098	0.000266	1.66	4.19
	25	215	0.021	327	0.097	0.705	2163	0.0000695	3290	0.000321	1.52	4.62
		240	0.021	352	0.084	0.776	1993	0.0000765	2923	0.000306	1.47	4.00
		176	0.021	249	0.086	0.617	2312	0.0000608	3270	0.000249	1.41	4.10
		189	0.022	290	0.115	0.701	1923	0.0000724	2951	0.000378	1.53	5.23
		236	0.022	352	0.097	0.758	2054	0.0000783	3063	0.000345	1.49	4.41
		235	0.021	362	0.097	0.78	1931	0.0000769	2975	0.000355	1.54	4.62

Key:

Yield – Load at yielding
Peak – Maximum load
Displacement – displacement at either yield or peak
PEL – maximum tensile stress corresponding to yield load
PEL strain – strain corresponding to PEL
MOR – maximum tensile stress corresponding to peak load
MOR strain – strain corresponding to MOR
MOR/PEL – ratio of MOR to PEL – This is a measure of the loss of strength due to aging.
MOR STR./PEL STR. – ratio of MOR strain to PEL strain – This is a measure of the loss of ductility due to aging.

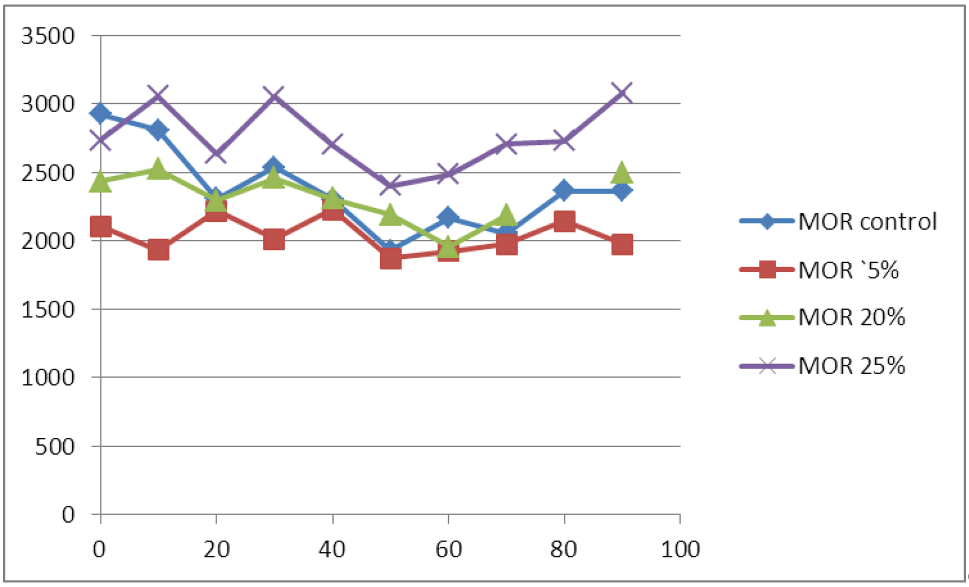

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Figure 2. *Modulus of Rupture Stress vs. Time Aged at*

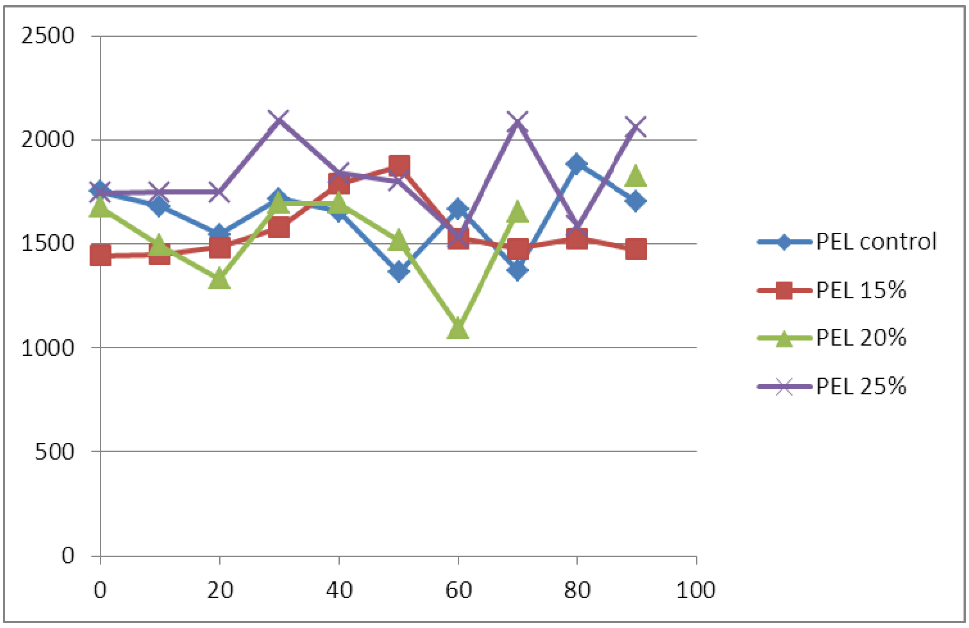

Figure 3. *Proportional Elastic Limit Stress vs. Time Aged at*

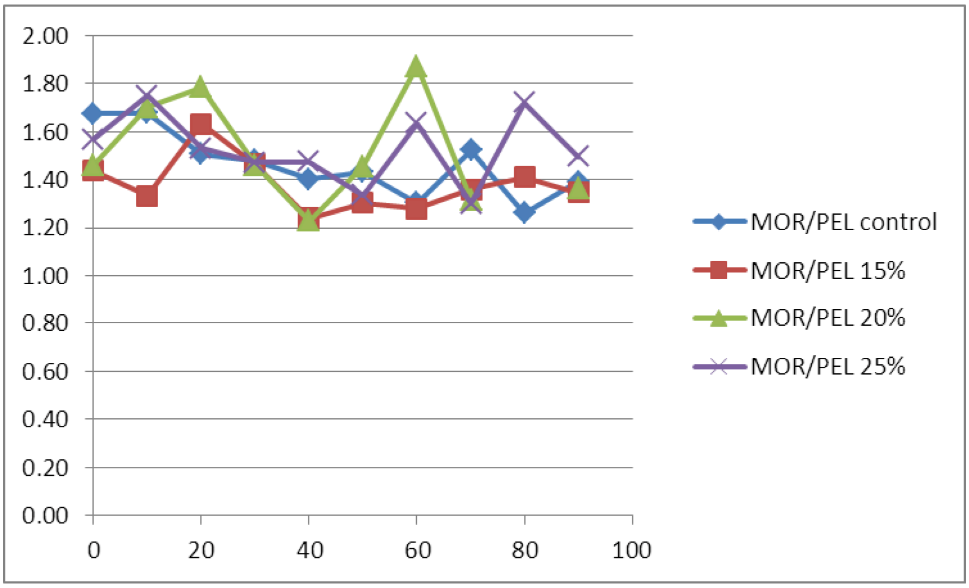

Figure 4. *Ratio of Modulus of Rupture Stress to Proportional Elastic Limit Stress vs. Time Aged at*

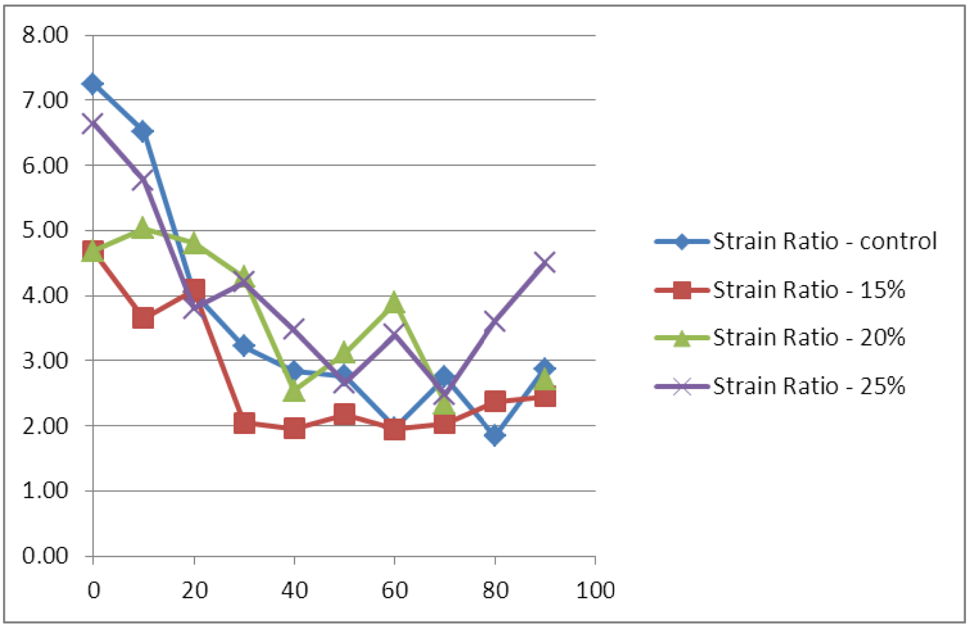

Figure 5. *Ratio of Modulus of Rupture Strain to Proportional Elastic Limit Stain vs. Time Aged at*

Concrete Strength Development

Table 3. *Basic Mixture Design to Produce 1 Cubic Foot of concrete*

Mix Number	Cement (lb) ASTM Type II/V	UltraPozz Pumice (lb)	Coarse Aggregate (lb)	Fine Aggregate (lb)	Water (lb)
1	20.9	0	67	53	10
2	16.7	4.2 (20%)	67	53	10
3	14.6	6.3 (30%)	67	53	10

Table 4. *Compressive Strength of 4" x 8" cylinders*

Mix Number	Strength at 7 days (psi)	Strength at 28 days (psi)
1 control	5836	7400
2 (20%)	4648	7083
3 (30%)	------	-----

Activity Index of Mortar Mixes

Activity index was determined in accordance with ASTM C 595 Annex 1. ASTM Type II/V cement was used with 20% and 30% UltraPozz pumice. Three mortar cubes were made for each mixture in accordance with ASTM C 109 and water added was based on the flow requirement of 100 to 115. The specimens were de-molded after 24 hours in a moist room. The specimens were placed in an air tight glass container and stored at 38 +/- 1.7 C for 27 days. Compressive strength of the specimens were determined at 28 days in accordance with ASTM C 109 after allowing them to cool to 23 +/- 1.7 C.

Activity Index is calculated by dividing the average compressive strength by the compressive strength of the control mixture. As shown below in Table 5, the 20% UltraPozz addition is higher than the 30% addition.

Table 5.*: Activity Index of UltraPozz Pozzolan*

Mix Number	UltraPozz Pumice	Activity Index
1	0	1
2	20%	1.31
3	30%	1.22

Particle Size Distribution of UltraPozz

Specific Surface Area (/)	18093
Median (µm)	3.755
Mean (µm)	3.995
Standard Deviation (µm)	1.695
Mode (µm)	4.711

Workability
Workability time with cement replacements higher than 20% of UltraPozz pumice pozzolan in GFRC mixes can be less than 5 minutes if the mixture does not have the correct water content. Workability time can be extended by selecting low alkali cements and the addition of specialty admixtures. Please contact your local Nippon Electric Glass fiber distributor for additional information.

CONCLUSIONS

1. The addition of 15% or 20% UltraPozz in the GFRC mixes did not improve the strength and had little effect on ductility as measured by either stress or strain ratio. This was probably due to the lack of water in these two mix designs, which resulted in an incomplete reaction between the UltraPozz and free lime.
2. The addition of 20% UltraPozz in the concrete mix showed rapid hydration characteristics and very good compressive strength at 28 days.
3. The addition of 20% UltraPozz in the mortar mixture had the highest Activity Index compared to the 30% mixture.
4. The GFRC mix with 25% pozzolan performed very well and had the highest PEL, MOR, stress ratio, and strain ratio values over time.
5. The GFRC control mix has the highest initial ductility ratio (ratio of deflection at the MOR value to deflection at the LOP value), but the ductility ratio deteriorated over time to values significantly less than the value of the mix with 25% pozzolan.
6. The GFRC mix with 25% pozzolan performed very well and surprisingly appeared to improve over the last month of the testing period. This apparent improvement was fairly convincing and raises interesting questions regarding longer test periods and perhaps higher doses of pozzolan. A clear understanding of this apparent phenomenon might be very useful.
7. NEGA recommendation is to use mix formulation number 4, UltraPozz pozzolan at 25% cement replacement, 0.37 water/cementitious material for optimal improvement in flexural strength.
8. All 4 GFRC mix designs contained Polyplex acrylic curing compound. Use of other acrylic polymers may interfere with cement binder formation which could result in a less durable composite. It is therefore necessary to fully test other polymers to demonstrate how they perform with UltraPozz.

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