



Minnesota Experience on RDM

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U.S. Department of Transportation
Federal Highway Administration



Acknowledgements

- FHWA/AASHTO
- GSSI
- MnDOT district materials and constructions

Why MnDOT is interested in?

- MnDOT Uses Cores Density for Acceptance
 - Need a tool for continuous assessment: RDM
- Longitudinal Joint deterioration
- IC and IR Implementation
 - IC&IR are QC tools
 - RDM (GPR) can be a QA tool
- RDM in 2015

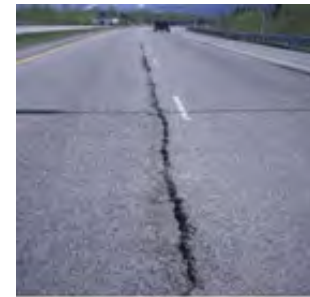


Photo 1



MnDOT Equipment

➤ Push Cart Type RDM

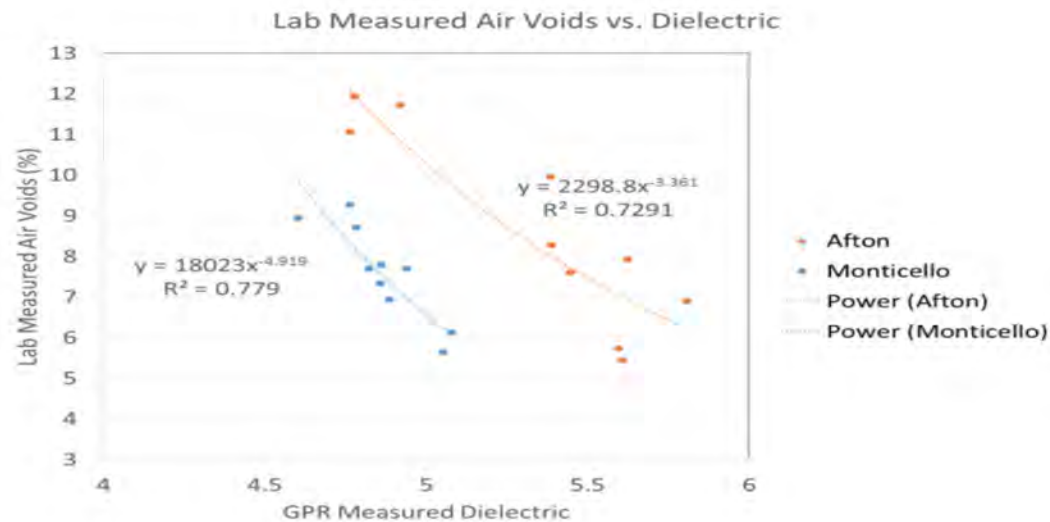


➤ Vehicle Mounted RDM

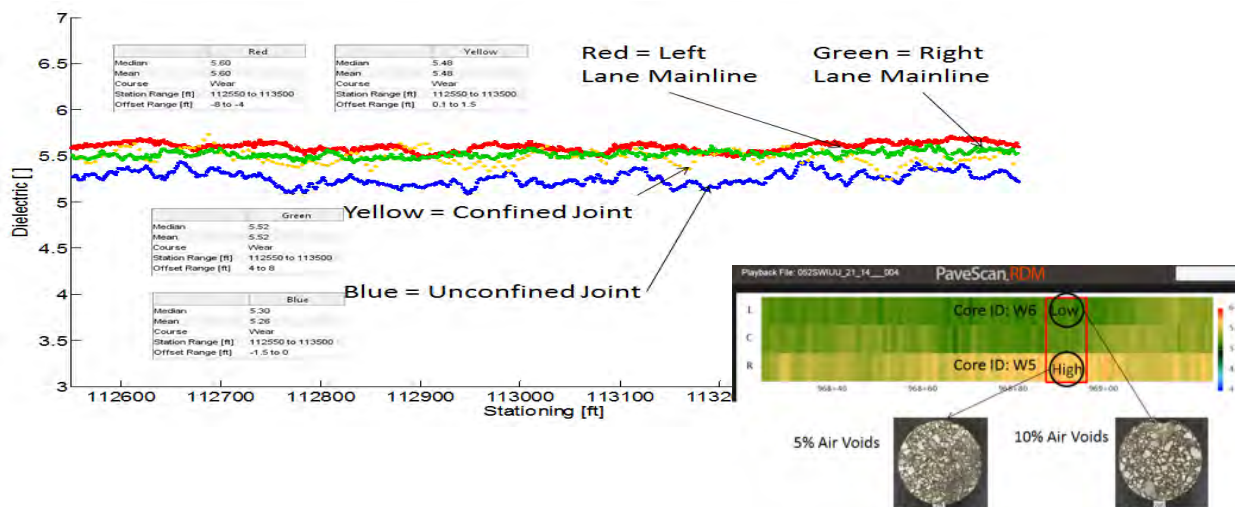


RDM Principal

- **Mainline Survey: multiple passes**



- **Joint Survey: one antenna close to joint**

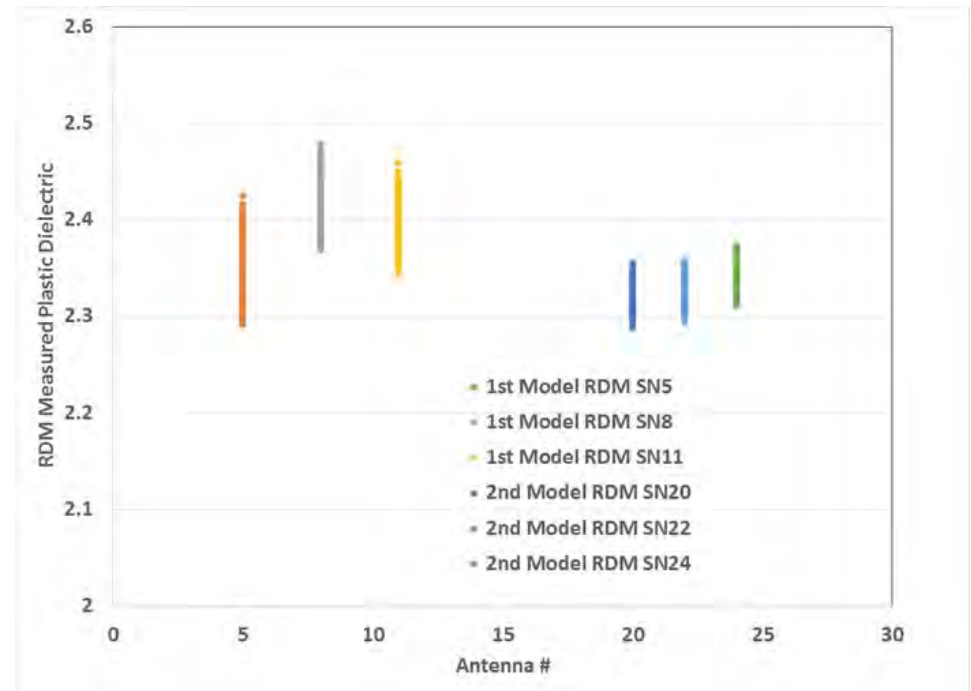
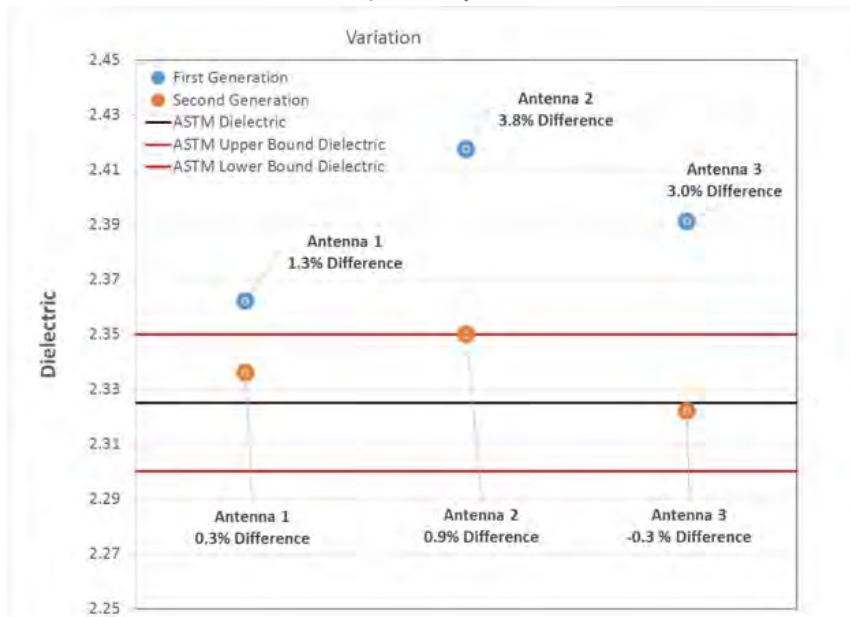


Equipment Calibration

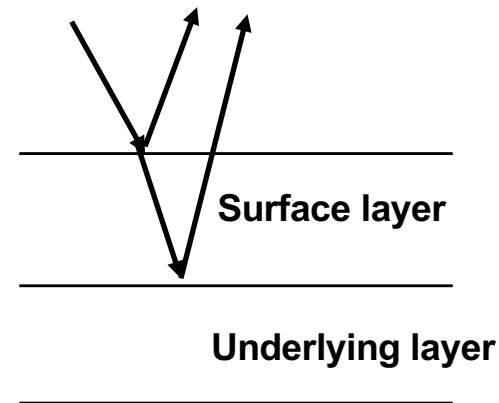
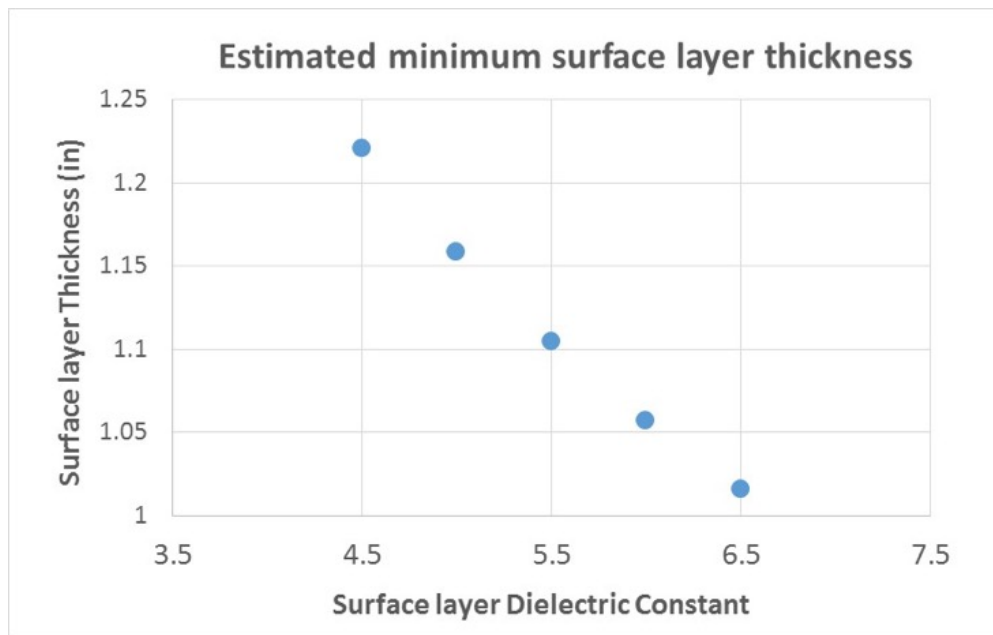
➤ High Density Polyethylene (HDPE)

➤ Reported dielectric: 2.3-2.35

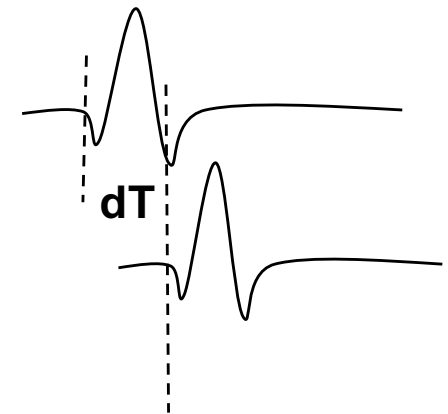
$$\epsilon_{HMA} = \left(\frac{1 + \frac{A_0}{A_P}}{1 - \frac{A_0}{A_P}} \right)^2$$



- Underlying layer effect on surface measurement?
 - How thick does the HMA layer need to be so that the underlying layer (agg. base) has no effects?



$$h_1 = v * \Delta t_1 / 2$$
$$v = c / \sqrt{\epsilon_1}$$

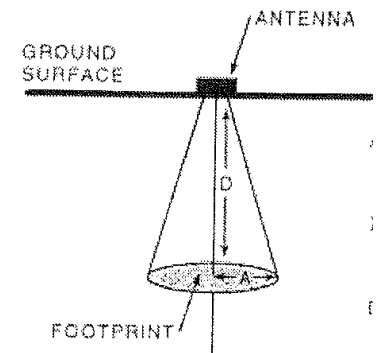
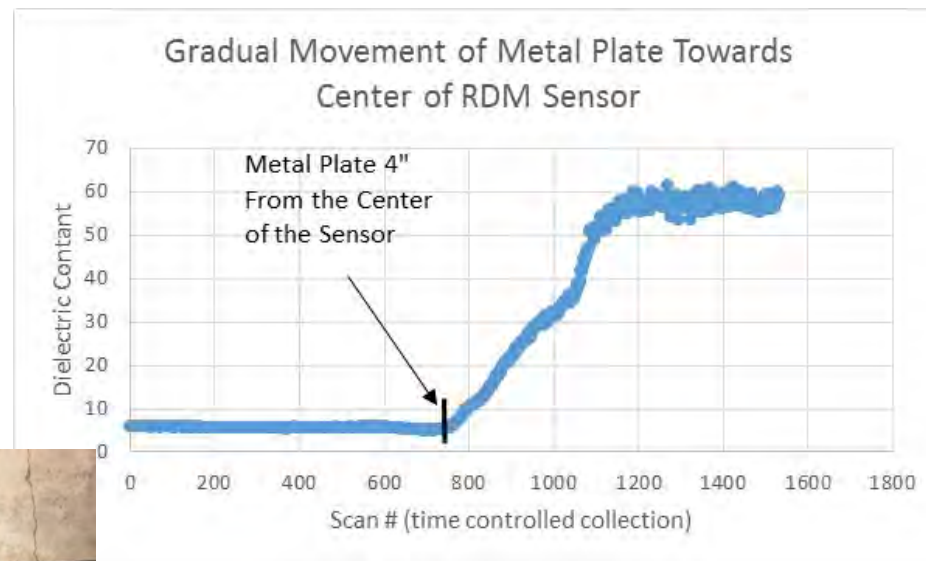
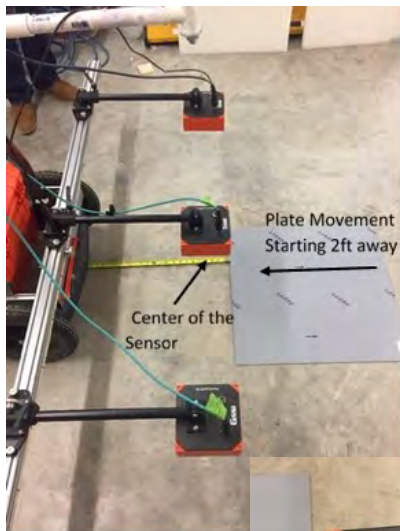


$$dT \sim 0.439 \mu s$$

➤ Footprint area of an antenna (Fresnel Zone)?

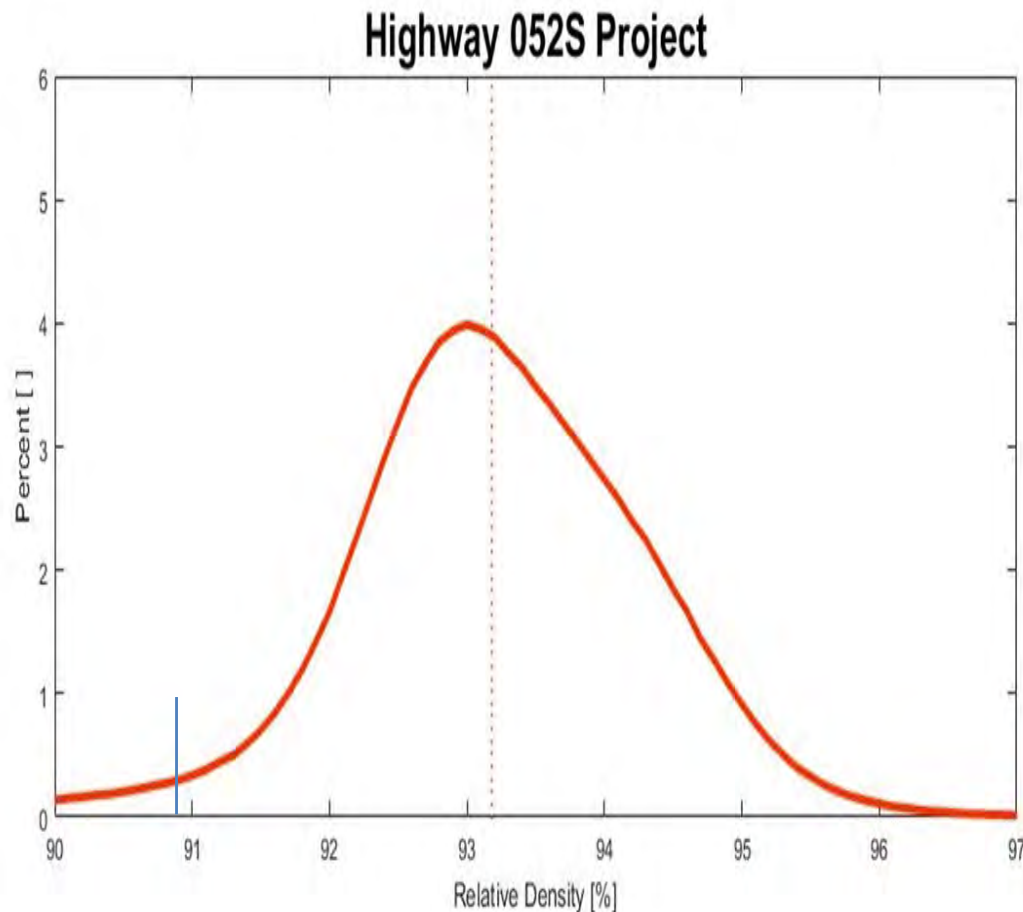
$$Fr \sim 0.5 \lambda (tr/fc)^{1/2}$$

D=12", Fr (Radius) ~ 3.6" (for 2.7Ghz-RDM)



Histogram

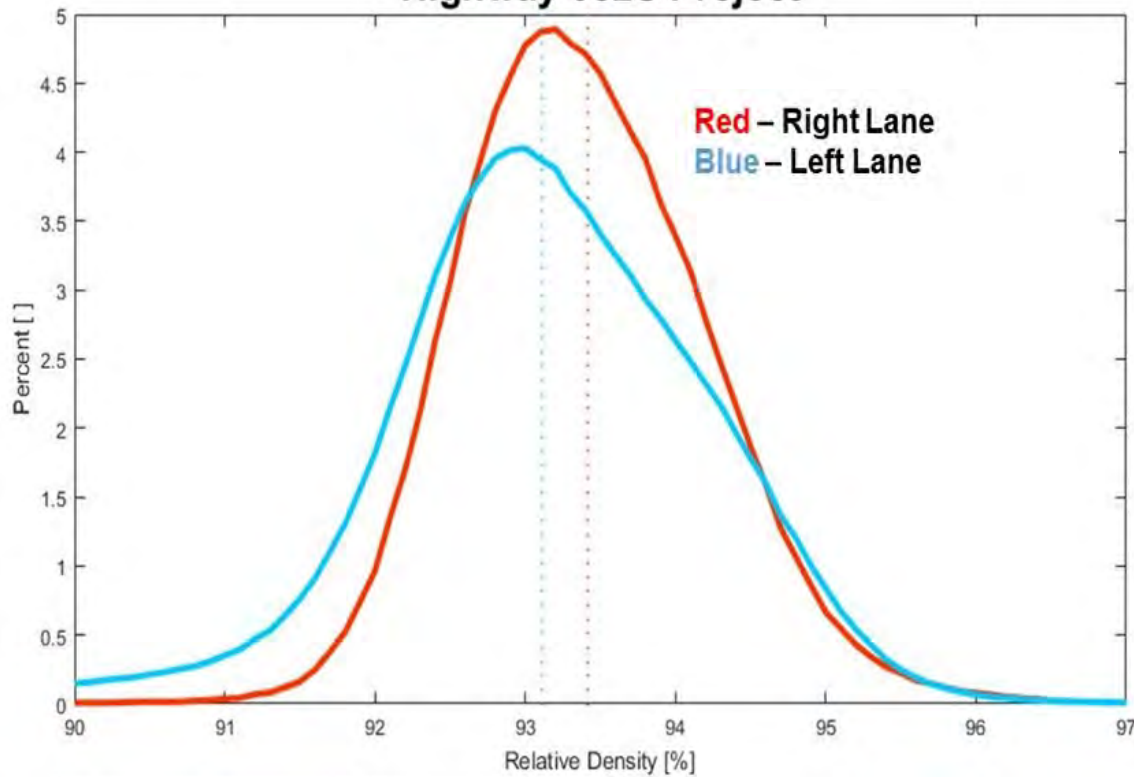
- Use histogram to assess uniformity and quality.



- All Data Collected
- Sampling Rate = 0.4 in/scan.
- > 26 million measurements
- Analysis based on 4 in. moving average
- Equivalent to >1 million cores
- Summary Stats
- **93.2%** median density
- STD: 1.18
- **97.5%** locations density > **90.8%**

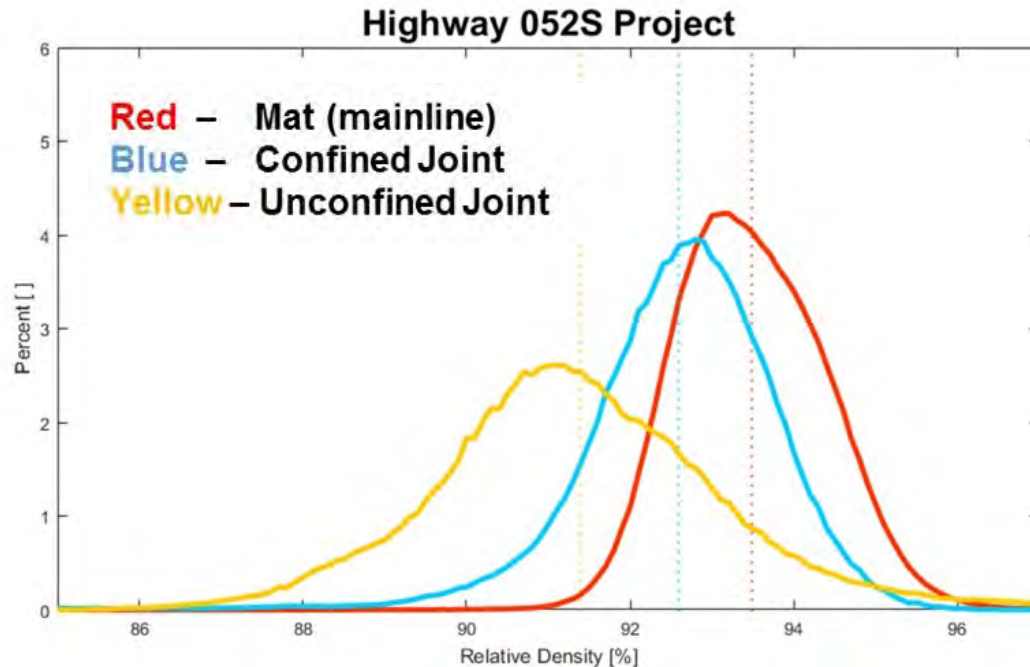
Examples: TH 52 – Left and Right Mainline

Highway 052S Project

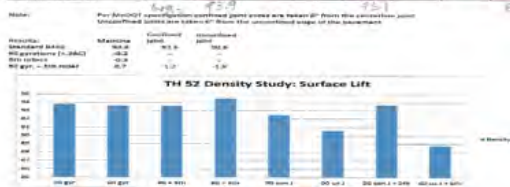


- Median Density
 - Right: 93.4%
 - Left: 93.1%
- STD: 0.92(R) and 0.96(L)
- 97.5% locations:
 - > **91.6% (R)**
 - > **91.2% (L)**

TH 52 – Longitudinal Joint



Area	3/7/2019	3/7/2018	3/7/2017	3/7/2016	3/7/2015	3/7/2014	3/7/2013	3/7/2012	3/7/2011	3/7/2010	3/7/2009	3/7/2008	3/7/2007	3/7/2006	3/7/2005	3/7/2004	3/7/2003	3/7/2002	3/7/2001	3/7/2000	3/7/1999	3/7/1998	3/7/1997	3/7/1996	3/7/1995	3/7/1994	3/7/1993	3/7/1992	3/7/1991	3/7/1990	3/7/1989	3/7/1988	3/7/1987	3/7/1986	3/7/1985	3/7/1984	3/7/1983	3/7/1982	3/7/1981	3/7/1980	3/7/1979	3/7/1978	3/7/1977	3/7/1976	3/7/1975	3/7/1974	3/7/1973	3/7/1972	3/7/1971	3/7/1970	3/7/1969	3/7/1968	3/7/1967	3/7/1966	3/7/1965	3/7/1964	3/7/1963	3/7/1962	3/7/1961	3/7/1960	3/7/1959	3/7/1958	3/7/1957	3/7/1956	3/7/1955	3/7/1954	3/7/1953	3/7/1952	3/7/1951	3/7/1950	3/7/1949	3/7/1948	3/7/1947	3/7/1946	3/7/1945	3/7/1944	3/7/1943	3/7/1942	3/7/1941	3/7/1940	3/7/1939	3/7/1938	3/7/1937	3/7/1936	3/7/1935	3/7/1934	3/7/1933	3/7/1932	3/7/1931	3/7/1930	3/7/1929	3/7/1928	3/7/1927	3/7/1926	3/7/1925	3/7/1924	3/7/1923	3/7/1922	3/7/1921	3/7/1920	3/7/1919	3/7/1918	3/7/1917	3/7/1916	3/7/1915	3/7/1914	3/7/1913	3/7/1912	3/7/1911	3/7/1910	3/7/1909	3/7/1908	3/7/1907	3/7/1906	3/7/1905	3/7/1904	3/7/1903	3/7/1902	3/7/1901	3/7/1900	3/7/1899	3/7/1898	3/7/1897	3/7/1896	3/7/1895	3/7/1894	3/7/1893	3/7/1892	3/7/1891	3/7/1890	3/7/1889	3/7/1888	3/7/1887	3/7/1886	3/7/1885	3/7/1884	3/7/1883	3/7/1882	3/7/1881	3/7/1880	3/7/1879	3/7/1878	3/7/1877	3/7/1876	3/7/1875	3/7/1874	3/7/1873	3/7/1872	3/7/1871	3/7/1870	3/7/1869	3/7/1868	3/7/1867	3/7/1866	3/7/1865	3/7/1864	3/7/1863	3/7/1862	3/7/1861	3/7/1860	3/7/1859	3/7/1858	3/7/1857	3/7/1856	3/7/1855	3/7/1854	3/7/1853	3/7/1852	3/7/1851	3/7/1850	3/7/1849	3/7/1848	3/7/1847	3/7/1846	3/7/1845	3/7/1844	3/7/1843	3/7/1842	3/7/1841	3/7/1840	3/7/1839	3/7/1838	3/7/1837	3/7/1836	3/7/1835	3/7/1834	3/7/1833	3/7/1832	3/7/1831	3/7/1830	3/7/1829	3/7/1828	3/7/1827	3/7/1826	3/7/1825	3/7/1824	3/7/1823	3/7/1822	3/7/1821	3/7/1820	3/7/1819	3/7/1818	3/7/1817	3/7/1816	3/7/1815	3/7/1814	3/7/1813	3/7/1812	3/7/1811	3/7/1810	3/7/1809	3/7/1808	3/7/1807	3/7/1806	3/7/1805	3/7/1804	3/7/1803	3/7/1802	3/7/1801	3/7/1800	3/7/1799	3/7/1798	3/7/1797	3/7/1796	3/7/1795	3/7/1794	3/7/1793	3/7/1792	3/7/1791	3/7/1790	3/7/1789	3/7/1788	3/7/1787	3/7/1786	3/7/1785	3/7/1784	3/7/1783	3/7/1782	3/7/1781	3/7/1780	3/7/1779	3/7/1778	3/7/1777	3/7/1776	3/7/1775	3/7/1774	3/7/1773	3/7/1772	3/7/1771	3/7/1770	3/7/1769	3/7/1768	3/7/1767	3/7/1766	3/7/1765	3/7/1764	3/7/1763	3/7/1762	3/7/1761	3/7/1760	3/7/1759	3/7/1758	3/7/1757	3/7/1756	3/7/1755	3/7/1754	3/7/1753	3/7/1752	3/7/1751	3/7/1750	3/7/1749	3/7/1748	3/7/1747	3/7/1746	3/7/1745	3/7/1744	3/7/1743	3/7/1742	3/7/1741	3/7/1740	3/7/1739	3/7/1738	3/7/1737	3/7/1736	3/7/1735	3/7/1734	3/7/1733	3/7/1732	3/7/1731	3/7/1730	3/7/1729	3/7/1728	3/7/1727	3/7/1726	3/7/1725	3/7/1724	3/7/1723	3/7/1722	3/7/1721	3/7/1720	3/7/1719	3/7/1718	3/7/1717	3/7/1716	3/7/1715	3/7/1714	3/7/1713	3/7/1712	3/7/1711	3/7/1710	3/7/1709	3/7/1708	3/7/1707	3/7/1706	3/7/1705	3/7/1704	3/7/1703	3/7/1702	3/7/1701	3/7/1700	3/7/1699	3/7/1698	3/7/1697	3/7/1696	3/7/1695	3/7/1694	3/7/1693	3/7/1692	3/7/1691	3/7/1690	3/7/1689	3/7/1688	3/7/1687	3/7/1686	3/7/1685	3/7/1684	3/7/1683	3/7/1682	3/7/1681	3/7/1680	3/7/1679	3/7/1678	3/7/1677	3/7/1676	3/7/1675	3/7/1674	3/7/1673	3/7/1672	3/7/1671	3/7/1670	3/7/1669	3/7/1668	3/7/1667	3/7/1666	3/7/1665	3/7/1664	3/7/1663	3/7/1662	3/7/1661	3/7/1660	3/7/1659	3/7/1658	3/7/1657	3/7/1656	3/7/1655	3/7/1654	3/7/1653	3/7/1652	3/7/1651	3/7/1650	3/7/1649	3/7/1648	3/7/1647	3/7/1646	3/7/1645	3/7/1644	3/7/1643	3/7/1642	3/7/1641	3/7/1640	3/7/1639	3/7/1638	3/7/1637	3/7/1636	3/7/1635	3/7/1634	3/7/1633	3/7/1632	3/7/1631	3/7/1630	3/7/1629	3/7/1628	3/7/1627	3/7/1626	3/7/1625	3/7/1624	3/7/1623	3/7/1622	3/7/1621	3/7/1620	3/7/1619	3/7/1618	3/7/1617	3/7/1616	3/7/1615	3/7/1614	3/7/1613	3/7/1612	3/7/1611	3/7/1610	3/7/1609	3/7/1608	3/7/1607	3/7/1606	3/7/1605	3/7/1604	3/7/1603	3/7/1602	3/7/1601	3/7/1600	3/7/1599	3/7/1598	3/7/1597	3/7/1596	3/7/1595	3/7/1594	3/7/1593	3/7/1592	3/7/1591	3/7/1590	3/7/1589	3/7/1588	3/7/1587	3/7/1586	3/7/1585	3/7/1584	3/7/1583	3/7/1582	3/7/1581	3/7/1580	3/7/1579	3/7/1578	3/7/1577	3/7/1576	3/7/1575	3/7/1574	3/7/1573	3/7/1572	3/7/1571	3/7/1570	3/7/1569	3/7/1568	3/7/1567	3/7/1566	3/7/1565	3/7/1564	3/7/1563	3/7/1562	3/7/1561	3/7/1560	3/7/1559	3/7/1558	3/7/1557	3/7/1556	3/7/1555	3/7/1554	3/7/1553	3/7/1552	3/7/1551	3/7/1550	3/7/1549	3/7/1548	3/7/1547	3/7/1546	3/7/1545	3/7/1544	3/7/1543	3/7/1542	3/7/1541	3/7/1540	3/7/1539	3/7/1538	3/7/1537	3/7/1536	3/7/1535	3/7/1534	3/7/1533	3/7/1532	3/7/1531	3/7/1530	3/7/1529	3/7/1528	3/7/1527	3/7/1526	3/7/1525	3/7/1524	3/7/1523	3/7/1522	3/7/1521	3/7/1520	3/7/1519	3/7/1518	3/7/1517	3/7/1516	3/7/1515	3/7/1514	3/7/1513	3/7/1512	3/7/1511	3/7/1510	3/7/1509	3/7/1508	3/7/1507	3/7/1506	3/7/1505	3/7/1504	3/7/1503	3/7/1502	3/7/1501	3/7/1500	3/7/1499	3/7/1498	3/7/1497	3/7/1496	3/7/1495	3/7/1494	3/7/1493	3/7/1492	3/7/1491	3/7/1490	3/7/1489	3/7/1488	3/7/1487	3/7/1486	3/7/1485	3/7/1484	3/7/1483	3/7/1482	3/7/1481	3/7/1480	3/7/1479	3/7/1478	3/7/1477	3/7/1476	3/7/1475	3/7/1474	3/7/1473	3/7/1472	3/7/1471	3/7/1470	3/7/1469	3/7/1468	3/7/1467	3/7/1466	3/7/1465	3/7/1464	3/7/1463	3/7/1462	3/7/1461	3/7/1460	3/7/1459	3/7/1458	3/7/1457	3/7/1456	3/7/1455	3/7/1454	3/7/1453	3/7/1452	3/7/1451	3/7/1450	3/7/1449	3/7/1448	3/7/1447	3/7/1446	3/7/1445	3/7/1444	3/7/1443	3/7/1442	3/7/1441	3/7/1440	3/7/1439	3/7/1438	3/7/1437	3/7/1436	3/7/1435	3/7/1434	3/7/1433	3/7/1432	3/7/1431	3/7/1430	3/7/1429	3/7/1428	3/7/1427	3/7/1426	3/7/1425	3/7/1424	3/7/1423	3/7/1422	3/7/1421	3/7/1420	3/7/1419	3/7/1418	3/7/1417	3/7/1416	3/7/1415	3/7/1414	3/7/1413	3/7/1412	3/7/1411	3/7/1410	3/7/1409	3/7/1408	3/7/1407	3/7/1406	3/7/1405	3/7/1404	3/7/1403	3/7/1402	3/7/1401	3/7/1400	3/7/1399	3/7/1398	3/7/1397	3/7/1396	3/7/1395	3/7/1394	3/7/1393	3/7/1392	3/7/1391	3/7/1390	3/7/1389	3/7/1388	3/7/1387	3/7/1386	3/7/1385	3/7/1384	3/7/1383	3/7/1382	3/7/1381	3/7/1380	3/7/1379	3/7/1378	3/7/1377	3/7/1376	3/7/1375	3/7/1374	3/7/1373	3/7/1372	3/7/1371	3/7/1370	3/7/1369	3/7/1368	3/7/1367	3/7/1366	3/7/1365	3/7/1364	3/7/1363	3/7/1362	3/7/1361	3/7/1360	3/7/1359	3/7/1358	3/7/1357	3/7/1356	3/7/1355	3/7/1354	3/7/1353	3/7/1352	3/7/1351	3/7/1350	3/7/1349	3/7/1348	3/7/1347	3/7/1346	3/7/1345	3/7/1344	3/7/1343	3/7/1342	3/7/1341	3/7/1340	3/7/1339	3/7/1338	3/7/1337	3/7/1336	3/7/1335	3/7/1334	3/7/1333	3/7/1332	3/7/1331	3/7/1330	3/7/1329	3/7/1328	3/7/1327	3/7/1326	3/7/1325	3/7/1324	3/7/1323	3/7/1322	3/7/1321	3/7/1320	3/7/1319	3/7/1318	3/7/1317	3/7/1316	3/7/1315	3/7/1314	3/7/1313	3/7/1312	3/7/1311	3/7/1310	3/7/1309	3/7/1308	3/7/1307	3/7/1306	3/7/1305	3/7/1304	3/7/1303	3/7/1302	3/7/1301	3/7/1300	3/7/1299	3/7/1298	3/7/1297	3/7/1296	3/7/1295	3/7/1294	3/7/1293	3/7/1292	3/7/1291	3/7/1290	3/7/1289	3/7/1288	3/7/1287	3/7/1286	3/7/1285	3/7/1284	3/7/1283	3/7/1282	3/7/1281	3/7/1280	3/7/1279	3/7/1278	3/7/1277	3/7/1276	3/7/1275	3/7/1274	3/7/1273	3/7/1272	3/7/1271	3/7/1270	3/7/1269	3/7/1268	3/7/1267	3/7/1266	3/7/1265	3/7/1264	3/7/1263	3/7/1262	3/7/1261	3/7/1260	3/7/1259	3/7/1258	3/7/1257	3/7/1256	3/7/1255	3/7/1254	3/7/1253	3/7/1252	3/7/1251	3/7/1250	3/7/1249	3/7/1248	3/7/1247	3/7/1246	3/7/1245	3/7/1244	3/7/1243	3/7/1242	3/7/1241	3/7/1240	3/7/1239	3/7/1238	3/7/1237	3/7/1236	3/7/1235	3/7/1234	3/7/1233	3/7/1232	3/7/1231	3/7/1230	3/7/1229	3/7/1228	3/7/1227	3/7/1226	3/7/1225	3/7/1224	3/7/1223	3/7/1222	3/7/1221	3/7/1220	3/7/1219	3/7/1218	3/7/1217	3/7/1216	3/7/1215	3/7/1214	3/7/1213	3/7/1212	3/7/1211	3/7/1210	3/7/1209	3/7/1208	3/7/1207	3/7/1206	3/7/1205	3/7/1204	3/7/1203	3/7/1202	3/7/1201	3/7/1200	3/7/1199	3/7/1198	3/7/1197	3/7/1196	3/7/1195	3/7/1194	3/7/1193	3/7/1192	3/7/1191	3/7/1190	3/7/1189	3/7/1188	3/7/1187	3/7/1186	3/7/1185	3/7/1184	3/7/1183	3/7/1182	3/7/1181	3/7/1180	3/7/1179	3/7/1178	3/7/1177	3/7/1176	3/7/1175	3/7/1174	3/7/1173	3/7/1172	3/7/1171	3/7/1170	3/7/1169	3/7/1168	3/7/1167	3/7/1166	3/7/1165	3/7/1164	3/7/1163	3/7/1162	3/7/1161	3/7/1160	3/7/1159	3/7/1158	3/7/1157	3/7/1156	3/7/1155	3/7/1154	3/7/1153	3/7/1152	3/7/1151	3/7/1150	3/7/1149	3/7/1148	3/7/1147	3/7/1146	3/7/1145	3/7/1144	3/7/1143	3/7/1142	3/7/1141	3/7/1140	3/7/1139	3/7/1138	3/7/1137	3/7/1136	3/7/1135	3/7/1134	3/7/1133	3/7/1132	3/7/1131	3/7/1130	3/7/1129	3/7/1128	3/7/1127	3/7/1126	3/7/1125	3/7/1124	3/7/1123	3/7/1122	3/7/1121	3/7/1120	3/7/1119	3/7/1118	3/7/1117	3/7/1116	3/7/1115	3/7/1114	3/7/1113	3/7/1112	3/7/1111	3/7/1110	3/7/1109	3/7/1108	3/7/1107	3/7/1106	3/7/1105	3/7/1104	3/7/1103	3/7/1102	3/7/1101	3/7/1100	3/7/1099	3/7/1098	3/7/1097	3/7/1096	3/7/1095	3/7/1094	3/7/1093	3/7/1092	3/7/1091	3/7/1090	3/7/1089	3/7/1088	3/7/1087	3/7/1086	3/7/1085	3/7/1084	3/7/1083	3/7/1082	3/7/1081	3/7/1080	3/7/1079	3/7/1078	3/7/1077	3/7/1076	3/7/1075	3/7/1074	3/7/1073	3/7/1072	3/7/1071	3/7/1070	3/7/1069	3/7/1068</
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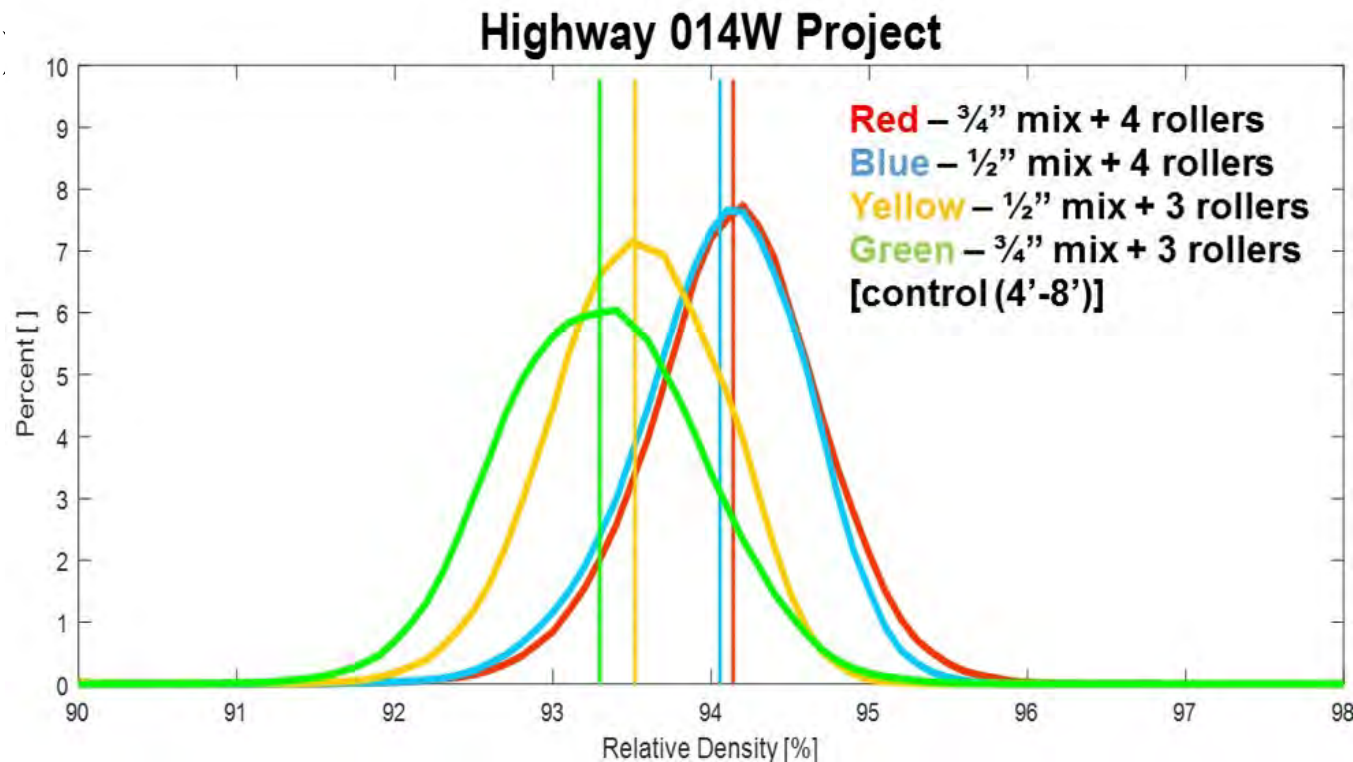


- Top lift Mainline vs Confined and Unconfined Joints Summary:
 - 93.5% (ML), 92.6%(CJ) and 91.4%(UCJ)
 - SD: 0.94(ML); 1.22(CJ); 1.8(UCJ)
 - Density:
 - UCJ/ML=97.7%; CJ/ML=99%
 - Core data: UCJ/ML=95.1%
CJ/ML = 99.1%
 - 97.5% locations:
 - > 91.6%(ML),
 - > 90.2% (CJ)
 - > 87.8% (UCJ)

TH 14 – Mainline

➤ Comparison of Test Sections

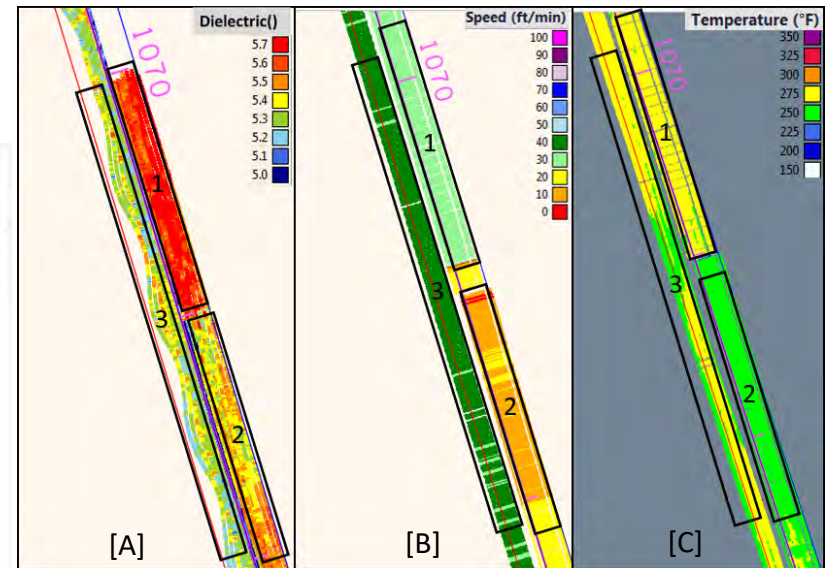
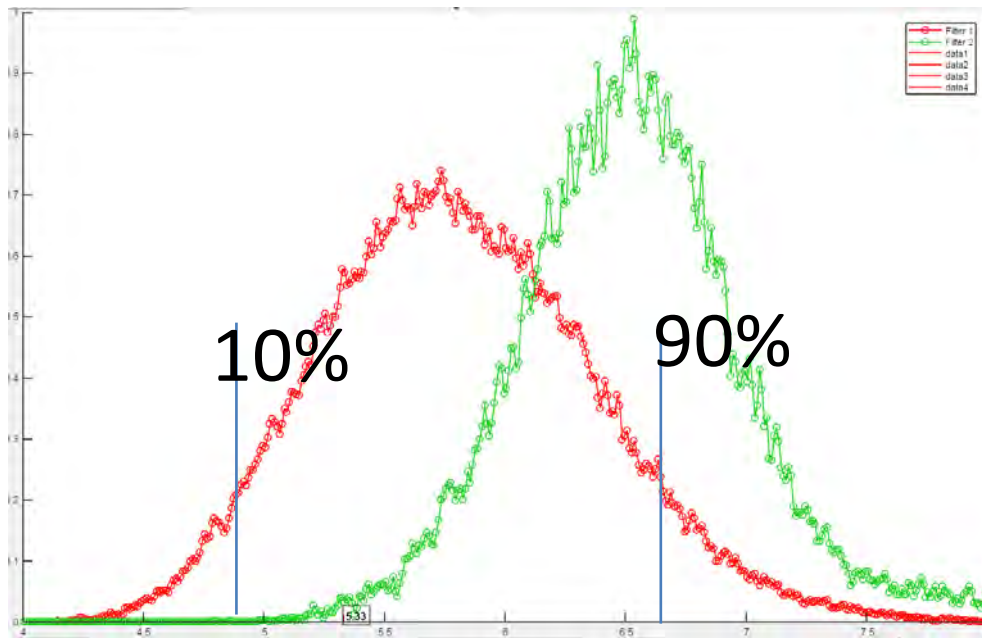
- Mix B (3/4-) to A(1/2-): not much difference on compaction.
- Adding a roller: density slightly increased on this project.



- Median Density:
Blue: 94.1%
Red: 94.2%
Yellow: 93.5%
Green: 93.3%

Core Locator for Implementation

- Automatic to identify core locations at the end of each paving day
 - At low and high dielectric locations
 - Ex: 10% and 90%



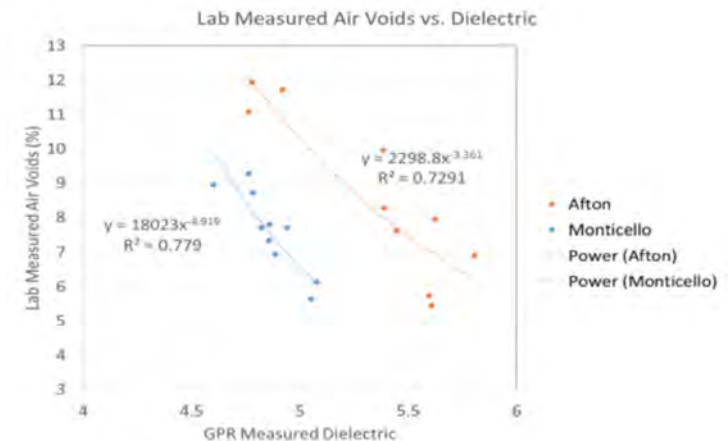
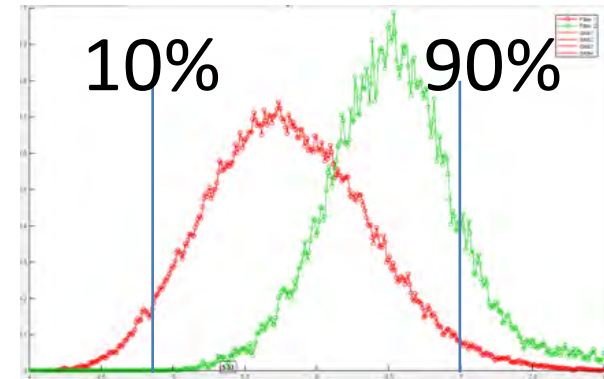
➤ Generate core location text file and load to a GPS device to automatically guide field person to the core location for obtaining the core.

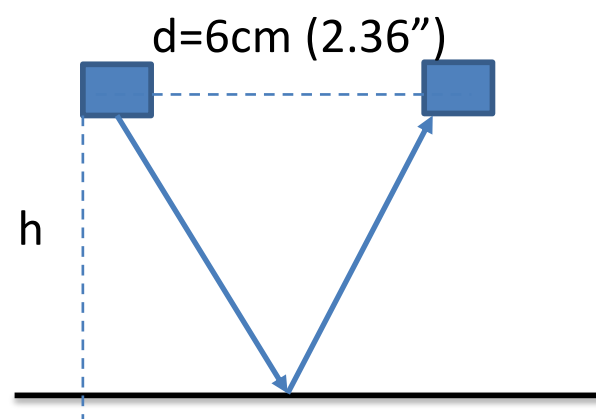
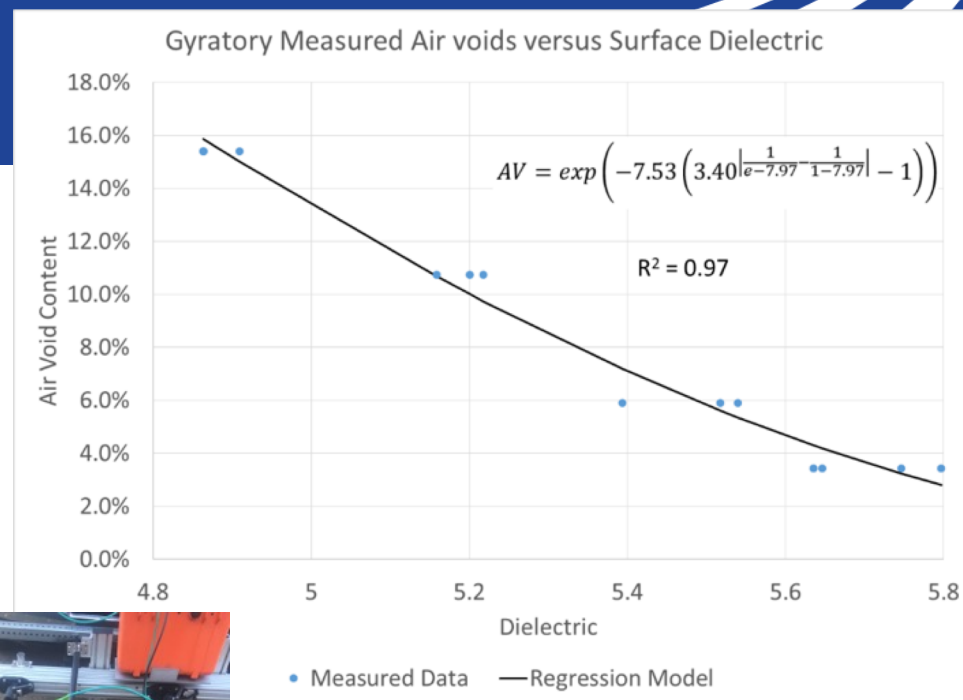
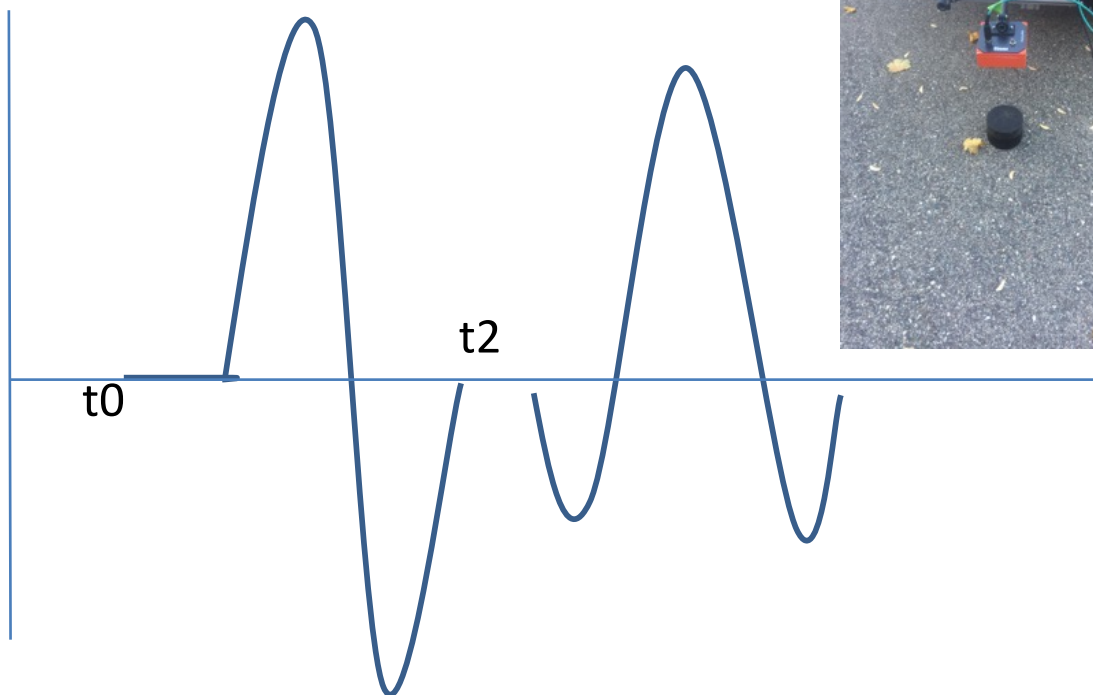
R293.1	298478.7227	519108.2862
R294.1	302565.1707	520114.0246
R295.1	299279.1239	519298.2314
R296.1	299599.5422	519377.6685
R297.1	300540.5022	519610.8459
R298.1	300331.6291	519559.0812
R299.1	301378.5352	519818.6575
R300.1	301907.3905	519951.4897
R301.1	303106.5117	520228.2346
R302.1	302670.5928	520139.8712
R303.1	304480.9524	520289.7976
R304.1	304360.0461	520297.9872



Research on Laboratory Calibration

- Measure dielectric constant on a gyratory specimen?
- Establish Calibration Curve in Lab & Sensitivity Study
 - Currently use field cores for calibration: ex: 10% and 90%
 - Hope to establish calibration curve at lab in future
 - How does each component in a mixture affect dielectric constant, such as aggregate type, gradation, binder type and content?





Activities

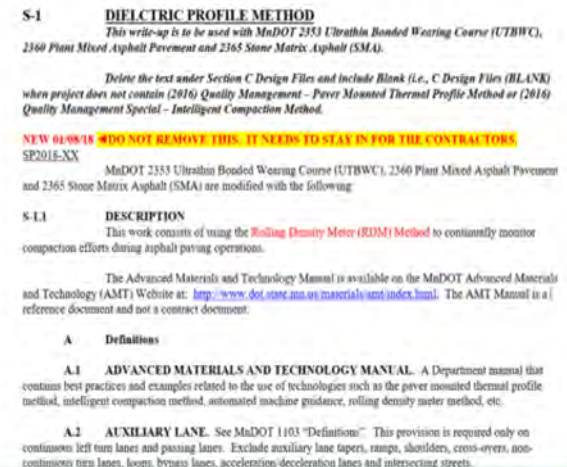
➤ Calibration of Equipment

➤ Field Testing:

- 2016: TH52 and TH14: Surveyed about 18miles.
- 2017: I35; Th52; Th22; Th60; CR86; Th110; CSAH13 and MnROAD
 - Hired American Engineering Testing (AET) to collect data
 - Educating consultant and contractors on this new technology
 - Testing application feasibility of vehicle mounted RDM system on construction projects.
- 2018: “Ghost” specification and core locator – 1 or 2 projects
TH47, TH14, TH109 and TH50 so far
Work with GSSI on software improvements

➤ Research on Laboratory Calibration

- Gyratory Specimen



Summary

- RDM is a good tool for mapping a continuous coverage of the relative compaction levels (higher dielectric = higher compaction)
- Histograms and general statistics can be used to give a complete assessments of the in-place compaction
- Potential Uses:
 - Assess compaction density and uniformity for QC/QA.
 - Provide on-site feedback to contractor of high and low compaction locations that they can cross-check with differences in mix or paving strategies in those locations to determine optimal construction procedures
 - Identification of trends in the air void content maps that can be cross-checked with IC and other data to determine the most critical factors in achieving higher density