Development of an Instrumented Probe System to Measure Asphalt Concrete Temperatures During Transport

By: Isaac L. Howard

Overview

This paper describes development, materials, fabrication, and laboratory verification of an instrumentation system capable of being quickly installed onto an asphalt transport truck to measure temperature inside the mix in real time at multiple locations. Howard et al. (2012) presents data where the instrumentation was successfully used to measure temperature profiles for haul times up to 10.5 hours. Howard et al. (2012) also contains all information in this document, though not in a standalone form, which was the purpose for developing this paper. The information in this paper, is what would be needed to fabricate and verify a similar system for use by others.

Instrumented Probe System Development

Table 1 is a list of major components needed to fabricate the probe system. The instrumented probe system can be divided into three categories: data acquisition; thermocouples, cable, and connectors; and probe inserted into asphalt mix. Several of the materials used could likely be substituted by other materials, though this was not investigated.

Table 1. Major Components of Instrumented Truck System

Model	Description
Dell E5520	Notebook computer
NI LabView™	Data acquisition software
NI 9211	Thermocouple analog input module
NI 9172	CompaqDaq chassis
Omega MTC-IT	Insertion tool
Omega MTC-RT	Removal tool
Omega MTC-CT	Crimping tool
Omega MTC-24-MC	In line male cord connector
Omega MTC-24-FC	In line female cord connector
Omega MTC-24-SHL	Backshell cable clamp
Omega HPC-CU-P	Hollow pins (male) Copper (+)
Omega HPC-CO-P	Hollow pins (male) Constantan (-)
Omega MTC-CU-S	Sockets (female) Copper (+)
Omega MTC-CO-S	Sockets (female) Constantan (-)
Omega 8TX20PP	8 Pair thermocouple extension cable
Omega TC-TT-T-20-72	Bead type-T thermocouples
Gilson GP-200	D-tube sampler used as probe

NI = National Instruments™ Omega = Omega Engineering, Inc.
Gilson = Gilson Company, Inc.

Data Acquisition

Data acquisition was performed with a notebook computer running a program written in *LabView*™. Figure 1 shows the data acquisition system placed into a box to secure components in the truck cab's passenger floor board, that also prevented connections from being loosened due to being jarred repeatedly for an extended haul time.

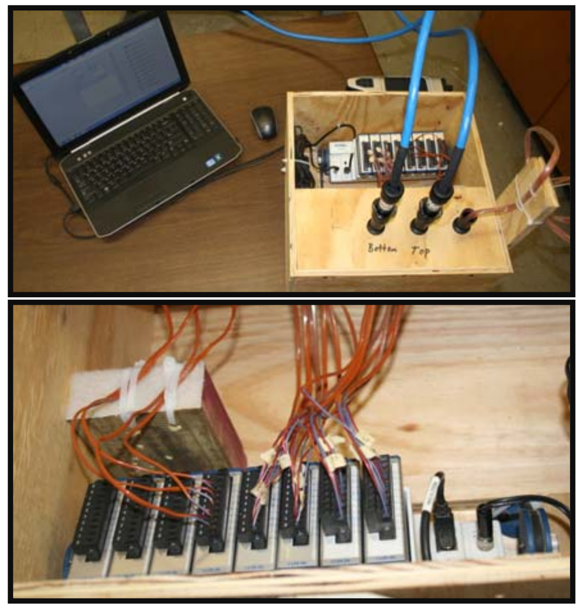

Figure 1. Data Acquisition System

Thermocouples and Cable

Bead thermocouples and durable, yet efficient, connections were key factors when selecting items directly related to temperature measurement. Manufacturer supplied insertion, crimping, and removal tools were mostly used to fabricate connections, and manufacturer supplied instructions were largely followed. Connections were fitted with backshell cable clamps for support, and consisted of connectors, pins, and sockets. Male and female 24 cavity connectors were used along with hollow pins (male) and sockets (female). Stamped copper and constantan hollow pins were used with corresponding machined sockets made of the same metals. Eight pair thermocouple extension cable (12.2 m long) was used in conjunction with PFA insulated type –T bead thermocouples with 0.18 m leads.

Probe

A commercially available D-tube sampler was used as the probe. Photos from several views are provided in Figure 2. Key components were a robust driving tip, adequate length to reach near the center of the mix in a typical truck, ability to be opened after driving as thermocouples were bonded to the inner portion of the probe, and a cavity to protect thermocouples and cable during insertion.

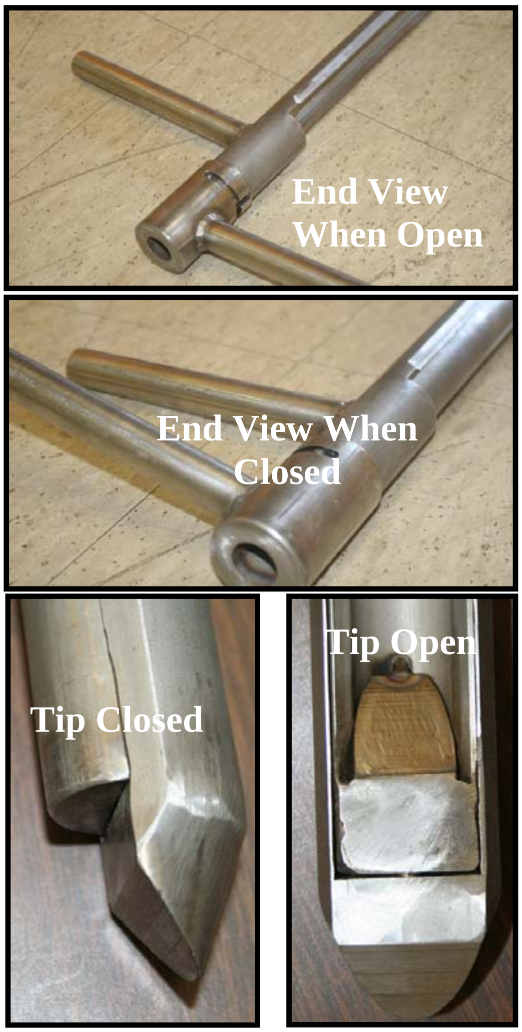

Figure 2. Probe Inserted into Trucks

Instrumented Probe Laboratory Evaluation

The most important parameter associated with the instrumentation approach was whether accurate temperature measurements could be made using the probe as the carrier for bead thermocouples. Lab testing was performed with thermocouples wired directly to the data acquisition system (i.e. no trunk line or connectors), and the probe cavity was not filled with silicone as it ultimately was during field testing. The purpose of the experiments was to determine if the approach of instrumenting a hollow probe with thermocouples, pushing the probe into a truck, opening the probe to expose thermocouples directly to asphalt, and recording data over an extended period was feasible.

Laboratory tests were performed in metal buckets with an 18,900 cm^3 volume that was filled with asphalt. A 19 mm NMAS plant mixed asphalt (79% limestone and 4.3% PG 67-22 binder and maximum mixture specific gravity (G_{mm}) of 2.553) was used for the experiments. Estimated air voids of the mix in the bucket was 23%, as the mix mass was 37.2 kg for all experiments. Three items were of interest during the laboratory experiments:

1. Can the same temperatures be measured in the same mix by the same type of thermocouple with and without the probe?
2. Can the potential of the probe transferring heat to the mix be negated when the probe is warmer at another location than it is where the measurement is being taken?
3. Can the potential of the probe transferring heat from the mix be negated when the probe is cooler at another location than it is where the measurement is being taken?

Figure 3 summarizes the lab tests; control experiment and probe experiment. Each experiment used one bucket of asphalt. Both buckets were filled with heated asphalt, covered with a metal lid, and allowed to cool to room temperature. The instrumented buckets were placed into an oven with the thermocouples attached to the data acquisition system. The oven had $\pm$ 2 ^oC temperature uniformity at 150 ^oC and a 0.79 m^3 volume.

Both buckets were initially at room temperature sitting in the oven that was shut off. The oven door was closed, the oven temperature was set to 166 ^oC, and the material sat in that environment over night to ensure all material was essentially the same temperature and that temperature gradients were minimized. Some temperature gradient will always exist in an asphalt mass of this size and the temperature within the asphalt is usually slightly cooler than the oven temperature.

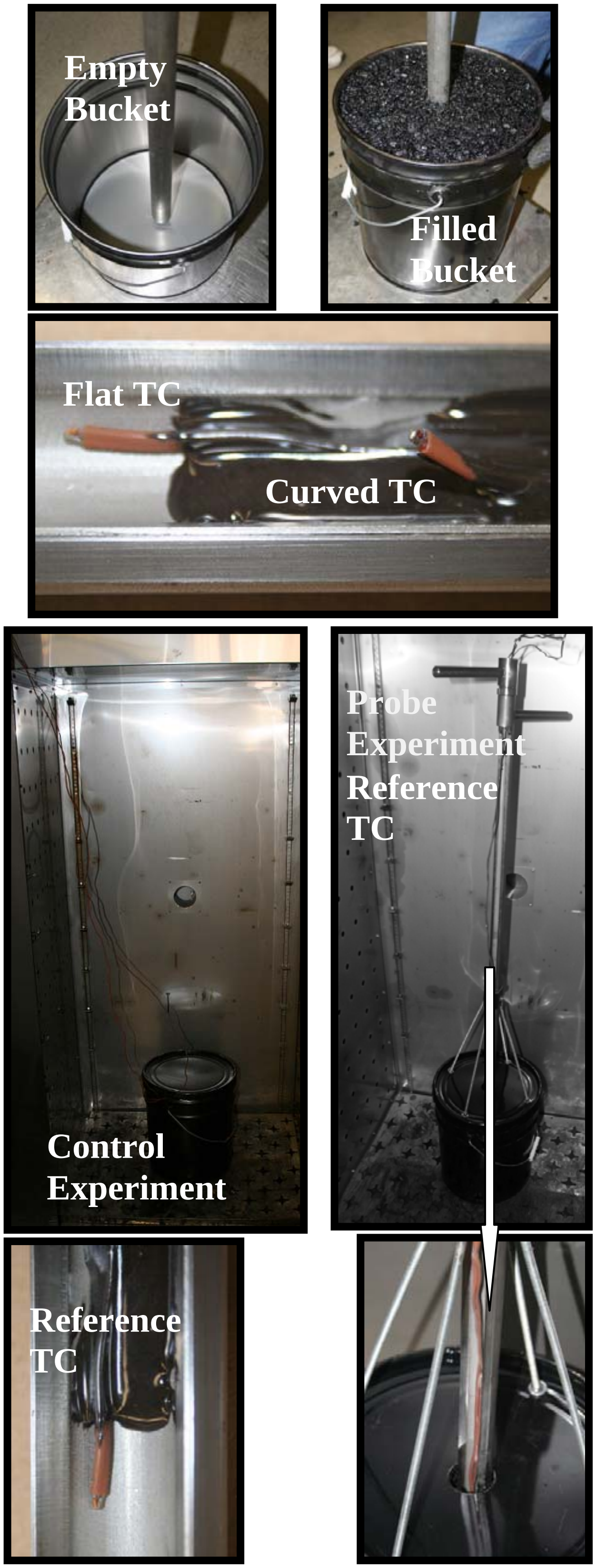

Figure 3. Lab Temperature Experiments

Measured temperatures were 1 to 3 ^{o}C below the oven setting when the buckets were removed from the oven, sat in the laboratory floor (a cloth was placed over the hole in the probe bucket lid), and allowed to cool. Temperatures were recorded beginning with the buckets in the room temperature oven through heating and until the asphalt cooled to approximately 80 ^{o}C.

Results of the laboratory temperature experiments are plotted in Figure 4. There is no practical difference between the control and probe experiments indicating the same temperatures can be measured in the same mix with and without the probe. Figure 4b shows the probe transferring heat to the mix as the reference thermocouple is much warmer than the mix. There is some difference between the flat thermocouple configuration and the curved thermocouple configuration, as the flat configuration is noticeably higher than the control while the curved configuration is practically the same as the control. In the curved configuration, the temperature measurements appear to have been isolated from the probe. Figure 4c shows a small influence of the probe on the flat configuration while cooling, but the difference dissipates rather quickly until there is no practical difference in any of the thermocouple configurations while cooling (Figure 4d). Test results indicated that the measurements of interest can be isolated from the probe, and that the curved thermocouple configuration is the most appropriate choice for full scale testing.

The control experiment incorporated two bead thermocouples attached to a small wooden rod that allowed both to be placed in the center of the bucket (radially and vertically). Half the asphalt was placed, the thermocouples were inserted, and the rest of the asphalt was placed. The average reading of these thermocouples is denoted *Control* hereafter.

The probe experiment incorporated three bead thermocouples (*TC's*): 1) *Reference TC*-placed near the upper end of the probe in a manner where the measuring junction contacted the probe; 2) *Flat TC*-placed at the center of the bucket (radially and vertically) with the cable laid flat so that the measuring junction contacted the probe; 3) *Curved TC*-placed at the center of the bucket (radially and vertically) by curving the thermocouple cable in a manner where the measuring junction was not touching the probe (the measuring junction was a few millimeters above the probe).

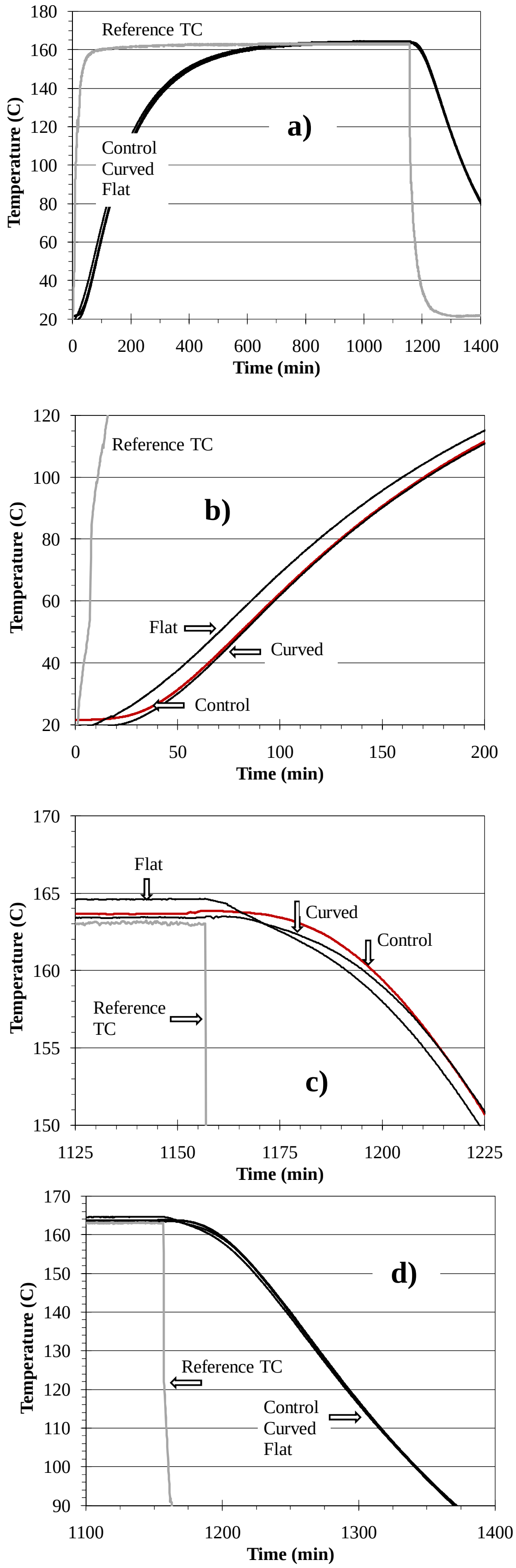

Figure 4. Lab Temperature Experiments

The probe tip was touching the bottom of the bucket. *Flat* and *Curved* thermocouples were within a few millimeters of each other, and are shown in a close up view in Figure 3. The probe (with thermocouples mounted inside) was placed in the bucket while closed, then the bucket was filled with asphalt. A pre-fabricated bucket lid with a hole and a support bracket was used to keep the probe aligned during testing. Once the support bracket was in place, the probe was opened to expose the bead thermocouples to the asphalt (Figure 3 shows a close up photograph of the probe opened where the bead thermocouple cables can be seen entering the asphalt mixture).

Instrumentation Fabrication

The data acquisition box and thermocouple bundles (discussed later in this section) were equipped with male quick connectors, and the trunk line (large cable) was equipped with female quick connectors. Each thermocouple had a copper wire and a constantan wire, making it necessary for the path to the data acquisition system to be made from these two materials. The thermocouple, trunk line, pins, and sockets were a continuous series of either copper or constantan that were wired directly to the data acquisition modules.

The male quick connects required a 4.4 to 5.2 mm stripped wire. Figure 5a shows the end of the wire for the male end of a quick connector that has been stripped and separated. To make the connection on the male wire end, a male pin was crimped onto the wire (Figure 5b). There are tight tolerances on the strip length because the insulation must enter the end of the tip, but the wire must extend until it can be seen in the pins peep hole (Figure 5c). Once all of the pins and wires have been crimped and the tabs removed, the pins are inserted into the male quick connector. The quick connector is lubricated with a silicone oil and the wire is started into the quick connector. The insertion tool is placed against the back of the tip and the wire is placed into the channel on the tool so it can be pushed into place. All wires were placed using the aforementioned steps, and Figure 5d shows a completed male connector, which has 16 pins (8 copper, 8 constantan) and accommodates eight thermocouple measurements.

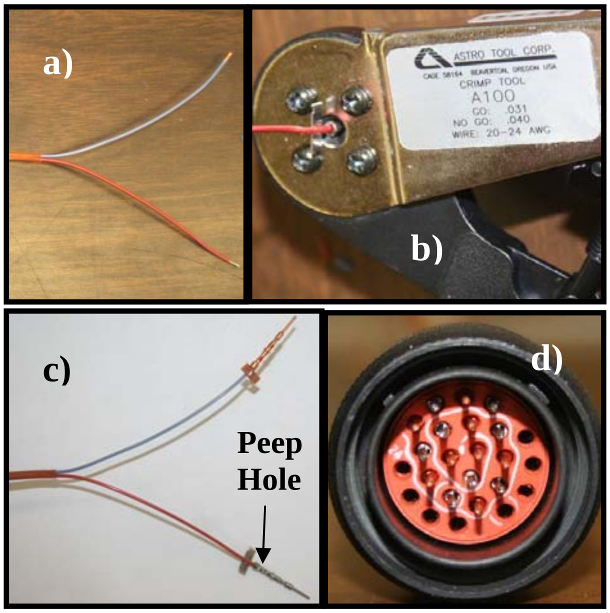

Figure 5. Male Connector Fabrication

Figure 6 shows the wiring component (referred to as chassis bundle) connecting the trunk line to the data acquisition box. Each wire was covered with heat shrink tubing for insulation and protection. The wires were separated into two groups of four thermocouples as the data acquisition modules used each accommodate four thermocouples. Wires were traced using labeling on the trunk wires and connectors.

Figure 6. Male Connector (To Trunk Line) and Stripped Ends (To Modules)

To create a female connector, the sixteen (8 copper, 8 constantan) numbered wires in the trunk line were separated, stripped, and sockets placed on each wire (Figure 7a). Two ground wires were present in the trunk line, but they were not used. The trunk line wires with sockets were placed into the female connector; Figure 7b shows the wires prior to insertion and Figure 7c shows the connector with the sockets in place. Heat shrink tubing and the backshell cable clamp were then placed (Figure 7d) to protect the ends of the trunk line from damage due to twisting and pulling. Both trunk line ends were equipped with female connectors.

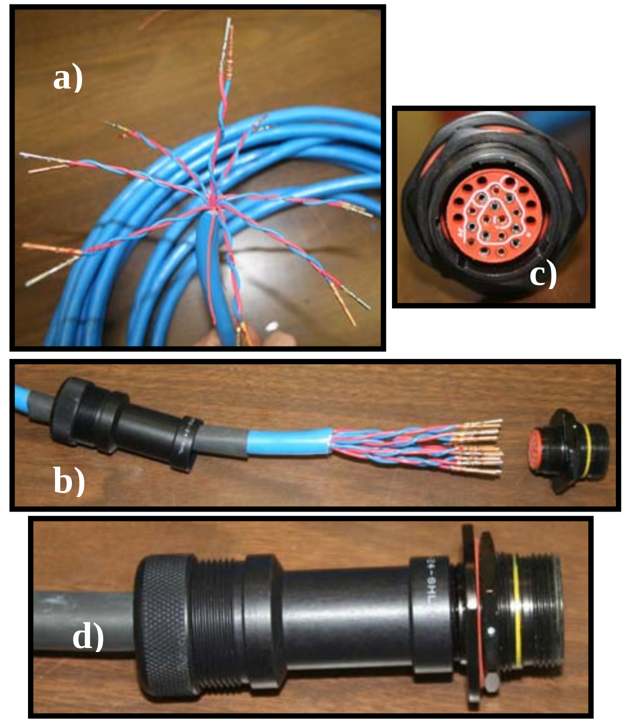

Figure 7. Female Connector Fabrication For Trunk Lines

Thermocouple bundles were made to fit into the Figure 2 probe and allow measurement at four locations along its length as shown in Figure 8. Two thermocouples were placed at each location for redundancy, making the total number of thermocouples per probe equal to eight. Thermocouple bundles used male quick connectors (Figure 5) and attached directly to the trunk line. To create a thermocouple bundle, bead thermocouple leads were trimmed to lengths of 35.6, 73.7, 111.8, and 149.9 cm for placement in locations L1 to L4, respectively, while allowing all thermocouples to fit into the make quick connector. All eight thermocouples were then bundled together with heat shrink tubing for insulation, protection, and ease of loading into the probes.

Spots were etched inside the probes to facilitate thermocouple alignment and subsequent re-alignment as the thermocouple bundles can be removed when needed. Thermocouples were aligned within approximately 1 cm of the etched locations. JB Kwikweld (referred to hereafter as JB) was used to attach the eight thermocouples (two per location) to the metal probe in the curved configuration discussed previously. Figure 9a is an example of JB locations, and Figure 9b shows two thermocouples curved and awaiting JB treatment. RTV silicone (referred to hereafter as RTV) was used to fill the remaining air space to minimize air movement in the probe as it was learned during preliminary field testing that errors could otherwise result. RTV was also used to fill all remaining space in the hole at the end of the probe where wires exited the probe; Figure 9d shows the inside of the hole and Figure 9e shows the outside of the hole.

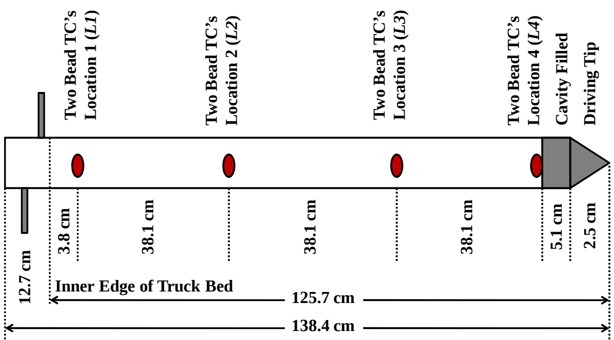

Figure 8. Thermocouple Probe Locations

Figure 9c is a close up view of a location showing the thermocouple measuring junctions covered with a small piece of heat shrink tubing that was shrunk to the point it fully covered the junction but could still be easily removed by hand once the JB and RTV were in place and had solidified. The tubing was placed to protect the measurement junction during fabrication; Figure 9b shows thermocouples without the tubing with the measurement junction exposed.

When needed, thermocouple bundles can be removed from the probe. Howard et al. (2012) describes removal procedures. Removal of a thermocouple bundle and replacement with a new bundle took one operator approximately two hours, and was performed using the safety procedures discussed in Howard et al. (2012).

Verification of Full Scale Instrumentation

Once the instrumentation system was fabricated (i.e. chassis bundle, trunk line, and thermocouple bundle), it was verified by placing the probe in a calibrated oven and verifying temperatures recorded matched the oven settings within the tolerance of the oven. Externally calibrated thermometers were also placed in the oven as another check. Once temperatures were successfully recorded with all wiring and connectors in place, proper labeling and similar quality control operations were performed prior to taking the system to the field for full scale testing.

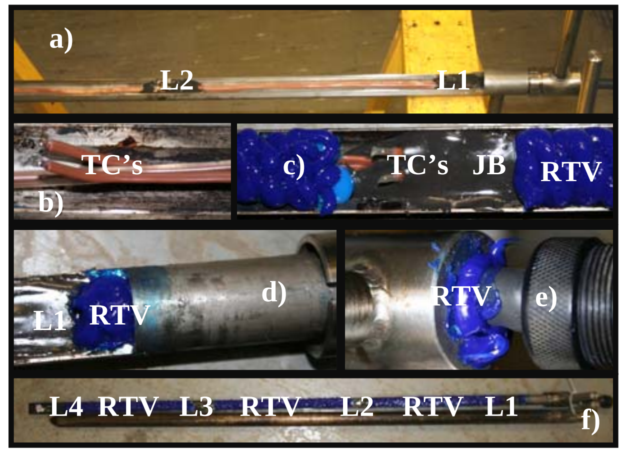

Figure 9. Placing Thermocouple Bundles

References

Howard, I.L., B.A. Payne, M. Bogue, S. Glusenkamp, G.L. Baumgardner, and J.M. Hemsley. *Full Scale Testing of Hot-Mixed Warm-Compacted Asphalt for Emergency Paving.* SERRI Report 70015-011, US Dept. of Homeland Security Science & Technology Directorate, pp. 125, 2012.

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