An Investigation of Low-Strength Concrete and Resulting Structural Failure in a Bridge Deck

James H. Havens
Kentucky Department of Highways
Research Report

AN INVESTIGATION OF LOW-STRENGTH CONCRETE
AND RESULTING STRUCTURAL FAILURE IN A BRIDGE DECK

APD 640(4), Ky. 80, Elkhorn City, Pike County

KYP-56

by

Jas. H. Havens
Director

Division of Research
DEPARTMENT OF HIGHWAYS
Commonwealth of Kentucky

February 1970
INTRODUCTION

This investigation concerns the discovery of weak concrete in a portion of the deck of the Elkhorn City bridge, APD 640(4), within a year after it was opened to traffic. The deck concrete was placed between April 14 and June 14, 1968. The bridge serves heavy coal-trucks traffic. Failures occurred in the eastern-most span (No. 5) in April or May of 1969. Undoubtedly, the heavy loading contributed to early disclosure of defective concrete.

A preliminary investigation was made in May 1969, and reported by memorandum May 21, 1969. The bottom third or half of concrete in the affected portion, Span 5, was found to be atypical. The color was light tan — contrasting from a greenish gray prevailing elsewhere.

The bridge is pictured in Fig. 1. Span 5 is at the far end. A coal-truck is shown on Span 2. Fig. 2 shows the failure zone from underneath. Fig. 3 is a diagram showing the approximate limits of the affected area of Span 5 and the location of cores is pictured in Fig. 4.

During the May 1969 investigation, rebound readings were made with a Swiss Hammer, on top of the deck, in the failed area. Low readings were obtained near the hole in the deck and along some transverse cracks. However, in general, the readings were not extremely low nor did the top surface of the deck appear abnormal. The cause of the high rebound readings is revealed by the cores (Nos. 1, 2, and 3). Obviously, the lower portions were not strong enough to withstand coring. Remnants of the bottoms of cores and spalls from the deck appeared to be crumbly and light in weight. From microscopic examination, it appeared to contain sufficient -- if not excessive -- cement and also appeared to contain excessive air bubbles. It was hypothesized, in the original report, that either the cement had come from an alien source or was "spent" or "poisoned". The defective concrete was the first poured (April 24, 1968) on the deck and was, possibly, the first batched in the season. It was spread rather uniformly and covered with normal concrete.

The defective concrete was removed and replaced with new concrete by the contractor later in 1969.

By letter of September 5, 1969, the Bureau of Public Roads urged further inquiry into the matter -- from the standpoint of discerning or defining cause of the trouble.

ANALYSIS OF MIX-DESIGN FORMULA

Apparantly, three cylinders were made when Span 5 was poured (April 24, 1968). The strengths were satisfactory. The corresponding mix-design form indicates that adjustment for water underrun was made at 2 PM on the beginning day. Copies of these report forms are included herein (see Appendix).
Figure 3: Diagram Showing Approximate Area of Defective Concrete and Core Locations.
Figure 4. Cores Obtained from Deck; 5 and 6 are from Unaffected Area
An analysis of the mix-design formula -- from the standpoint of unit weights and void volumes -- is given in Table I.

The dry unit weight of cured concrete is a significant measure or check upon the batching and placing operations. In other words, the cured, dry, in-place concrete should have a unit weight at least approximately equal to the theoretical, cured, dry, unit weight calculated from the mix-design formula (cf "An Investigation of Core-Strengths of a Portland Cement Concrete Pavement, I 64-6(15) 130, Rowan County", December 1969.)

**TABLE I: ANALYSIS OF MIX-DESIGN FORMULA**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Unit Weight (air-free basis)</td>
<td>152.384 lb/cuft</td>
</tr>
<tr>
<td>Design Unit Weight (for 6% air)</td>
<td>143.570 lb/cuft</td>
</tr>
<tr>
<td>Net Mixing Water (for 6% air)</td>
<td>9.815 lbs</td>
</tr>
<tr>
<td>Water Required for Hydration</td>
<td>5.61 lbs</td>
</tr>
<tr>
<td>SSD Unit Weight of Aggregate and Cement</td>
<td>133.756 cuft</td>
</tr>
<tr>
<td>Weight of Dry Cement ((94 \times \frac{6.6}{27}))</td>
<td>22.978 lbs</td>
</tr>
<tr>
<td>SSD Weight of Aggregates</td>
<td>110.778 lbs</td>
</tr>
<tr>
<td>Evaporable Water in Aggregates (1% Estimate)</td>
<td>1.108 lbs</td>
</tr>
<tr>
<td>Total Evaporable Water ((9.815 - 5.61 + 1.108))</td>
<td>5.313 lbs</td>
</tr>
<tr>
<td>Theoretical Dry Unit Weight of Cured Concrete ((143.570 - 5.313))</td>
<td>138.257 lb/cuft</td>
</tr>
</tbody>
</table>

**Summation of Voids in Mortar:**

- **Voids Due to Evaporable Water** \((4.205/62.4) \times 100\) | 6.739% |
- **Voids Due to Densification of Hydration Water** \((1.00 - 0.7161) \times 5.61/62.4\) | 2.552% |
- **Total Voids Attributed to Mixing Water** | 9.291% |
- **Voids Due to Entrained Air** | 6.000% |
- **Total Theoretical Voids; Dry, Cured Concrete** | 15.291% |

**Theoretical, Maximum Dry Unit Weight of Solids** \([138.257/(1.000 \times \text{- } 0.15291)\] | 163.214 lb/cuft |

**Theoretical Apparent Specific Gravity of Solids** \((163.214/62.4)\) | 2.616 |

- 6 -
ANALYSIS OF DEFECTIVE CONCRETE, BY UNIT WEIGHTS

Remnants of the defective concrete were found to have the following composite unit weights.

<table>
<thead>
<tr>
<th>O.D. Unit Wt.</th>
<th>133.35 lbs. per cu. ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.S.D. Unit Wt.</td>
<td>144.02 lbs. per cu. ft.</td>
</tr>
<tr>
<td>Theoretical Solid Unit Wt.</td>
<td>160.93 lbs. per cu. ft.</td>
</tr>
</tbody>
</table>

The volume of absorbed water \([\frac{(144.02 - 133.35)}{62.4}] \times 100\) yields 17.10% saturable voids. The total voidage, computed from 100 \([1 - \frac{133.35}{160.93}]\) is 17.14%. The total voidage computed from the theoretical solid unit weight is: 100 \([1 - \frac{133.35}{163.21}]\) = 18.30%.

Assuming that air content and voids attributable to mixing water vary in proportion to O.D. Unit Weight:

\[6 + 100\left(1 - \frac{133.35}{138.26}\right) + 9.29\left(\frac{133.35}{138.26}\right) = 18.51\%\text{ Voids}\]

Then, assuming that the saturable voids combined with air content (same as first expression in equation above) yields total voids, we have:

\[100\left(\frac{144.02 - 133.35}{62.4}\right) + 6 + 100\left(1 - \frac{133.35}{138.26}\right) = 26.65\%\text{ Voids}\]

The latter equation introduces a severe disparity -- which, at first glance, seems to refute the hypothesis or assumption stated. Further inquiry, however, discloses that the disparity is meaningful. The first term in the equation accounts rather completely for total voidage as obtained by \([1 - \frac{133.35}{163.21}] \times 100\), that is, 18.30%; the second term is, therefore, fictitious or unreal. This surplus or excess (8.35%) is approximately equal to the volume of water theoretically allowed for hydration; \((5.61/62.4) \times 100 = 8.99\%\). The interpretation is that very little hydration took place. There was no commensurate gain in dry weight of the concrete -- that is, over and above the theoretical dry weight of mix ingredients. The theoretical dry weight of the concrete was 138.26 lbs. per cu. ft. Subtracting the actual unit weight (133.35) leaves 4.91 lbs., as a deficit in weight gain. The theoretical weight gain was 5.61 lbs. per cu. ft. Giving full faith to these figures would permit calculation of the percentage of hydration which occurred, as follows:

\[\frac{5.61 - 4.91}{5.61} \times 100 = 12.5\%\]

Neither a large over-run of water nor deficient proportioning suffices to account fully or as well for the disparity described. Re-tempering might be indicated.
Now, beginning anew, we may reconstruct the real concrete. Only one assumption is needed: the concrete was batched normally. Table II reflects the necessary adjustments in analysis of the mix-design formula.

**TABLE II: REVISED ANALYSIS OF MIX-DESIGN FORMULA**

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit Wt. (air-free basis)</th>
<th>Design Unit Wt. (for 6% air)</th>
<th>Net Mixing Water (for 6% air)</th>
<th>Water Used for Hydration</th>
<th>SSD Unit Wt. of Aggregate and Cement</th>
<th>Weight of Dry Cement (94 x 6.6/27)</th>
<th>SSD Wt. of Aggregates</th>
<th>Evaporable Water in Aggregate (1%, estimated)</th>
<th>Total Evaporable Water (9.815 - .70 + 1.108)</th>
<th>Theoretical Dry Unit Wt. of Cured Conc. (143.570 - 10.223)</th>
<th>Summation of Voids in Mortar:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Unit Wt. (air-free basis)</td>
<td>---</td>
<td>152.384 lbs./cu. ft.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.223 lbs.</td>
<td>133.347 lbs./cu. ft.</td>
<td>Voids Due to Evaporable Water (9.115/62.4) x 100: 14.61%</td>
</tr>
<tr>
<td>Design Unit Wt. (for 6% air)</td>
<td>---</td>
<td>143.570 lbs./cu. ft.</td>
<td></td>
<td>.70 lbs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.223 lbs.</td>
<td>133.347 lbs./cu. ft.</td>
<td>Voids Due to Densification of Hydration Water 100 x (1-0.7161) x .70/62.4: 0.32%</td>
</tr>
<tr>
<td>Net Mixing Water (for 6% air)</td>
<td>---</td>
<td></td>
<td>9.815 lbs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.223 lbs.</td>
<td>133.347 lbs./cu. ft.</td>
<td>Voids Attributable to Mixing Water: 14.93%</td>
</tr>
<tr>
<td>Water Used for Hydration</td>
<td>---</td>
<td></td>
<td></td>
<td>.70 lbs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.223 lbs.</td>
<td>133.347 lbs./cu. ft.</td>
<td>Voids Due to Entrained Air: 6.00%</td>
</tr>
<tr>
<td>SSD Unit Wt. of Aggregate and Cement</td>
<td>---</td>
<td>133.756 lbs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.223 lbs.</td>
<td>133.347 lbs./cu. ft.</td>
<td>Total Voids, Cured, Dry: 20.93%</td>
</tr>
<tr>
<td>Weight of Dry Cement (94 x 6.6/27)</td>
<td>---</td>
<td>22.978 lbs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.223 lbs.</td>
<td>133.347 lbs./cu. ft.</td>
<td>Theoretical, Maximum, Dry Unit Wt. of Solids [133.347/(1-.2093)]: 168.644 lbs./cu. ft.</td>
</tr>
<tr>
<td>SSD Wt. of Aggregates</td>
<td>---</td>
<td>110.778 lbs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.223 lbs.</td>
<td>133.347 lbs./cu. ft.</td>
<td>The complement of voids, of course, is solids. Taking the weights of solids from Table II, we have:</td>
</tr>
</tbody>
</table>
22.978 lbs. cement / 3.14 x 62.4 \[\text{---} \quad 0.1173 \text{ cu.ft.}/\text{cu.ft.}\]

110.778 lbs. agg. x 0.40 / 2.60 x 62.4 \[\text{---} \quad 0.2731 \text{ cu.ft.}/\text{cu.ft.}\]

110.78 lbs. agg. x 0.60 / 2.70 x 62.4 \[\text{---} \quad 0.3945 \text{ cu.ft.}/\text{cu.ft.}\]

0.70 lbs. water of hydr. x 0.7161 / 62.4 \[\text{---} \quad 0.0080 \text{ cu.ft.}/\text{cu.ft.}\]

Vol. of Solids \[\text{---} \quad 0.7929 \text{ cu.ft.}/\text{cu.ft.}\]

Respecting the totality of voids and solids, we have:

\[(1 - 0.7929) \times 100 = 20.71\% \text{ Voids}\]

The theoretical, maximum unit weight of solids becomes:

-wet aggr. basis: \[133.347 / 0.7929 = 168.176 \text{ lbs./cu.ft.}\]
-dry aggr. basis: \[168.176 - 1.108 = 167.068 \# / \text{ft.}^3\]

MICROSCOPIC ANALYSES

Voids larger than two microns were measured by the linear traverse method (ASTM C 457); the averages by this method were in the range of 3 to 5\% voids.

It was very difficult to saw and polish smooth surfaces for the linear traverses. The specimens were soaked in carnauba wax, but particles of sand were easily plucked out -- leaving open sockets. Undoubtedly, it was difficult to distinguish these from true voids. Bubble-type air voids were discernible, and it seems quite possible that the proper amount of air was entrained. Remembering that the specimens actually absorbed 17.10\% water by volume, and recalling an earlier hypothesis:

\[17.10\% + 100 \left[1 - \frac{144.02}{152.387}\right] = 22.59\% \text{ Voids}\]

\[22.59\% - 17.10\% = 5.10\% \text{ Unsaturable Voids}^*\]

* Presumed to be somewhat analogous to entrained air.

Similar approximations based on mix-design calculations yield:

\[20.93\% - 17.10\% = 3.83\%\]

\[20.71\% - 17.10\% = 3.61\%\]

The cement was examined microscopically also. Well-cemented, relatively well-hydrated agglomerates were apparent. The specimen was taken from the interior surface of an air void. This does not mean necessarily that the cement was pre-hydrated or that it hydrated in an excess of water. Peculiarly, no isolated
crystals of calcium hydroxide were formed. This rather precludes the possibility of hydration having taken place in excess water if the cement was a true portland type. The whiteness of the cement undoubtedly has some significance -- but it is not directly discernible. Comparatively, no differences between cements from the upper and lower layers were detectable at 940 x magnification.

A photomacrograph of a polished surface of the concrete is shown in Fig. 5.

SUMMARY

The voids analysis alone suffices to account for the low strength of the offending concrete. It was not possible to explain, with certainty, the cause or attending circumstances. The possibility remains that the cement was pre-hydrated. This and other possible causes considered are only conjectural. Pre-hydration might be inferred to mean re-tempering if the concrete were withheld in the mixer for an extended time.

Fig. 6 summarizes some previous data from other projects where problems with strength arose and shows, relatively, the percentage of voids attributed to the concrete from the Elkhorn City bridge.

It appears that concretes made with normal aggregates should have cured, dry, unit weights in the order of 138 lbs. per cu. ft. Measurement of O.D. Unit Weight should be considered a first-order diagnostic rule when strength is suspect.
Figure 6. Strength-vs-Voids Relationships Resulting from Other Concretes; only Percent Voids is shown for Defective Concrete from Elkhorn City Bridge; Concrete was not Strong Enough to Withstand Coring
**HD 64-305**  
Division of Materials  
Department of Highways  
Frankfort, Ky.

**Rev. 12/64  
Project No. APD 640 (4)  
Date. April 24, 1968**

**County.** Pike  
**Road.** Elkhorn City - Virginia State Line Road

**CLASS of CONCRETE:** "AA"  
**MIN. CEMENT FACTOR:** 1.65

### AGGREGATE RATIO

<table>
<thead>
<tr>
<th>TIME of DAY</th>
<th>FINE AGGREGATE DATA</th>
<th>COARSE AGGREGATE DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:00PM</td>
<td>Fine Aggr. 40 % by Volume</td>
<td>Coarse Aggr. 60 % by Volume</td>
</tr>
</tbody>
</table>

### SPECIFIC GRAVITY

- **2.60**
- **2.70**

### DESIGN DRY WEIGHTS

- **1261'**
- **1967'**

### DESIGN DRY WTS. ADJ. FOR AIR

- **1156'**
- **1203'**

### PERCENT AIR ENTRAINED

- **6.0**

### PERCENT AGGREGATE DEDUCTED

- **8.34**

### PERCENT MOISTURE CORRECTION

- **3.0**

### WEIGHTS PER BAG

- **FINE 191 lbs.**  
- **COARSE 298 lbs.**

### DATA FOR 66 BAG BATCH

<table>
<thead>
<tr>
<th>TIME of DAY</th>
<th>FINE</th>
<th>COARSE</th>
<th>FINE</th>
<th>COARSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:00PM</td>
<td>1197</td>
<td>-1818</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### MAXIMUM ALLOWABLE FREE WATER

- **5.00**

### CORRECTION FOR MOISTURE

- **40**

### WATER ADDED AT THE MIXER

- **225**

### TOTAL WATER PER SACK OF CEMENT

- **4.81**

### TOTAL WATER USED

- **265**

### ACTUAL WATER UNDERRUN (lbs.)

- **10**

### RESULTS OF SLUMP TESTS

- **(1) 2' 3/4 inches**
- **(2) 3 inches**
- **(3) 3 inches**

**Concrete Inspector**

**James B. Allison**

**CC:** Director of Materials  
Resident Engineer

**Director of Construction**  
Asst. Dist. Engineer Materials  
Retained Copy
DIVISION OF MATERIALS  
KENTUCKY DEPARTMENT OF HIGHWAYS  
CONCRETE CYLINDER OR BEAM REPORTS  

COUNTY: Pike  
PROJECT: APD 640 (4)  

Name of Highway: Elkhorn City - Virginia State Line Road  
Submitted By: W. C. Hopkins  
Address: P.O. Box 2468 Pikeville, Ky. 41501  
Ph. No.  

Class of Concrete: "AA" Type "D"  
Type of Construction: Bridge Slab  

Design Dry Wts. per Bag: 191# fine agg. 298# coarse agg.  
Actual Damp Wts.: 181# fine agg. 275# coarse agg.  

Aggregate Ratio: 40% fine 60% coarse  
% Water added at the Mixer: 4.09 gallons  

Total Water used: 4.81 gallons per sack cement. Slump in inches: 2 3/4  
Mixing Time: 1 min.  

No. of Bags per Batch: 6.6  
Used at Span #5  
Ident. 28 A station number  

Per cent of Moisture: 3.0% fine agg. 0.3% coarse agg.  
Air Content: 6.5%  

Made from Cement Lab. No.: C # 7  
Date Tested: Not Reported  
Made from Fine Agg. Lab. No.: 43323  
Date Tested: 12-29-67  
Made from Coarse Agg. Lab. No.: 43324  
Date Tested: 12-29-67  
Date Made: April 24, 1968  
Date Shipped to Lab.  

FIELD STRENGTH OF BEAM: LBS. MODULUS OF RUPTURE AT _____ Days  

Remarks: Made by T. A. Burchett - Inspector  

DO NOT WRITE BELOW THIS LINE  

Date Received:  
Date Broken: 5-22  
Age: 30  

End Condition:  
Strength Lbs. Sq. In.: 5340  

Results:  
Satisfactory /  
Fair  
Low  
Poor  

Remarks:  

cc: Lab. No. 61593
COUNTY: Pike
Name of Highway: Elkhorn City - Virginia State Line Road
Submitted By: W. C. Hopkins
Address: P.O. Box 2468, Pikeville, Ky. 41501
Class of Concrete: "AA" Type "D"
Type of Construction: Bridge Slab
Design Drv Wts. per Bag: 191# fine agg., 298# coarse agg.
Actual Damp Wts.: 181# fine agg., 275# coarse agg.
Aggregate Ratio: 40% fine, 60% coarse
Water added at the Mixer: 4.09 gallons
Total Water used: 4.81 gallons per sack cement
Slump in inches: 2 1/2
Mixing Time: 1 minute
No. of Bags per Batch: 6.6
Used at Span #: 5
Ident. #: 28 C
Per cent of Moisture: 3.0% fine agg., 0.3% coarse agg.
Air Content: 6.5%
Date Made: April 24, 1968
Date Shipped to Lab: ________________
Date Tested: Not Reported
Made from Cement Lab. No.: C # 7
Made from Fine Agg. Lab. No.: 43323
Made from Coarse Agg. Lab. No.: 43324
Date Tested: 12-27-67
Date Tested: 12-29-67
Date Tested: ________________
LAB. MODULUS OF RUPTURE AT ___________ days
FIELD STRENGTH OF BEAM ___________ LBS.
End Condition: ________________
Strength Lbs. Sq. In.: ________________
Date Broken: 5-22
Age: 30
Results: Satisfactory / Fair Low Poor
Remarks: Made by T. A. Burchett - Inspector

Date Received: ________________
Date Broken: 5-22
Age: 30
End Condition: ________________
Strength Lbs. Sq. In.: ________________
Results: Satisfactory / Fair Low Poor
Remarks: ________________

cc: Lab. No. 61584
<table>
<thead>
<tr>
<th>Name of Highway</th>
<th>Elkhorn City - Virginia State Line Road</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submitted By</td>
<td>W. C. Hopkins</td>
</tr>
<tr>
<td>Address</td>
<td>P.O. Box 2468 Pikeville, Ky. 41501</td>
</tr>
<tr>
<td>Class of Concrete</td>
<td>&quot;AA&quot; Type &quot;D&quot;</td>
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<tr>
<td>Design Dry Wts.</td>
<td>191# fine agg. 298# coarse agg.</td>
</tr>
<tr>
<td>Actual Damp Wts.</td>
<td>181# fine agg. 275# coarse agg.</td>
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<tr>
<td>Aggregate Ratio</td>
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</tr>
<tr>
<td>Water added at the Mixer</td>
<td>4.09 gallons</td>
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<td>Total Water used</td>
<td>4.81 gallons per sack cement</td>
</tr>
<tr>
<td>No. of Bags per Batch</td>
<td>6.6</td>
</tr>
<tr>
<td>Span #</td>
<td>5</td>
</tr>
<tr>
<td>Station number</td>
<td>28 E</td>
</tr>
<tr>
<td>Per cent of Moisture</td>
<td>3.0% fine agg. 0.3% coarse agg.</td>
</tr>
<tr>
<td>Air Content</td>
<td>6.5%</td>
</tr>
<tr>
<td>Made from Cement Lab.</td>
<td>No. C # 7</td>
</tr>
<tr>
<td>Made from Fine Agg. Lab.</td>
<td>No. 43323</td>
</tr>
<tr>
<td>Made from Coarse Agg. Lab.</td>
<td>No. 43324</td>
</tr>
<tr>
<td>Date Made</td>
<td>April 24, 1968</td>
</tr>
<tr>
<td>Date Shipped to Lab.</td>
<td></td>
</tr>
<tr>
<td>FIELD STRENGTH OF BEAM</td>
<td>LBS. MODULUS OF RUPTURE AT 30 Days</td>
</tr>
<tr>
<td>Remarks:</td>
<td>Made By T. A. BURCHETT * INSPECTOR</td>
</tr>
</tbody>
</table>

| DO NOT WRITE BELOW THIS LINE |

<table>
<thead>
<tr>
<th>Date Received</th>
<th>Date Broken</th>
<th>5-22</th>
<th>Age</th>
<th>30</th>
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<tbody>
<tr>
<td>End Condition</td>
<td>Strength Lbs. Sq.In.</td>
<td>5480</td>
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<td></td>
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<tr>
<td>Results: Satisfactory</td>
<td>/</td>
<td>Fair</td>
<td>Low</td>
<td>Poor</td>
</tr>
<tr>
<td>Remarks:</td>
<td></td>
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<table>
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<th>cc:</th>
<th>Lab. No.</th>
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