Rapid Strength Concrete for Rehabilitation and Improvement of Pavements

B. Stein  
*Twining, Inc., California, United States*

B. Kramer  
*Twining, Inc., California, United States*

T. Kumar  
*Twining, Inc., California, United States*

T. Pyle  
*California Department of Transportation, United States*

S. Shatnawi  
*California Department of Transportation, United States*

**ABSTRACT**

During the past decade rapid strength concrete (RSC) has been extensively used for rehabilitation and improvement of highways, city streets, and airfields. The authors, who were involved in the development and implementation of RSC, construction methods, and testing procedures and techniques, summarize laboratory and field mix design experience, and illustrate recommended approaches with examples of projects built in California.

These examples explain principles of proportioning of RSC with respect to project requirements, site and ambient conditions, and provide field and laboratory test data demonstrating the actual performance of the different types of mixes.

The paper contains an overview of factors influencing workability and strength gain of RSC, and provides practical recommendations on controlling these two most important performance characteristics that enable the replacement of pavements within short-time partial closures of roadways. The paper also deals with other aspects of RSC performance, defining quality of pavements.

In conclusion, the authors provide their view of the needs of future research and development in the field of RSC and construction practices of pavement rehabilitation and improvements within short-time closures.
Types of Rapid Strength Concrete

RSC for rehabilitation and construction of pavements may be classified by:
• Performance – rate of strength gain in early age,
• Proportions (mainly type of hydraulic cement and combination of chemical admixtures used), and
• Method of batching and mixing.

Rate of strength gain in early age defines the approach to proportioning RSC. When curing time\(^1\) is limited to 1 to 3 hours, RSC has been typically proportioned with rapid hardening cements. The two cement brands more often used in California are CTS Rapid-Set\(^6\) Cement and Ultimax Cement DOT\(^7\). In 2000, for longer curing periods of more than 3 hours, the industry also started using 4x4\(^TM\) Concrete, the system developed by BASF and containing Type III portland cement, Glenium family superplasticizer, non-chloride accelerator of hardening Pozzolith NC 534, and hydration controlling admixture Delvo\(^\text{[1, 2]}\). RSC with Type III portland cement, non-chloride accelerators of hardening, superplasticizers and set controlling admixtures have been extensively used since then utilizing the W.R. Grace system of chemical agents as well.

Generally both types of RSC can be produced either by batch plant proportioning and transit mixing (ASTM C94), or by volumetric proportioning and mixing in mobile mixers (ASTM C685). However, field experience has proved that it is more convenient and practical to produce RSC with rapid hardening cements by mobile (volumetric) mixers, allowing for the immediate discharge and placement of such mixes. The requirement in hydration controlling admixtures (or retarders) is efficiently reduced and uniformity and predictability of both workability and strength gain are improved.

In contrast, RSC with Type III portland cement typically has been produced using transit mixers. Superplasticizer and set controlling admixture are added at the batch plant, where the accelerator of hardening is added on site. Delivery time in this case is not specifically limited and may be considered the same as for regular ready mixed concrete. Limited experience obtained with mobile mixers demonstrates that the capacity of dispensers for chemical admixtures may not be sufficient for dosing high quantities of accelerators of hardening needed for production of 4-hour RSC. RSC for longer curing time (i.e. 6 hours to 12 hours) requiring less accelerator, can be produced without modifying mobile mixers.

Design of Rapid Strength Concrete

Rapid strength concrete pavement mixtures are typically designed for:
• Consistency, cohesiveness, and time within which fresh RSC retains workable consistency, the three most important characteristics defining workability,
• Ability to be finished promptly after placement,
• Flexural strength:
  — Minimum flexural strength prior to opening lanes to traffic,
  — Maximum curing time allowed prior to opening lanes to traffic,
  — Minimum flexural strength in final specification age\(^2\), and

\(^1\) For the purpose of this paper, field curing time is considered to be time between completion of finishing operations and opening lanes to traffic.

\(^2\) Federal Aviation Administration specifies flexural strength of 650 psi in 28 days when tested per ASTM C78 using beams fabricated and cured per ASTM C31; Caltrans specifies flexural strength of 600 psi in 7 days using beams fabricated and tested according to California Test Methods 524 or 523 modified by project technical specifications. Formula used by the California Test Methods increases flexural strength results by 5% compared to ASTM C78 and AASHTO T97 by applying multiplication coefficient of 1.05.
Final specification age,
• Temperature of application, and
• Freezing and thawing resistivity.

Less frequently, RSC is specified and designed for resistance to exposure conditions or for drying shrinkage. These cause misconceptions that RSC cannot be used in contact with soils containing water soluble sulfates, or that drying shrinkage of RSC cannot be controlled. This is addressed in the next paragraphs.

Proportioning for ultra-rapid strength gain in early age differentiates design of RSC from regular pavement concrete. It necessitates the proper selection of hydraulic cements and combinations of chemical admixtures allowing for achieving early age strength and required workability, as provided in Table 1 and as further explained in paragraphs Proportioning for Early Age Strength.

<table>
<thead>
<tr>
<th>Minimum Curing Time prior to Opening Lanes to Traffic</th>
<th>Proportioning of Cement Paste for Early Age Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Time to Achieve MOR=400 psi</td>
<td>Type of Cement</td>
</tr>
<tr>
<td>1 to 2 hours</td>
<td>Rapid hardening cements, ASTM C1600</td>
</tr>
<tr>
<td>3 to 4 hours</td>
<td>Portland cement Type III, ASTM C150</td>
</tr>
<tr>
<td>8 to 12 hours</td>
<td>Portland cement Type III, ASTM C150</td>
</tr>
<tr>
<td>≥16 hours</td>
<td>Portland cement Type II</td>
</tr>
<tr>
<td></td>
<td>Non-Chloride Accelerator of Hardening, fluid ounces per 100 pounds of cement</td>
</tr>
<tr>
<td></td>
<td>~ 0.41-0.43</td>
</tr>
<tr>
<td></td>
<td>70 to 100</td>
</tr>
<tr>
<td></td>
<td>20 to 40</td>
</tr>
<tr>
<td></td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>~ 0.37-0.39</td>
</tr>
</tbody>
</table>

Proportioning for Workability, General Notes on Plastic Properties of RSC

RSC mixes for short-time lane closures are naturally cohesive because of high fineness of hydraulic cements used for their production, higher binder content than in regular pavement mixes, and relatively low W/C, as depicted. Slump of RSC varies in the range of 4 to 9 inches. Although placing RSC with 6 to 9 inches slump is more convenient, an existence of slope or other site conditions may necessitate slump limitations.

Analysis of test data of more than 100 projects built in California indicates that in at least 80 percent of instances, penetration of fresh RSC was equal to or exceeded 4 inches, which approximately corresponds to 6 to 8 inches plus slump (ASTM C143). High consistency (penetration or slump) of RSC is almost always achieved by using high range water reducing admixtures.

RSC mixes are frequently used for pavement rehabilitation projects. They are placed by hand methods, consolidated with internal vibrators, leveled and preliminarily finished with roller screeds, and finally fin-

3 Type III portland cement (ASTM C150) and rapid hardening hydraulic cements (ASTM C1600) used for production of RSC have specific surface areas of 5000 to 7000 cm\(^2\)/g.
4 Consistency of concrete mix by penetration of Kelly Ball, California Test Method 533
ished with hand tools. Therefore, consistency limitations typical for slip forming (slump not to exceed 1.5 to 2 inches) are not applicable. High consistency of RSC and its cohesiveness are important factors contributing to the acceleration of construction of pavements.

Another important factor accelerating construction is the limited bleeding of RSC allowing for its prompt finishing. The known concern with using low or non-bleeding mixes is the increased potential for plastic shrinkage cracking of fresh concrete. However, as confirmed by field observations, fast setting of RSC and subsequent accelerated gain of tensile strength reduce risk of plastic shrinkage cracking. Still, RSC pavement shall be protected from moisture losses by application of curing compound immediately upon completion of finishing.

**Proportioning for Workability, Amount of Water Added**

We recommend that the minimum design water content of RSC is to provide slump prior to addition of superplasticizer of 0.75 inch +/- 0.5 inch. Amount of water needed to achieve this slump is influenced by maximum size, combined gradation, and surface condition of aggregate particles, factors determining their total surface area. Water requirement is also influenced by the type and fineness of hydraulic cement, and type and dosage rates of chemical admixtures introduced into the mix prior to the addition of superplasticizer. Actual water requirement of RSC shall be established by preconstruction trial batches.

Field experience demonstrates that insufficient initial water content may cause “overdosing” of high range water reducers, and lead to segregation. Even moderate segregation tends to cause shallow surface cracking of RSC pavement due to differential volume changes and differential strength gain over the thickness of pavement section.

**Proportioning for Workability, Selection of Chemical Admixtures**

In proportioning RSC, retention of workable consistency within time is as important, as initial consistency or workability of the mix. All types of RSC used in California for short-time lane closures contain superplasticizers. Use of superplasticizers allows for achieving required flowable or near-flowable consistency, better dispersing and more complete hydration of cement, and reducing its content while maintaining required water to cement ratio (W/C).

Use of hydration controlling admixtures (hydration stabilizers) allows for extending time within which RSC retains workable consistency. Their dosage rate is selected depending on the anticipated initial concrete and ambient temperatures and required time of stabilization of workability. The higher the temperature, the more hydration controlling admixture is needed. When ambient temperature is below approximately 55-60 F and concrete temperature is below approximately 65-70 F, the use of hydration stabilizers may be minimized or even completely eliminated. Dosage rate of hydration stabilizers shall be selected with respect to both workability retention and early age strength gain. An increase in dosage rate of a hydration stabilizer extends time within which RSC retains workable consistency, however, it slows down early age strength gain. Although use of hydration stabilizers may somewhat improve later age strength, for the purpose of mix design for laboratory and/or field evaluation their effect may be neglected. Table 2 provides examples illustrating dosage rates of hydration stabilizers used in production of RSC in California.

**Proportioning for Early Age Strength**

Gain of modulus of rupture in early age defines minimum curing time needed for opening replacement pavement to traffic. It has a major impact on construction schedule, and also on public safety and traffic. Early age strength gain of RSC is influenced by materials used and mixture proportions:
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- Type of hydraulic cement,
- Use of chemical admixtures modifying setting and very early age strength gain of concrete (such as accelerators, retarders, hydration controlling agents) and their addition rates,
- Use of supplementary cementitious materials (such as Class F fly ash and GGBFS, especially in high quantities, retard setting and strength gain in early age), and
- Water to cement (cementitious) material ratio (early age strength gain typically accelerates, as water to cement ratio reduces).

### Proportioning for Early Age Strength, Selection of Hydraulic Cement

For pavement thinner than 10 inches, Caltrans special provisions provide for minimum flexural strength prior to opening pavements to traffic of 400 psi. Hydraulic cements are selected depending on the minimum curing time allowed prior to opening lanes to traffic. The following examples demonstrate possible choices:

- One to three hours: Rapid hardening hydraulic cements,
- Three to sixteen hours: Type III portland cement and rapid hardening hydraulic cements, and
- More than sixteen hours: Type I, Type II, Type III or Type V portland cements and rapid hardening hydraulic cements.


### Table 2. Approximate Dosage Rates of Hydration Stabilizers

<table>
<thead>
<tr>
<th>Minimum Curing Time to Achieve MOR=400 psi, hours</th>
<th>Type of Hydraulic Cement</th>
<th>Non-Chloride Accelerator of Hardening, fluid ounces per 100 pounds of cement</th>
<th>Method of RSC Production and Delivery</th>
<th>Approximate Dosage Rate of Hydration Stabilizer (Retarder) Depending on the Range of Ambient Temperatures, fluid ounces per 100 pounds of cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 2</td>
<td>Rapid hardening, CTS</td>
<td>None</td>
<td>RSC is produced using mobile mixers at the point of placement; time within which RSC retains workable consistency after discharge is ~ 15 minutes.</td>
<td>45-60 °F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0 to 6</td>
<td>6 to 7</td>
</tr>
<tr>
<td>3 to 4</td>
<td>Portland cement Type III</td>
<td>~80</td>
<td>Transit mixed RSC, delivery time is ~ 40 minutes. Superplasticizer and hydration stabilizer are introduced initially at the batch plant, and accelerating agent is added on-site.</td>
<td>0 to 1</td>
</tr>
</tbody>
</table>
RSC proportioned with rapid hardening hydraulic cements do not require chemical accelerators. Rapid development of high-early strength of concrete is provided by the binder. RSC proportioned with Type III Portland cement to achieve minimum flexural strength of 400 psi in 3 to 12 hours requires an addition of chemical accelerator of hardening. Non-chloride accelerators of hardening have proved their efficiency and are preferred over chloride accelerators because of dramatically less impact on increase of drying shrinkage. Protective properties of concrete towards steel are greatly improved as well. Dosage rate of an accelerator increases with decrease of curing time. The following dosage rates (per 100 pounds of Type III Portland cement) may be used for preliminary proportioning of mixtures for pre-construction trial batches, where ambient temperatures are in a range of 60 F to 85 F:
- 4 hours curing – 70 to 100 fluid ounces,
- 12 hours curing – 20 to 40 fluid ounces,
- Curing longer than 16 hours – typically accelerator is not needed.

Required dosage rate of an accelerator may noticeably increase when ambient temperature decreases below approximately 55 F, especially when initial concrete temperature is not adjusted properly.

Water to cementitious materials ratio influences both early age and later age strength of RSC. Therefore, when water to cementitious material ratio is selected, both strength requirements shall be considered for proportioning, as well as the maximum time allowed for achieving early age strength. For example, for achieving flexural strength of 400 psi in 3 to 4 hours, mixes with Type III portland cement should be designed with water to cement ratio equal to or less than 0.34, where for achieving the minimum 7-day flexural strength of 600 psi the water to cement ratio shall be limited only to approximately 0.43.

Initial concrete and ambient temperatures noticeably impact strength gain. Strength gain accelerates with an increase of temperature and retards when concrete and ambient temperatures decrease. Therefore, RSC mixes shall be designed for specific temperature ranges. Typically this is achieved by specifying addition rates of hydration controlling admixtures and accelerators depending on the ambient temperature (Reference: Table 2). Mix design shall indicate the minimum initial concrete temperature. Based on our data, when most types of RSC are placed at relatively low positive ambient temperatures of 45 F to 55 F, minimum initial concrete temperature should be specified in a range of 60 F to 70 F, depending on the type of hydraulic cement used. In practice, control of initial concrete temperature during cold weather periods is achieved by using hot water.

Resistence of concrete to sulfates mainly depends on chemical and mineral composition of hydraulic cement and permeability of hardened material to ingress of sulfate solutions. In selecting cement for sulfate resistance, a principal consideration is given to tricalcium aluminate (C₃A) content. Permeability is controlled by limiting water to cement ratio.

Because RSC may be produced using different hydraulic cement types, proportioning for sulfate resistance is recommended to be based on performance specifications. ASTM C1157 provides limits for sulfate expansion.
(test method ASTM C1012) for Type MS (moderate sulfate resistance) and Type HS (high sulfate resistance) hydraulic cements. ASTM C1600 provides optional limits for sulfate expansion (ASTM C1012) for rapid hardening hydraulic cements, which are equal to limits specified by ASTM C1157 for hydraulic cement Class HS.

For example, research performed by UCLA and CTL demonstrates that Rapid-Set® Cement (rapid hardening hydraulic cement manufactured by CTS) meets expansion limits for Type HS hydraulic cement specified by ASTM C1157. One-year expansion per ASTM C1012 was 0.02 percent, where ASTM C1157 expansion limit for Class HS hydraulic cement and ASTM C1600 optional requirement are 0.10 percent [3].

Type III portland cement can be specified for moderate or high sulfate resistance as well. According to ASTM C150, Type III portland cement for moderate and high sulfate resistance shall be specified for maximum content of C₃A of 8 percent and 5 percent correspondingly.

ACI 318 limits water to cementitious material ratio for the most aggressive exposures Classes S3 and S4 to 0.45. RSC rarely exceeds this limit because of strength gain consideration.

**Proportioning for Drying Shrinkage**

In proportioning for maximum drying shrinkage, the following RSC-specific factors are recommended to be considered:

- Type III portland cement and rapid hardening cements are generally finer than hydraulic cements used for regular concrete, a factor known to contribute to higher drying shrinkage,
- RSC typically contains more binder than regular portland cement concrete for pavements contributing to higher paste content,
- Some RSC types contain high doses of accelerators of hardening, known to increase drying shrinkage,
- RSC are produced with superplasticizers, which reduce water and paste content, and
- Relative amount of water combined by hydraulic cements in RSC may be higher than the one in regular portland cement concrete, thus decreasing the relative amount of water left for evaporation.

For example, studies by CTS demonstrate that CTS Rapid-Set® Cement combines higher amount of water than portland cements [3]. Twining Laboratories tested RSC with 1-inch maximum size aggregate containing CTS Rapid-Set® Cement. Drying shrinkage of laboratory fabricated bars in 28 dry days after 6 hours of moist curing was in a range of 0.022% to 0.025%. Testing performed by Capitol Laboratories in Sacramento, CA [1] demonstrated that drying shrinkage of laboratory fabricated bars in 28 dry days after 7 days of initial moist curing was 0.030%. For reference, drying shrinkage of regular concrete with 1-inch maximum size California-mined aggregates containing normal-range water reducers, when tested in the laboratory, in 28 dry days after 7 days of initial moist curing may be in a range of 0.040 to 0.060%.

Limited test data by Twining Laboratories demonstrated drying shrinkage of RSC with Type III portland cement and BASF system of chemical admixtures (4x4™ Concrete) approximately within the range of regular concrete. Initial moist curing was performed for 9 hours and for 7 days. Use of BASF shrinkage reducer Tetruguard efficiently limits drying shrinkage of 4x4™ Concrete.

Should drying shrinkage be limited, RSC is recommended to be pretested in the laboratory for compliance with technical specifications. RSC is typically exposed to traffic in one to four hours after placement, which limits duration of its “undisturbed” moist curing. Developing a standard test method for drying shrinkage of RSC is, in our opinion, one of the pending research goals.
Notes on the Selection of Aggregates for RSC

Selection of aggregates is an important step in proportioning RSC. Typical design considerations related to impact of aggregates on water requirement, workability, strength, drying shrinkage, coefficient of thermal expansion, cracking resistance, abrasion resistance, and durability of concrete are true for RSC as well. Additional RSC-specific concerns are:

- Cohesiveness and segregation potential of near-flowable fresh pavement concrete,
- Finishability of concrete, and
- Rapid development of strong bonding at the interface of coarse aggregates to cement paste in early age.

The authors recommend continuously graded aggregates, proportioned for example in general compliance with Federal Aviation Specifications FAA C150, P-501 for hand placement. Higher workability factor is typical for RSC, since the mixes contain relatively high amounts of cement (typically 7 to 8.5 sacks per one cubic yard depending on type of RSC). The mix shall not be excessively rocky for the ease of placement, consolidation, and finishing within extremely short time windows.

Although use of crushed aggregates may impact consistency of RSC, they benefit development of early age bonding strength with cement paste and overall flexural strength of RSC, which is the deciding consideration.

Preconstruction Evaluation of RSC in the Course of Mix Design

For a given set of materials (hydraulic cement, aggregates, chemical admixtures, and water) early age strength of rapid strength concrete is influenced by:

- Water to cement (cementitious) material ratio,
- Addition rates of accelerators and/or retarders/hydration stabilizers,
- Initial concrete temperature, and
- Curing temperature.

For better understanding of the cumulative effect of these factors on the early age strength and strength in final specification age, we recommend evaluating RSC prior to construction by performing field trial batches. Statement of concrete mix design should refer not only to flexural strength, slump (penetration), and exposure conditions, but also to temperature of application and time within which RSC retains workable consistency. Examples of RSC proportions are provided in the next paragraphs.

Case Studies – California Project Examples

The following examples illustrate strength gain of RSC designed for different durations of curing prior to opening lanes to traffic:

- 1-hour to 2-hour curing,
- 3.5-hour to 4-hour curing, and
- 12-hour curing.

These examples refer to pavement rehabilitation projects in California. All mixes were specified for achieving flexural strength of 400 psi prior to opening lanes to traffic and of 600 psi in 7 days. Curing of test specimens was performed to match as closely as possible the temperature history of RSC pavement.

Figure 1 shows an example of temperature measurements performed in the course of a trial slab construction. RSC was produced with CTS Rapid-Set® Cement.

Test beams were cured under thermal-insulating boxes and blankets, a temperature matching system proposed by Twining Laboratories and used on numerous pavement rehabilitation projects.
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Caltrans Contract 07-244704
Performance of RSC with CTS Rapid Set® Cement

This project, executed from September 2005 through October 2006, involved the replacement of concrete pavement slabs on Route 710 in Los Angeles County. Most sections to be reconstructed were less than a mile in length but extended into more than one lane. The Contractor, All American Asphalt, was permitted by Caltrans to close one lane at a time in each section for approximately six hours. Construction was permitted only during night time in order to minimize traffic impact and commuter inconvenience.

The following activities were performed during the 6-hour window:

- Traffic control and closure of lanes,
- Removal of old pavement by non-impact method,
- Installation of bond-breaker over the existing base left in place,
- Installation of foam-material insulation at contact joints,
- Placement, consolidation, roller-screeding, and finishing of RSC,
- Application of curing compound,
- Curing for achieving flexural strength required for opening lanes to traffic (Note: limiting time is the time since placing the last RSC load),
- Saw cutting transverse joints, where needed,
- Testing for flexural strength prior to opening lanes to traffic, and
- Opening lanes to traffic.

The Contractor used RSC with CTS Rapid Set® Cement. The mix was designed to achieve flexural strength of 400 psi in approximately 1.5 hours. RSC was produced by Short Load Concrete using mobile mixers. Mix proportions are provided in Table 3. Testing during construction of the trial slab demonstrated that the mix attained more than 500 psi within the first hour after finishing of beam specimens and over 600 psi within the first 24 hours (Figure 2).
During construction, quality control testing was performed in accordance with the Project Special Provisions. We analyzed strength data for a total of 74 sets of beams fabricated and tested over the course of construction. Each set consisted of three beams tested prior to opening lanes to traffic and three beams tested at 7 days. Ambient and concrete temperatures were recorded at the time of sampling of concrete. Our analysis is summarized in Table 4.

**Table 4. Analysis of Flexural Strength Data, CT 07-244704**

<table>
<thead>
<tr>
<th>Duration of analyzed period</th>
<th>September 2005 through October 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of analyzed sets of data</td>
<td>74</td>
</tr>
<tr>
<td>Flexural strength @ 1.5 hours</td>
<td>Average (psi) 480</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation (psi) 52</td>
</tr>
<tr>
<td></td>
<td>Coefficient of Variation (%) 9</td>
</tr>
<tr>
<td>Flexural Strength @ 7 days</td>
<td>Average (psi) 731</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation (psi) 48</td>
</tr>
<tr>
<td></td>
<td>Coefficient of Variation (%) 7</td>
</tr>
<tr>
<td>Initial Concrete Temperature</td>
<td>Minimum (°F) 62 (in December)</td>
</tr>
<tr>
<td></td>
<td>Maximum (°F) 89 (in July)</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>Minimum (°F) 49 (in January)</td>
</tr>
<tr>
<td></td>
<td>Maximum (°F) 72 (in July)</td>
</tr>
</tbody>
</table>
Caltrans Contract 07-193104

Performance of RSC with Ultimax Cement DOT®

This project has been built since April 2006 and involved replacement of randomly located concrete pavement panels on Route 5 in Downtown Los Angeles. Traffic requirements did not permit more than one closure per bound and also limited the maximum duration of closures to approximately 8 hours. Pavement replacement was performed night time during weekends.

The contractor Flatiron West used RSC achieving flexural strength of 400 psi in one to two hours. This allowed for moving lane closures, where the initially replaced sections were opened as soon as the RSC pavement achieved the required flexural strength. RSC was produced by fleet of volumetric mixers operated by Flatiron West. Scope of work was generally the same as explained in the above paragraph.

Proportions of RSC used on the project are provided in Table 5. Figure 3 shows the development of flexural strength as tested in the course of trial slab construction.

<table>
<thead>
<tr>
<th>Hydraulic Cement Type</th>
<th>W/Cm</th>
<th>Max Aggregate Size</th>
<th>Air</th>
<th>High-Range Water Reducer</th>
<th>Accelerator Dose</th>
<th>Set-Retarder or Hydration Stabilizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimax DOT® 705, lb/yd³</td>
<td>0.38</td>
<td>1-inch</td>
<td>1.5%</td>
<td>Sika 2100</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

Test data consisting of ambient and concrete temperatures and early age and 7-day flexural strength was collected for the entire duration of the project. However, considering that the coldest months of the year are the most detrimental to the development of flexural strength of RSC, statistical analysis was performed for the months of November 2006 through January 2007. A summary of this analysis is presented in Table 6.
Table 6. Analysis of Flexural Strength Data, CT 07-193104

<table>
<thead>
<tr>
<th>Duration of analyzed period</th>
<th>November 2006 through January 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of analyzed sets of data</td>
<td>27</td>
</tr>
</tbody>
</table>

Flexural strength @ 1 hours
- Average (psi): 543
- Standard Deviation (psi): 55
- Coefficient of Variation (%): 10

Flexural Strength @ 7 days
- Average (psi): 742
- Standard Deviation (psi): 58
- Coefficient of Variation (%): 8

Initial Concrete Temperature
- Minimum (°F): 57 (in January)
- Maximum (°F): 74 (in December)

Ambient Temperature
- Minimum (°F): 45 (in January)
- Maximum (°F): 68 (in December)

Caltrans Contract 04-3A0304
Performance of RSC with Type III Portland Cement and Non-Chloride Accelerator

This project was executed on Route 101 in Sonoma County in September 2008 (general contractor Pave Tech, Inc.). The mix (Table 7) was designed to achieve 400 psi flexural strength in approximately 3 to 4 hours. Testing during the trial slab construction showed that the required strength was achieved in less than 3 hours after finishing of beam specimens (Figure 4). Summary of field strength and temperature data is provided in Table 8.

Table 7. Mix proportions - CT 04-3A0304

<table>
<thead>
<tr>
<th>Hydraulic Cement Type Content</th>
<th>W/Cm</th>
<th>Max Aggregate Size</th>
<th>Air</th>
<th>High-Range Water Reducer</th>
<th>Accelerator Dose</th>
<th>Set-Retarder or Hydration Stabilizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC Type III, Lehigh 800, lb/yd³</td>
<td>0.31</td>
<td>1-inch</td>
<td>1.5 %</td>
<td>Glenium 7500</td>
<td>NC-534 80 fl.oz. per 100 # cmt.</td>
<td>Delvo</td>
</tr>
</tbody>
</table>
Figure 4. Flexural strength development data from trial slab construction, CT 04-3A0304

Table 8. Analysis of Flexural Strength Data, CT 04-3A0304

<table>
<thead>
<tr>
<th>Duration of analyzed period</th>
<th>September 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of analyzed sets of data</td>
<td>20</td>
</tr>
<tr>
<td>Flexural strength @ 3 hours</td>
<td>Average (psi)</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation (psi)</td>
</tr>
<tr>
<td></td>
<td>Coefficient of Variation (%)</td>
</tr>
<tr>
<td>Flexural Strength @ 7 days</td>
<td>Average (psi)</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation (psi)</td>
</tr>
<tr>
<td></td>
<td>Coefficient of Variation (%)</td>
</tr>
<tr>
<td>Initial Concrete Temperature</td>
<td>Minimum (°F)</td>
</tr>
<tr>
<td></td>
<td>Maximum (°F)</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>Minimum (°F)</td>
</tr>
<tr>
<td></td>
<td>Maximum (°F)</td>
</tr>
</tbody>
</table>

Caltrans Contract 07-166824

Performance of RSC with Type III Portland Cement and Non-Chloride Accelerator

This project is currently under construction on Route 10 in Los Angeles County. Replacement of HOV lanes is performed during 55-hour weekend closures starting Friday night and ending Monday 5:00 AM. Unlike other projects discussed above, this project involves complete replacement of HOV lanes. During the 55-hour closure existing pavement section is removed followed by:

- Preparation of the subgrade,
- Placement of rapid strength lean concrete base (RSLCB),
- Intermediate curing of RSLCB,
- Testing of RSLCB for compressive strength,
- Application of bond breaker,
- Installation of load transferring devices,
- Preparation of contact joints,
Placement of new RSC pavement,
Application of curing compound,
Saw cutting joints,
Curing for achieving flexural strength required for opening lanes to traffic (Note: limiting time is the time since placing the last RSC load),
Testing for flexural strength, and
Opening lanes.

The RSLCB is required to achieve a compressive strength of 725 psi (5 MPa) before construction traffic can be opened on it. For pavement construction the contractor Griffith Company elected to use RSC achieving flexural strength of 400 psi in 12 hours. Table 9 provides proportions of the RSC used for pavement section. Transit mixed RSC is supplied by Robertson’s. Figure 5 presents the strength gain as tested during construction of the trial slab.

Table 9. Mix proportions – CT 07-166824

<table>
<thead>
<tr>
<th>Hydraulic Cement Type Content</th>
<th>W/Cm</th>
<th>Max Aggregate Size</th>
<th>Air</th>
<th>High-Range Water Reducer</th>
<th>Accelerator Dose</th>
<th>Set-Retarder or Hydration Stabilizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC Type III, Mitsubishi 752, lb/ yd³</td>
<td>0.35</td>
<td>1.5-inch</td>
<td>2 %</td>
<td>ADVA 190</td>
<td>Polarset</td>
<td>Recover</td>
</tr>
</tbody>
</table>

Acceptance testing for flexural strength prior to opening HOV to traffic, due to logistics of the project, is performed at varying ages. Therefore early age flexural strength data is not analyzed statistically. However, it shall be noted that that during the production RSC has always achieved the specified flexural strength in 12 hours of curing or less.
Table 10 presents 7-day statistical analysis of field data obtained November 2008 through February 2009.

Table 10. Analysis of Flexural Strength Data, CT 07-166824

<table>
<thead>
<tr>
<th>Duration of analyzed period</th>
<th>November 2008 through February 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of analyzed sets of data</td>
<td>59</td>
</tr>
<tr>
<td>Flexural Strength @ 7 days</td>
<td>Average (psi) 782</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation (psi) 57</td>
</tr>
<tr>
<td></td>
<td>Coefficient of Variation (%) 7</td>
</tr>
<tr>
<td>Initial Concrete Temperature</td>
<td>Minimum (°F) 77</td>
</tr>
<tr>
<td></td>
<td>Maximum (°F) 88</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>Minimum (°F) 49 (in January)</td>
</tr>
<tr>
<td></td>
<td>Maximum (°F) 78 (in February)</td>
</tr>
</tbody>
</table>

Discussion of Field Strength Data

Analysis of strength data presented in Tables 3, 5, 7, and 9 demonstrates the following:

- Coefficient of variation of flexural strength of RSC in 7 days is similar to the one of regular concrete in 28 days,
- Uniformity of early age flexural strength is somewhat higher than in 7 days, however, is comparable with uniformity of flexural strength of regular portland cement concrete for pavements in 28 days,
- To the extent the ambient temperature can be accounted for and proper adjustments made to dosage rates of hydration stabilizers (or retarders), accelerators of hardening, and to initial temperature of concrete (during cooler weather periods), early age strength of RSC can be maintained uniform and predictable,
- In general gain of flexural strength of RSC appears to be more predictable and field data more uniform than often it is deemed to be, and
- Statistical field strength data can be used for establishing required flexural strength upon proportioning of RSC.

CONCLUSIONS

Rapid strength concrete (RSC) types discussed in the paper can be specified and designed for workability and strength, as well as for exposure conditions and drying shrinkage.

Design for workability should include both consistency (slump or penetration) and time within which the mix retains workable consistency. The minimum required time within which RSC retains workable consistency is an important mix design parameter and shall be specified with respect to the method of production and delivery of concrete.

Proportioning shall account for ambient temperature with respect to both strength gain and workability of RSC. Proper adjustments to dosage rates of hydration stabilizers (or retarders), accelerators of hardening (where required), and to initial temperature of concrete allow for maintaining predictable and uniform workability and strength gain of RSC.

Field strength data of RSC proportioned with similar types of materials can be used for establishing required flexural strength, provided the minimum curing period of the backup mix is the same as of the design
mix and the previous ambient temperature history and temperature anticipated during new construction are accounted for.

Proper specifications for resistance of RSC to special exposure conditions shall be established and implemented. These specifications shall consider sulfate and other performance requirements set by the relevant ASTM standards for hydraulic cement types used for RSC.

Procedure for testing of RSC for drying shrinkage shall be revisited and standardized with respect to the duration of moist curing prior to the initial length reading.

REFERENCES

Rapid Strength Portland Cement Concrete, Tom Pyle and Robert Sugar, Caltrans, Materials Engineering and Testing Services, November, 2001

Products in Practice - 4x4™ Concrete Very High-early Strength Concrete Mixture, BASF