
DEVELOPMENT OF HIGH EARLY-STRENGTH CONCRETE FOR ACCELERATED BRIDGE CONSTRUCTION CLOSURE POUR CONNECTIONS

Rahul¹, Mr. Pardeep²

¹M. tech Scholar, Satpriya group of institutions, Rohtak, India.

²Assistant Professor, Satpriya group of institutions, Rohtak, India.

DOI: <https://www.doi.org/10.58257/IJPREMS31256>

ABSTRACT

Accelerated Bridge Construction (ABC) has become a popular alternative to using traditional construction techniques to build new bridges and replace existing bridge decks due to the reduction in time spent on field activities. A key feature of bridges built using ABC techniques is the extensive use of prefabricated components. Precast components are joined on site using small volume closure castings using high quality materials (steel and concrete) to ensure adequate transfer of forces between components. Until now, materials developed for capping were based on proprietary ingredients, so there was a need to develop compounds that used generic ingredients. The objective of this research was to develop a method for developing concrete mixes that are designed using generic ingredients and that meet the performance requirements of accelerated backfills for bridge structures in New England, particularly high initial strength and long-term durability. Two concrete mixes were developed with the primary objective of achieving high initial strength while maintaining workability. A secondary objective of the concrete mixes was durability; therefore, in the development of the concrete mix, measures were taken to create a mix that also has durable properties.

Keywords: Prefabricated components, proprietary components, constructability, durability

1. INTRODUCTION

Currently, most materials used for closure pours contain proprietary components, such as ultra-high-performance concrete (UHPC) that contains steel fibers, or rapid setting concrete that contains proprietary cements (Ultimax Cement, Rapid Set DOT Cement, etc.). The proprietary nature of these materials makes it difficult to specify in federally funded projects making their use sparse and only on selected projects. Research has been conducted by the Federal Highway Administration (FHWA), the American Concrete Institute (ACI) and the New Jersey Department of Transportation (NJDOT) that demonstrates UHPC and rapid setting concrete can successfully meet the demands required of connections between prefabricated components (Al-manaseer et al. 2000; Balaguru and Bhatt 2001; Najm and Balaguru 2005; Russell and Graybeal 2013). Rapid setting concrete mixtures have shown to reach 2000 psi (14 MPa) in as little as 3 hours. UHPC has displayed a range of ultimate strengths from 20 to 30 ksi (140 to 200 MPa). An example of an UHPC in a recently constructed bulb-tee bridge can be seen in Figure 1-1. As mentioned, the materials currently used for ABC closure pours utilize properties of proprietary components, making it expensive for extensive use and hindering the widespread application of these materials. It is also difficult to sole-source proprietary materials in state bridge projects, which often makes it impractical to specify these materials for ABC. Consequently, a need for the development of concrete mixtures comprised of generic component has emerged. These concrete mixtures must still satisfy some of the performance requirements of ABC closure pours, including a high strength gain rate and long-term durability for their use in highway bridge projects. Most of the past research on UHPC and rapid setting concrete has not incorporated the working and environmental conditions specific to New England (Najm and Balaguru 2005; Russell and Graybeal 2013). During both construction and operation, bridges in New England are subjected to unique demands. The very wide range in temperatures that are encountered need to be considered for construction; temperatures in New England range from highs above 90°F in the summer to lows near 0°F in the winter. Even if measures are taken to avoid casting concrete for closure pours in extreme temperatures, a wide range of temperatures need to be accommodated for concrete mixtures with intended use in New England. Temperature at the time of placement affects short-term and long-term concrete properties, including set time, strength gain rate, ultimate strength, plastic shrinkage, drying shrinkage and workability. During the winter, bridges are also subjected to freeze-thaw cycles and the use of deicing chemicals, both of which could negatively affect the durability of the concrete used for closure pours.

Research Objective-The main objective of this research project was to develop and validate concrete mixtures that develop high-early strength without detrimentally affecting their long-term performance. The concrete mixtures designed for this research project were developed for use in ABC in New England; therefore, attention was paid to conditions specific to the environment in the region when developing the mixtures, such as freeze-thaw cycles, the use of deicing materials and concrete placement under a varied range of temperatures.

2. LITERATURE REVIEW

Chaurpagar.et.al. (2004), the author investigated physical and mechanical properties of RCA with and without steel fibres and polymer against controlled concrete. Specimens (cubes/beams/cylinders) were prepared by varying the parameters like water cement ratio and volume of polymer (2.5%, 5.0%, and 10% by parts weight of cement) and constant 0.5% steel fibre by volume of concrete. Recycled Aggregate and Natural Aggregate shows that the former has high specific gravity, high absorption capacity and low fineness modulus. Resistance to mechanical actions such as crushing strength, impact value and abrasion value of recycled aggregates are significantly higher than that of conventional aggregates. There is a marginal increase in the compressive strength due to the addition of polymer-steel fiber in recycled concrete. There is significant increase in split tensile strength and flexure strength at 90 days in polymer steel fiber recycled aggregate concrete as compared to conventional as well as recycled aggregate concrete. Area under stress strain curve is higher, shows the high toughness properties of concrete that it indicates that polymer concrete is more suitable for the earthquake resisting structures. It is observed that there is an improvement in the ductility with addition of 10% polymer & 0.5% steel fiber in the concrete as compared to recycled aggregate concrete as well as conventional concrete.

Limbachiya.et.al. (2004), the report aimed at examining the performance of Portland Cement Concrete produced with natural and coarse aggregates. The study showed that because of attached cement paste in RCA, the density of these materials is about 3- 10% lower and water absorption is about 3-5 times higher than the corresponding natural aggregates. The results also indicate that for RCA samples obtained from four different sources, there was no significant variation in strength of concrete at a given RCA content.

Natesan.et.al. (2005), an experimental investigation was conducted to study the mechanical properties of concrete where natural coarse aggregate is partially replaced with recycled coarse aggregate. It was concluded that RCA increases the mechanical properties of conventional concrete and it was observed that a mix of 75% RCA and 25% Natural Aggregates has good mechanical properties. RCA with rough surface allows better bonding with cement mix.

Naik.et.al. (2006), this paper throws some light on the production of recycled aggregates, their properties and their suitability in the production of concrete. Also, the properties and the application of recycled aggregate concrete are discussed in detail along with bringing out the limitations of recycled aggregate concrete. This study showed that recycled aggregates had higher water absorption value than natural aggregates but less density and strength.

Choudary.et.al. (2006), the author investigated workability and strength properties of RCA. The recycled aggregate concrete is made by mixing 60% of recycled aggregates with 40% of crushed stone chips. The aggregates used for concrete batching are maintained at *saturated surface dry condition*. The workability of the recycled aggregate concrete is slightly lower than that of the conventional concrete. The compressive strength of the recycled aggregate concrete is slightly lower than that of the conventional concrete and recycled concrete aggregate or recycled with conventional concrete can be used in normal plain and reinforced concrete construction. The recycled and conventional concrete containing 60% of recycled aggregate and 40% of crushed natural stone chips occupies almost an intermediate position in terms of workability and strength consideration between the other types of concrete. So from economy and performance point of view, this type of concrete is suitable only next to conventional concrete.

3. EXPERIMENTAL INVESTIGATION

Strength Compressive Strength The compressive strength was measured for every batch of every concrete mixture prepared during this project. A table providing the compressive strengths measured for each batch can be found in APPENDIX B. As stated in Section 1.3: Scope of Work, the compressive strength goal for the concrete mixtures developed in this project was to reach 4000 psi in 12 hours. When developing the concrete mixtures, the compressive strength was a major factor used in determining two concrete mixtures that would be selected for further testing. This development process was explained in detail in Chapter 3. Strength gain curves of trial batch concrete mixtures are shown in Figure 5-1. Each line in the plot represents a different concrete mixture with compressive strength values plotted at 12 and 24 hours as well as 7 and 28 days. This plot is presented only to provide an idea of the general trends

in the compressive strength data, not to provide compressive strength values of specific trial batch concrete mixture. The compressive strength that trial batch concrete mixtures reached in 12 hours ranged from 1000 to 5900 psi. The compressive strength increased an average of 2000 psi in the following 12 hours, reaching between 3800 and 7600 psi at 24 hours of curing. The compressive strength after 7 days of curing was between 6500 and 9400 psi, yielding an overall average 7-day compressive strength equal to 8000 psi. The compressive strength at 28 days of curing ranged from 7500 to 12000 psi, yielding an overall average 28-day compressive strength equal to 10000 psi. These ranges result in compressive strengths of approximately 36, 55 and 80% of the 28-day compressive strength reached at 12 hours, 24 hours and 7 days, respectively. The effect of fly ash replacement level on strength gain rates was also evaluated in Figure 5-1. Darker lines correspond to higher amounts of fly ash used in each concrete mixture. The lightest lines have 0% fly ash replacement. The darkest lines have 25% fly ash replacement, which is the highest replacement percentage used in this project. In general, the concrete mixtures with a higher fly ash replacement had strengths that developed later than those with a lower fly ash replacement. However, there were outliers in this trend, such as the concrete mixture which achieved the lowest 28-day compressive strength, as shown in Figure 5-1 as a dark line. The concrete mixture contained 25% fly ash but had very little strength gain between 7 and 28 days, only 2000 psi.

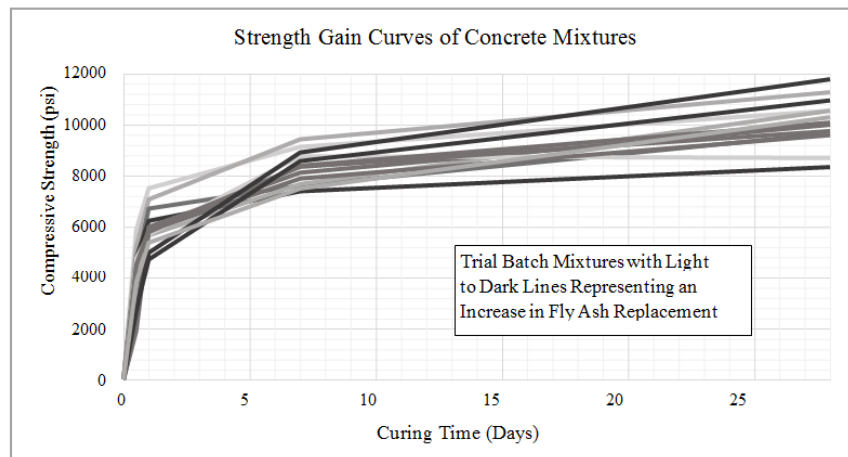


Figure 3-1: Strength Gain Curves of Trial Batch and Selected Concrete Mixtures

The effect of w/cm on the 12-hour compressive strength of concrete mixtures was also evaluated, as shown in Table 5-1. The average 12-hour compressive strength of concrete mixtures with a w/cm ratio equal to 0.26 was 5030 psi. The average 12-hour compressive strength dropped by about 40% to 3550 psi when the w/cm ratio was increased to 0.29. However, with a subsequent increase in w/cm ratio of the same amount to 0.32, the 12-hour compressive strength only decreased by approximately 10%.

Table 3-1: Comparison of Average Compressive Strength Values with Varying w/cm Ratios

w/cm ratio	12-HOUR CompressiveStrength (psi)
0.26	5030
0.29	3550
0.32	3200

An assessment was also performed on the effect of the V_{paste}/V_{voids} ratio used in a concrete mixture. The concrete mixtures used to compare V_{paste}/V_{voids} had other proportions that were equal. The w/cm ratio was equal to 0.29, 1/2" coarse aggregate was used and each concrete mixture contained 15% fly ash replacement. As seen in Table 5-2, the 12-hour compressive strengths were not significantly affected by a change in the V_{paste}/V_{voids} ratio. The largest difference in strength was 2%. The effect of coarse aggregate size on compressive strength was also assessed. In order to compare only the coarse aggregate size, the other parameters were kept constant. The w/cm ratio was equal to 0.29, the V_{paste}/V_{voids} ratio was equal to 1.75 and the average was taken from trial batches contained 15 and 20% fly ash replacement. As shown in Table 5-3, the 12-hour strength was significantly affected by a change in coarse aggregate size. Trial batches with 3/8" coarse aggregate had a 12-hour compressive strength 2.5 times greater than those with 1/2" coarse aggregate. However, the constructability of trial batches containing 3/8" coarse aggregate was unacceptable.

Table 3-2: Comparison of Average Compressive Strength Values with Varying V_{paste}/V_{voids} Ratios

V_{paste}/V_{voids} ¹	HOUR CompressiveStrength (psi)
1.75	3880
1.50	3810
1.25	3880
1 - Averaged from concrete mixtures with w/cm = 0.29, 15% fly ash replacement and 1/2" coarse aggregate	

Compressive strength values of the two selected concrete mixtures, MIX 6-HD and MIX 15-HD, at 12 and 24 hours after curing are shown in Figure 5-2. These strength values are also reported in Table 5-4, along with 7- and 28-day compressive strengths of the two selected concrete mixtures. As seen in Figure 5-2, the average compressive strength reached in 12 hours was slightly below 4000 psi for both MIX 6-HD and MIX 15-HD. MIX 6-HD reached an average compressive strength of 4000 psi in approximately 13.1 hours and MIX 15-HD reached an average compressive strength of 4000 psi in approximately 13.4 hours, as shown in Figure 5-2 by linear interpolation between the 12 and 24hour strengths. If this strength gain is inadequate for the application desired, there are options for increasing strength gain of the concrete mixtures.

Table 5-3: Comparison of Average Compressive Strength Values with Varying Coarse Aggregate Size

Coarse Aggregate Size(inches)*	HOUR CompressiveStrength (psi)
1/2	1560
3/8	3770
*Averaged from concrete mixtures with w/cm = 0.29, 15 & 20% fly ash replacement and $V_{paste}/V_{voids} = 1.75$	

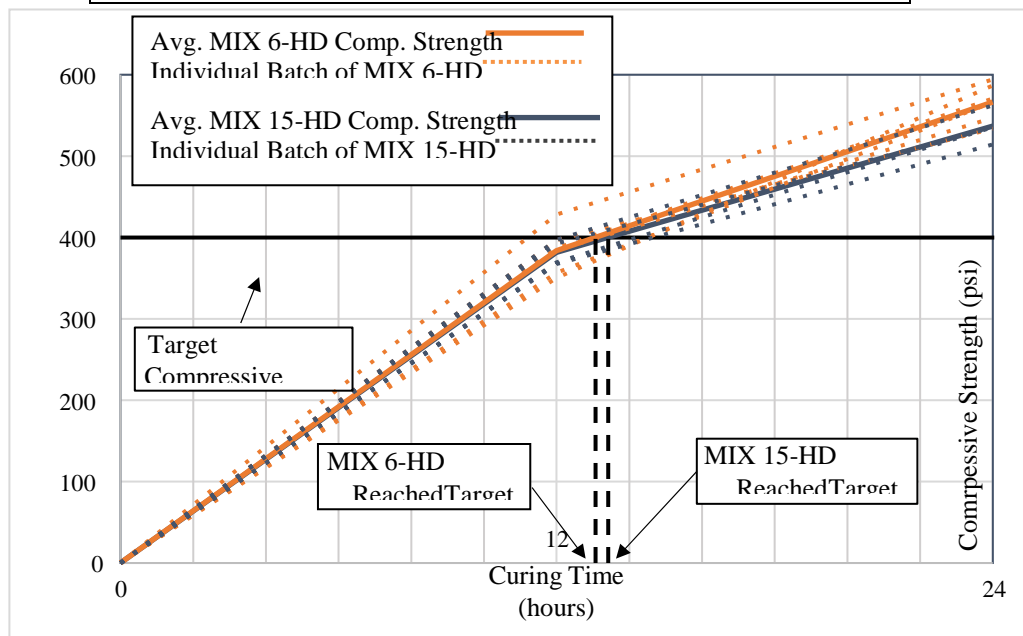


Figure 5-2: Compressive Strength Curves of Selected Concrete Mixtures

Compressive strength specimens in this project were cured at 80°F and 100% relative humidity. The option of curing compressive strength specimens at a higher temperature was explored as an option of increasing compressive strength in a short time period. MIX 6-HD and MIX 15-HD were cured at 110°F and 100% relative humidity, creating trial batches MIX 6-HD-H and 15-HD-H, respectively. The results of this experiment are provided in Table 5-4. By increasing the curing temperature to 110°F, the target compressive strength of 4000 psi was reached in approximately 9 hours for both selected concrete mixtures. The compressive strength reached in 12 hours was 5140 and 5200 psi for MIX 6-HD-H and 15-HD-H, respectively.

Table 3-4: Compressive Strength Values for Selected Concrete Mixtures

ConcreteMixture	Batch	Compressive Strength (psi)			
		12-HOUR	24-HOUR	7 DAY	28 DAY
MIX 6-HD	A	4280	5940	-	-
	B	3500	5870	-	-
	C	3870	5710	7680	10560
	D	3570	5660	-	-
	E	3970	5340	-	-
	F	3840	5470	-	-
	Average	3840	5660	7680	10560
MIX 6-HD-H	A	5140	6160	-	-
	Average	5140	6160	-	-
MIX 15-HD	A	3970	5620	-	-
	B	3700	5360	-	-
	C	3930	5350	7500	10300
	D	3670	5140	-	-
	Average	3820	5370	7500	1030
MIX 15-HD-H	A	5200	6160	-	-
	Average	5200	6160	-	-

The compressive strength that the two selected concrete mixtures, MIX 6-HD and MIX 15-HD reached in 12 hours is only about 5% under the target strength. If it is necessary to reach the exact target compressive strength of 4000 psi in 12 hours, the curing temperature can be increased. By increasing the curing temperature, a 12-hour compressive strength 30% greater than the target was attained during this project.

4. CONCLUSION

To develop the concrete mixtures, various proportioning methods were studied. There were three methods considered: (1) building upon past experience by using state-of-practice concrete mixtures; (2) following ACI 211.4R Guidelines; and (3) targeting a mixture with maximum aggregate compaction. The first method used was the state-of-practice concrete mixtures, which were collected from DOTs and pre-casters throughout New England. For this method, the state-of-practice concrete mixtures were used as baseline designs. However, when state-of-practice concrete mixtures were replicated during this project, the strength and/or constructability goals of this project were not met. This was expected since the reported strength and/or constructability were also less than the goals of this project. Chemical admixture dosages were altered in an attempt to achieve strength and constructability goals with the state-of-practice concrete mixtures, but it was not successful. The second method considered for concrete proportioning was to follow the guidelines presented by ACI Committee 211, ACI 211.4R: *Guide for Selecting Proportions for High-Strength Concrete Using Portland Cement and Other Cementitious Materials*. The trial batch concrete mixtures developed using this method produced baseline results that were relatively close to acceptable strength and constructability limits. Through the use of chemical admixtures and slight alterations to the proportions, it appeared that this method would provide satisfactory results. However, this method was not chosen to be used as the primary proportioning method in this research project because proportioning is based on tables and equations without the exact constituent proportions necessarily being provided. The final method considered for concrete proportioning, maximum compaction of aggregates, also produced baseline results that had strength and constructability results that were within acceptable limits, and this method allowed for easier manipulation of the concrete mixture designs, given the knowledge of exact proportions. The final method, maximum compaction of aggregate was developed using five parameters: aggregate gradation, coarse aggregate size, w/cm ratio, percent fly ash replacement and volume of paste to volume of voids (V_{paste}/V_{voids}) ratio. Aggregate gradation was designed to create maximum compaction of aggregates, which was achieved using Fuller-Thompson curves. The coarse aggregate size, w/cm ratio, percent fly ash replacement and V_{paste}/V_{voids} ratio were modified throughout the development of the concrete mixtures. The initial

values used were as follows: coarse aggregate size equal to 1/2 inch, w/cm equal to 0.26, 0% fly ash replacement and $V_{\text{paste}}/V_{\text{voids}}$ equal to 1.75. Using this method, an iterative process was followed to find two concrete mixtures which reached strength and constructability goals, while still showing promise for having durable properties. The target compressive strength of 4000 psi in 12 hours of curing was the primary strength requirement. The constructability goals were for the concrete mixture to have a slump greater than 3 inches without segregation occurring and a set time that allowed for the concrete to be placed using common construction techniques. It was found that concrete mixtures with a w/cm ratio equal to 0.26 had consistencies which were too stiff and thick to have acceptable constructability. Alternatively, concrete mixtures with w/cm ratios equal to 0.32 had consistencies that were too fluid, causing the coarse aggregates to segregate from the cement paste and strength to be compromised. A w/cm ratio equal to 0.29 yielded compressive strength and constructability results within acceptable limits.

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