RESEARCH TRENDS IN THE CELLULOSE REINFORCED FIBROUS CONCRETE IN USA

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ABSTRACT

The growth in fast-track construction and repair has prompted major efforts to develop high-early-strength concrete mix compositions. Such mixtures rely on the use of relatively high cement contents and accelerator dosages to increase the rate of strength development. These measures, however, seem to compromise the long-term performance of concrete in applications such as full-depth patches as evidenced by occasional premature deterioration of such patches. The hypothesis successfully validated in this research was that traditional methods of increasing the early-age strength of concrete, involving the use of high cement and accelerator contents, increase the moisture and thermal movements of concrete. Restraint of such movements in actual field conditions, by external or internal restraining factors, generates tensile stresses which introduce microcracks and thus increase the permeability of concrete. This increase in permeability accelerates various processes of concrete deterioration, including freeze-thaw attack.

Fiber reinforcement of concrete is an effective approach to the control of microcrack and crack development under tensile stresses. Fibers, however, have not been known for accelerating the process of strength gain in concrete. The recently developed specialty cellulose fibers, however, were found in this research to be highly effective in increasing the early-age strength of concrete. This provides a unique opportunity to increase the rate of strength gain in concrete without increasing moisture and thermal movements, which actually controlling the processes of microcracking and cracking in concrete. Laboratory test results confirmed the desirable resistance of specialty cellulose fiber reinforced High-early-strength concrete to restrained shrinkage microcrakcing and cracking, and to different processes of deterioration under weathering effects.

Keywords
cellulose fibers; cement content; durability; high-early-strength concrete; mix proportioning; moisture and temperature movements; restrained shrinkage microcracking.

RESEARCH SIGNIFICANCE

The research reported herein makes a contribution towards improvement of the longevity of high-early-strength concrete in fast-track construction and repair projects. In particular, a new high-early-strength concrete mix incorporating specialty cellulose fibers was developed which is more resistance to restrained shrinkage microcracking.

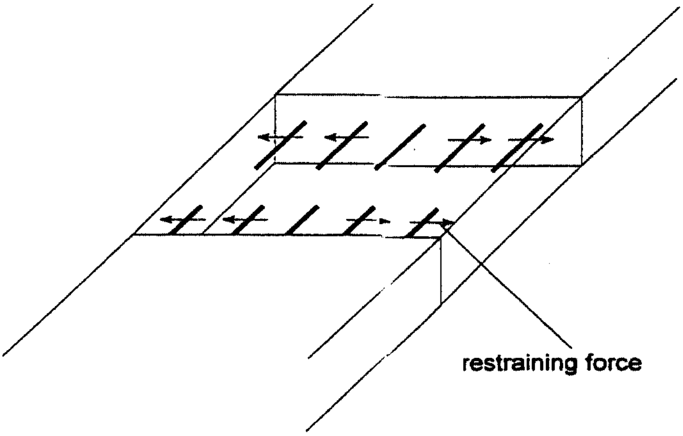
INTRODUCTION

The recent growth in fast track construction and repair of concrete pavements has prompted major developments in the field of high-early-strength concrete.[1,2] Existing high-early-strength concrete mixtures suiting 4 to 24-hour opening to traffic are characterized by high cement (or cementitious binder) contents and relatively high accelerator dosages. Typical cementitious binder contents in normal-strength and high-early-strength concrete mixtures are 325 kg/m^3 (550 lb/yd^3) and 475 kg/m^3 (800 lb/yd^3), respectively.[1-4] Laboratory specimens of such high-early-strength concrete mixtures generally exhibit reasonable durability characteristics.[3] Long-term performance in field conditions, however, has been occasionally less than satisfactory. For example, some full-depth patches made in Michigan with conventional high-early-strength concrete mixtures for 8-hour opening to traffic deteriorated rapidly and had to be replaced in few years.

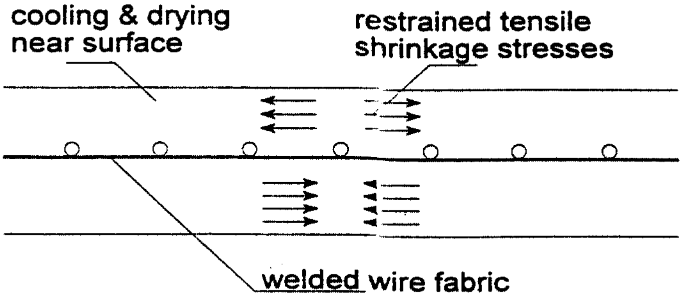
The objective of this project was to determine the causes of premature deterioration of high-early-strength concrete, emphasizing full-depth patches, and to develop concrete mixtures which offer both rapid strength gain and long-term durability.

The approach in this project was based on the hypothesis that the damage caused by restrained shrinkage stresses is largely responsible for premature deterioration of high-early-strength concrete full-depth patches. The relatively high cement content and the presence of accelerators in high-early-strength concrete mixtures tend to increase their thermal and drying shrinkage movements. Thermal shrinkage increases because rapid exothermic hydration reactions cause a rapid increase in concrete temperature at early age. Concrete temperature peaks when it has already developed substantial strength and stiffness. Any internal or external restraint of the subsequent thermal shrinkage movements could thus generate stresses in concrete. Drying shrinkage movements of concrete also increase in high-early-strength concrete because at high cement contents, which characterize high-early-strength concrete, low water-cement ratios do not necessarily reduce drying shrinkage movements. This has been attributed to autogeneous shrinkage due to self-desiccation; interestingly, this type of drying shrinkage can occur even when careful curing prevents moisture loss from concrete to outside environment.[5] Hence, irrespective of the moist curing practice, drying and thermal shrinkage movements initiate in high-early-strength concrete at early ages.

Small laboratory-scale concrete specimens made with high-early-strength concrete generally exhibit acceptable durability characteristics.[3] The key difference between these specimens and field placements is the relatively high degree of restraint against shrinkage movements which is typically present in field. Such restraint can be both external (Figure 1a) which in full-depth patches are due largely to the action of dowel bars normal to their longitudinal direction, or internal (Figure 1b) due to moisture and temperature gradients. The relatively high elastic modulus of high-early-strength concrete tends to raise restrained shrinkage stresses. Welded wire fabric is commonly used to control restrained shrinkage cracking in full-depth patches. The fact that welded wire fabric is located near the mid-depth of the patch, however, reduces its effectiveness at the surface, and could even pronounce the adverse effects of internal restraint. Restrained shrinkage and thermal stresses could produce microcracks in young concrete, which increase its permeability and accelerate long-term deterioration processes under weathering and load effects. An effective approach to the production of high-early-strength concrete with sufficient durability could involve finding new means of increasing the early-age strength of concrete without increasing its drying and thermal shrinkage movements, while also increasing the resistance of concrete to microcracking.



(a) External Restraining Effect of Dowel bars



(b) Internal Restraining Effects of Moisture and Temperature Gradients

Figure 1. External and Internal Restraint Stresses in Full-Depth Patches.

EVALUATION OF DIFFERENT MEANS OF ACCELERATING STRENGTH GAIN

Based on trial-and-adjustment experimental runs, we established one plain high-early-strength (HES) concrete mix and one plain normal-strength (NS) mix for use in this investigation (see Table 1). The high-early-strength mixture suits opening to traffic after 8 hours. The basic mix ingredients were Type I Portland cement, crushed limestone with 25 mm maximum aggregate size, natural sand, and air-entraining agent. The high-early-strength mixe targeted 2.2 MPa (320 psi) flexural strength after 8 hours. All mixes provided slump of 30-70 mm (1.2-2.8 in) and air content of 4-7%.

Table 1. The Established Mix Proportions (1 kg/m^3 = 0.5933 lb/yd^3; 1 ml/m^3 =0.0258 0z/yd^3).

Mix	Water (kg/m^3)	cement (kg/m^3)	Coarse Agg. (kg/m^3)	Fine Agg. (kg/m^3)	Air-Ent.-Agent (ml/m3)	Calcium Chloride (kg/m^3)
High-Early-Strength (HES)	190	500	1040	585	500	16
Normal-Strength (NS)	164	290	1136	770	270	0

Fiber reinforcement was considered in this investigation as an alternative means of accelerating the strength gain. If fibers prove to be effective in this role, they actually help control restrained shrinkage microcracking and cracking of concrete.

Two fibers were considered in this investigation: fibrillated polypropylene fibers of 37 mm (1.48 in) length, and specialty (processed) cellulose fibers. Polypropylene fibers were added to concrete mixtures of Table 1 at 0.9 kg/m^3 (1.5 lb/yd^3), and specialty cellulose (fabroset®) fibers at 1.2 kg/m^3 (2lb/yd^3).

Processed cellulose fibers offer a desirable balance of some key mechanical and geometric attributes which are critical to their reinforcement efficiency in concrete. Table 2 compares the properties of a specialty cellulose (fabroset®) fibers used for the reinforcement of concrete with those of polypropylene fibers. Cellulose and polypropylene fibers are now available at comparable costs. Cellulose fibers offer distinctly high levels of elastic modulus, fiber count (per unit weight), specific surface area, and bond strength to cement-based materials. Their tensile strength is comparable to that of polypropylene fibers. In spite of the extremely high fiber count (about 2 million fibers per gram), the hydrophilic nature of cellulose fiber surfaces facilitate their uniform dispersion in concrete. The high fiber count of cellulose fibers leads to a relatively close spacing of fibers in concrete, which benefits their microcrack control action.

Table 2. Some Key Properties of Cellulose fibers (fabroset®) Versus Polypropylene Fibers.

property	Preferred	Fiber Type	
		Specialty Cellulose	Polypropylene
Elastic Modulus, GPa (Ksi)	High	60 (8,700)	4 (580)
Bond Strength, Mpa (Ksi)	High	1.5 (0.2)	0.4 (0.06)
Tensile Strength, Mpa (Ksi)	High	500 (72)	600 (87)
Effective Diameter, mm (in)	Low	0.15 (0.0006)	0.1 (0.004)
No. of Fibers Per Gram	High	2,000,000	12,000
Length-to-Diameter Ratio	High	200	120
Surface Characteristics	Hydrophilic	Hydrophilic	Hydrophobic
Density, g/cm^3 (lb/ft^3)	Medium	1.5 (94)	0.9 (56)
Alkali Resistance	High	High	High
Fiber Spacing, mm (in)*	Low	0.53 (0.021)	2.8 (0.11)
Fiber Count, 1/cm^3 (1/in^3)*	High	90 (1,475)	0.6 (10)
Specific Surface, 1/cm (1/in)*	High	0.13 (0.33)	0.033 (0.083)

* at 1.2 kg/m^3 (2 lb/yd^3)

Compression (ASTM C 39) and flexure (ASTM C 78) tests were performed at different ages for all concrete mixtures. Compression tests were conducted on cylindrical specimens of 100 mm (4 in) diameter and 200 mm (8 in) length. Prismatic specimens of 100 mm (4 in) square cross section were subjected to four-point flexure tests on a span of 300 mm (12 in). All specimens stayed in their molds under wet burlap and plastic covering up to the test age or 24 hours, whichever shorter. After 24 hours, the specimens were moved to the moist room and kept there up to the test age.

Compressive Strength

Figures 2 present the trends in the development of early-age compressive strength with time for the plain and fiber reinforced high-early-strength concrete mixtures. The introduction of polypropylene fibers to the high-early-strength mix tends to reduce its early-age compressive strength. Unlike polypropylene fibers, cellulose (fabroset®) fibers are observed to be highly effective in increasing the early-age strength of high-early-strength concrete. This result is quite significant because the addition of cellulose fibers for accelerating strength gain, unlike the addition of cement and chemical accelerators for the same purpose, does not increase the potential for restrained drying and thermal shrinkage microcracking and cracking in concrete. On the contrary, the addition of cellulose fibers would reduce the extent of restrained shrinkage microcracking and cracking. We have thus found a new means of enhancing the early-age strength of concrete which, unlike conventional means, actually enhances the deterioration resistance of concrete.

Figure 3 presents a global view of the strength development with time for all mixes considered, including high-early-strength and normal-strength mixtures. The 28-day compressive strengths for high-early-strength mixtures are all in the 40-55 MPa range.

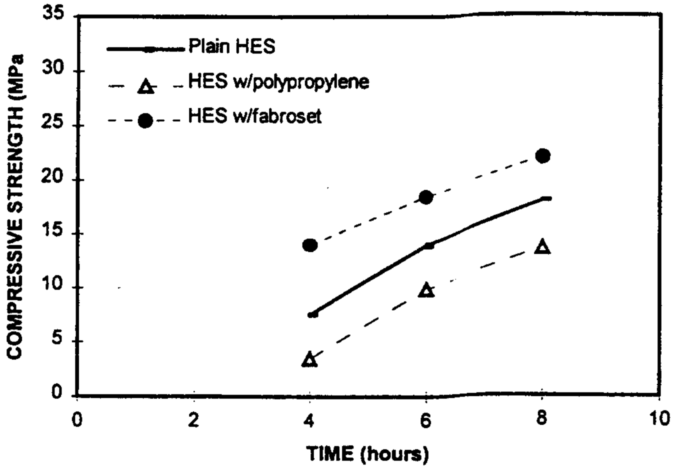


Figure 2. Early-Age Compressive Strength of Plain and Fiber Reinforced High-Early-Strength (HES) Concrete Mixtures.

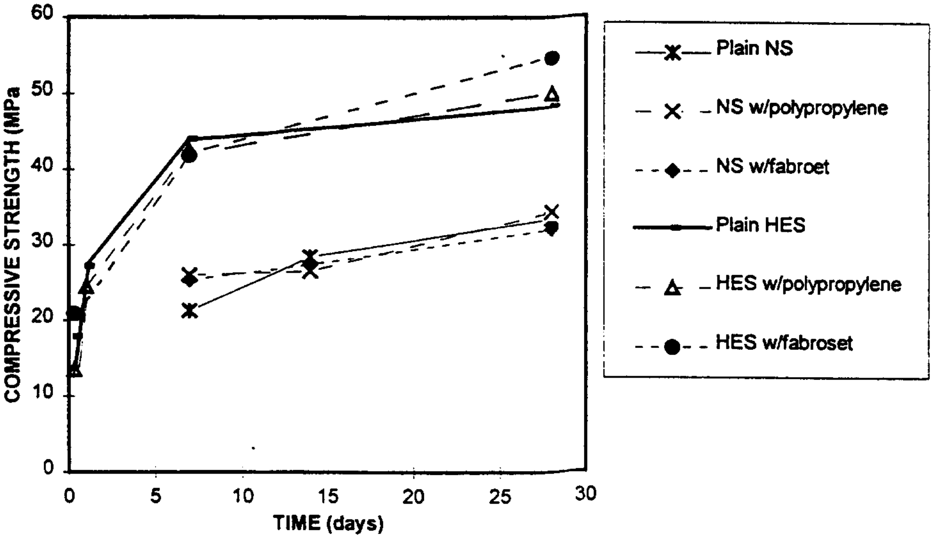


Figure 3. Longer-Range Strength Development with Time in High-Early-Strength (HES) and Normal-Strength (NS) Mixtures.

Flexural Strength

The trends in early-age flexural strength development with time in plain and fiber reinforced high-early-strength concrete mixtures are presented in Figure 4. The introduction of polypropylene fibers at 0.9 kg/m^3 does not significantly alter the early age flexural strength of high early strength concrete. The results, however, confirm the high effectiveness of processed cellulose fibers in enhancing the early-age strength characteristics of high-early-strength concrete. Cellulose fibers also benefit later-age flexural strength of concrete mixtures (Figure 5).

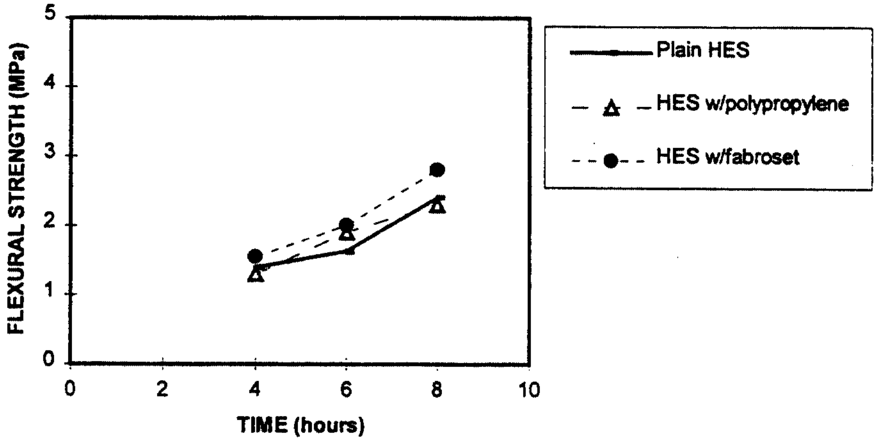


Figure 4. Early-Age Flexural strength Development with Time in Plain and Fiber Reinforced High-Early-Strength (HES) Concrete Mixtures.

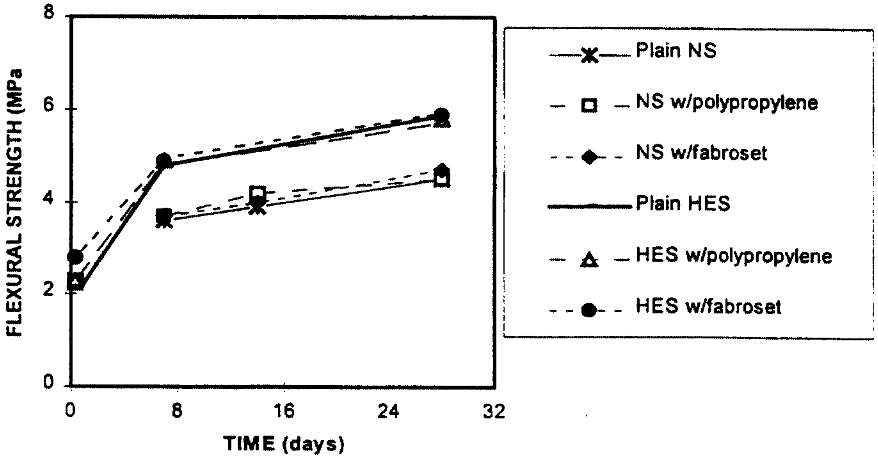


Figure 5. Longer-Range Flexural Strength Development with Time in High-Early-Strength (HES) Normal-Strength (NS) Concrete Mixtures.

The relationships between compressive and flexural strengths at different ages, for all mixtures considered in this investigation, are presented in Figure 6. The results do not exhibit any particular trends which could distinguish between different mixtures.

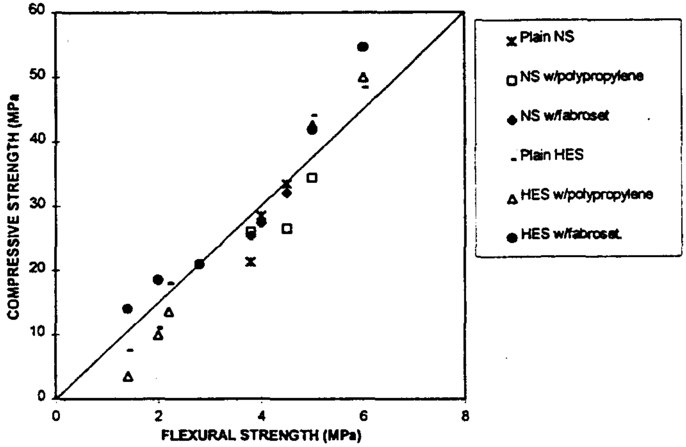


Figure 6. Relationships Between Compressive and Flexural Strength.

STRENGTH DEVELOPMENT IN INSULATED SPECIMENS

In order to create the insulated curing conditions which characteristize of larger concrete placements, molded cylindrical specimens were stored inside a styrofoam insulation up to the testing age or 24 hours, whichever occurred first. After 24 hours, all specimens were removed from insulation, demolded and moist cured up the test age. The trends in early-age compressive strength development with time for insulated specimens are presented in Figure 7. Insulation seems to increase early age-strengths; the results confirm the effectiveness of processed cellulose fibers in enhancing the early-age strength of high-early-strength concrete.

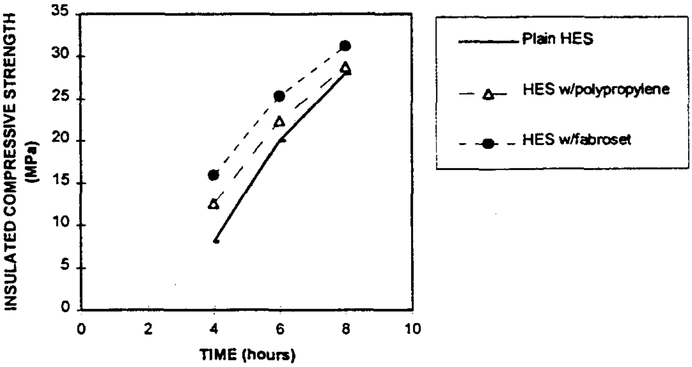


Figure 7. Early-Age Compressive Strength Development in Insulated Specimens.

A comparison between the insulated and uninsulated compressive strengths of different concrete mixtures at different ages (Figure 8) indicates that plain high-early-strength concrete benefits from insulation at early ages (i.e. for lower strength values in Figure 8), but insulation damages longer-term (28-day) strength of plain HES concrete. Fibers in general, and cellulose fibers in particular, seem to reduce this adverse effect of insulation on the later-age strength of HES concrete. This trend could be explained by the potential for microcracking and uneven development of huydration products in HES concrete under the effects of elevated temperatures caused by insulation.

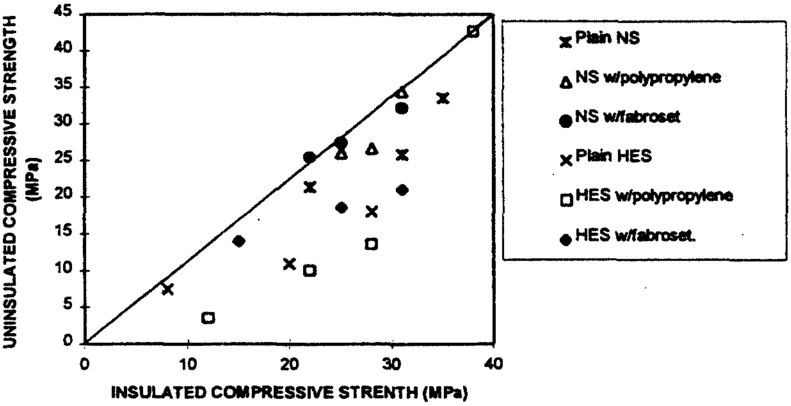
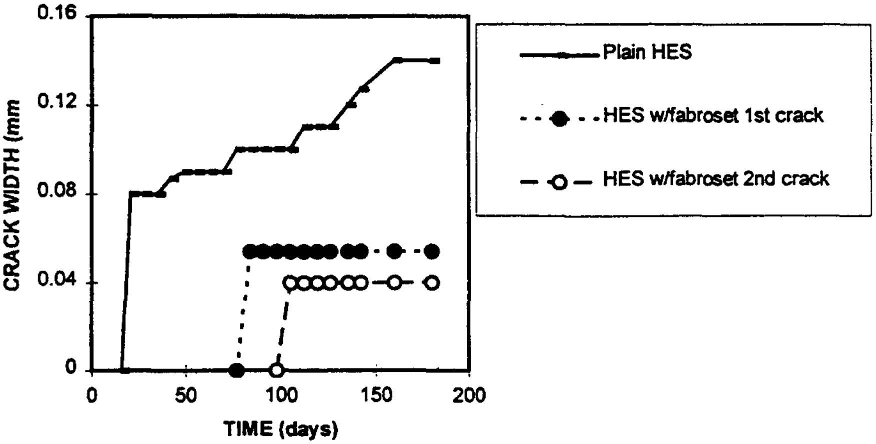


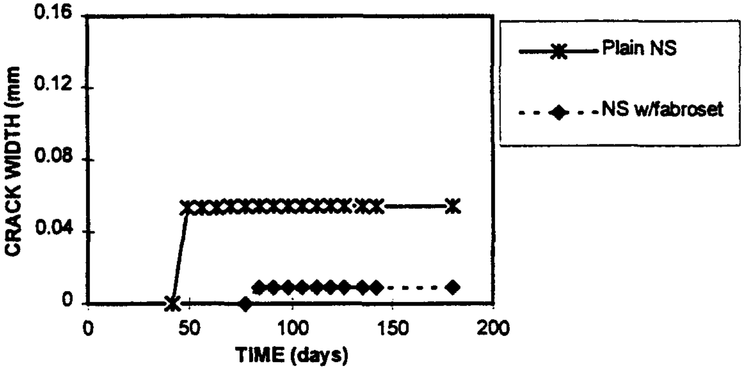
Figure 8. Insulated Vs. Uninsulated Compressive Strengths.

RESTRAINED SHRINKAGE CRACKING

The restrained shrinkage test procedure used at this stage subjected a concrete ring cast around a rigid steel ring to air drying at 35% RH for five hours after casting. The restraint of shrinkage movements in concrete ring by the rigid steel ring generates stresses which cause cracking of concrete. Measurement of crack width, over time thus provides indications for the restrained drying shrinkage characteristics of concrete. The restrained shrinkage test results are presented in Figure 9. Specialty cellulose (fabroset®) fibers are observed in Figures 9a and 9b to control the restrained shrinkage crack widths of both high-early-strength and normal-strength concrete. Fibers tend to cause formation of multiple cracks and thus reduce maximum crack widths in high-early-strength concrete, which is beneficial to impermeability and durability of concrete.



(a) High-Early-Strength Concrete



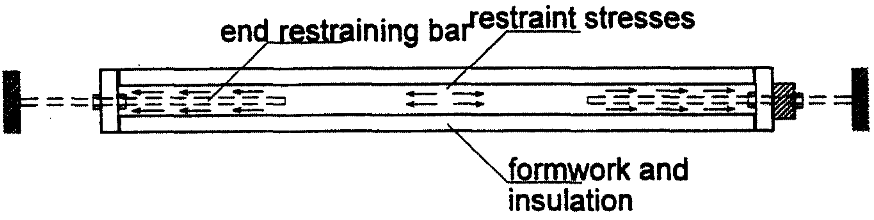
(b) Normal-Strength Concrete

Figure 9. Restrained Shrinkage Test Results.

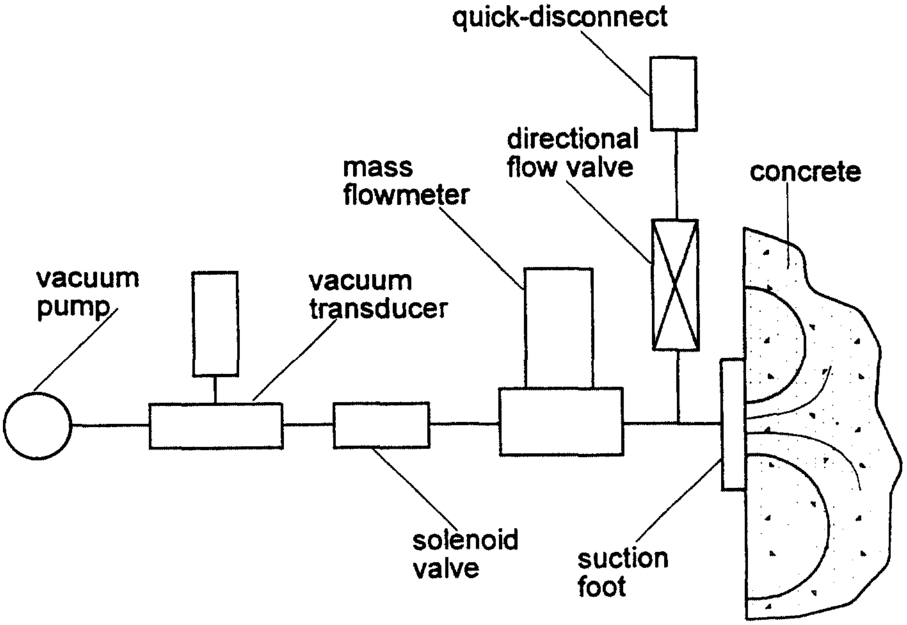
CONSEOVENCES OF MICROCRACKING UNDER RESTRAINED SHRINKAGE STRESSES

Visible cracks represent extreme damages resulting from restraint of shrinkage movements in concrete. Our hypothesis regarding the lack of durability in high-early-strength-concrete implies that microcrakcs associated with restrained shrinkage, which are not readily visible, raise the permeability of concrete and thus damage its durability. At this stage, the impact of restrained shrinkage stresses on air permeability of concrete was measured to validate this hypothesis.

Air permeability tests were performed directly on concrete systems Figure 10a) cast indoor (and not on specimens cored from them); hence, in the case of restrained systems, air permeability tests were performed as concrete was subjected to restrained shrinkage tensile stresses. Unrestrained (free) systems were similar to the restrained ones (Figure 10a) except that end restraining bars were removed. None of the restrained (or unrestrained) specimens showed cracking (#3 restraining bars were used in restrained specimens to provide a moderate degree of restraint). The air permeability tests were performed 60 days after placementof concrete. The air permeability test followed SHRP 2031 test procedures (Figure 10b).



(a) Axial restrained Shrinkage Test Set-Up



(b) Air Permeability

Figure 10. The Axial Restrained Shrinkage and Air Permeability Test Set-Up.

The air permeability test results are presented in Figure 11. The key finding here is that restraint stresses substantially increase the permeability of concrete. This increase is about 130% for plain high-early-strength concrete, and about 90% for high-early-strength concrete reinforced with 1.35 kg/m^3 specialty cellulose (fabroset®) fibers.

Given the crucial effect of permeability on concrete durability, the substantially increased permeability of concrete under restraint stresses would translate into reduced durability of concrete.

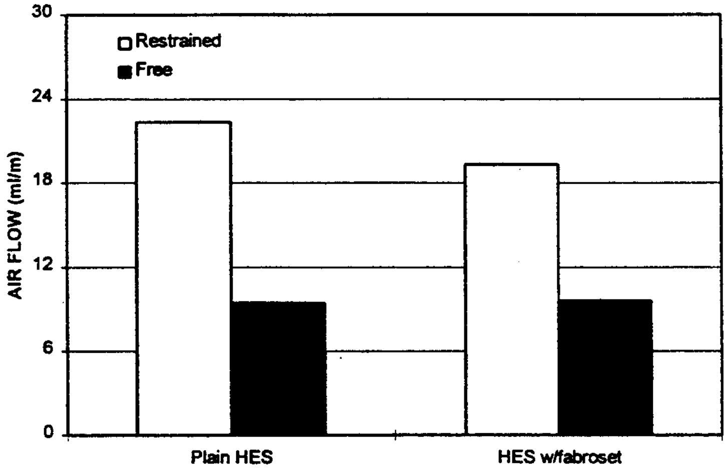


Figure 11. Air permeability Test Results for Free and Restrained High-Early-Strength Concrete Mixtures (1 ml/m = 0.0310z/in).

DURABILITY OF UNRESTRAINED LABORATORY SPECIMENS

Our key hypothesis in this research is that high-early-strength concrete as a material does not have particular durability problems. It is the system conditions (restraint stresses in particular) which damage its performance. In order to validate this hypothesis, high-early-strength concrete specimens, with and without fiber reinforcement, were prepared in laboratory (without any major restraint against shrinkage movements), and were subjected to various accelerated aging effects.

The abrasion (ASTM C 779) test results are presented in Figures 12, and Table 3 summarizes the scaling (ASTM C 672) test results. When compared with normal-strength concrete, unrestrained high-early-strength concrete is observed to exhibit excellent durability characteristics. Unrestrained fiber reinforced and plain high-early-strength concretes are all highly durable except that polypropylene fibers slightly damage the deicer salt scaling resistance of concrete.

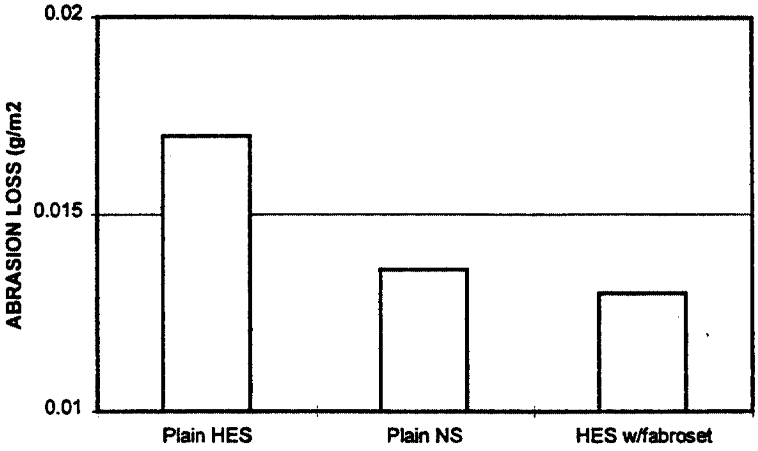


Figure 12. Abrasion Test Results.

Table 3. Deicer Salt Scaling Resistance Test Results.

Salt Deice Scaling Test (0=best, 5=worst)			
Mix ID	25 Cycle	50 Cycle	75 Cycle
NS	0	0	2
NS + Polypropylene	0	1	2.5
NS + Cellulose Fabroset®	0	0	2
HES	0	0	0
HES+Polypropylene	0	0	1
HES+ Cellulose Fabroset®	0	0	0

A NEW DURABLE HIGH-EARLY-STRENGTH CONCRETE WITH PROCESSED CELLULOSE FIBERS

The traditional approach to increasing the early-age strength of concrete relies on relatively high cement and accelerator contents. This approach, increases the drying and thermal shrinkage of concrete, and thus adversely influence the long-term durability of concrete systems. Specialty cellulose fibers, on the other hand, raise the early-age strength of concrete while simultaneously reinforcing the system against drying and thermal shrinkage cracking. Hence, with specialty cellulose fiber reinforcement one could reduce the excess amounts of cement and accelerator content to achieve high early strength without compromising long-term performance. In order to validate this hypothesis, the high-early-strength mix for 8-hr opening to traffic was modified with the addition of specialty cellulose fibers and reduction of the cement and accelerator (calcium chloride) contents. We used the particular high-early-strength concrete mix of this investigation as an example; the same procedure could be applied to other high-early-strength mixtures.

A trial-and-adjustment experimental program was conducted, focusing on early-age-strength, through which we concluded that the addition of specialty cellulose (fabroset®) fibers to concrete at 1.2 kg/m^3 allows for 20% reduction of both cement and calcium chloride contents in the high-early-strength concrete mix without compromising the 8-hr strength of the mix. Table 4 compares the mix proportions of the conventional HES mix and the new HES mix with specialty cellulose fibers. Both conventional HES and new HES mixtures satisfy the 2.2 MPa flexural strength required at eight hours for opening to traffic. Slumps for both mixtures are within 30-70 mm range.

Table 4. Eight-Hour Opening Mixtures With and Without Specialty cellulose Fibers (1 kg/m^3 = 0.5933 lb/yd^3; 1 ml/m^3 =0.0258 0z/yd^3).

Mix	Water (kg/m3)	Cement (kg/m3)	Coarse Ag. (kg/m3)	Fine Ag. (kg/m3)	A.E.A. (ml/m3)	Accelerator (kg/m3)	Fabroset® (kg/m3)
New HES	166.4	415	1068	617.5	415	13	1.2
Conventional HES	190	500	1040	585	500	16	0

Figures 13 through 15 compare the trends in flexural strength, compressive strength, and impact resistance development with time in new HES mixtures with and without specialty cellulose fibers. All aspects of concrete development considered here, at early and later ages, are observed to strongly benefit from the addition of 1.2 kg/m^3 of specialty cellulose fibers.

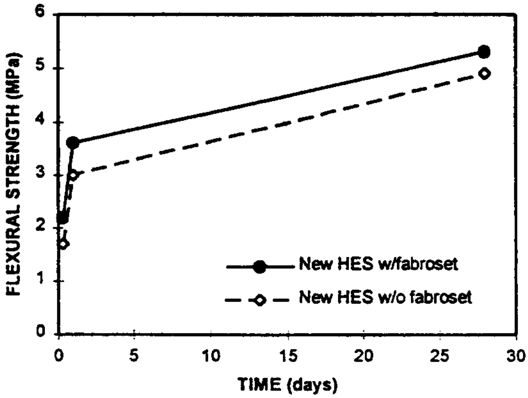


Figure 13. Effects of Specialty Cellulose Fibers on Flexural Strength Development (1 Mpa = 145 psi).

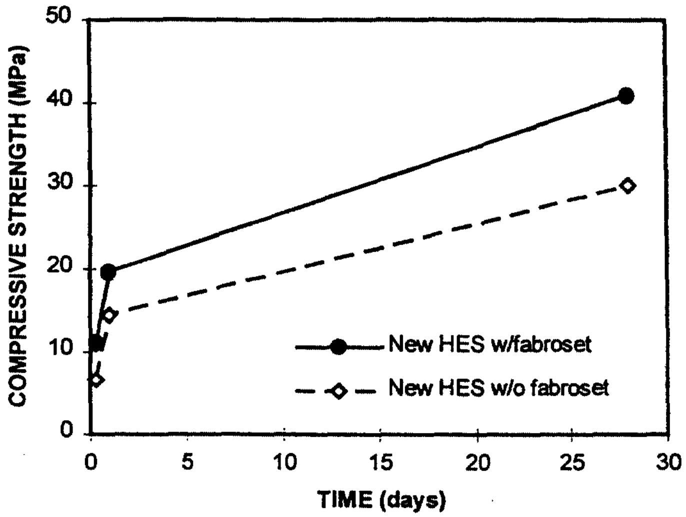


Figure 14. Effects of Specialty Cellulose Fibers on Compressive Strength Development (1 Mpa = 145 psi).

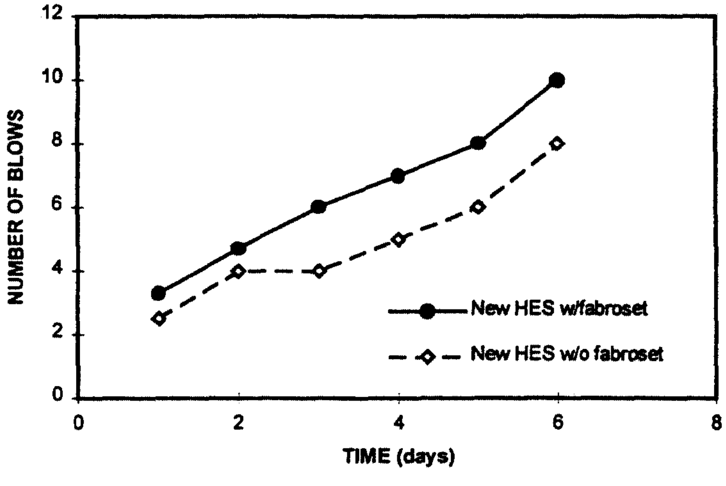


Figure 15. Effects of Specialty Cellulose Fibers on Impact Strength Development.

Abrasion tests were also conducted on the finished surfaces of NFS mixtures with and without specialty cellulose fibers at the age of 24 hours. As shown in Figure 16, the addition of specialty cellulose (fabroset®) fibers leads to major improvements in the early-age abrasion resistance of concrete.

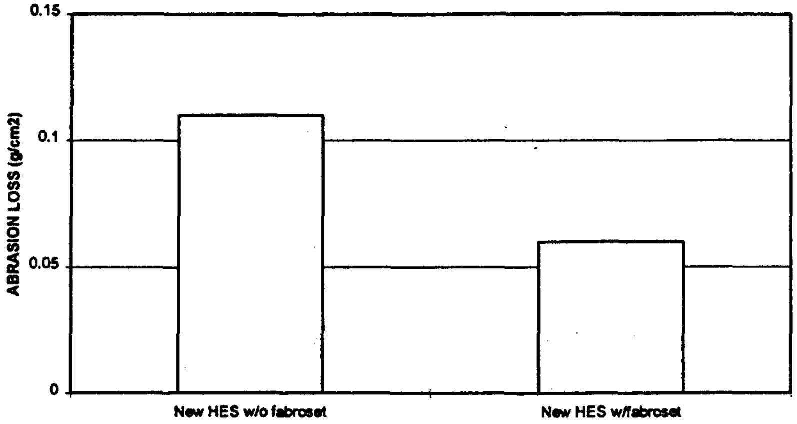


Figure 16. Effect of Specialty Cellulose Fibers on 24-Hour Abrasion Resistance
(1 $g/m^2 = 1.42\ lb/in^2$)

The effectiveness of specialty cellulose fibers in high-early-strength concrete can be attributed to their high surface area (i.e. fine diameter), strong bonding to matrix, and relatively high elastic modulus and tensile strength.

FIELD INVESTIGATION

The key product of the laboratory phase of this research was a new class of high-early-strength concrete mixtures which use specialty cellulose fibers to satisfy the early-age strength requirements without compromising the long-term performance of concrete systems. The addition of specialty cellulose fibers allows for the reduction of cement and accelerator contents and thus reduction of the restrained drying and thermal shrinkage stresses. Fibers also reinforce concrete against restrained shrinkage stresses.

The lack of durability of high-early-strength concrete systems can be attributed to restrained shrinkage microcracking (and occasionally cracking) of such systems at early age, which increases their permeability and damages their durability. The actual external and internal restraint levels placement temperature and relative humidity, and thickness of the system are critical to the development of restrained drying and thermal shrinkage stresses in concrete. Laboratory specimens are largely free from restraint stresses and thus cannot reflect the durability problems observed in field placements. Hence, durability studies of high-early-strength concrete systems can best be performed under actual field placement and restraint conditions. Since the focus of this project was on full-depth patching of rigid pavements, a field project was selected to investigate the performance of the new high-early-strength concrete mixture incorporating specialty cellulose fibers.

The filed project involved full-depth patching of the 496 highway (west bound) between Lansing and East Lansing. Most patches which were subject of this study were in the fast lane. Casting of concrete in this field project was performed in the morning of June 21, 1997. The temperature during casting of concrete ranged from 22°C to 33°C (70°F to 90°F), and the relative humidity was about 45%. Two high-early-strength concrete mixtures suiting 8-hr opening to traffic were used in this project: conventional (plain) high-early-strength concrete, and the new high-early-strength concrete with specialty cellulose (fabroset®) fibers. All mix ingredients except calcium chloride were mixed in the batch plant. A central mixer prepared the plain mix which was then charged to the ready-mix truck; for fiber reinforced mixtures, the fibers were added to the ready-mix truck before the addition of the already mixed plain mixture. Manufacturers of specialty cellulose fibers require the addition of fibers after all other mix ingredients are thoroughly mixed. With fibers, the ready-mix truck was operated at the mixing speed for about 4 minutes after it was charged with the plain mixture. This mixing time was required to ensure uniform dispersion of specialty cellulose fibers. Calcium chloride was added to all mixtures at the job site. Further mixing action at mixing speed ensured thorough dispersion of calcium chloride flakes in concrete.

The patches were prepared overnight for the placement of concrete. Deteriorated concrete was saw-cut and removed, and dowel bars as well as welded wire fabric were placed in the patch area (Figure 17). The welded wire fabric was supported on dowel bars and steel chairs.

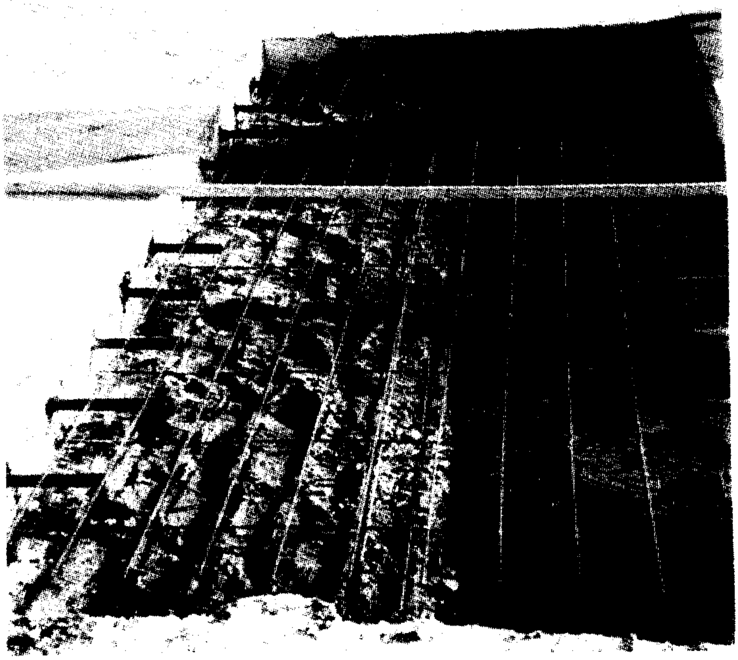


Figure 17. Picture of a Patch with Dowel bars and Welded Wire Fabric in Place.

The patch area was sprayed with water prior to the placement of concrete. Concrete was placed in the patch from ready-mix trucks (Figure 18), consolidated through internal vibration, finished, jointed, broomed, and finally sprayed with curing membrane. A view of a completed patch is presented in Figure 19. Close to 40 cubic meters of the new HES mixture with cellulose fiber were placed in about 20 full-depth patches, and close to 5 cubic meters of the conventional HES mix were placed in 2 full-depth patches.

Figure 18. Placement of Concrete in the Patch.

Figure 19. A Completed Patch.

Samples for tests on the new HES mix (with fibers) were taken from four trucks; one sample of the conventional HES mix was taken from one truck. The average trends in the development of compressive and flexural strengths with time are presented in Figures 20 and 21. The new HES mixture with specialty cellulose (fabroset®) fiber is observed to be superior to the conventional HES mixture of higher cement and calcium chloride contents (without fibers). The fresh mix slump of field concrete was quite variable, ranging from 65 to 165 mm; the air contents ranged from 5 to 6.5.

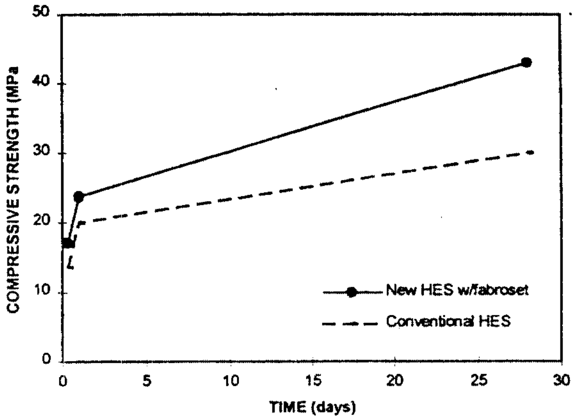


Figure 20. Compressive Strength Development with Time.

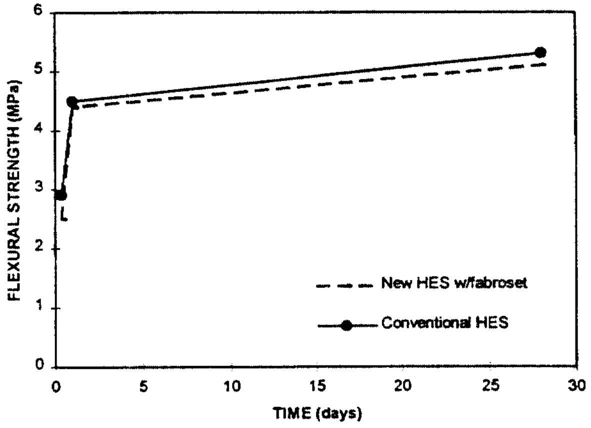


Figure 21. Flexural Strength Development with Time.

The field project will be subject of long-term monitoring and tests in order to assess the competitive performance of the new HES mix with specialty cellulose (fabroset®) fibers under field exposure conditions.

CONCLUSION

High-early-strength concrete is assuming an increasingly significant role in highway projects due to the growth of fast-track pavement construction and repair. Traditional high-early-strength concrete mixtures utilize high cement contents and relatively high dosages of accelerators in order to hasten the strength gain process. Such measures, however, increase the drying and thermal shrinkage movements of concrete, which lead to the development of relatively large tensile restraint stresses in actual placement conditions. The restrained stresses, which peak at early age, would produce microcracks which are damaging to the permeability and long-term durability of high-early-strength concrete under actual restraint conditions. Such restraints are not present in small-scale laboratory specimens; hence, the durability problems of high-early-strength concrete cannot be detected through tests on small laboratory specimens. Tests on large laboratory specimens with restraint conditions simulating those of field placements confirmed the increase in air permeability under restrained shrinkage tensile stresses.

Synthetic fibers are not effective in increasing the early-age strength of concrete. Specialty cellulose fibers, with relatively high surface are elastic modulus, tensile strength and bond strength to concrete, however, were found in this research to increase the early-age strength of concrete. The addition of specialty cellulose fibers, unlike the increase in cement and accelerator contents, does not increase the restrained shrinkage stresses of concrete; specialty cellulose fibers actually increase the resistance of concrete to restrained shrinkage microcracking and cracking. Laboratory studies confirmed that the air permeability of large restrained specimens can be reduced with the addition of specialty cellulose fibers.

New concrete mixtures incorporating specialty cellulose fibers were developed. The addition of cellulose fibers helped reduce the cement and accelerator contents by about 20% while still satisfying the early-age strength requirements at acceptable levels of fresh mix workability.

A field project was implemented using a commercially available specialty cellulose (fabroset®) fibers. Full-depth patches were placed for 8-hr opening to traffic using conventional high-early-strength mixtures (without fibers) and the newly developed mixture with specialty cellulose fibers. Mixtures with specialty cellulose fibers were quite easy to place, consolidate and finish; they did not require any special treatment during construction. Early-age compression and flexure test results were indicative of the superior performance of the mixtures incorporating specialty cellulose fibers. Plans have been developed for long-term monitoring of the field project.

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