Curing

Immediately after batching and casting, compressive strength and time of setting specimens were placed in chambers adjusted to the appropriate temperature. All specimens were moist cured. "Moist" conditions were achieved by covering the specimens with wet burlap and plastic sheeting. Specimens were maintained in moist conditions at the appropriate temperatures until testing.

Since the study examined the effects of low temperatures on the mixtures, four chambers were required for curing the test specimens. Those batches cured at 70°F (21°C) were placed in an environmental chamber which was already in place in the laboratory. To cure mixtures at 40, 50, and 60°F (4, 10, 16°C), three chambers were constructed by the research team. These chambers, shown in Figure 1, were made of wood and placed adjacent to one another, with wooden "ducts" connecting them. The chambers were approximately 4 ft wide by 4 ft long by 2 ft deep (1.2 m x 1.2 m x 600 mm). They were insulated by 0.75 in. (20 mm) insulation sheets. An air-conditioning (A/C) unit, which was re-wired to allow the fan and compressor to be controlled separately, was installed in the 40°F (4°C) chamber, which was the first in the series. A small 1500 watt (1500 J/s) ceramic heater was placed inside each chamber. These heaters were also reconfigured to allow the heating elements and fans to work independently. The heaters were used to raise the temperatures in each chamber to 10°F (5.5°C) above that of the previous chamber. For example, the A/C unit brought the air below 40°F (4°C), and the heater in the first chamber maintained the temperature at 40°F (4°C). Then, the heater in the second chamber raised the temperature to 50°F (10°C), and the heater in the third chamber raised the temperature to 60°F (16°C). At the end of the system (outside the 60°F (16°C) chamber) a flexible HVAC duct was installed to route the air leaving the system into a small insulated box containing the A/C unit, allowing the unit to cool the 60°F (16°C) air instead of room temperature air to 40°F (4°C).

Time of setting tests

Two studies, time of setting and strength gain, were conducted during this research program. In the time of setting study, specimens were prepared in accordance with ASTM C 403. These specimens were subjected to the same curing environment as the compressive strength cylinders. Each time of setting was based on the average of at least three specimens. When possible, four specimens were cast and tested. However, on some occasions there was not enough material to cast a fourth. The specification required only three specimens. To determine time of setting, a needle of known cross-sectional area was pushed one inch into the specimen in ten seconds. The penetration resistance [pounds (kilograms)] required for this act was recorded and divided by the area of the needle used. As the setting process proceeded, the area of the needle decreased from 1 to 0.025 in.^{2} (0.65 to 0.02 mm^2). A minimum of six readings were taken for each of the samples tested. These points were plotted and a trendline was fit to the data using a spreadsheet. The equation for the trendline was used to calculate the times of initial and final setting. The time of initial setting is defined as the time required to achieve penetration resistance of 500 psi (3.5 MPa). The time of final setting is defined as the time required to attain penetration resistance of 4000 psi (28 MPa).

Compressive strength tests

Compressive strength (ASTM C39) was also measured for each of the mixtures at each of the temperatures: 70, 60, 50, and 40°F (21, 16, 10, and 4°C). These tests were conducted when samples reached 1, 3, 7, 28, and 90 days of age. For the strength study, 4 x 8 in. (100 x 200 mm) cylinders were cast according to ASTM C31. Three cylinders were tested at each age. The compressive strength corresponding to each test was the average of the compressive strengths of these three cylinders. The compressive strength was measured using a 400 kip (1800 kN) capacity testing machine. Sample ends were placed on neoprene pads (70 durometer hardness), which were seated in steel rings. The use of 70 durometer neoprene pads is allowed in determining concrete compressive strengths when the strength is between 7000 and 12000 psi (50 and 85 MPa) if the tests are qualified by testing similar specimens with a capping compound (ASTM C 1231). Similar mixtures were tested prior to this research program, and experience from those tests showed that when the compressive strength is less than 12000 psi (85 MPa), there is little difference between specimens tested using neoprene pads and those tested with a capping compound.

RESULTS

Fresh concrete properties

The fresh concrete tests performed on the concrete mixtures included concrete temperature, slump, unit weight, and air content. Results of these tests are presented in Table 3. Because each mixture was prepared five times (once for each curing temperature), each of the values in this table represents an average of five tests. In this section, mixtures will be identified by the PC replacement rates (%SC/%FA). For example, Mixture 40/20 is that mixture in which 40 % of the PC is replaced by SC and 20 % is replaced by FA. Further, individual batches will be identified as follows: %SC/%FA (Curing Temperature). To ensure quality control, concrete temperature was observed and recorded for each batch that was prepared. The study was intended to model the properties of concrete prepared for field use. Thus, the concrete was batched to exhibit a fresh temperature ranging from 60 to 80°F (16 to 27°C).

Time of setting

Times of initial and final setting were determined for each of the 24 batches to examine the effect of curing temperature and SCM content on setting times. These times were determined using the method prescribed in ASTM C 403. The setting times for each of the batches tested are shown in Table 4. The times listed in this table are the averages of four individual test specimens for each batch. Figures 3 and 4 illustrate the effect of curing temperature on the elapsed time between initial and final set. Figure 3 includes all mixtures with less than 80% total replacement and comparisons to the control mixture. Figure 4 includes those mixtures with 80% total replacement (Mixtures 40/40 and 20/60) and comparisons to the control mixture (Mixture 0/0).

Time of initial setting—Generally, times of initial setting increased as curing temperature decreased. Also, the intervals between initial and final setting typically increased as curing temperature decreased. Times of initial setting and the interval between initial and final setting both increased as replacement rates increased. The times of initial setting of high-replacement mixtures experienced the largest increases with respect to curing temperature. Times of initial setting for Mixture 40/40 ranged from 11.86 to 57.72 hours, increasing as curing temperature decreased. Mixture 20/60, also with 80% PC replacement, did not exhibit such a drastic increase in setting time with decreasing curing temperature, although an increase did occur. Mixture 20/60 contained a higher volume of Class C FA, which exhibits some cementitious properties. Thus, the early hydration reaction of Mixture 20/60 occurred more quickly than in the mixtures containing higher volumes of SC. Mixture 20/20, did not completely follow this trend. The longest time of initial setting for this mixture belonged to the batch cured at 50°F (10°C).

Time of final setting—The times of final setting displayed trends similar to those of initial setting. Mixture 0/0 experienced statistically significant increases in setting time as curing temperatures decreased, with times ranging from 6.05 to 10.07 hours. Times of final setting for this mixture increased as curing temperature decreased. Mixture 20/20 followed the same trend for final set as for initial set for all batches except the 40°F (4°C) mixture. Mixtures 40/20 and 20/40 also followed the same general trends for final set as for initial set, with the time of final setting generally increasing as curing temperature decreased. The setting times of Mixture 40/20 increased significantly as curing temperature decreased. When the mixture was cured at 70, 60, 50, and 40°F (21, 16, 10, and 4°C), the differences in curing temperatures were of no concern, ranging from 11.81 to 13.6 hours. Setting times for all batches of Mixture 20/40 were statistically different. Batch 20/40 (60) displayed decreased setting time (9.81 hours) when compared to the same mixture cured at 70°F (21°C) (11.41 hours) and 50°F (10°C) (14.25 hours). The ambient temperature on the day Batch 20/40 [60°F (16°C)] was prepared was nearly 90°F (32°C), while the temperature when Batch 20/40 [70°F (21°C)] was prepared was only about 80°F (27°C). While the fresh concrete temperature was similar for Batches 20/40 (70°F (21°C)) and 20/40 [60°F (16°C)] [62 and 67°F (17 and 19°C)], respectively), the elevated ambient temperature for Batch 20/40 [60°F (16°C)] rapidly increased the concrete temperature and allowed the hydration reaction to occur faster.

The final setting time of Mixture 40/40 also followed a trend much like that of the initial setting, with times of final setting ranging from 39.29 to 192.24 hours. Mixture 20/60, however, displayed somewhat different trends for final setting than for initial setting. This mixture took longer to reach final set than any other mixture. The mixture's time of initial setting was comparable to that of other mixtures due to the content of cementitious Class C FA. The pozzolanic reaction which occurs in mixtures containing SC and/or FA proceeds slowly (Mindess et al 2003). With a high content of SCMs (80% of the cementitious materials) the pozzolanic reaction of this mixture was most likely slowed much more than with mixtures containing a lower replacement rate. Mixture 20/60 was the worst performing mixture with respect to the time required to reach final setting.

Interval between initial and final setting—The relative times of setting were determined for each of the mixtures. Specifically, this time is the interval between initial and final setting of a mixture. These times are plotted as a function of curing temperature in Figures 3 and 4. When cured at or above 50°F (10°C), Mixture 20/20 and Mixture 40/20 exhibited a trend similar to that of the control mixture. These mixtures, as well as Mixture 20/40, all progressed from initial set to final set in about 4 hours or less at these temperatures. Furthermore, significantly more time elapsed between initial and final setting for Mixture 20/40 cured at 40°F (4°C) than the Control Mixture cured at the same temperature. The mixtures with 80% of the PC replaced (Mixtures 40/40 and 20/60) experienced a dramatically greater delay between initial and final setting than all other mixtures at all temperatures, as illustrated in Fig. 4.

Compressive strength determination

The compressive strength of the concrete mixtures was tested at 1, 3, 7, 28, and 90 days of age, as described previously. Average compressive strengths at each of these ages are included in Table 5. Each value reported in Table 8 was the average of three compressive strength tests. The compressive strength gain curves of the control mixture, Mixture 20/20, and Mixture 40/20, the best performing mixtures, are shown in Figures 5 through 7. Also shown (Fig. 8 through 10) are strength gain curves showing all mixtures cured at 50, 60, and 70°F (10, 16, and 21°C), the temperatures at which the mixture performed best.

One-day compressive strength—The one-day compressive strength decreased as the curing temperatures decreased. The curing temperature affected the strength of low replacement mixtures (less than or equal to 60% total SCMs) more than the mixtures with 80% total replacement, due to the longer setting times of these high replacement mixtures. In general, the strength of all mixtures was significantly different from the control at like temperatures. The strengths decreased as the total cement replacement increased. The control mixture and the mixture with 40% total replacement attained a minimum of 1300 psi (9 MPa) when cured at 70°F (21°C). Replacement by FA tended to have more adverse effects on the one-day compressive strength than replacement by SC, especially at high replacement rates, though increasing rates of SC resulted in somewhat lower compressive strengths. Mixtures containing more than 20% FA performed poorly at one day of age, not exceeding 300 psi (2.1 MPa).

Three-day compressive strength—Generally, the three-day compressive strength decreased as the curing temperatures decreased. The strengths of mixtures with higher SCM contents were widely variable as temperature decreased. Mixtures with lower replacement rates were not so widely affected by curing temperature. In general, the strength of all mixtures was significantly different from the control at like temperatures. The strengths decreased as the total cement replacement increased. The decrease in compressive strength was proportional to the increase in replacement rate up to 60% total replacement. Mixtures with 80% total replacement were not affected by decreasing curing temperatures, as these mixtures performed poorly at all temperatures. The strongest batch at this replacement attained less than 200 psi (1.4 MPa).

In most cases, compressive strength decreased as curing temperature decreased. An exception, however, is in the case of Mixture 0/0 when cured at 50°F (10°C). Batch 0/0 [50°F (10°C)] attained a significantly higher compressive strength [4710 psi (32 MPa)] than when the same mixture was cured at 60°F (16°C) [3670 psi (25 MPa)]. In addition, the strength of the batch cured at 40°F (4°C) [3710 psi (26 MPa)] was not significantly different from the 60°F (16°C) batch. The 50 and 40°F (10 and 4°C) batches had slumps much lower than that of the 60°F (16°C) batch. The concrete temperatures of Batches 0/0 [60°F (16°C)], 0/0 [50°F (10°C)], and 0/0 [40°F (4°C)] were 68, 65, and 58°F (20, 18, 14°C), respectively. Ambient weather conditions were not recorded when Batch 0/0 [60°F (16°C)] was prepared. No logical explanation for this phenomenon was determined.

Mixtures 40/40 and 20/60 were practically unaffected by decreases in curing temperatures. While the 90% confidence interval showed a statistical difference between some of the different batches of these two mixtures, the compressive strength at three days remained so low that the difference was irrelevant. Mixture 40/40 displayed an almost constant strength at three days of age regardless of curing temperature, ranging from 50 to 60 psi (0.34 to 0.41 MPa). The compressive strength of Mixture 20/60 was only slightly more variable than Mixture 40/40, ranging from 60 to 80 psi (0.41 to 0.55 MPa) for all batches.

Seven-day compressive strength—The compressive strength at seven days tended to decrease with decreasing temperatures for the mixtures containing SCMs. Mixtures containing low replacement rates were again less affected than those with moderate replacements (60%). Mixtures with the highest replacements (80%) tended to, again, remain unaffected by curing temperature. This effect was independent of the amount of FA or SC in the mixture.

At the two warmest curing temperatures, Mixture 20/20 performed similarly to Mixture 0/0 at seven days of age. According to the 90% confidence intervals, Batches 20/20 [70°F (21°C)] and 20/20 [60°F (16°C)] are not significantly different from Batches 0/0 [60°F (16°C)] and 0/0 [50°F (10°C)]. These two low-replacement batches [Batches 20/20 (70°F (21°C)] and 20/20 [60°F (16°C)] attained seven-day compressive strengths of 5200 and 5490 psi (35 and 40 MPa), exceeding the required 28-day strength of 4000 psi (28 MPa), as described previously. Even when cured at 40 and 50°F (4 and 10°C), the compressive strength of Mixture 20/20 still exceeded 4000 psi (28 MPa) at 7 days.

Mixture 40/20 displayed significantly lower seven-day strengths when compared to Mixtures 0/0 and 20/20, except when cured at 70 and 60°F (21 and 16°C). Batches 40/20 [70°F (21°C)] and 40/20 [60°F (16°C)] [4430 and 3870 psi (31 and 27 MPa], respectively are not significantly different from Batch 20/20 [40°F (4°C)]. Examining the strength gain curves for Mixture 40/20 reveals that compressive strength decreases nearly proportionately to the decrease in curing temperature (an approximate strength decrease of 20 to 25% for each 10°F (5.5°C) drop in curing temperature). The increasing PC replacement rate (from 40% for Mixture 20/20 to 60% for Mixture 40/20) most likely led to the decreases in compressive strength, as the pozzolanic reactions occur more slowly than cementitious reactions.

Mixture 20/40 achieved compressive strength similar to that of Mixture 40/20. Batches 20/40 [70°F (21°C)] and 20/40 [60°F (16°C)] [3740 and 3670 psi (26 and 25 MPa), respectively] were statistically similar to Batch 40/20 [60°F (16°C)]. At seven days of age, these particular batches nearly attained the required 28-day strength of 4000 psi (28 MPa) as discussed previously. The 50 and 40°F (10 and 4°C) batches of Mixture 20/40 performed reasonably well, each exceeding 2000 psi (14 MPa).

Mixture 40/40 performed very poorly at all temperatures when compared to the compressive strength of Mixtures 0/0, 20/20, and 40/20. This mixture attained only 1160 psi (8.0 MPa) when cured at 70°F (21°C). The batch cured at 60°F (16°C) was not statistically different from the 70°F (21°C) batch, but the strength decreased sharply as the curing temperatures fell below 60°F (16°C). At all temperatures, Mixture 20/60 had strengths ranging from 60 to 90 psi (0.41 to 0.62 MPa) and performed similarly to the colder curing temperatures of Mixture 40/40 [40°F (4°C)]. These poor seven-day strengths were related to the long times of setting for Mixtures 40/40 and 20/60.

The strengths of Mixture 0/0 and the lowest replacement mixture (Mixture 20/20) were unaffected by curing temperature at and after 7 days of age. Other mixtures (60% total replacement) were only slightly affected by curing temperature. Strength decreased somewhat as replacement increased, but the difference was minor until the replacement exceeded 60%. Mixtures with 80% replacement displayed compressive strengths significantly lower than those of other mixtures. Increased FA content tended to result in lower compressive strengths. Two of the mixtures contained 60% replacement (Mixtures 40/20 and 20/40). Mixture 20/40 displayed slightly lower compressive strength than Mixture 40/20. A similar trend was observed between Mixtures 40/40 and 20/60, which each contained 80% replacement. Mixture 20/60, with a higher FA content than Mixture 40/40, displayed lower strength at all temperatures than Mixture 40/40.

Twenty-eight-day compressive strength—In general, the control mixture and low-replacement mixtures (60% and less) performed well at 28 days of age. These mixtures – specifically, Mixtures 0/0, 20/20, 40/20, and 20/40 – consistently exceeded the AHTD minimum 28-day compressive strength. The strength of Mixtures 40/40 and 20/60, with 80% of the PC replaced, decreased drastically as curing temperatures decreased. In general these mixtures failed to attain 4000 psi (28 MPa), except Mixture 40/40 when cured at 70 and 60°F (21 and 16°C). Mixture 40/40 contained an equal weight of SC and FA (40% each). Mixture 40/40, with less FA than Mixture 20/60, performed somewhat better than Mixture 20/60, which contained 60% FA and only 20% SC.

Mixture 20/20 had higher average compressive strengths than Mixture 0/0 at the 70, 60, and 50°F (21, 16, and 10°C) curing temperatures, though the difference is not significant. When cured at 70°F (21°C), Mixture 20/20 reached 28-day strength of 7170 psi (50 MPa), while the control mixture only attained 6090 psi (40 MPa) at this temperature. Mixture 20/20 is also similar to Mixture 0/0 when cured at 40°F (4°C), according to the 90% confidence interval. When cured at 70°F (21°C), Mixture 40/20 displayed the highest 28-day compressive strength of all the batches tested with 7760 psi (55 MPa). However, compressive strength of this mixture decreased more rapidly as curing temperature decreased. Thus, Mixture 40/20 was less consistent than Mixtures 0/0 or 20/20.

Mixture 40/40 displayed markedly lower 28-day compressive strength than the mixtures discussed previously, with the 70°F (21°C) batch achieving only 4270 psi (29 MPa) - barely exceeding the minimum 28-day strength discussed previously. According to the 90% confidence interval, the strength of the batch cured at 60°F (16°C) [3770 psi (26 MPa)] was similar to Batch 40/40 [70°F (21°C)] and to 40/40 [50°F (10°C)] [3090 psi (21 MPa)], though 40/40 [70°F (21°C)] and 40/40 [50°F (10°C)] were not similar to each other. When cured at temperatures colder than 50°F (10°C), the 28-day compressive strength of Mixture 40/40 decreased drastically. Batch 40/40 [40°F (4°C)] [1770 psi (12 MPa)] achieved only 57% of the strength of Batch 40/40 [50°F (10°C)].

Mixture 20/40 exhibited compressive strength similar to that of the cooler batches of Mixture 40/20. This trend was not surprising in that 60% of the PC was replaced in each of the two mixtures. In Mixture 40/20, a larger percentage of this was SC, while in Mixture 20/40 the majority of the replacement material was FA. The high-SC mixture attained higher compressive strengths at warmer temperatures, but the high-FA mixture exhibited a more consistent strength. The average 28-day strengths of Mixture 20/40 decreased less than those of Mixture 40/20 as curing temperature decreased. Mixture 20/40 reached its highest strength, 6280 psi (45

MPa), when cured at 70°F (21°C). The 60 and 50°F (16 and 10°C) batches of Mixture 20/40, with respective 28-day strengths of 5870 and 5890 psi (40 and 40 MPa), were not statistically different from Batch 20/40 [70°F (21°C)]. The compressive strength of Batch 20/40 [40°F (4°C)], 5400 psi (40 MPa), was similar to those of Batches 20/40 [60°F (16°C)] and 20/40 [50°F (10°C)], according to the 90% confidence intervals. When cured at 70, 60, 50, and 40°F (21, 16, 10, and 4°C), Mixture 20/40 exceeded the minimum average 28-day compressive strength required.

Mixture 20/60 was the worst performing mixture examined in the study. This mixture attained peak 28-day compressive strength of 2480 psi (17 MPa) when cured at 70°F (21°C). A sharp decrease in strength occurred when the curing temperature was reduced to 60°F (16°C). Batch 20/60 [60°F (16°C)] reached only 1560 psi (11 MPa), 63% of the strength reached by the 70°F (21°C) batch. From the 90% confidence intervals, no significant difference was detected between the strengths of Batches 20/60 [50°F (10°C)] [1460 psi (10 MPa)] and 20/60 [60°F (16°C)]. Strength decreased again when curing temperature decreased to 40°F (4°C), falling to only 580 psi (4.0 MPa). Batch 20/60 [40°F (4°C)] did not reach final set until the samples reached about 36 days of age, explaining the sharp decrease in compressive strength for Mixture 20/60 when curing temperature was decreased from 50 to 40°F (10 to 4°C). The 50°F (10°C) batch reached final set in about 13 days.

Ninety-day compressive strength—In general, mixtures in which 60% of the PC or less was replaced with SC or FA and cured at or above 50°F (10°C) performed the best, attaining higher average 90-day compressive strengths than the control mixture. Mixtures containing 80% SCMs (Mixtures 40/40 and 20/60) displayed significantly less compressive strength than other mixtures.

Mixture 0/0 attained between 7270 and 8120 psi (45 and 55 MPa), with the lowest strength being the batch cured at 40°F (4°C). The highest strength achieved by Mixture 0/0 occurred in the batch cured at 50°F (10°C). This trend is not surprising, as concrete tends to reach higher late-age compressive strength when cured at lower temperatures (Mindess 2003). According to the 90% confidence interval, Batches 0/0 [60°F (16°C)], 0/0 [50°F (10°C)], and 0/0 [40°F (4°C)] are statistically similar to Batch 0/0 (70°F (21°C)). The batches of Mixture 20/20 cured above 40°F (4°C) exceeded 8000 psi (55 MPa) at 90 days in all cases, and there is no significant difference in these batches, according to the 90% confidence interval. The batch cured at 40°F (4°C) attained an average strength of 9040 psi (60 MPa), which is statistically greater than the strength of the same mixture cured at 60°F (16°C), but not statistically different from those batches cured at 70 and 50°F (21 and 10°C). This increased strength for a low-temperature batch may be attributed to a late-age strength increase for mixtures cured at low temperatures (Mindess 2003).

When cured at or above 40°F (4°C), Mixture 40/20 attained strength statistically equivalent to those batches of Mixture 20/20 cured at the same temperatures. These batches reached compressive strengths ranging from 8230 to 9020 psi (57 to 62 MPa). The highest value, 9020 psi (60 MPa), was obtained by Batch 40/20 [50°F (10°C)], which was cured at 50°F (10°C). Statistically, however, the differences in the strengths of these four batches of Mixture 40/20 were not significant. These four batches also were not significantly different from the strengths of Mixture 20/20 when cured at the same range of temperatures.

Mixture 40/40 exceeded the minimum strength at 90 days of age when cured at or above 40°F (4°C). However, the mixture was inconsistent and sporadic, with compressive strengths ranging from 4100 to 6650 psi (28 to 45 MPa). The greatest strength attained by this mixture occurred when cured at 60°F (16°C). None of the other batches of Mixture 40/40 reached strengths statistically similar to this batch. Mixture 20/40 performed similarly to the control mixture when cured at or above 50°F (10°C). This mixture performed best when cured at 50°F (10°C), attaining compressive strength of 8080 psi (55 MPa). When cured at 60°F (16°C), the strength was only slightly less at 8030 psi (55 MPa). When cured at 40°F (4°C), the compressive strength of this mixture [6430 psi (45 MPa)] was 20% lower than that of the same mixture cured at 50°F (10°C). All these values exceed the AHTD minimum 28-day compressive strength.

Mixture 20/60, like Mixture 40/40, attained lower strengths than mixtures with lower replacement rates, and was somewhat inconsistent, although Mixture 20/60 was more consistent than Mixture 40/40. When cured at 70°F (21°C), the 90-day strength of the mixture exceeded the AHTD minimum strength, attaining 6320 psi (45 MPa), though the same mixture under the same conditions attained less than 2500 psi (17 MPa) at 28 days of age. The compressive strength decreased severely, however, when Mixture 20/60 was cured at 60°F (16°C). This batch attained only 3290 psi (23 MPa), about 50% of the strength of the same mixture cured at 70°F (21°C).

CONCLUSIONS

This study explored the setting and strength gain characteristics of ternary concrete mixtures cured at low temperatures [at and below 70°F (21°C)]. Specifically, the study was intended to provide a better understanding of the strength gain characteristics of various ternary mixtures containing different volumes of SCMs but otherwise identical. Each of the mixtures tested contained the same total weight of cementitious materials, coarse aggregate, and water, and identical w/cm. The only variables between mixtures were the replacement rates of SC and FA, fine aggregate content, and the temperatures at which the mixtures were cured. The study also intended to provide a better understanding of the impact of subjecting these mixtures to curing temperatures at and below 70°F (21°C), what replacement rates can practically be employed, and at what temperatures each mixture should be used.

The research program showed that, at appropriate replacement rates and reasonable curing temperatures, ternary concrete mixtures perform adequately; in fact, in many respects these ternary mixtures proved to be superior to ordinary PC concrete. The following is a summary of the conclusions drawn from the examinations of the fresh concrete properties, the times of setting, and the compressive strengths and strength gain:

1. Slump tended to increase as FA content increased. Mixtures containing more FA than SC displayed the highest average slumps. Mixtures containing more SC showed lower slumps, but in mixtures with equal quantities of FA and SC, the slumps were increased. The slumps of the mixtures also depended on the fresh concrete temperatures. Specifically, slump decreased at higher fresh temperatures.
2. Generally, time of initial setting increased as replacement rates increased. These times ranged from nearly 5 hours for the control mixture to almost 58 hours for Mixture 40/40. Practically, the times of initial setting were unaffected by curing temperature for the control mixture, ranging from 4.78 hours to 7.64 hours. Ternary mixtures displayed significant increases in initial set times as curing temperature was decreased. At replacement rates of 60% and higher, this effect was greater than in mixtures with lower replacement rates.
3. Times of final setting followed the same general trends as the times of initial setting, with time increasing as replacement rates increased and curing temperatures decreased. The mixture containing 100% PC was significantly affected by varying curing temperatures, with setting times ranging from 6 to 10 hours. Mixtures with very high total replacement rates (80%) experienced the greatest increase in time of final setting.
4. The interval between initial and final setting tended to increase as curing temperature decreased. When mixtures containing less than 80% total replacement were cured at or above 50°F (10°C), the increase in this time interval was of little concern, ranging between 1 and 5 hours. Mixtures containing 80% total replacement experienced significant increases in elapsed time between initial and final set when compared to mixtures with lower replacement rates. Also, some mixtures experienced longer setting times when cured below 50°F (10°C). Mixtures 0/0 and 20/20 did not experience severe delays at low curing temperatures.
5. At late ages (28 and 90 days), the use of total replacement rates of 60% or less increased the compressive strength relative to the control mixture. At 90 days of age, Mixtures 20/20 and 40/20 displayed more than adequate compressive strength, exceeding 8000 psi (55 MPa) in most cases. Mixture 40/40 attained approximately 6000 psi (40 MPa) when cured at or above 60°F (16°C), and the average compressive strength was greater than 4000 psi (28 MPa) when this mixture was cured at or above 40°F (4°C). Mixture 20/40 performed reasonably well at both 28 and 90 days of age. Mixture 20/60 performed poorly at all curing temperatures.
6. Strength tended in many cases to be less as curing temperature decreased, especially up to 28 days of age. At 90 days of age, however, some mixtures displayed greater compressive strengths at lower temperatures. Mixture 40/20 attained its highest strength (9020 psi [60 MPa]) when cured at 50°F (10°C), as did Mixture 20/40 (8080 psi [55 MPa]). The highest strength attained by Mixture 20/20 (9040 psi [60 MPa]) occurred when cured at 40°F (4°C), and Mixture 20/20 displayed a general trend of increasing compressive strength as temperature decreased.

RECOMMENDATIONS

The results of the research program showed that ternary concrete mixtures can produce strength comparable to ordinary PC concrete (at 90 days) when cured below 70°F (21°C). PC replacement of 40% resulted in average 90-day compressive strengths exceeding those of the control mixture at all temperatures. Quality concrete was produced with total replacements as high as 60% when cured at or above 50°F (10°C). Mixtures containing more SC than FA displayed decreased workability; however, this effect could be overcome with the addition of high-range water reducer (HRWR). Mixtures with 80% replacement performed significantly worse than other mixtures, and, based on the results of the study, should not be used in most circumstances, specifically in structural applications with loading concerns. These mixtures were also very inconsistent, producing widely varying results under similar conditions.

In general, when cured at or above 50°F (10°C), mixtures containing 60% total replacement or less displayed more than adequate times of setting and compressive strengths. Mixtures containing 40% total replacement may prove successful when cured at or above 40°F (4°C).

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Table 1—Chemical composition and fineness of cementitious materials

	Portland cement	Slag cement	Fly ash
	Chemical composition, %		
SiO_2	20.5	40.0	37.1
Al_2O_3	4.7	8.0	19.6
Fe_2O_3	2.79	0.40	6.19
CaO	63.4	36.4	24.7
MgO	2.6	12.2	4.6
SO_3	2.78	1.06	1.70
Loss on ignition	1.7	0.8	0.3
Compound composition, %			
C_3S	56	—	—
C_2S	16	—	—
C_3A	8	—	—
C_4AF	—	—	—
Na_2O	0.20	—	1.53
K_2O	0.55	—	0.42
Blaine air fineness			
Blaine, m^2/kg	390	476	—

1 $m^2/kg \times 0.542 = 1\ yd^2/lb$.

Table 2—Mixture proportions

Mixture ID*	*w/cm*	Cement, lb/yd^3 (kg/m^3)	Slag cement, lb/yd^3 (kg/m^3)	Fly ash, lb/yd^3 (kg/m^3)	Coarse aggregate, lb/yd^3 (kg/m^3)	Fine aggregate, lb/yd^3 (kg/m^3)	Water, lb/yd^3 (kg/m^3)
0/0	0.45	650 (386)	0	0	1900 (1128)	1164 (691)	293 (174)
20/20	0.45	390 (231)	130 (77)	130 (77)	1900 (1128)	1135 (674)	293 (174)
40/20	0.45	260 (154)	260 (154)	130 (77)	1900 (1128)	1114 (661)	293 (174)
40/40	0.45	130 (77)	260 (154)	260 (154)	1900 (1128)	1093 (649)	293 (174)
20/40	0.45	260 (154)	130 (77)	260 (154)	1900 (1128)	1113 (661)	293 (174)
20/60	0.45	130 (77)	130 (77)	390 (231)	1900 (1128)	1092 (648)	293 (174)

*Mixture ID represents % SC/% FA (for example, Mixture 40/20 represents 40% of PC replaced with SC and 20% of PC replaced by FA).

Table 3—Fresh concrete properties

Mixture ID	Concrete temperature,°F (°C)	Slump, in (mm)	Unit weight, lb/ft^3 (kg/m^3)	Air content, %
0/0	68 (20)	4.25 (110)	151.5 (2410)	1.4
20/20	63 (17)	5.25 (133)	150.1 (2400)	1.1
40/20	72 (22)	4.50 (114)	148.9 (2390)	1.1
40/40	71 (22)	5.75 (146)	148.1 (2370)	0.9
20/40	66 (19)	8.00 (203)	149.0 (2390)	0.8
20/60	66 (19)	8.25 (210)	148.5 (2380)	0.6

Table 4—Times of setting

Mixture ID	Curing temperature,°F (°C)	Initial, h	Final, h	Time interval, h
0/0	70 (21)	4.78	6.05	1.27
	60 (16)	6.67	8.73	2.06
	50 (10)	6.14	8.37	2.23
	40 (4)	7.17	10.07	2.90
20/20	70 (21)	8.00	10.33	2.33
	60 (16)	12.02	15.41	3.39
	50 (10)	12.23	16.45	4.22
	40 (4)	9.73	13.85	4.12
40/20	70 (21)	9.12	11.81	2.69
	60 (16)	10.05	13.42	3.37
	50 (10)	9.13	12.98	3.85
	40 (4)	10.67	13.60	2.93
40/40	70 (21)	11.86	39.29	27.43
	60 (16)	24.21	79.54	55.33
	50 (10)	37.45	175.35	137.90
	40 (4)	57.72	192.24	134.52
20/40	70 (21)	11.41	14.27	2.86
	60 (16)	9.81	12.33	2.52
	50 (10)	14.25	18.81	4.56
	40 (4)	16.34	22.50	6.16
20/60	70 (21)	11.00	260.00	249.00
	60 (16)	9.70	282.40	272.70
	50 (10)	14.80	314.30	299.50
	40 (4)	21.15	869.20	848.05

Table 5—Average compressive strength of mixtures studied

Mixture ID	Curing temp.,°F (°C)	Concrete compressive strength 1 day, psi (MPa)	3 days, psi (MPa)	7 days, psi (MPa)	28 days, psi (MPa)	90 days, psi (MPa)
0/0	70 (21)	3190 (22)	5210 (35)*	5730 (40)	6890 (50)	7720 (55)
	60 (16)	1620 (11)	3670 (25)	5180 (35)	6640 (45)	7270 (50)
	50 (10)	1650 (11)	4710 (32)	5450 (40)	6580 (45)	8120 (55)
	40 (4)	660 (4.6)	3710 (26)	5210 (35)	6780 (45)	7850 (55)
20/20	70 (21)	1300 (9.0)	3440 (24)	5200 (35)	7170 (50)	8720 (60)
	60 (16)	610 (4.2)	3270 (23)	5490 (40)	6960 (50)	8280 (55)
	50 (10)	270 (1.9)	2430 (17)	4420 (30)	7280 (50)	8650 (60)
	40 (4)	300 (2.1)	2190 (15)	4040 (28)	6840 (45)	9040 (60)
40/20	70 (21)	620 (4.3)	2660 (18)	4430 (31)	7760 (55)	8460 (60)
	60 (16)	450 (3.1)	2160 (15)	3870 (27)	6860 (45)	8230 (55)
	50 (10)	340 (2.3)	1490 (10)	3090 (21)	6570 (45)	9020 (60)
	40 (4)	150 (1.0)	960 (6.6)	2300 (16)	5860 (40)	8530 (60)
40/40	70 (21)	50 (0.34)	190 (1.3)	1160 (8.0)	4270 (29)	5650 (40)
	60 (16)	60 (0.41)	130 (0.90)	1020 (7.0)	3770 (26)	6650 (45)
	50 (10)	60 (0.41)	70 (0.48)	310 (2.1)	3090 (21)	4770 (33)
	40 (4)	50 (0.34)†	70 (0.48)	110 (0.76)	1770 (12)	4100 (28)
20/40	70 (21)	260 (1.8)	2020 (14)	3740 (26)	6280 (45)	7730 (55)
	60 (16)	200 (1.4)	1570 (11)	3670 (25)	5870 (40)	8030 (55)
	50 (10)	120 (0.83)	700 (4.8)	2620 (18)	5890 (40)	8080 (55)
	40 (4)	90 (0.62)	650 (4.5)	2250 (16)	5400 (35)	6430 (45)
20/60	70 (21)	60 (0.41)	70 (0.48)	80 (0.55)	2480 (17)	6320 (45)
	60 (16)	80 (0.55)	80 (0.55)	80 (0.55)	1560 (11)	3290 (23)
	50 (10)	40 (0.28)	60 (0.41)	60 (0.41)	1460 (10)	3380 (23)
	40 (4)	60 (0.41)	60 (0.41)	90 (0.62)	580 (4.0)	2890 (20)

*Test actually performed at six days due to inclement weather.
†Test actually performed at two days because concrete was too green to demold at one day.