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Fly Ash

Micron³™

Workability, Durability, and High Strength Concrete

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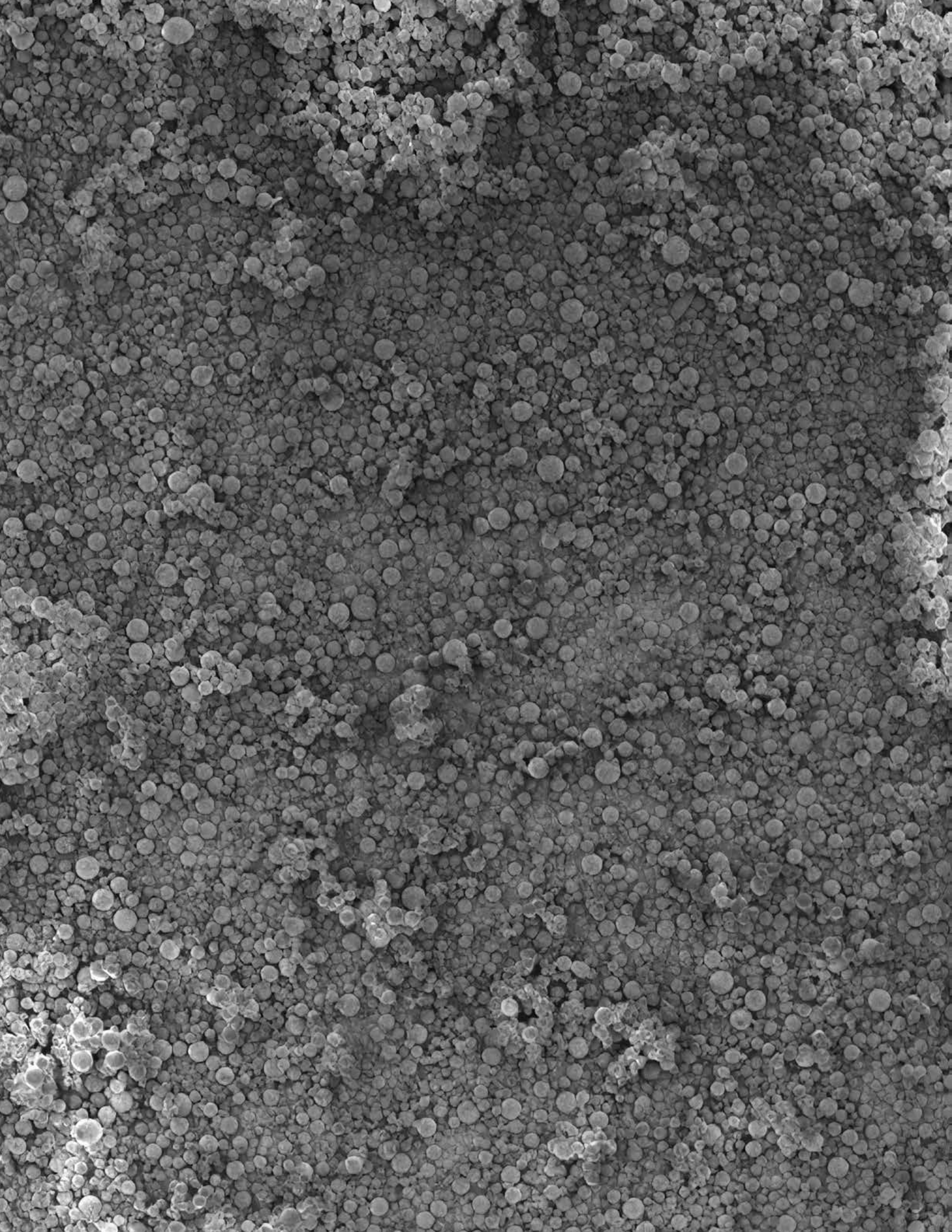

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Micron^{3} is an ultra fine fly ash with a typical median particle size of 2 to 4 microns. This is approximately 10 times smaller than the median particle size of ordinary fly ash, which typically ranges from 20 to 50 microns. The particle size distribution of Micron^{3} compared to regular fly ash is presented in Figure 1. The graph shows that while approximately 45% of the particles are smaller than 10 microns in regular as-produced fly ash, 100% of the particles in Micron^{3} are smaller than 10 microns. Figure 2 shows a micrograph of Micron^{3} compared to as-produced fly ash. A summary of the test results required by ASTM C618 is presented in Table 1. Micron^{3} greatly improves the durability of a concrete mix design while providing substantial increases to both early and late strength development.

PROPORTIONING CONCRETE AND FRESH PROPERTIES

Table 2 summarizes concrete mix designs where 5, 10, 15 and 20% of the cement content was replaced with Micron^{3}, Class F, and Class C fly ash, to compare their performance. A fixed amount of 9.3 oz/cwt of water reducer was used throughout all the mixtures. The water content was adjusted to maintain the concrete slump between 2.5 and 3.5”. Figure 3 shows the increasing water reduction provided by Micron^{3} as the cement replacement level increases. The graph also shows Micron^{3} outperforms the water reduction benefits of Class F and C fly ash.

Figure 1: Particle Size Distribution of Micron3 Compared to As-Produced Fly Ash

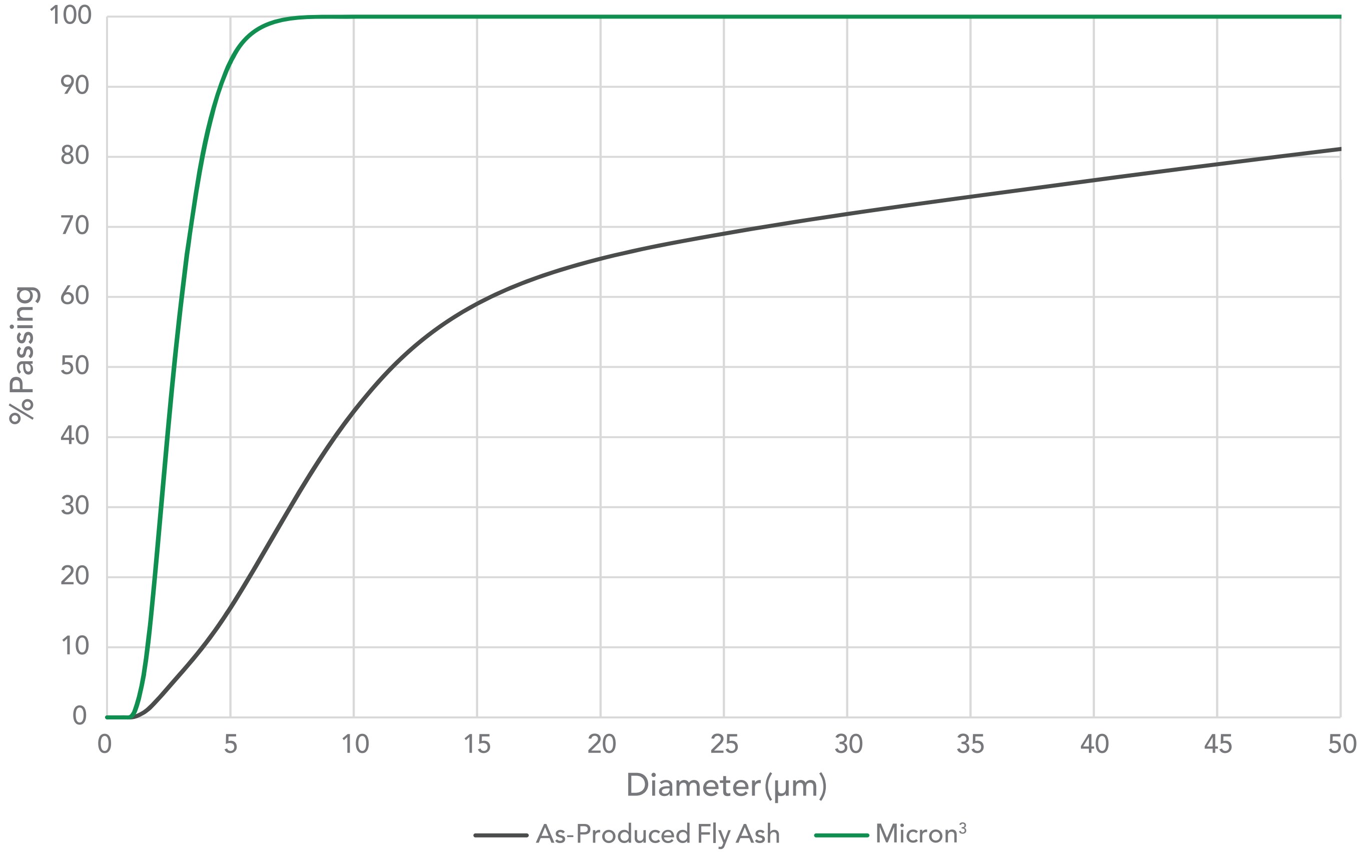

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Figure 2: Micrograph of As-Produced Fly Ash (left) and Micron^3 (right)

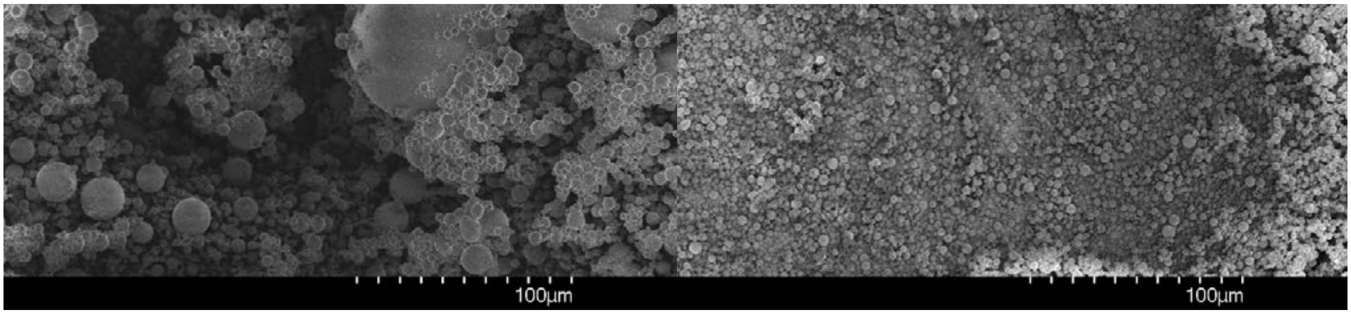


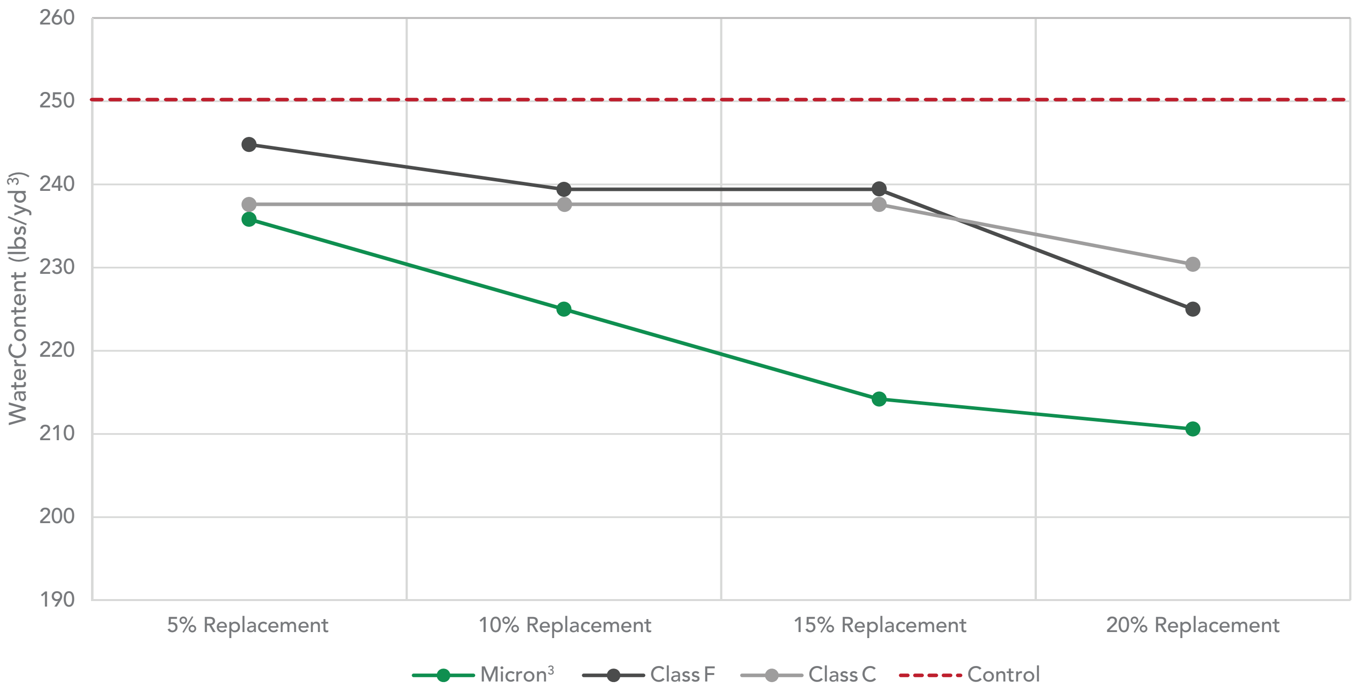
Table 1: ASTM C618 Requirements

	Micron^3	As-Produced Fly Ash	ASTM Class F Limit
Sum of Oxides (SiO_2+Al_2O_3+Fe_2O_3 %)	74.91	73.13	50% Min
CaO (%)	9.65	13.72	18% Max
SO_3 (%)	1.59	0.76	5% Max
Moisture (%)	0.09	0.05	3% Max
LOI (%)	0.52	0.27	6% Max
Fineness (% retained on 45 micron sieve)	0	21.32	34% Max
7 day SAI (% of control)	111	84	75% Min
28 day SAI (% of control)	125	91	75% Min
Water Requirement (% of control)	91	94	105% Max
Specific Gravity	2.69	2.59	-

Table 2: Concrete Mix Designs

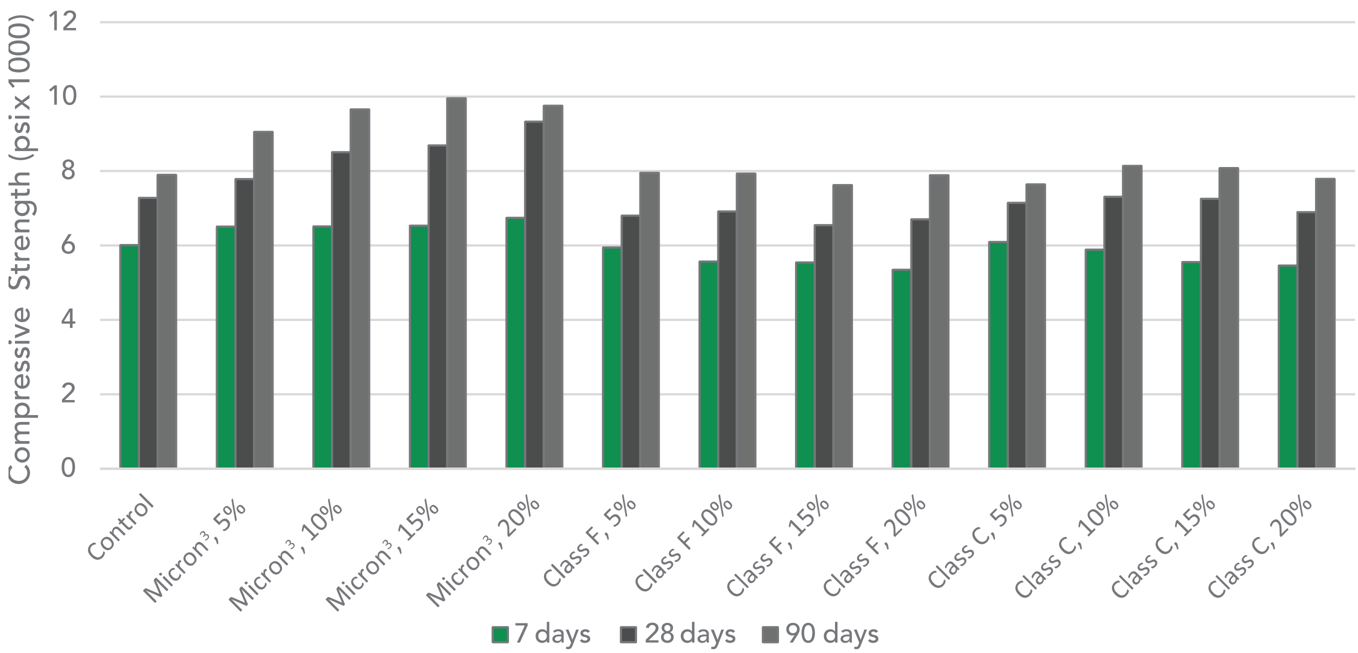
	Control	Micron^3 5%	Micron^3 10%	Micron^3 15%	Micron^3 20%
Cement (lb/yd^3)	550	523	495	468	440
Micron^3 (lb/yd^3)	0	28	55	83	110
Class F Fly Ash (lb/yd^3)	0	0	0	0	0
Class C Fly Ash (lb/yd^3)	0	0	0	0	0
Water (lb/yd^3)	250	235	225	215	210
Coarse Aggregate (lb/yd^3)	1925	1945	1955	1968	1972
Fine Aggregate (lb/yd^3)	1328	1343	1355	1365	1370
Unit Weight (lb/ft^3)	152.4	154.4	154.4	152.8	154.4
Slump (in)	3.5	3.5	2.5	2.75	2.5

Figure 3: Water Reduction



	Class F 5%	Class F 10%	Class F 15%	Class F 20%	Class C 5%	Class C 10%	Class C 15%	Class C 20%
	523	495	468	440	523	495	468	440
	0	0	0	0	0	0	0	0
	28	55	83	110	0	0	0	0
	0	0	0	0	28	55	83	110
	245	240	240	225	240	240	240	230
	1950	1950	1950	1950	1950	1950	1950	1960
	1311	1319	1314	1350	1320	1320	1320	1325
	152.4	152	152.8	152.4	152	152.4	152.4	152
	3.25	3.5	3.25	3.5	2.5	3.25	3.5	3

Figure 4: Strength Development



STRENGTH DEVELOPMENT

The strength development of these concrete mix designs is demonstrated in Figure 4. The results clearly show the benefit of including Micron^3 for both early and late age strength development. At 7 days, all of the concrete mixes containing Micron^3 have higher compressive strength than the control mix and the other fly ash-containing mixes. This trend continues both at the 28 day and 90 day testing ages. These results demonstrate that Micron^3 was able to develop higher compressive strength than cement or other ordinary fly ashes.

DURABILITY

Durability of concrete is a key consideration in the design of structures and pavements. Longer lasting concrete structures require fewer repairs over their service life, thus resulting in lower life cycle costs. Most deleterious reactions that can damage concrete and concrete structures are due in part to the ingress of potentially deleterious agents such as chlorides, sulfates and deicing salts. Denser, less permeable concrete limits the ingress of these potentially deleterious agents. Highly refined pozzolans such as Micron^3 may be used to dramatically increase concrete durability. This technical sheet also discusses the ways Micron^3 improves concrete durability, particularly with respect to corrosion, alkali silica reaction (ASR) and sulfate attack.

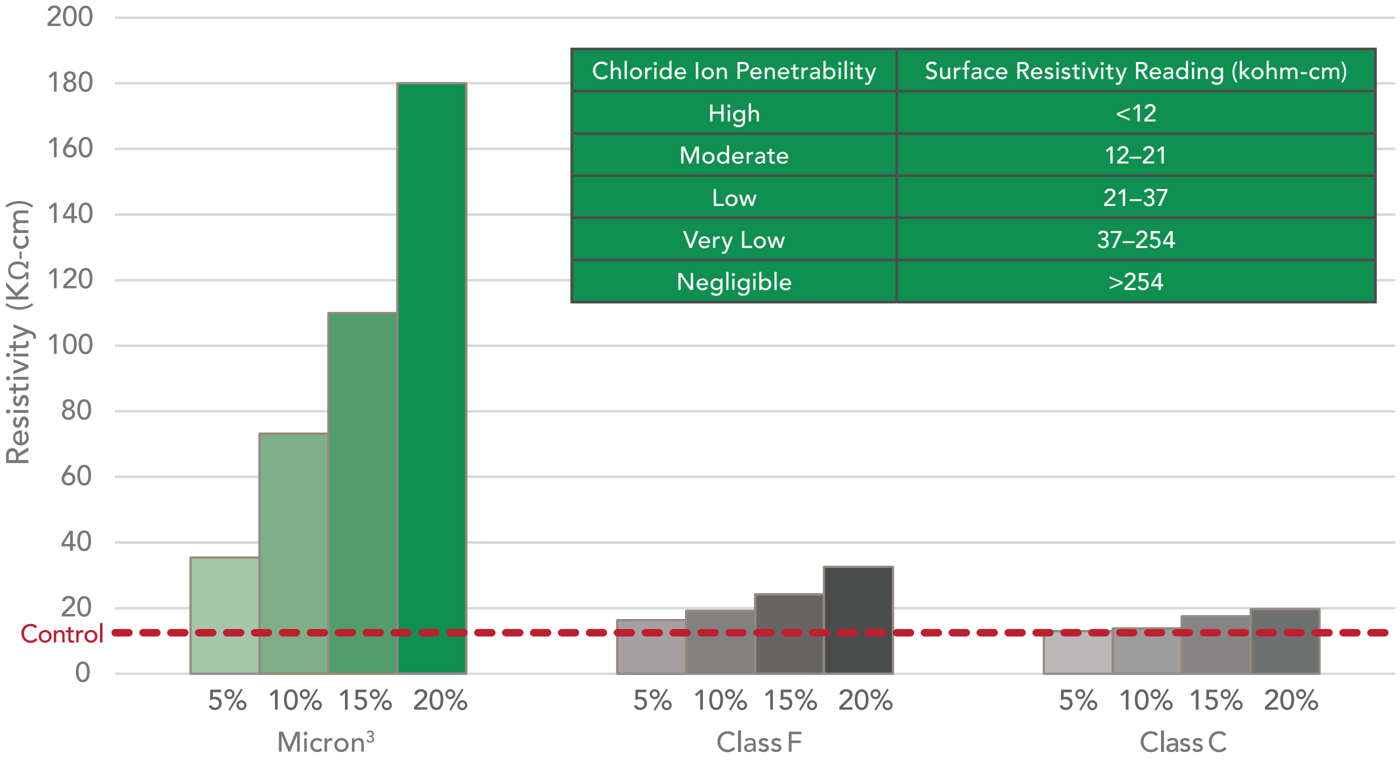
CORROSION

Exposure to chloride ions is the most common cause of premature deterioration of steel in reinforced concrete. Chlorides, originating from deicing salts and sea water, can migrate throughout the concrete and attack the passivating oxide layer that coats steel reinforcement. An electrochemical reaction ensues, leading to formation of ferric hydroxides, accompanied by an increase in volume. Tensile stresses develop within the concrete, ultimately leading to cracking and delamination. The steel cross sectional area is also reduced, decreasing the load carrying capacity of the structure. Resistivity and rapid chloride permeability are two ways of assessing the susceptibility of concrete to steel corrosion.

RESISTIVITY

Measuring the resistivity of a concrete sample involves using an electrical probe to determine how much the concrete interferes with the transmission of an electrical field. A higher measured resistance implies the concrete has a denser microstructure and thus lower permeability. The resistivity results measured at 90 days are shown in Figure 5. Not only do these results demonstrate superior performance of Micron^3, but they also show the increased resistivity gained by increasing the total cement replacement value. Higher resistivity will result in reduced corrosion rate.

Figure 5: Concrete Resistivity, 90 Days



Chloride Ion Penetrability	Surface Resistivity Reading (kohm-cm)
High	<12
Moderate	12–21
Low	21–37
Very Low	37–254
Negligible	>254

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SHRINKAGE RESISTANCE

Shrinkage is an important aspect to understand when considering both the long-term durability and appearance of concrete. The phenomenon of drying shrinkage can induce tensile cracking on concrete surfaces. Such cracking may mar the finish surface and accelerate rebar corrosion or alkali-silica reaction by providing pathways for the ingress of water. The ability for Micron^3 to improve shrinkage resistance was tested via two modified versions of ASTM C157, and its performance was compared with two other highly reactive pozzolans, silica fume and metakaolin. The first of these tests was performed by using the version of C157 presented in ASTM C311 at multiple cement replacement levels. Figure 6 demonstrates the results of this test, which shows how mortars containing Micron^3 both resist drying shrinkage more than mortars containing other highly reactive pozzolans, and in some cases shrink less than the control mortar. These findings are supported by the second test, the modified version of C157 presented in the AASHTO standard for highly reactive pozzolans, M321. Figure 7 shows how in this drying shrinkage test Micron^3 again both resists shrinkage more than silica fume and metakaolin, and reduces the shrinkage experienced by the control mixture. These results demonstrate how using Micron^3 can reduce the drying shrinkage experienced by cementitious systems, and thus improve the durability and finish quality of concrete.

Figure 6: 28-Day Shrinkage of C157 Mortar Bars

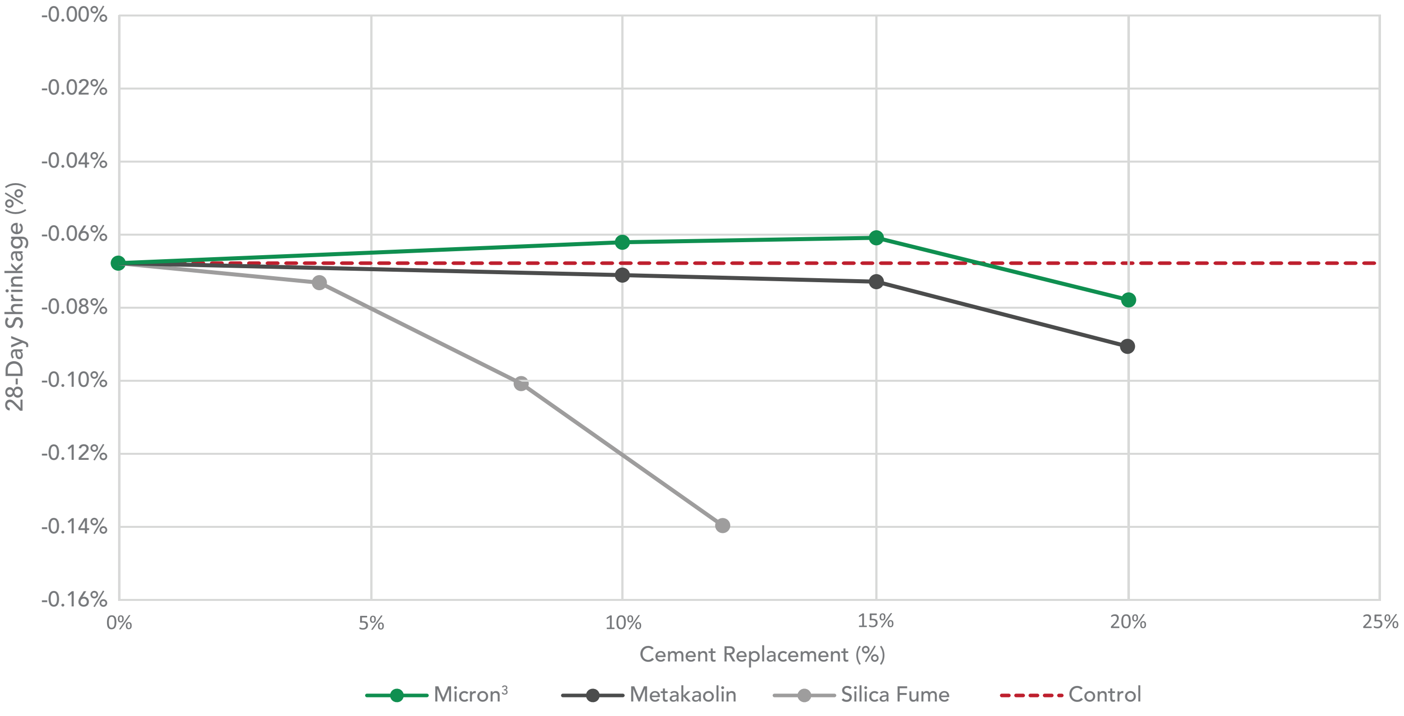
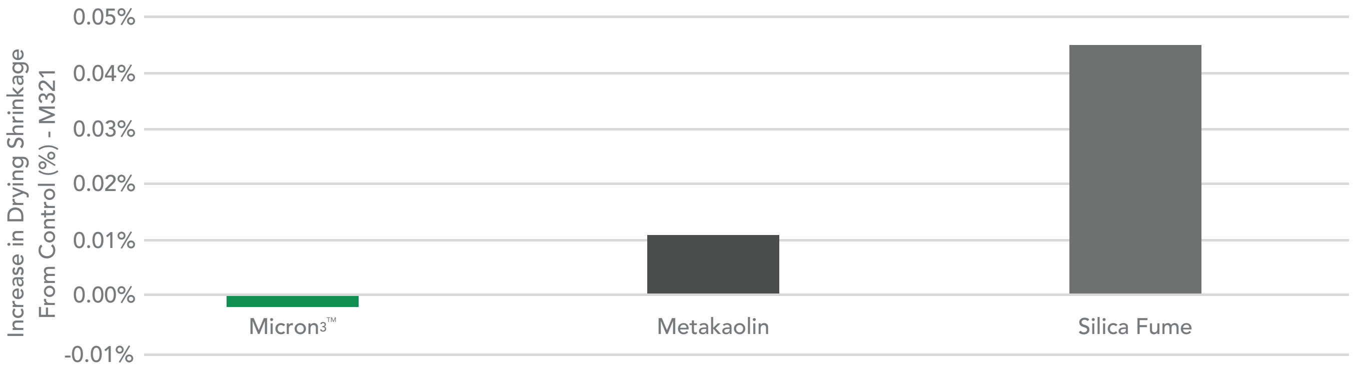


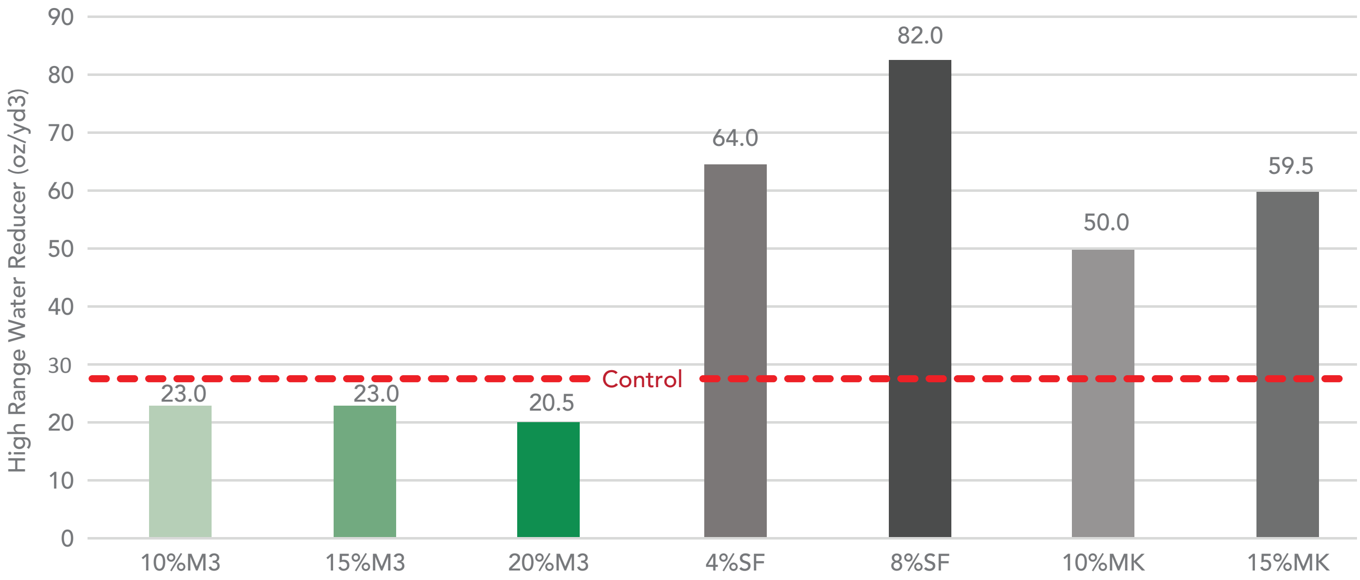
Figure 7: Drying Shrinkage per AASHTO M321



CONCRETE WORKABILITY

One of the difficulties encountered when working with concrete containing highly reactive pozzolans is the impact those materials have on concrete workability. Using pozzolans such as silica fume and metakaolin in a concrete mixture necessitates the inclusion of large amounts of high range water reducer (HRWR) or superplasticizer in order to make the concrete reasonably workable. In order to determine the impact Micron^3 has on concrete workability, concrete containing each pozzolan was batched and their dependence on HRWR was compared. The concrete mixtures contained identical coarse aggregate content and maintained a constant water to total cementitious content ratio of 0.35, while the HRWR dosage was varied so that a final slump of 5+/- 0.25" was obtained. The HRWR dosages required to reach this target slump are shown in Figure 8. These results verify silica fume and metakaolin's dependence on chemical admixtures while showing how concrete containing Micron^3 can achieve similar slumps with significantly lower dosages. This finding represents a reduction in overall batch cost, and demonstrates how the inclusion of Micron^3 in a mixture yields workable concrete.

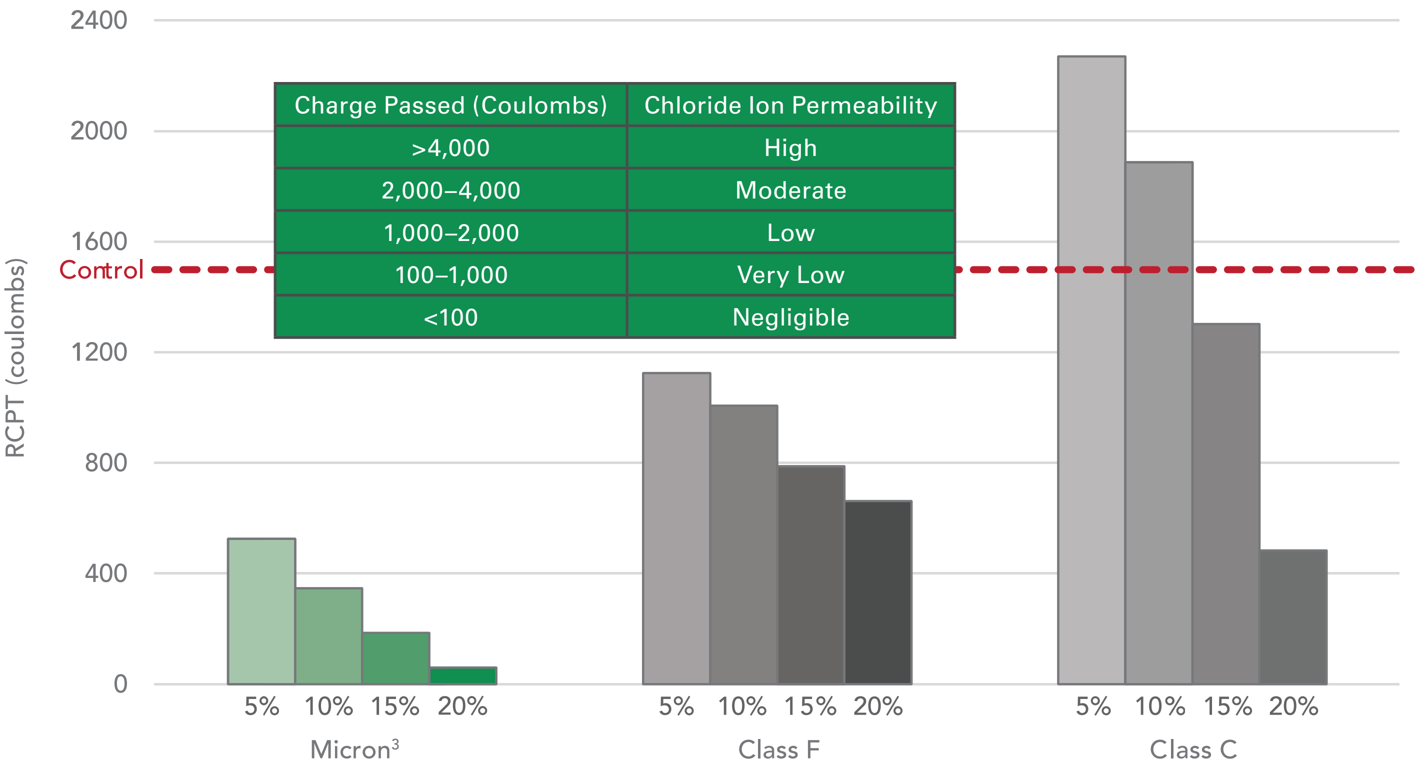
Figure 8: High Range Water Reducer Dosage



RAPID CHLORIDE PERMEABILITY TEST (RCPT)

The rapid chloride permeability test (RCPT) performed according to ASTM C1202 involves passing an electrical charge through a saturated cross section of a concrete cylinder. The charge is sent through one end of the cross section, and the charge passed through the sample is measured in coulombs on the other side. The charge that passes through the sample is directly proportional to the permeability of the concrete, as the charge is assumed to be passed through ions within the pore solution of the concrete, and thus can only reach the other side of the sample by passing through interconnected pores within the concrete. Therefore, the higher the coulombs passed, the higher the degree of porosity (and higher permeability) in the sample. The results of this test on 90 day cured samples are shown in Figure 9. As with the resistivity results, Micron^3 demonstrates excellent performance, which increases as the replacement values increase. Using Micron^3 in concrete, even in small amounts, results in less permeable concrete, which is more resistant to effects like ASR, sulfate attack and corrosion, as all these reactions rely on the ability of water to penetrate into and through the concrete.

Figure 9: Rapid Chloride Permeability, 90 Days

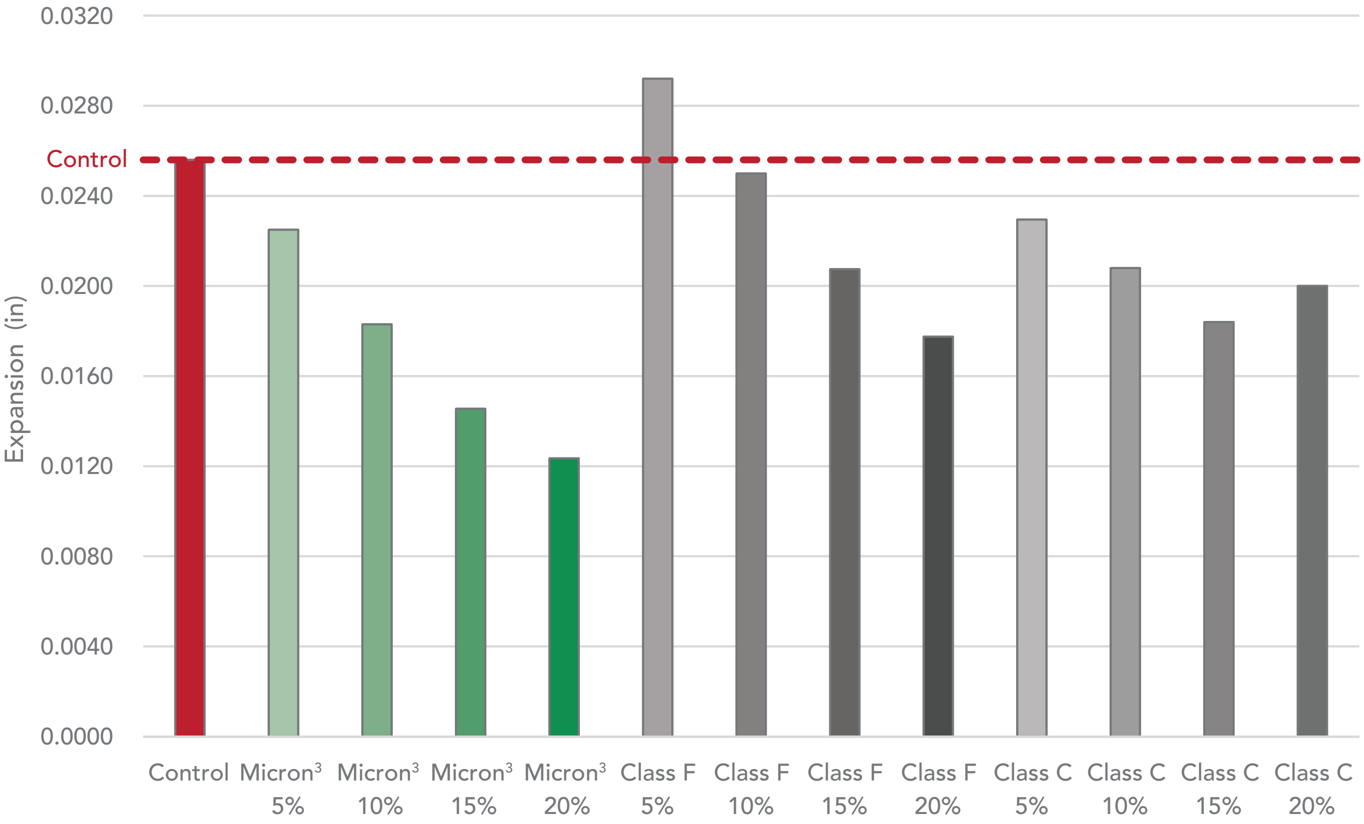


Charge Passed (Coulombs)	Chloride Ion Permeability
>4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
100–1,000	Very Low
<100	Negligible

ALKALI-SILICA REACTION (ASR)

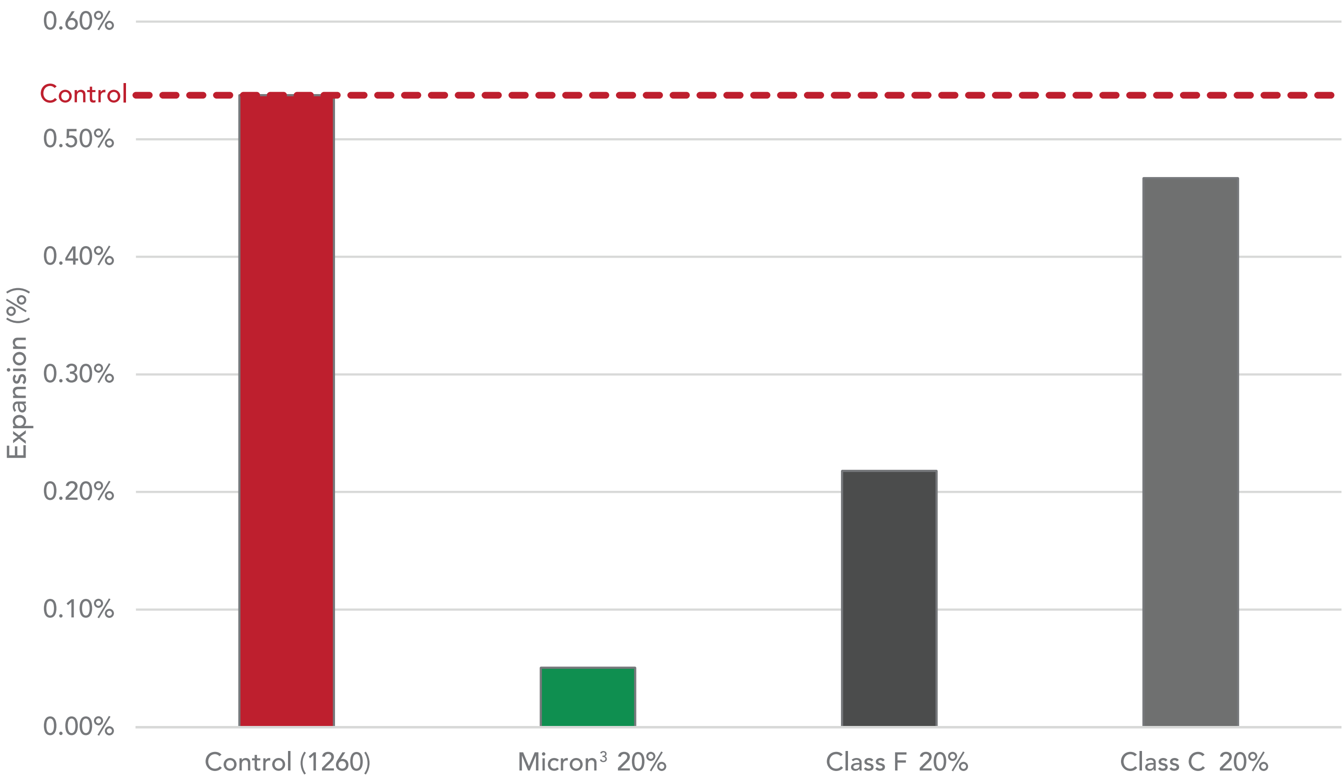
One of the most pervasive durability issues concerning concrete and concrete structures is ASR. ASR occurs when a reactive aggregate within concrete is exposed to water and high concentrations of alkalis present within the pore solution. The reaction that proceeds involves the growth of an expansive gel on the surfaces of the reactive aggregate. The development and expansion of this gel occurs well after the concrete has hardened; therefore the expansion results in significant internal pressures that lead to extensive cracking. The use of Micron^3 reduces the potential for ASR by two mechanisms: 1) reducing the concrete permeability, thus making movement of alkalis and moisture more difficult; and 2) contributing to the binding of alkalis through increased pozzolanic reactions made possible by the presence of a significantly larger amount of particles that can be more evenly distributed throughout the concrete matrix than can larger and more sparsely distributed particles. The ability for Micron^3 to mitigate ASR was verified by the test methods ASTM C441 and ASTM C1567. The results of these tests are shown in Figures 10 and 11, respectively. ASTM C441 involves the length change of mortar bars cured at elevated

Figure 10: ASTM C441 Results



temperature in which reactive glass is used in lieu of sand, and cement with high alkali content is used to accelerate the ASR reaction. The degree of expansion is measured at 14 days, and the bars containing supplementary cementitious materials are compared against the control bar in order to evaluate how much the materials mitigate ASR. Figure 10 demonstrates the overall effectiveness of Micron³ and how it outperforms both Class C and Class F fly ashes. At 20% replacement, Micron³ effectively reduces expansion by over 50%. This finding is significant as it demonstrates that expansion is being mitigated not only by the 20% dilution of cement, but also due to the Micron³ reacting and preventing the formation of expansive ASR gel. Similar results were obtained via ASTM C1567 as demonstrated in Figure 11. The expansion measured in this test is different in magnitude compared to ASTM C441 as the aggregate in the mortar bars for ASTM C1567 is made with a naturally occurring reactive aggregate rather than ground glass. However, both tests clearly demonstrate the significant effectiveness of Micron³ in mitigating ASR.

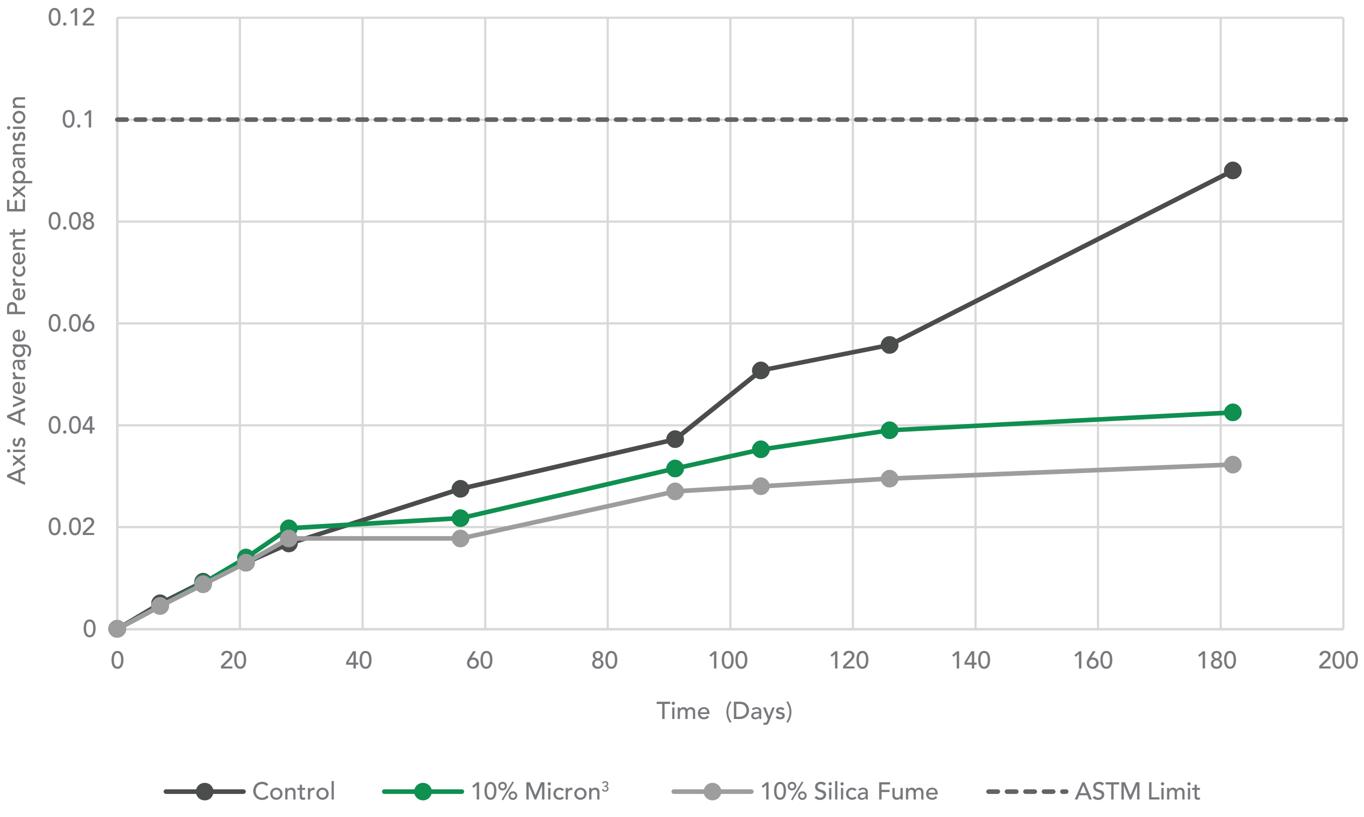
Figure 11: ASTM C1567 results



SULFATE ATTACK

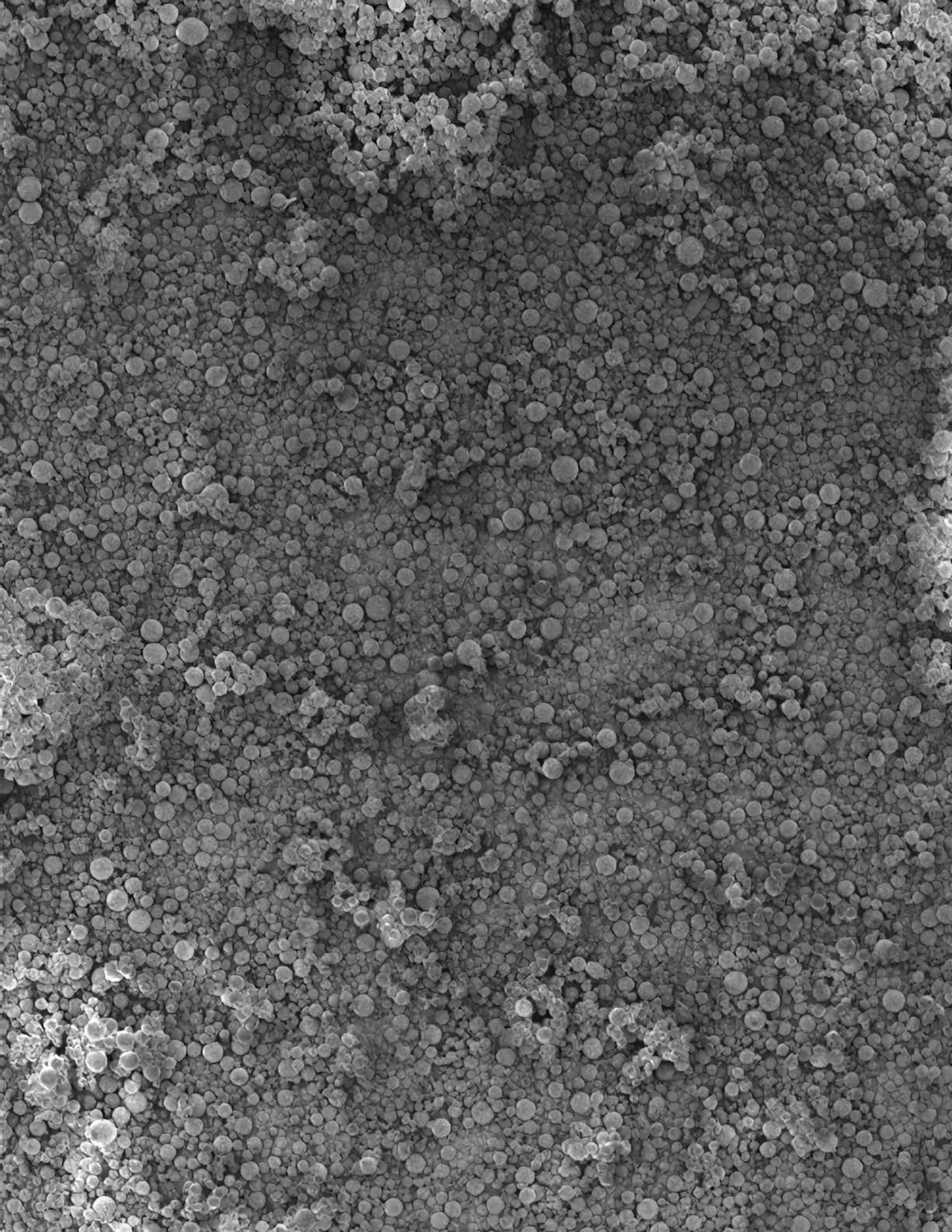
Another deleterious reaction that needs to be considered when designing a durable concrete mix is sulfate attack. Sulfates from sources such as ground water or soil can penetrate concrete and react with products formed during cement hydration. This results in the formation of sulfate phases such as ettringite that can lead to expansion and cracking. The use of Micron^3 mitigates sulfate attack by reducing permeability and inhibiting the ingress of sulfate ions. Calcium hydroxide is also consumed during the pozzolanic reaction. Figure 12 shows ASTM C1012 test results where the effectiveness of Micron^3 in mitigating sulfate attack is displayed.

Figure 12: ASTM C1012 Results



SUMMARY

1. The use of Micron^3 as a cement replacement significantly reduces water demand in concrete. In this study, Micron^3 reduced the water content by 16%, compared to 8-10% reduction by fly ash, relative to the cement control while maintaining similar workability.
2. Partially replacing cement with Micron^3, even in small amounts, results in significant strength improvements at early and later ages. Replacing 5% of the cement with Micron^3 resulted in an 8% increase in concrete strength at 7 days and a 15% increase at 90 days. At a higher replacement level of 15%, concrete strength was increased by 26% at 90 days.
3. Micron^3 can help to greatly reduce concrete permeability. This was shown by increases in concrete resistivity and decreases in coloumbs passed as the cement replacement level increased.
4. Micron^3 significantly reduces chloride ingress in concrete, thereby increasing the time to corrosion initiation of reinforced concrete structures. Replacing a mere 5% of the cement with Micron^3 results in approximately a 60% reduction in chloride permeability compared to the cement control. Using higher replacement levels, e.g., 20%, reduced the permeability by approximately 95%, resulting in concrete with negligible chloride permeability.
5. Another benefit of using Micron^3 in concrete is its effectiveness in mitigating ASR. Micron^3 increases concrete's resistance to ASR by reducing permeability, thereby limiting the ingress of moisture, and via the pozzolanic reaction. Micron^3 was found to outperform regular fly ash when replacing as little as 5% of cement.
6. Concrete proportioned with Micron^3 experiences less drying shrinkage than concrete proportioned with other highly reactive pozzolans, such as silica fume and metakaolin. This study shows there is especially a stark contrast between Micron^3 and silica fume, the latter causing drying shrinkage several orders of magnitude greater than in Micron^3 mixes.
7. Another important difference between Micron^3 and other highly reactive pozzolans is the water demand or demand for HRWR to maintain a given w/c ratio and slump. Concrete with silica fume and thus higher amounts of HRWR is often harder to place as it is more cohesive and finishers often report it is "sticky." While Micron^3 reduces the amount of HRWR needed to achieve a given slump and w/c ratio compared to portland cement alone, silica fume and metakaolin require more than double and at high replacements more than triple the amount of HRWR than that required by Micron^3 to achieve the same slump and w/c. Thus, Micron^3 concrete is generally easier to place and finish than concrete containing other highly reactive pozzolans.
8. Micron^3 is also effective in reducing the risk of expansion due to sulfate attack.



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