EVALUATION OF A BLENDED CEMENT AND A MINERAL ADMIXTURE CONTAINING CALCINED CLAY NATURAL POZZOLANS FOR HIGH PERFORMANCE CONCRETE

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ABSTRACT

A blended cement system (Duracem™) meeting the requirements of ASTM C 595 (IP, IPMS) and C 1157 (GU, MS AND HS) was developed and commercially produced in 1993 by Ash Grove Cement Company in its efforts to address the durability problems related to alkali-silica reactivity (ASR) and sulfate attack in concrete pavement. The cement product is manufactured by combining a calcined clay manufactured pozzolan, gypsum and Portland cement. In 1995 the mineral admixture (Durapoz™) which meets ASTM C 618 was produced and subsequently introduced into the market. Careful selection of the raw clay materials followed by proper thermal activation, and finish grinding are used to "engineer in" the desired performance properties. Ash Grove Cement Company was issued a patent for the above mentioned products in May of 1997.

During the last three years, more than 110 miles of highway and municipal pavements have been placed in Nebraska, Kansas, and Iowa using these new products. The manufactured pozzolan addition rate in the blended cement is typically 16-21%. Paving operations managers have been pleased with the workability of the concrete mixes when compared to Type I mixes.

Long term testing of both the Type IP cement and the mineral admixture confirms their ability to mitigate ASR using ASTM methods C 227, C 441, C 1260, and C 1293. Excellent sulfate resistance characteristics are shown using the ASTM C 1012 test method when comparing specimens of Type V, Type IP and Type IP with 10% Class C Fly Ash substitution. Significant reductions in concrete permeability are shown with data from method ASTM C 1202, as well as, corroborative testing by AASHTO T 259, chloride ponding, and diffusion coefficient calculation comparisons. Freezing and thawing resistance, and deicer scaling resistance data were similar to the control Type I concrete mixes when tested using the ASTM C 666 and C 672 methodologies, respectively.

In summary, the calcined clay modified blended hydraulic cements and manufactured mineral admixtures can provide many benefits to highway paving, public works, and other structural applications. When compared to Type I Portland cement concrete, a few of the benefits of the calcined clay modified systems are:

1. Reduced susceptibility to ASR when used with potentially reactive aggregates.
2. Improved sulfate resistance.
3. Reduced permeability.
4. Lower Heat of Hydration.
5. Increased ultimate compressive and flexural strengths.
6. Improved workability.
7. Cost effectiveness.

INTRODUCTION

The use of raw or calcined natural pozzolans to counter the effects of Alkali-Silica Reaction (ASR), as well as, sulfate attack has been known for many years, however in modern times, infrequently utilized[1,2,3]. For cement manufacturers, the incorporation of raw or calcined natural pozzolans into blended cement materials has been scarce due to high water demand and low early strengths. This has restrained the interests of cement manufacturers and concrete producers. However, advancements in formulation and manufacturing technology (U.S. Patent 5,626,665)[4] have corrected these disadvantages allowing practical use of calcined natural pozzolans to address concrete durability issues.

Efforts, however, are in progress by paving engineers to improve the long-term durability of concrete highway pavements and structures through the incorporation of changes in both design and materials. Distress mechanisms, such as alkali-silica reaction (ASR), have been documented extensively in the Midwestern United States since the 1940's. Each state, however, has its own protocols for combating ASR. One Midwestern state, for instance, uses a standard pavement mix design that requires "sweetening" of potentially alkali reactive sand/gravels with 30% limestone coarse aggregate by weight to mitigate ASR. Some states require both a substitution and addition of Class F fly ash for ASR mitigation. The depletion of durable aggregate sources and the subsequent increased occurrences of ASR damage in concrete highway pavements have led to renewed research to improve the life cycle cost benefits of Portland cement concrete.

Ash Grove Cement Company has introduced into the market a blended cement (see figure 1 and 2) containing a calcined clay natural pozzolan to address concrete durability concerns in pavements. The development objectives of this product were to be as similar in initial setting and early strength properties to Type I cements as possible and ultimately exhibit the following properties:

- Mitigate ASR
- Sulfate resistant
- Reduced permeability
- Freeze/thaw and salt scaling resistance
- Cost effective

To obtain the desired properties the clays to be calcined are selected to be low alkali (<3.0% Na_2O equivalent) and low crystalline quartz content. The clays are calcined at the lowest possible temperature to achieve nearly complete dehydroxylation to maximize pozzolanic reactivity. Table 1 shows the composition of the calcined clays currently in commercial production and the composition of the other materials in this study. The calcined clays are then either interground with Portland cement clinker and gypsum or ground separately with sufficient gypsum to assure optimum sulfate content in the final cementitious system. The grinding process is controlled in such a manner to prevent the calcined clay component from being ground excessively fine. Figure 3 compares the particle size distribution of Portland Cement #5 to interground Blended Cement #1 containing 17.5% Calcined Clay A, 1.5% gypsum, and 81% Portland Cement #5. The control of the particle size distribution of the calcined clay component is important for controlling water demand. The processing methods to achieve the desired properties are disclosed in an U.S. patent.

EXPERIMENTAL

Evaluation Of Effect On Potential For Alkali Silica Reaction

The effect of increasing amounts of Calcined Clay A replacement in cement on expansion in ASTM C 227 is shown in Figure 4. Figure 5 shows mortar expansion comparisons of a low alkali portland cement to commercially produced Blended Cement #1 in ASTM C 1260 Tests using a reactive aggregate. Also shown are the results of the commercially produced Blended Cement #1 spiked to 0.8% and 1.2% Na_2O equivalent with NaOH.

The evaluation of the potential for alkali silica reactivity included cementitious systems using a 10% replacement by Class C fly ash for the blended cement. The results of the ASTM C 1293 Concrete Prism Test for ASR with low alkali Type I cement (Cement 5) as a reference and Cement #5 containing two different blended pozzolan substitution rates (18.6% and 26.4%) are shown in Figure 6. These same systems, with a 10% replacement of Class C fly ash, still show excellent performance. Figure 7 shows the results of ASTM C 441 testing Blended Cement #1 relative to Cement #3 (high alkali Type I). Also tested are two mixes with 10% replacement by two different Class C fly ashes for the blended cement. All examples show excellent mitigation of ASR.

Sulfate Resistance

Figure 8 shows the results of ASTM C 1012 Sulfate Resistance tests with high alkali Cement #3 both with and without the Blended Pozzolan. Figure 9 compares the performance of a commercial Type V cement to commercially available Blended Cement #2, and the same cement containing a 10% replacement with Class C fly ash. The data has been carried out for two years. The blended cement systems containing calcined clay, even with 10% Class C fly ash replacement, are much more sulfate resistance than a Type V. The expansions exhibited by these products are well below the limits of ASTM C 595 Moderate Sulfate (MS) and C 1157 High Sulfate (HS) resistance.

Freeze/Thaw Durability And Salt Scaling

A proper air void system in concrete is the key to freezing and thawing resistance. The reduction in concrete permeability, provided by the calcined clay blended cement or the blended pozzolan systems, also contributes to producing concrete with similar frost resistance and deicer scaling protection as concrete containing Type I cements. Table 2 shows the results of ASTM C 666 and ASTM C 672 tests with mixes containing approximately 18% and 20% pozzolan replacement.

Permeability

Figure 10 shows the effect of increasing replacement contents of calcined clay on the electrical conductance through concrete in Test Method ASTM C 1202 Rapid Chloride Permeability Test. For reference, Portland Cement #5 (see Table I), Portland Cement #5 with 5%, 15%, 25%, and 35% calcined clay replacements, Portland Cement #5 with 10% silica fume replacement, and Portland Cement #5 with 15% Class F fly ash replacement are shown.

A testing program to evaluate the permeability characteristic of concrete containing calcined clay was recently completed at the Construction Technologies Laboratories (CTL) for Ash Grove[5]. Mix designs from a project currently underway, using Blended Cement #2 for a concrete parking garage at Kansas City International Airport requiring high performance concrete, were evaluated for permeability by both ASTM C 1202 Rapid Chloride Permeability and AASHTO T 259 Chloride Ponding Tests. The mix designs and corresponding results are shown in Table 3. One of the mixes was repeated with and without W.R. Grace's DCI corrosion inhibitor to evaluate the effect of the DCI on the ASTM C 1202 measurements. The commercially available Blended Cement #2 outperformed the control mix containing Cement #6 and silica fume when tested by both ASTM C 1202 and AASHTO T 259 methods.

Another set of concrete mix designs was evaluated using a high alkali Type I cement and Ash Grove's commercially available blended pozzolan. Table 4 shows the mix designs and the comparison of the ASTM C 1202 and AASHTO T 259 results. The AASHTO T 259 test was modified in that ponding continued for 180 days rather than 90 days. One slab of each concrete was cast, cured, and then ponded. After 180 days a 4-inch diameter core was drilled from each slab and milled in approximately 1-mm. layers. The dust from each layer was analyzed for acid-soluble chloride ion concentration. The concentration of chloride ion vs. distance from the surface was plotted and Frick's Second Law of Diffusion was imposed on each plot and an apparent diffusion coefficient was computed. The results of the permeability testing show that a level of resistance to chloride penetration previously associated with premium silica fume containing concrete is now available from economically produced blended cements containing calcined clays.

Heat Of Hydration

Where heat of hydration in mass structures is of concern, the calcined clay blended cement has proven to be effective at maintaining low differential temperature requirements (See Projects Summary, Item 4). Table 5 shows the results of ASTM C 186, 7-day heat of hydration for blended cement systems and Type II, Type IV, and Type V portland cements.

Workability

Paving superintendents have been pleased with the workability of the concrete mixes when compared to Type I mixes. Improved flow properties are produced when compared to equivalent concrete mixes containing Type I cement due to the increased paste volume of the concrete containing Duracem™ cement or Durapoz™ mineral admixture. The increased paste volume is the result of the lower specific gravity of the cementitious system. The increase in plastic concrete flow properties of the calcined clay systems allows for better consolidation of the paving mixture at lower vibration frequencies. The use of high vibration frequency consolidation has been linked to entrained air loss at the surface of concrete pavements. Since loss of entrained air can result in reduced freezing/thawing durability, this improved consolidation characteristic will benefit highway pavement durability.

Strength

Concrete containing the blended cement system typically shows a slightly slower early age strength gain when compared with concrete made using Type I. When the 28-day compressive strength values are compared, however, the concrete that contains the blended cement has surpassed those containing Type I cement. Typical compressive strength development curves of the blended cement system are shown in figure 11 as compared to Type I cement. Early age strength gain in this set of data are, however, very similar.

DISCUSSION

The calcined (dehydroxylated) kaolinitic clay contains approximately 85% kaolinite, 10% quartz, and 5% other clay types. These clays have a typical elemental composition (as determined by X-Ray Fluorescence Analysis [XRFA]) of approximately 54% SiO_2, 38% Al_2O_3, and 2% Fe_2O_3 (See Table I). The clay is soft fired in a rotary kiln at a temperature of between approximately 550° C and 750° C which converts the clay's crystalline structure to an amorphous phase (see the x-ray diffraction analysis [XRDA], figure 12). The use of an amorphous aluminosilicate to react with the calcium hydroxide in hydrating Portland cement is an effective means of increasing the production of C-S-H gel and lowering the inherent porosity of the paste microstructure. Soft firing of the clay, therefore, is one key to its optimum reactivity.

Soft fired kaolinitic clays also contribute significantly more Al_2O_3 to the chemical reaction products than do typical coal combustion fly ashes or the silicon or ferro-silicon by-product silica fume substitutions. XRD and DTA results show the increased formation of C-S-H gel and calcium sulfoaluminate phases (AFt and AFm) in the hydrating pastes (figures 13 and 14). Strätlingite (C_2ASH_8) may also form at higher substitution rates of the calcined clays. The consumption of the $Ca(OH)_2$ and the formation of these compounds has two net effects. First, it reduces porosity of the paste microstructure by the formation of more C-S-H gel, and secondly, the formation of ettringite ($C_6A\bar{S}_3H_{32}$), monosulfate ($C_4A\bar{S}H_{12}$), and potentially, Strätlingite (C_2ASH_8) provides more stable aluminate reaction products which makes the system less susceptible to sulfate attack and provides better volume stability.

Distress mechanisms, such as, ASR are greatly dependent on the transport properties and pore solution chemistry of the hydrated cement paste. The reduction in permeability restricts the transport of pore solution alkalis to potential reaction sites. Mitigation of ASR by the calcined clay pozzolan system appears to be the result of this reduction in permeability, as well as, the consumption of calcium hydroxide during hydration to form lower Ca/Si ratio C-S-H gel. This composition of gel may contribute to alkali absorption or binding.

SUMMARY

The manufacturing of pozzolans from various raw material sources and their use in blended cements, or as mineral admixtures in concrete, shows great promise for the reduction of the deleterious effects of ASR and sulfate attack. The reduced permeability characteristics provided by these types of cementitious systems limits the influence of chloride migration through concrete and their effects on the corrosion of reinforcing steel. Manufactured pozzolans are a cost effective means of providing high performance concrete properties to all levels of concrete consumer. The environmental benefits, which have not been discussed in this paper, include significantly reduced CO_2 emissions during cement production and reduced cement kiln dust generation. The use of these materials can provide a competitive edge in life cycle costing for pavements and steel reinforced concrete structures for rebuilding of the United States infrastructure.

Examples of projects where Duracem™ has been specified:

Completed #1: Sioux City, Iowa - Gateway Airport Runway

Specifications:	FAA 501 Spec. (59,000 yd^3) **DURACEM**
Field Data:	Flexural PSI (3rd point loading) 775 PSI @ 28-day, 3.7% C.V.
Contractor:	Irving F. Jensen
Mix Proportions:	611 C.F.(IP with 10% Class C fly ash substitution), w/c = 0.44

Completed #2: FHWA High Performance Bridge Deck Project, Sarpy Co., Nebraska

Specifications:	8000 PSI @ 56-Day, C1202 <1800 Coulombs
Field Data:	10,433 PSI (Avg.) @ 56-Day, C1202 589 Coulombs (Avg.)
Mix Proportions:	750 lbs., Duracem cement, 75 lbs. Class "C" Fly Ash, w/(c+p) = 0.30

Completed #3: Burns & McDonnell "Circle Drive Paving", Kansas City Headquarters

Specifications:	4500 PSI, AE 28-D
Field Data:	6700 PSI @ 28-Day, 7510 PSI @ 56-Day
Mix Proportions:	611 lbs. Duracem, W/C = 0.40
Concrete Supplier:	Fordyce Concrete Company

Completed #4: Kemper Sports Arena, Kansas City, Missouri "Mass Footing" Project: Two, 2,200 yd^3 pours (8 hours each)

Specifications:	Low heat of hydration, 40°F maximum temperature differential
Field Data:	29°F Max. Differential during initial 6 days
Mix Proportions:	450 lbs. Duracem, 80 lbs. Class C fly ash, w/(c+p) = 0.45
Concrete Supplier:	Fordyce Concrete Company

Completed #5: Nebraska Dept. of Roads, State Highway 2 project, Otoe County. Two 20 mile sections of 4 lane divided highway pavements (40 miles total ≈ 511,000 yd^3)

Specifications:	611 lbs. Duracem, 0.45 w/c containing 9.5 % Class "C" Ash Substitution

Completed #6: Nebraska Dept. of Roads Project: Kennedy Expressway, 9 miles, 4 lane divided highway pavements, Bellevue to Omaha, Nebraska (115,000 cy)

Mix Proportions:	508 lbs. Duracem, 56 lbs. Class "C" Ash, w/(c+p) = 0.42 to 0.44
Field Data:	5980 PSI compressive @ 28-Day
	1026 PSI M.O.R. (Center Point Loading) @ 28-Day

In-progress #7 : **Kansas City International Airport Project: Terminal C Parking Garage, Initial Construction Started 7/96, Expected Completion Date 4/98**

Owner:	Kansas City, Missouri
Contractor:	J.E. Dunn
Structural Engineer:	George Butler and Associates
Consultants:	Carl Walker & Associates
	Leigh & O'Kana Structural Engineers
Specifications:	750,000 ft^2 Parking Area (2232 parking spaces)
	28,000 yd^3 of concrete
	6000 PSI @ 28-Day, Target
	C1202 Maximum < 1577 Coulombs with 3 gallons/yd. DCI
	C1202 Maximum < 1100 Coulombs without DCI
Lab Data:	C1202 = 640 Coulombs, pre-project mixes without DCI
Field Data:	8730 PSI @ 28-Day, Average of all 6" X 12" cylinders
	C1202 <1120 Coulombs with 3 gal. DCI (Avg. of 17 tests)
	6.8% Hardened Air Content with a 0.0048" spacing factor
Concrete Supplier:	Fordyce Concrete Company



TABLE 1: XRF Compositions of Materials

	Calcined Clay A	Calcined Clay B	Blended Pozzolan	Cement #1 (Blended)	Cement #2 (Blended)	Cement #3 (High Alkali)	Cement #4 Type V
SiO_2	53.6	63.3	49.2	26.5	28.9	19.9	21.7
Al_2O_3	37.6	19.7	35.0	9.97	7.40	4.83	4.15
Fe_2O_3	2.33	6.68	2.44	3.61	3.67	2.71	3.91
CaO	0.50	1.63	3.38	50.7	51.0	62.6	62.7
MgO	0.34	2.33	0.46	1.91	2.37	3.78	2.31
SO_3	0.02	1.05	2.24	3.20	2.71	3.43	3.00
Na_2O	0.11	0.36	0.12	0.09	0.37	0.16	0.36
K_2O	1.00	2.69	0.94	0.59	0.75	1.14	0.16
TiO_2	2.07	0.80	1.70	0.58	0.50	0.23	0.35
P_2O_5	0.18	0.27	0.28	0.08	0.13	0.07	0.11
Mn_2O_3	0.00	0.18	0.01	0.07	0.12	0.06	0.14
SrO	0.05	0.03	0.12	0.07	0.19	0.04	0.22
L.O.I.	2.39	0.50	3.99	1.69	1.74	1.79	1.64
Total	100.2	99.5	99.9	99.1	99.8	100.7	100.8
Na Eqv. Alk.	0.77	2.13	0.74	0.48	0.86	0.91	0.47

	Cement #5 Type I	Cement #6 Type I	Cement #7 (High Alk.)	Fly Ash #1 Class C	Fly Ash #2 Class C	Fly Ash #3 Class C	Fly Ash #4 Class C
SiO_2	21.7	20.7	21.2	39.6	32.9	35.4	31.4
Al_2O_3	4.31	4.70	5.06	19.0	19.9	17.3	17.2
Fe_2O_3	3.29	3.18	2.38	4.60	5.40	6.0	4.90
CaO	62.4	63.7	64.3	24.1	28.0	26.5	29.1
MgO	3.51	2.36	1.06	4.80	4.60	6.0	7.50
SO_3	2.53	2.69	3.10	1.12	1.74	2.02	2.47
Na_2O	0.10	0.31	0.28	1.53	1.96	1.99	2.54
K_2O	0.62	0.29	0.83	0.51	0.37	0.21	0.25
TiO_2	0.27	0.37	0.18	1.31	1.52	1.11	1.09
P_2O_5	0.08	0.10	0.17	1.22	1.37	0.86	0.68
Mn_2O_3	0.08	0.10	0.12	0.02	0.04	0.02	0.05
SrO	0.09	0.23	0.19	0.34	0.48	0.48	0.59
L.O.I.	1.10	1.01	1.04	0.90	0.71	0.90	0.97
Total	100.1	99.7	99.9	99.1	99.0	98.8	98.7
Na Eqv. Alk.	0.50	0.50	0.83	1.87	2.20	2.13	2.70

TABLE 2: Freezing and Thawing Testing Using Blended Cements #1 and #2

Mix	Cementitious Composition	ASTM C 666, Method A Relative Dynamic Modulus	ASTM C 672 Deicer Scaling Test Visual Rating (0=None 5=Severe)
1	Cement #6 (Type I)	94%	0
2	Type I w/15% Fly Ash Subst.	97%	1
3	Blended Cement #2 (Type IP)	96%	1
4	Type IP w/15% Fly Ash Subst.	93%	1
5	Cement #5 (Type I)	97%	0
6	Type I w/10% Fly Ash Subst.	93%	1
7	Cement #1 (Type IP)	95%	1
8	Type IP w/10% Fly Ash Subst.	92%	0

Note: Mixes 3 and 4 contained 20% Calcined Clay B as the manufactured pozzolan in Blended Cement #2.
Note: Mixes 7and 8 contained 18% Calcined Clay A as the manufactured pozzolan in Blended Cement #1.
Note: All mixes in Table 4 were cast at a w/(c+p) = 0.45 and cement factor of 600 lb/yd^3 (356 kg/m^3).

TABLE 3: Concrete Characteristics of Systems Containing Calcined Clay and Silica Fume

Mix Design Parameters:	Cement #6 Type I + 7% Silica Fume	Cement #2 without Silica Fume	Cement #2 + 3.4% Silica Fume	Cement #2 + 3.4% Silica Fume, no DCI
Cement 6 (Type I), lb/yd^3 (kg/m^3)	680(403)	0	0	0
Blended Cement 2, lb/yd^3 (kg/m^3)	0	730(433)	650(386)	650(386)
Silica Fume, lb/yd^3 (kg/m^3)	51 (30)	0	23(14)	23(14)
Sand, lb/yd^3(kg/m^3)	1044(619)	1062(630)	1062(630)	1062(630)
Coarse Aggregate, lb/yd^3(kg/m^3)	1728(1025)	1724(1023)	1724(1023)	1724(1023)
Water, lb/yd^3(kg/m^3)	237(141)	244(145)	244(145)	244(145)
DCI, ml/yd^3	11357	11357	11357	0
Daravair, ml/yd^3	118	118	269	269
DARACEM-100, ml/yd^3	1893	1893	1990	1990
P-150	1301	1301	1183	1183
w/(c+p) (DCI H_2O=21 lb/yd^3)	0.35	0.36	0.39	0.36
Critical Pore Diameter: (MIP)				
28 Days, µm	0.025	0.030	0.032	0.033
56 Days, µm	0.034	0.023	0.022	0.015
Apparent Diffusion Coeff., m^2/s (AASHTO T-259 Ponding)	5.1 X 10^{-12}	2.0 X 10^{-12}	3.2 X 10^{-12}	1.8 X 10^{-12}
Rapid Chloride Permeability, (ASTM C1202)				
56 Days, Coulombs	1740	1090	830	460

TABLE 4: Concrete Characteristics of Systems Containing Commercially Available Blended Pozzolan Mineral Admixture

	Blended Pozzolan Replacement %			
Mix Design Parameters:	**Cement #7 (Type I)**	**20%**	**17% + 15% Fly Ash**	**30%**
Cement #7, lb/yd^3 (kg/m^3)	629(373)	503(298)	422(250)	429(255)
Blended Pozz., lb/yd^3 (kg/m^3)	0	126(74.8)	105(62.3)	184(109)
Fly Ash #4, lb/yd^3 (kg/m^3)	0	0	93(55.2)	0
Sand, lb/yd^3(kg/m^3)	1252(743)	1250(742)	1233(732)	1218(723)
Coarse Aggregate, lb/yd^3(kg/m^3)	1827(1084)	1825(1083)	1800(1068)	1777(1054)
Water, lb/yd^3(kg/m^3)	252(150)	251(149)	248(147)	245(145)
Daravair, ml/yd^3	340	530	530	670
WRDA-19, ml/yd^3	770	2780	1350	2250
w/(c+p)	0.40	0.40	0.40	0.40
Physical Properties:				
Slump, in.(mm)	3¾(82.6)	3½(88.9)	3¼(82.6)	3½(88.9)
Unit Wt., lb/yd^3(kg/m^3)	3960(2350)	3955(2346)	3900(2314)	3852(2285)
Air, %	5.9	6.1	6.5	7.3
Critical Pore Diameter: (MIP)				
28 Days, μm	0.047	0.024	0.030	0.031
56 Days, μm	0.044	0.021	0.026	0.027
Apparent Diffusion Coeff., m^2/s (AASHTO T-259 Ponding)	5.4×10^{-12}	1.7×10^{-12}	0.46×10^{-12}	1.9×10^{-12}
Rapid Chloride Permeability, (ASTM C1202)				
56 Days, Coulombs	2480	510	810	550
391 Days, Coulombs	2310	310	410	290

TABLE 5: Comparison of Heat of Hydration Between Blended Cement Systems With Type II, Type IV, and Type V Portland Cements

	Heat of Hydration, 7-Day (C186)
Blended Cement #1	74.5 Cal./g
Blended Cement #2	68.1 Cal./g
ASTM Study of N. American Portland Cements*	
Type II	73.7 Cal./g
Type V	61.4 Cal./g
Type IV	60.7 Cal./g

* Averages of T-II, T-IV, and T-V data published in the ASTM Journal, "Cement, Concrete, and Aggregates," Gebhardt R.F., Table 8, December 1995, vol. 17 #2.

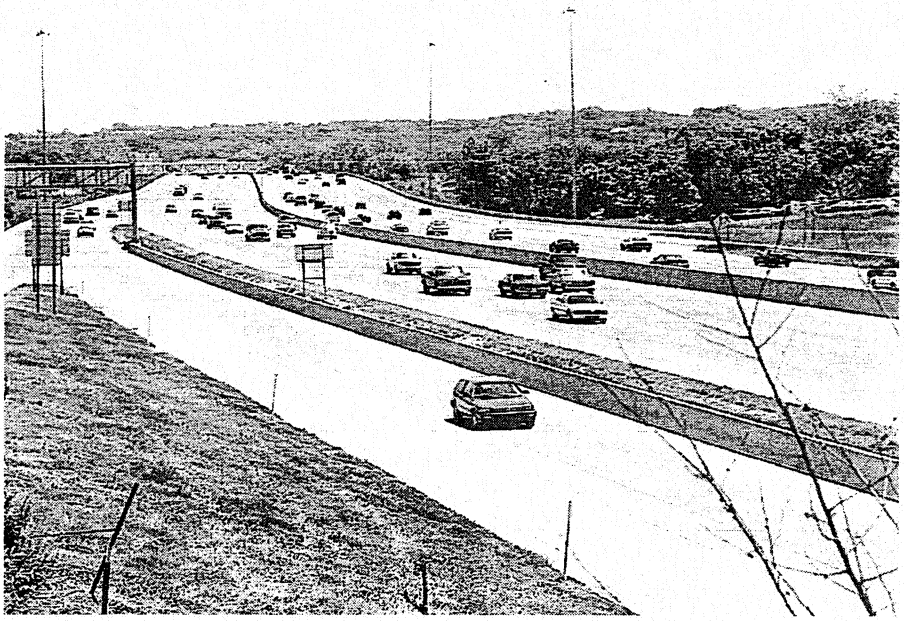


Figure 1: I-435/Roe Avenue interchange in Overland Park, Kansas.

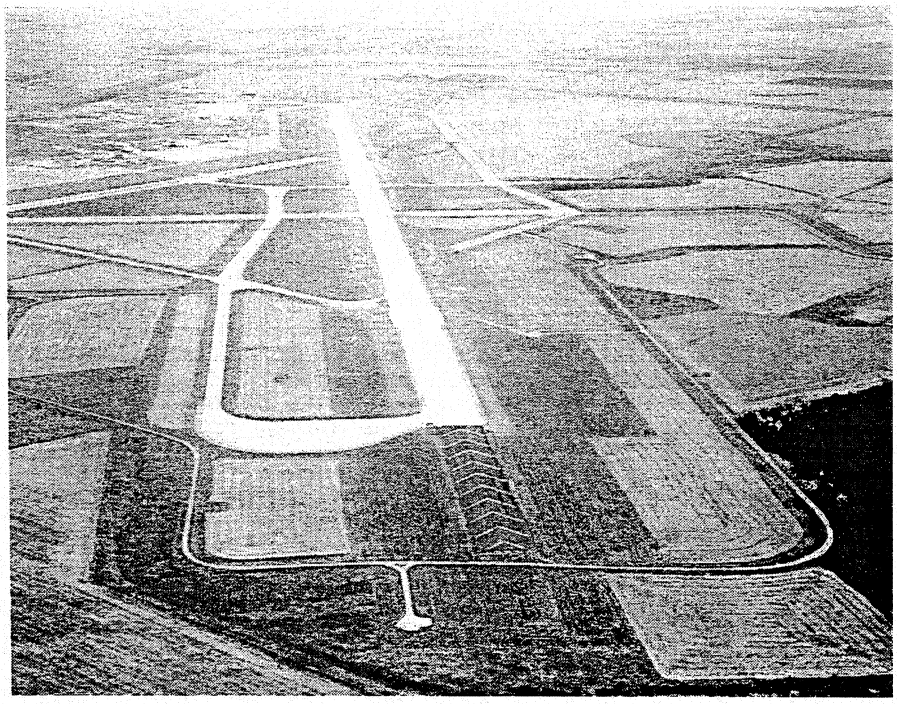


Figure 2: Aerial view of the new Sioux City, Iowa Airport runway.

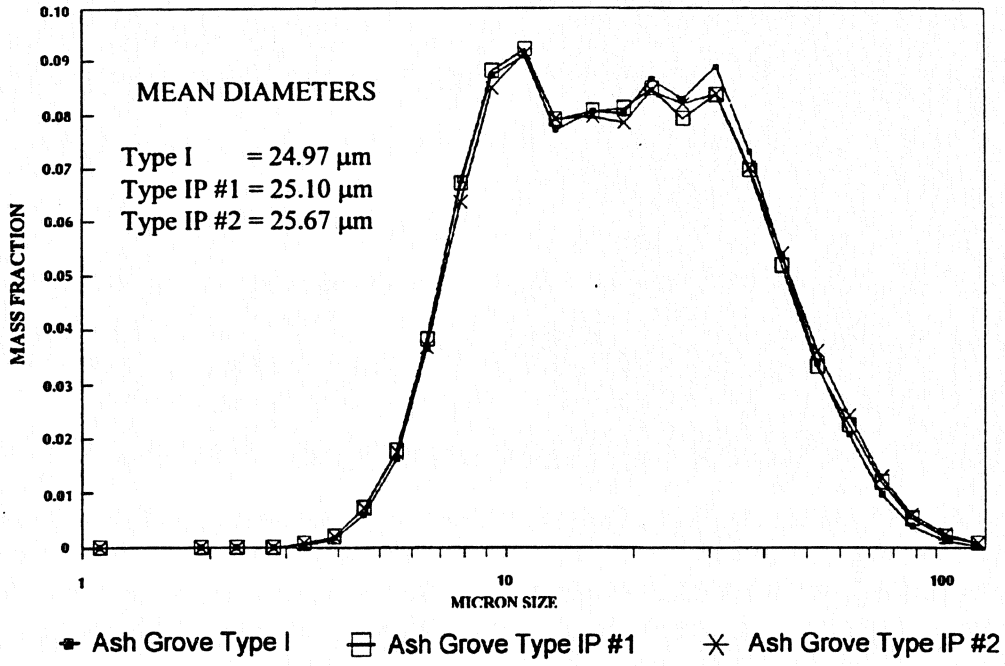


Figure 3: Comparison of a Type I cement and two different production runs of Type IP cements shows the uniformity of the Type IP, as well as, the similar particle size distribution as the Type I.

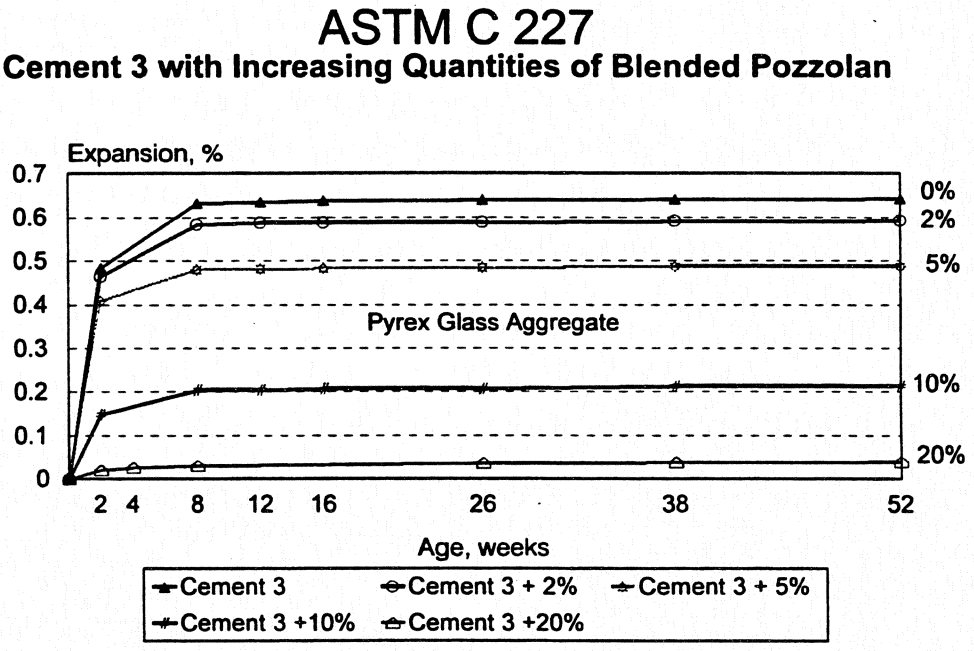


Figure 4: The chart above illustrates the increasing ASR mitigation with increasing replacement of Type I cement with Durapoz™. The Type I cement used for this study had an equivalent alkali of 0.91%

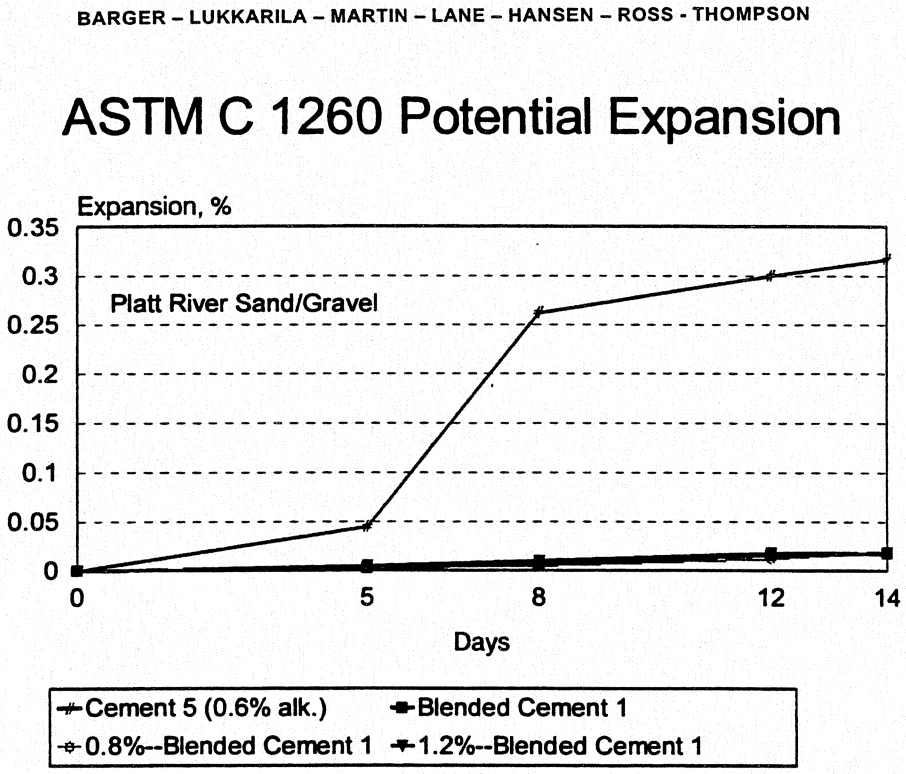


Figure 5: Chart illustrating the ASR mitigation potential of the Blended Cement #1 mixes at 0.6%, 0.8%, and 1.2% Na_2O equivalent alkali.

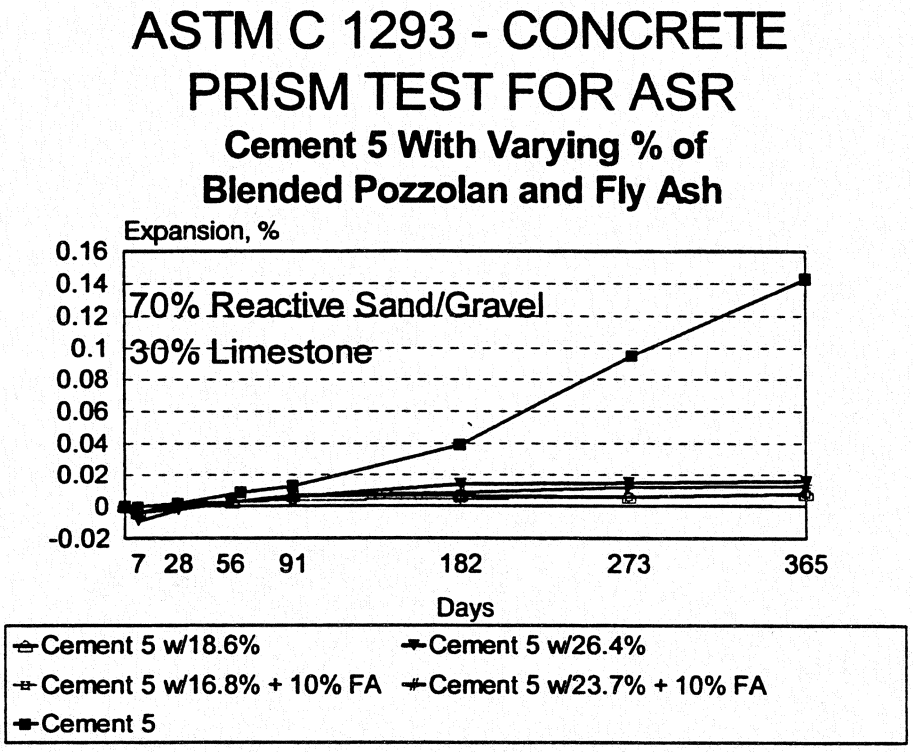


Figure 6: Chart illustrating the ASR mitigation of the Blended Cement mixes in the ASR expansion method, ASTM C 1293.

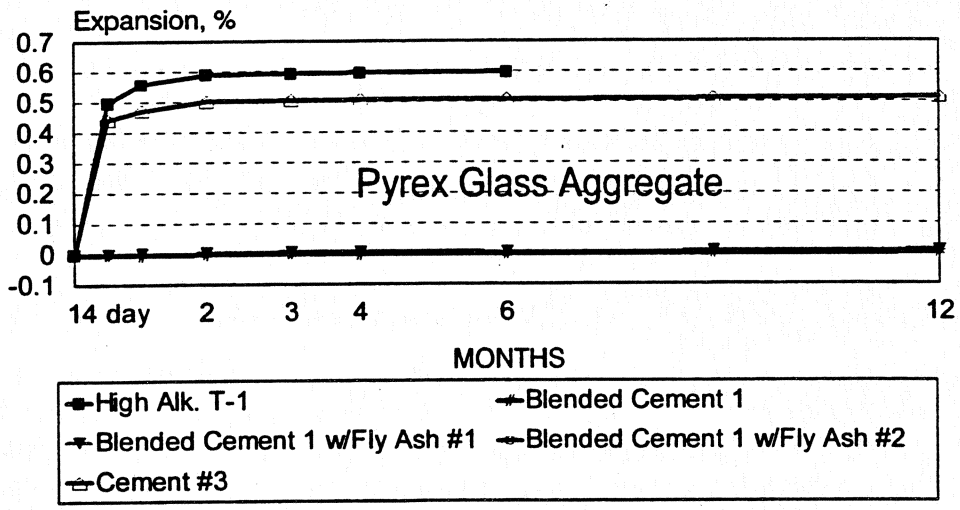


Figure 7: Chart illustrating the ASR mitigation of the Blended Cement #1 in the ASR expansion method, ASTM C 441.

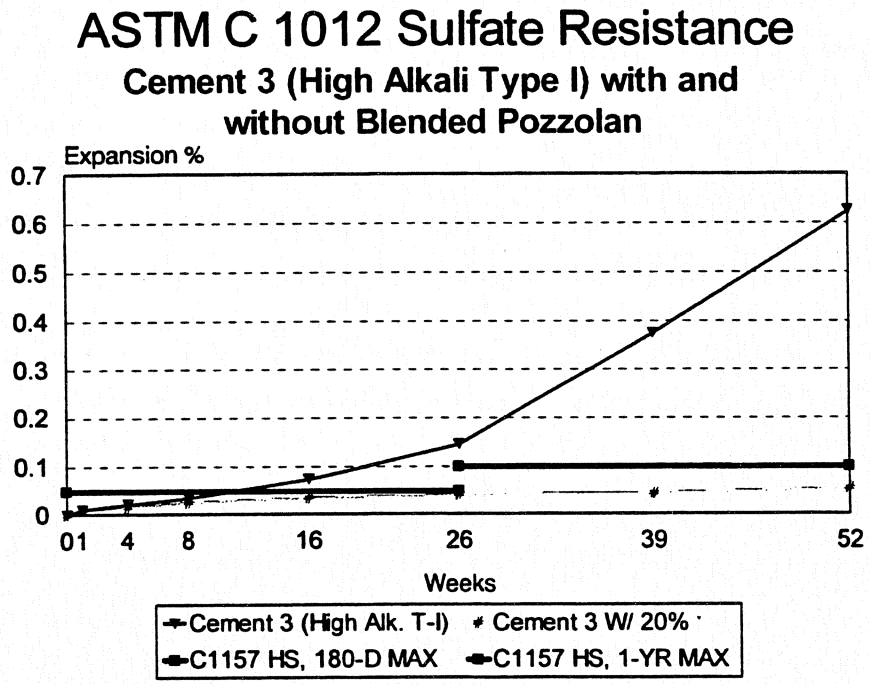


Figure 8: Chart illustrating the sulfate resistance capability of high alkali Cement #3 containing 20% Blended Pozzolan relative to Cement #3 alone.

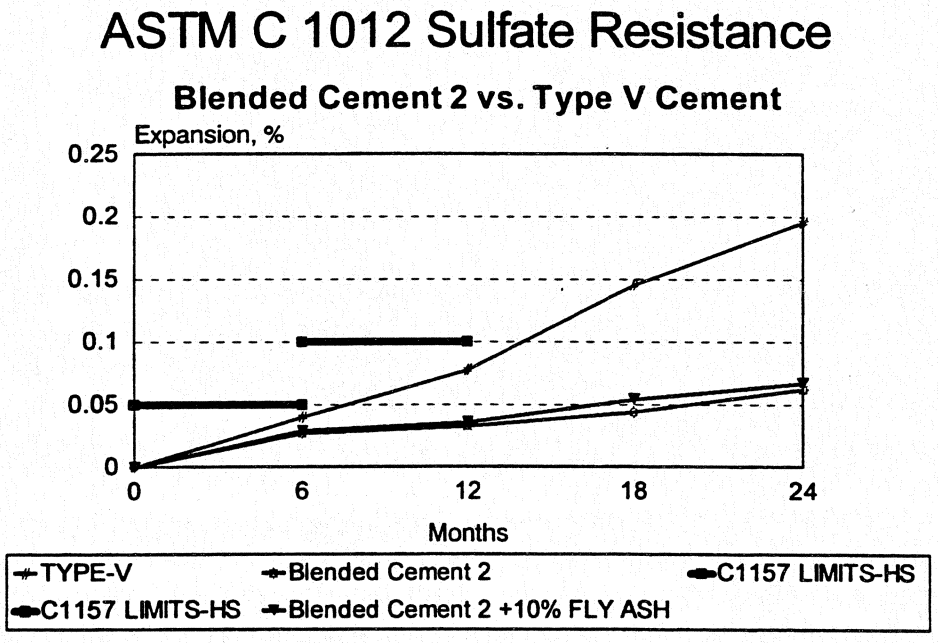


Figure 9: Chart illustrating the sulfate resistance capability of Blended Cement #2 vs. a Type V cement.

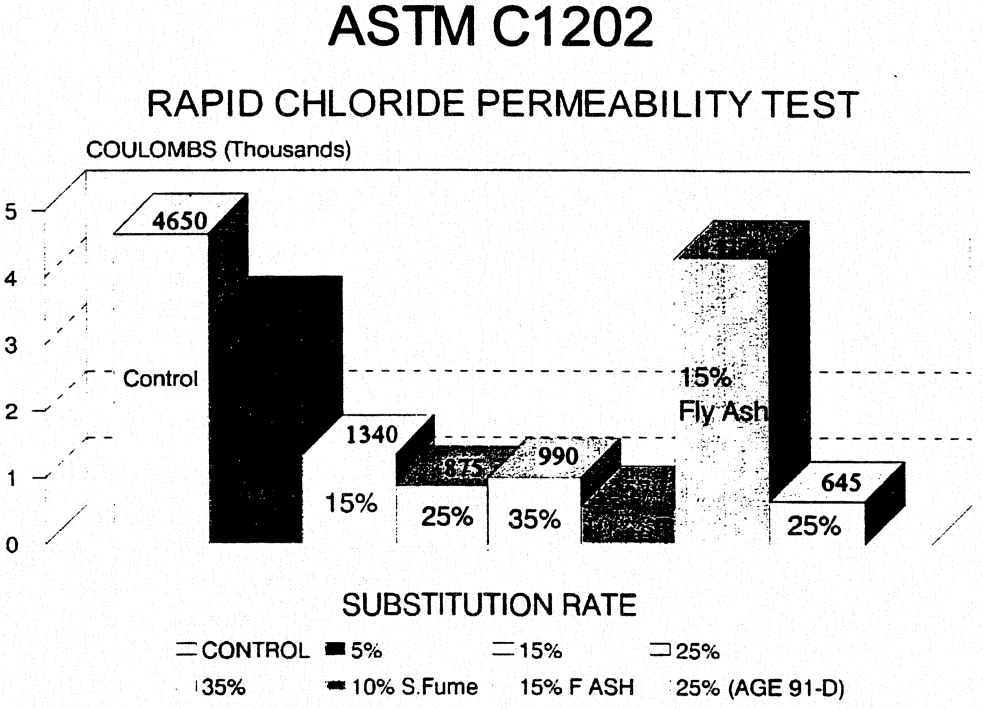


Figure 10: Rapid Chloride Permeability data showing the reduction in permeability with increasing quantities of the Blended Pozzolan substitution rates.

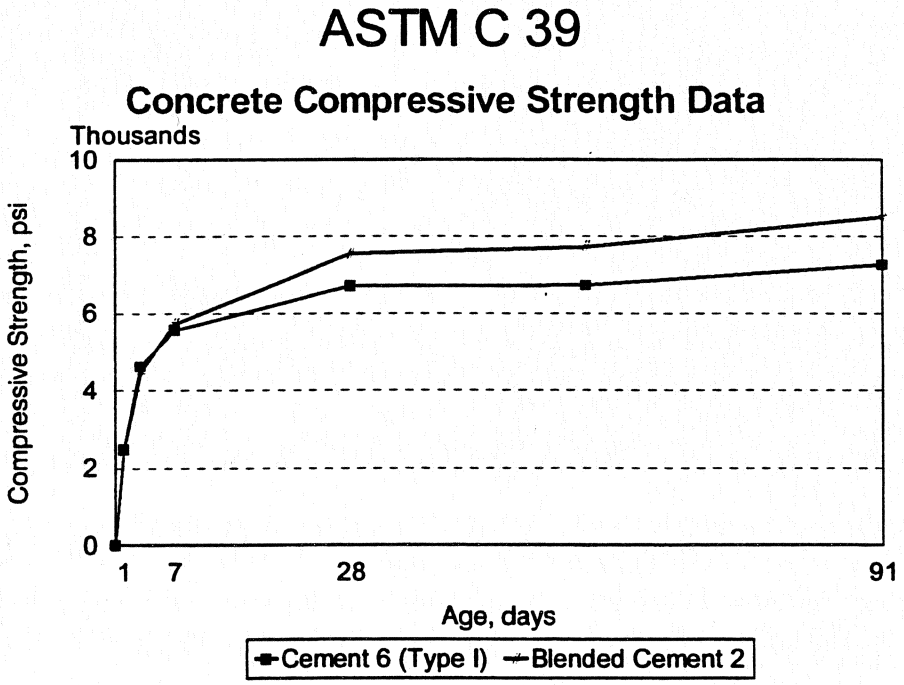
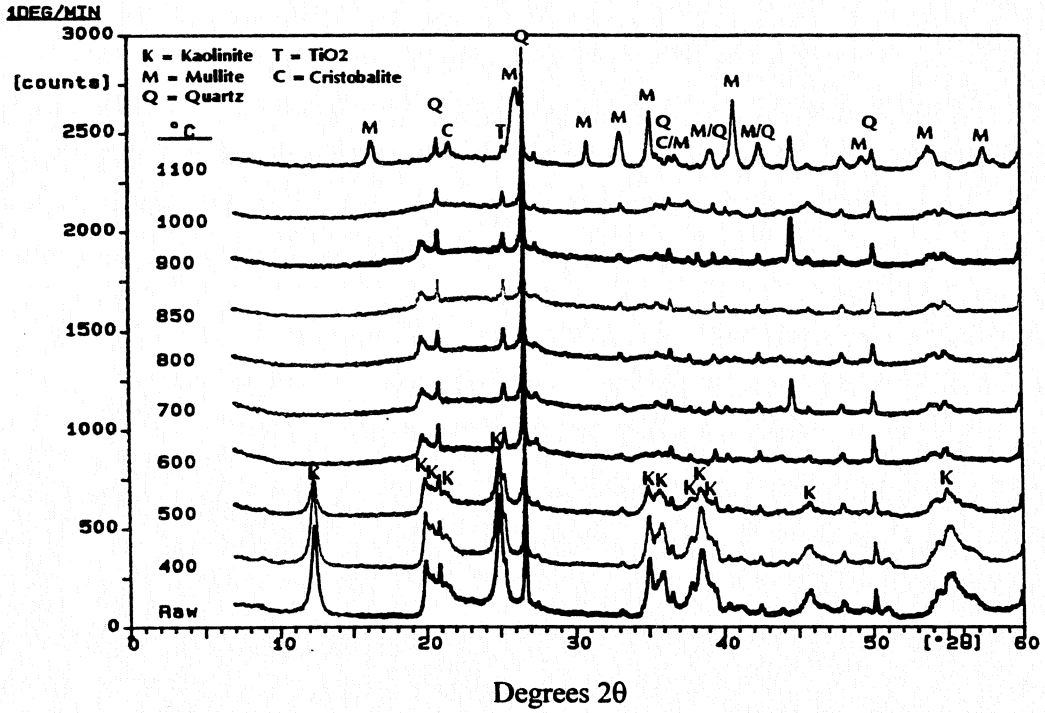


Figure 11: ASTM C 39 concrete compressive strength comparison between Cement #6 (Type I) and Blended Cement #2.



Degrees 2θ

Figure 12: XRDA scans illustrating the collapse of the kaolinitic clay crystal structure at temperatures above 500° C with subsequent amorphous phase formation, as well as, mullite formation between 1000° and 1100° C.

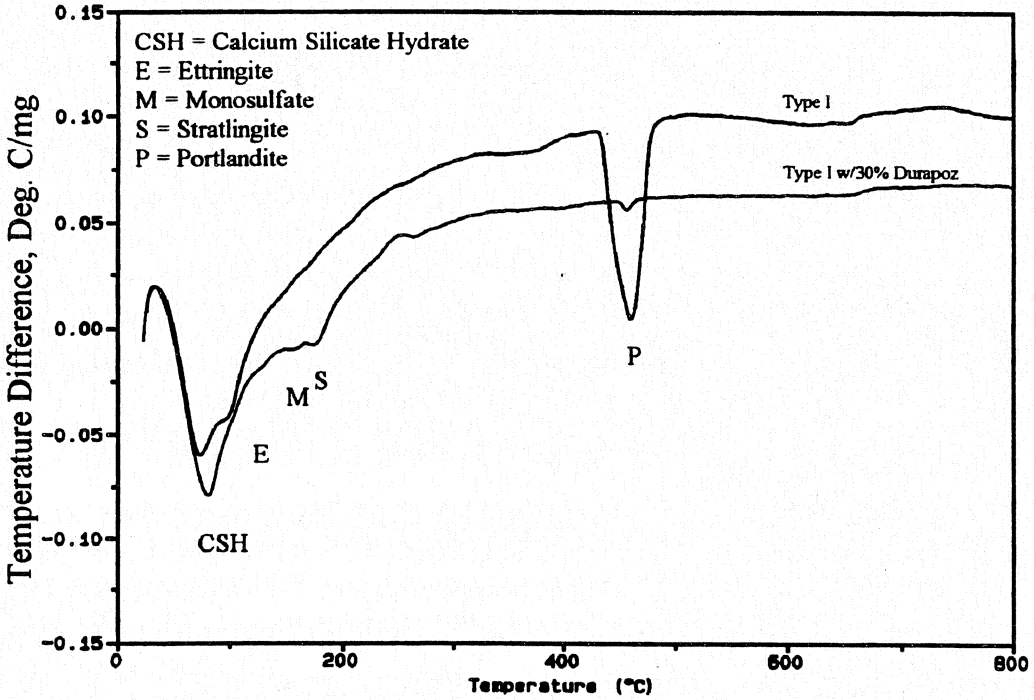


Figure 13: DTA curves of 56 day hydrated cement pastes made using an ordinary Type I and Type I with 30% Durapoz replacement.

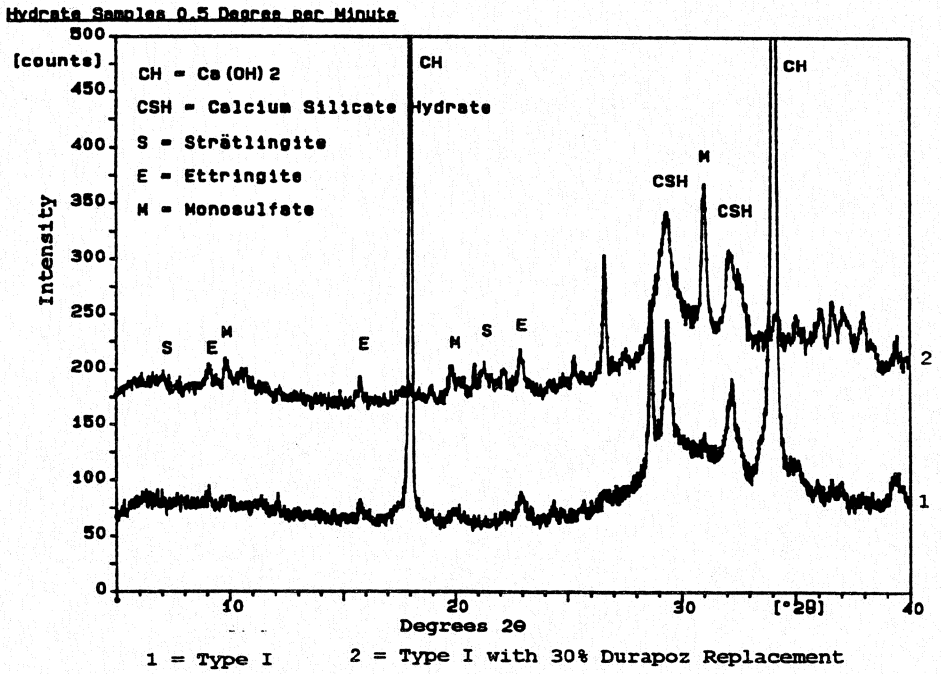


Figure 14: XRDA of hydrated cement pastes moist cured for 6 months made using Cement #5 and the same cement with 30% Blended Pozzolan replacement.

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