AGGREGATE REACTIVITY AND CONCRETE DURABILITY IN NEW MEXICO

A Report of Research by

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Prepared for

New Mexico State Highway & Transportation Department,
Research Bureau
1001 University Boulevard, Suite 103
Albuquerque, NM 87106

September 1998

Abstract—Our objective was to understand why some older New Mexico concrete is more durable than some younger concrete. Our approch was to determine (1) what is present in New Mexico concrete of varying ages, and (2) what is in present-day New Mexico concrete aggregate. We examined hardened New Mexico concrete of varying ages by coring dated concrete ranging in age from about 75 years (poured in 1923) to 1 year (1997) for part 1. The concrete was from Socorro, Albuquerque, and Gallup. Principal methods of study involved petrography and scanning electron microscopy. We examined the aggregate produced at six operations in the state for part 2. The mineralogy of these aggregates was determined by X-ray diffraction, petrography, and scanning electron microscopy. Splits of our sampled aggregates were sent to the New Mexico State Highway and Transportation Department Central Materials Laboratory in Santa Fe for mortar-bar expansion tests.

Our analysis of hardened concrete leads to several conclusions: (1) There appears to be no less use of reactive aggregate earlier in this century than now and therefore it is not the cause of the perceived more durable older concretes and less durable recently produced concretes. (2) We speculate the reasons for durability problems with recent concretes are: (a) the modern tendency to use cement formulated to set up in a relatively short time; (b) the care, or lack of it, taken during hydration of concrete; (c) the long-term effects of additives and admixtures that initially modify cement durability and setting positively, but are detrimental over extended periods of time; or (d) a combination of these factors and others of which we are unaware. (3) Delayed ettringite formation (DEF) does not appear to cause expansion problems in concretes that we examined. (4) Reactive aggregate is very common and used extensively in New Mexico concrete. (5) Reactive silica (chert and chalcedony), and high-alkali volcanic rocks (rhyolite, trachyte, and andesite), and alkali-rich minerals (feldspars) are common in New Mexico concretes of varying ages and appear to be responsible for most problems with concrete durability.

Our examination of aggregate from several pits and quarries resulted in several conclusions: (1) Microcrystalline silica (chert and chalcedony) and sheared or strained quartz (in gneiss and schist) appear to be some of the principal reactive minerals in the fluvial sediments that supply aggregate in many parts of the state. (2) Abundant alkali-rich feldspar, both in volcanic and intrusive rocks, is present in all sizes in the fluvial sand and gravel. Depending on the mineralogy, particle size, drainage, and environment within the concrete, these minerals react rapidly or slowly, producing alkali-silica reaction (ASR) gels through time. (3) Common weathering products and effects in both aggregate pits and aggregate quarries contribute to durability difficulties. (4) Alternatives to aggregate derived from fluvial sediments include limestone bedrock units that are

quarried near Edgewood and Grants. Limestones are not always pure and cannot be assumed to produce only innocuous expansion. (5) One simple method of decreasing expansion is washing the aggregate to remove finer particles including reactive sand-, silt-, and clay-size material, clay minerals, and weathering products.

Our recommendations for additional work include: (1) Analyze additional dated New Mexico concretes to determine if the use of a wide range of aggregates, both reactive and non-reactive, is as widespread as we believe. (2) In sampling additional concretes, use a large-scale coring devise and characterize the concrete with multiple thin sections. (3) Characterize the environment of the sampled concrete as completely as possible. (4) Characterize "distress" in hardened concretes as "shallow distress" or "deep distress." (5) Make an effort to sample concrete for which complete records are available. If this type of data is not available, it should be required for New Mexico State Highway & Transportation Department projects. (6) The value of washed versus unwashed aggregate should be determined and the value of washed versus scrubbed aggregate should be tested. (7) When testing a given aggregate for expansion in the laboratory, use material directly from the product pile without crushing, which would increase expansion by decreasing the particle size. (8) Characterize pits and quarries with expansion by an average value and the standard deviation of the data. (9) Determine the long-term effects of additives and admixtures used in New Mexico on the durability of concretes in the many climates of the state.

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INTRODUCTION

Concrete durability in New Mexico can be considered as principally a geological problem. The raw materials used in the production of cement and the aggregate used in combination with cement, admixtures, and water to form concrete consist of geological materials. These materials have mineralogies as well as chemistries that dictate their reactions in the production of cement, to the environment during hydration in concrete, and to post-emplacement weathering.

We cored dated, hardened concretes in Socorro, Albuquerque, and Gallup. The dates of the concretes range in age from 1923 to 1997. Samples were taken from concrete sidewalks, parking lots, roads, and a drainage channel, spillway, and railroad trestle foundation. To determine the condition and content, many of the 26 cores were examined with the petrographic microscope and with the electron microprobe.

To determine what modern aggregates contained and how they varied with time, we took samples from four aggregate pits at two times (spring and fall) during the year. These samples were washed, and the washings were analyzed by X-ray diffraction (XRD) for their clay-, silt-, and sand-size mineralogic composition. Splits of the washed aggregate were analyzed by petrography. Another split was tested for expansion characteristics. In addition, material from two other pits, one in the Albuquerque and another in the southwestern part of the state, were processed, analyzed by petrography, and tested for expansion. We also include the results of previous expansion tests on material from these pits from the New Mexico State Highway and Transportation Department (NMSHTD) and the results of tests on these pits from another project funded by NMSHTD. The aggregate operations contain material ranging from in-place limestone, which is removed, crushed, and screened for use, to unconsolidated river gravel, which contained a variety of igneous, sedimentary, and metamorphic rocks and is primarily only screened for use.

METHODS

New Mexico concrete of varying age

The concrete samples were taken from a number of sources in New Mexico and range in age from 1923 to 1997 (Table 1). Samples KC01–KC11 were taken in Socorro from several locations including the New Mexico Institute of Mining and Technology (NMT) campus, and came from sidewalks, driveways, and parking lots. Samples KC12–KC17 were taken from the Gallup area, and include a railroad trestle support, a drainage ditch and a spillway. Samples KC18–KC26 were taken from a section of Gibson Boulevard, in Albuquerque. A visual determination of the condition of the concrete at each sample site was made when collected. If a sample was near soil or lawn, a soil sample was taken to determine the pH of the area.

Table 1. Sample locations, source, approximate age, visual condition (distress), and the results of onsite soil pH testing.

Sample	Location	Structure	Age	Distress	Soil pH
KC01	Socorro, Neel Ave.	sidewalk	1960–61	no	8.03
KC02	Socorro, Neel Ave.	sidewalk	1960–61	no	8.03
KC03	Socorro, McCutcheon Ave.	sidewalk	1936	no	NA
KC04	Socorro, NMT, library	sidewalk	1988	map-cracking	7.77
KC05	Socorro, NMT, Brown Hall	sidewalk	1988	popouts	8.12
KC06	Socorro, NMT, Brown Hall	sidewalk	1988	popouts	8.12
KC07	Socorro, NMT, Brown Hall	sidewalk	1988	popouts	8.12
KC08	Socorro, NMT, Golf/P-Plant	parking lot	1993	no	7.96
KC09	Socorro, NMT, Workman	sidewalk	1997	no	7.76
KC10	Socorro, NMT, Weir Hall	sidewalk	1939	map-cracking	NA
KC11	Socorro, NMT, Gym, north	driveway	1988	popouts	7.53
KC12	Gallup, train trestle	drainage	1923	no	NA
KC13	Gallup, train trestle	drainage	1923	no	NA
KC14	Gallup, train trestle	drainage	1923	no	NA
KC15	Gallup, drainage channel	wall	1977–78	no	NA
KC16	Gallup, spillway into arroyo	drainage	1965–68	no	NA
KC17	Gallup, spillway into arroyo	drainage	1965–68	no	NA
KC18	Albuquerque, Gibson Blvd.	street	1979	no	NA
KC19	Albuquerque, Gibson Blvd.	street	1979	no	NA
KC20	Albuquerque, Gibson Blvd.	street	1979	no	NA
KC21	Albuquerque, Gibson Blvd.	street	1979	no	NA
KC22	Albuquerque, Gibson Blvd.	street	1979	no	NA
KC23	Albuquerque, Gibson Blvd.	street	1979	no	NA
KC24	Albuquerque, Gibson Blvd.	street	1979	no	NA
KC25	Albuquerque, Gibson Blvd.	street	1979	no	NA
KC26	Albuquerque, Gibson Blvd.	street	1963	map-cracking	NA

Note: NMT = New Mexico Institute of Mining and Technology, NA = data not available

We did not find records of the alkali concentration for any of the cement used in these concretes or the source of the aggregates. Before 1959, cement was shipped into New Mexico mainly from El Paso, Texas, and Florence, Colorado. The Colorado cement was reported to have an alkali content (Na_2O equivalent) of approximately 0.40% prior to 1959 (W. L. Barringer, personal communication, 1998). In 1959, the cement plant east of Albuquerque at Tijeras began supplying most of the northern two-thirds of the state. Until the early 1970s most cement plants used shale if necessary to supply alumina to the mixture of raw cement materials. In the early 1970s, the Tijeras plant stopped using alkali-rich shale and began to use a different material to lower alkali content. At present, the Rio Grande Portland Cement Company (the name of the cement plant since 1996) is using bottom ash from an electric power plant near Prewitt, New Mexico, to lower alkalis to less than 0.6 wt.% (R. L. Venable, Rio Grande Portland Cement, oral comm., 1997). However, problems relating to alkalis in cement may still remain (J. Barela, New Mexico Highway Department, oral comm., 1997). In our project, if a sampled concrete had a middle 1970s or later date, we assumed a low-alkali percent (<0.6%) for the cement. If it was older than the middle 1970s, we assume that the alkali percentage was probably greater than 0.6% regardless of the source.

All our hardened concrete samples were drilled cores of 1-inch diameter, approximately 2–4 inches long. The drill used was a hand-held, electric drill, converted to receive power from a 12-volt battery, with a water connection for cooling the bit. The cores were cut using a small water-cooled saw into circular sections for petrographic thin sections and electron microprobe slabs. The thin-section samples were sent to Spectrum Petrographics, Inc., in Winston, Oregon, to be made into 30-µm-thick thin sections. The concrete cores were characterized using American Association for Testing Materials (ASTM) method C856-83 *Standard practice for petrographic examination of hardened concrete* (Anon., 1995a). The scanning electron microprobe (SEM) slabs were attached to 1-in. round glass slides with epoxy. The surfaces were polished starting with a 60-mesh diamond-impregnated magnetic wheel. The final polish was on a cloth-covered wheel with ultra-pure 2-µm-diamond grit suspended in deionized water. After polishing, they were carbon-coated for the microprobe. A second set of microprobe slabs was left with a sawn surface from the water saw and coated with carbon. The polished samples were analyzed by backscatter electrons (BSE). Some elemental maps were constructed of areas believed to be ettringite, or other crystalline phases. The sawn samples were analyzed by secondary electrons (SE). Some of these areas were analyzed to determine chemical composition using wave dispersive spectrometer analysis (WDS).

New Mexico aggregate and alkali-aggregate reactivity

Kosmatka and Panarese (1988) listed some potentially reactive minerals, rocks, and synthetic materials (Table 2). They state (p. 41) that "several of the rocks listed [in table 4-5] (granite gneiss and certain quartz formations for example) react very slowly and may not show evidence of harmful degrees of reactivity until the concrete is over 20 years old." Leming (1996) states that potential reactivity of an aggregate is seen as a function of both the degree of crystallization of the silica in the aggregate and the amount of energy stored in the crystal structure, whether due to a large quantity of microcrystalline silica, a high strain energy stored in the crystals, or some combination of these factors. Stark and others (1993), commenting on reactive aggregates, mentioned that all are siliceous and that porous and glassy types react very quickly. Indeed, Stark and others (1993) use a reactive aggregate from the Albuquerque area and their notation about this aggregate indicates that they consider alkaline volcanics as the chief cause of the reactivity. Even if low-alkali cement is used with it to make concrete, the aggregate is considered highly reactive. The source of this aggregate probably was the Cal-Mat's Shakespeare pit (sec. 34, T11N R3E). Material from this pit has been used as a standard highly reactive aggregate in other studies, i.e., Barela, 1997.

Table 2. Potentially harmful reactive minerals, rocks, and synthetic materials (after Kosmatka and Panarese, 1988, table 4-5).

Alkali-silica reactive substances

- Andesites
- Argillities
- Chalcedonic cherts
- Chalcedony
- Cherts
- Cristobalite
- Dacites
- Glassy or cryptocrystalline volcanics
- Granite gneiss
- Graywackes
- Metagraywackes
- Opal
- Opaline shales
- Phyllites
- Quartzites
- Rhyolites
- Schists
- Siliceous limestones and dolomites
- Siliceous shales
- Strained quartz
- Synthetic and natural siliceous glass
- Tridymite

Although the Cal-Mat's Shakespeare pit in Albuquerque was not an aggregate source in our project, its aggregate is a standard in the Southwest for high reactivity. In order to judge the reactivity of our aggregates, we judged them against Shakespeare aggregate. In 1998, we were given a sample of the reactive aggregate from the Shakespeare pit and analyzed it with the standard ASTM procedure C 295-90, *Standard guide for petrographic analysis examination of aggregate for concrete* (Anon., 1995b). Our results are given in Table 3.

Our analysis indicates that Shakespeare aggregate consists of about one-quarter reactive particles. If weathered particles are added, particles that could most easily be attacked by alkali solutions amount to nearly 40% of the aggregate. Kosmatka and Panarese (1988) do not list feldspar as a reactive mineral group, but orthoclase/microcline feldspar ($KAlSi_3O_8$) clearly is a source of K^+, especially from weathered particles.

In the Shakespeare aggregate, feldspar is concentrated in the smaller sized particles. Stark and others (1993) point out that the site of chemical reaction is not always at the contact between the rock surface and the hardened cement paste. Existing cracks or channels in potentially reactive aggregate offer added access to alkalis and OH^- ions. They essentially act to increase the surface area of the particle. Zones of weakness along which cracks can form occur in flawed and strained crystals. The surface area is greatly increased by weathering of particles. The same result is accomplished by decreasing the particle size. This increases the surface area per unit. The large content of fine-grained feldspar (37%) probably contributes to the reactivity of the Shakespeare aggregate.

Table 3. Petrographic analysis of Cal-Mat's Shakespeare aggregate using ASTM C 295-90. The -4+8 refers to particles passing through No. 4 sieve and retained on No. 8 sieve. The most important numbers are the totals (right-hand column in bold). Rhyolite/trachyte, andesite, and chert/chalcedony are considered to be the most reactive materials.

Counts	**-4+8**	**-8+16**	**-16+30**	**-30+50**	**-50+100**	**Total**
Rhyolite/trachyte	6	19	8	3	0	**36**
Andesite	5	11	9	4	0	**29**
Dacite/basalt	10	21	11	9	3	**54**
Chert/chalcedony	14	17	15	9	16	**71**
Quartz	23	36	35	28	26	**148**
Feldspar	3	17	36	72	81	**209**
Ferromagnesian	0	0	0	2	4	**6**
Opaque	0	1	0	2	1	**4**
Limestone/dolomite	1	2	4	2	2	**11**
Total	62	124	118	131	133	**568**
Weathered	5	14	13	28	19	**79**

Percents	**-4+8**	**-8+16**	**-16+30**	**-30+50**	**-50+100**	**Total**
Rhyolite/trachyte	9.7	15.3	6.8	2.3	0.0	**6.3**
Andesite	8.1	8.9	7.6	3.1	0.0	**5.1**
Dacite/basalt	16.1	16.9	9.3	6.9	2.3	**9.5**
Chert/chalcedony	22.6	13.7	12.7	6.9	12.0	**12.5**
Quartz	37.1	29.0	29.7	21.4	19.5	**26.1**
Feldspar	4.8	13.7	30.5	55.0	60.9	**36.8**
Ferromagnesian	0.0	0.0	0.0	1.5	3.0	**1.1**
Opaque	0.0	0.8	0.0	1.5	0.8	**0.7**
Limestone/dolomite	1.6	1.6	3.4	1.5	1.5	**1.9**
Total	100	100	100	100	100	**100**
Reactive	40.4	37.9	21.3	12.3	12.0	**23.9**
Weathered	8.1	11.3	11.0	21.4	14.3	**13.9**
Percent of total	48.5	49.2	32.3	33.7	26.3	**37.8**

Aggregates selected and analyzed in the project

In November 1997 we took aggregate samples in 5-gallon buckets from the 1" product piles at the Placitas, Santa Ana, and Edgewood pits. We also sampled the 3/8" product pile at the Edgewood pit and the C-33 pile (concrete sand) at the Placitas pit. Although the primary rock material at the Edgewood pit is limestone, a crusher is on site only six months each year. Consequently, the stockpiled 3/8" material consists of limestone from the Edgewood quarry augmented by material from the Placitas pit. Lary Lenke, University of New Mexico Research Scientist working on another NMSHTD-funded aggregate project, gave us 5-gallon samples from the 1" product piles at the Tinaja and Mimbres pits. In order to check for seasonal variability we sampled the Placitas, Santa Ana, and Edgewood materials again in May 1998. At the same time, we also sampled the 1" material from the Tinaja pit. In the latter case, the aggregate sample actually was taken from the product yard in Grants, New Mexico, about 30 mi northeast of the pit, after which we visited the quarry for a visual inspection of the site. We processed all samples for analysis at the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) in Socorro.

To determine what each aggregate sample contained, we first washed the aggregate to recover the loosely attached finer-grained material, which was then screened. The sand-size material was retained on a No. 230 (63 μm) sieve. Coarse silt was retained on a No. 400 (38 μm) sieve. Both sized samples (sand and coarse silt) were dried and then the sand-sized samples were crushed with a mortar and pestle to pass a No. 100 (150 μm) sieve. Glass slides were thinly coated with Vaseline jelly and dried material of each size was poured onto separate slides for XRD study. Each slide was turned on its side and tapped lightly to remove loose material. Bulk XRD analysis of the sand and coarse silt fractions was performed to identify minerals present and to give an idea of their relative abundances.

Fine silt- and clay-size material passed through the No. 400 sieve. Clay-size material was separated from the fine-silt fraction with a settling technique. In this analysis, we used standard clay mineralogy XRD analysis that has been used at the NMBMMR for more than 20 years. We prepared the oriented <2 μm fraction by first separating it from the silt-size fraction in distilled water. The mixture is stirred and particles are allowed to settle. After 10 minutes, a portion of the <2 μm fraction is removed from the top of the suspension, placed on a glass slide, and dried. The resulting coat consists of the oriented clay-size fraction of the sample. The slide is examined with XRD from 2 to 35° 2θ, soaked in an ethylene glycol atmosphere and examined again with XRD from 2 to 15° 2θ, and heated to 350°C for 30 minutes and examined again from 2 to 15° 2θ. This test is considered "semiquantitative" because the results can be reported only as parts in ten of the following clay mineral groups: kaolinite, illite, chlorite, smectite, and I/S (mixed-layer illite-smectite). The mineralogy of the small amounts of non-clay minerals is determined as well. The common non-clay minerals in the clay-size fraction are calcite, dolomite, gypsum, orthoclase, plagioclase, and quartz. When only small amounts of the feldspars are present, it may not be possible to distinguish between orthoclase and plagioclase. In this case, feldspar is reported.

The washed aggregate was crushed and graded by size in the NMBMMR's Metallurgical Laboratory. Splits were made for petrographic analysis and sent to Spectrum Petrographics, Inc., in Winston, Oregon, to be made into 30-µm-thick thin sections. For analysis of the thin sections, we used ASTM C 295, *Practice for Petrographic Examination of Aggregate for Concrete* (Anon., 1995b).

To discover how our washed aggregate samples performed in the mortar bar expansion test, splits were sent to the NMSHTD Central Materials Lab. The procedure used by the NMSHTD Central Laboratory is the American Association of State Highway Transportation Officials (AASHTO) TP14, *Standard test method for accelerated detection of potentially deleterious expansion of mortar bars due to alkali-silica reaction* (Anon., 1993a). In this test, 1 x 1 x 11.25-inch mortar bars are made in accordance with procedure AASHTO T162, *Standard test method for mechanical mixing of hydraulic cement pastes and mortars of plastic consistency* (Anon., 1993b). The different aggregates were mixed with a single low-alkali cement, but with no admixtures. Bars were cured in 100% relative humidity and 21.3–24.7°C for 26 hours, measured for length, then put into a tap-water solution in an 80°C oven for 24 hours. The bars then were transferred to a 1.0 N sodium hydroxide (NaOH) solution at 80°C, where they were measured regularly for 14 days. Mortar bar measurements were made in accordance with AASHTO M210, *Apparatus for use in measurement of length change of hardened cement paste, mortar, and concrete* (Anon., 1992).

RESULTS AND DISCUSSION

Petrographic examination of hardened concretes

The results of the petrographic analysis of cored concrete samples collected in Socorro and Gallup are given in Table 4.

The size of our cores (1-inch in diameter and 2–4 inch long) from which we had a single thin section made, precluded the possibility of acquiring highly accurate analyses of the hardened concretes (Table 4). Clearly, the concretes from which we took samples KC04 and KC14 had less than 50% cement paste, but our one thin section per core did not give us the adequate area to quantitatively evaluate the concrete; however, all of the thin sections considered together do give a qualitative idea of the various materials present. These analyses do point out how common acid-volcanic rocks (rhyolite and trachyte), reactive silica (chert and chalcedony), and alkali-rich minerals (feldspars) are in New Mexico concretes of varying ages. Ettringite was not observed in any of these samples using this test.

Table 4. Results of the petrographic analysis of hardened concretes in percent (ASTM C856-83). We have included quartz sandstone with quartz.

Sample number	**KC01**	**KC03**	**KC04**	**KC05**	**KC06**	**KC08**	**KC09**	**KC10**	**KC11**	**KC14**	**KC15**	**KC16**
Rhyolite & trachyte	1.80	66.60	0.00	6.90	5.40	7.40	41.60	7.60	7.70	1.10	1.10	1.30
Andesite	0.00	0.00	tr	0.00	0.00	0.00	0.00	5.00	15.60	0.00	0.00	tr
Dacite & basalt	42.90	tr	tr	tr	tr	0.00	2.00	5.00	1.30	1.40	tr	4.60
Chert & chalcedony	0.00	0.00	tr	tr	8.50	6.00	4.20	31.80	18.80	2.00	tr	4.10
Quartz	21.00	9.10	22.60	26.70	34.60	54.00	19.00	9.20	14.20	14.10	8.00	12.50
Feldspar	5.50	4.20	11.90	7.50	8.10	4.10	6.10	7.30	7.60	11.00	5.00	7.90
Ferro-magnesian	tr	1.90	9.60	1.30	1.70	2.10	tr	tr	tr	1.70	tr	0.60
Opaque (Fe-rich)	1.06	tr	tr	2.10	1.10	1.10	2.80	tr	1.30	0.00	tr	0.00
Limestone	tr	tr	3.20	23.40	2.60	tr	tr	1.10	1.30	2.80	53.80	27.00
Voids	tr	2.80	tr	1.80	2.00	5.00	1.20	3.00	1.90	5.90	3.80	9.00
Cement paste	25.30	14.20	50.90	29.80	35.10	19.60	21.30	29.40	31.60	59.90	25.60	32.40
Total	97.56	98.80	98.20	99.50	99.10	99.30	98.20	99.40	99.30	99.90	97.30	99.40

Note: tr = trace; present, but <1%

From our samples, we see no evidence that the older concretes, which presumably were made with high-alkali cement (>0.6% alkalis), are more durable than concrete placed since the early 1970s when low-alkali (<0.6% alkalis) cement became the norm. Although our samples were taken from concrete of differing ages (from 1920s to 1997), the environment surrounding each concrete was different. All of the very old concretes (from the 1920s and 1930s) were well drained. All but one of the concretes showing distress were poorly drained sidewalks on the New Mexico Tech campus. The use of deicing salt (principally halite or NaCl) in winter undoubtedly contributed to problems. The other sample showing distress was from a well-drained concrete roadway in Albuquerque. Abundant moisture does accelerate concrete deterioration and thus the durability of the older concretes is in part due to the well-drained environment.

Because the concretes of many different ages that we examined contained both reactive and non-reactive aggregate, the aggregate is assumed not to be a factor when considering the durability of New Mexico concrete through time. We believe that the major factor could be one of several possibilities: (1) the modern tendency to use cement formulated to set up in a relatively short time; (2) the care, or lack of it, taken during hydration of concrete; or (3) the long-term effects of additives and admixtures that initially modify cement durability and setting positively, but are detrimental over extended periods of time. However, it may very well be a combination of factors listed above and others of which we are unaware.

Scanning electron microprobe examination of hardened concretes

Using the SEM, many instances of ettringite were found, mostly growing in open air voids in the concrete. In one instance, we found a crack lined with ettringite crystals (Fig. 1). The ettringite was confirmed chemically by the element mapping of Si, S, and Al in the suspected area. The mapping showed the crack area to be high in sulfur and aluminum and void of silica, which correlates with the chemical composition of ettringite ($Ca_6Al_2(SO_4)_3OH_{12}\cdot26H_2O$). Most of the ettringite we observed was in the form of elongated crystals, approximately 5–10 µm long (Fig. 2). However in sample KC12 from the Gallup train trestle support (placed in 1923), the ettringite was a fibrous mass that filled the air void (Fig. 3).

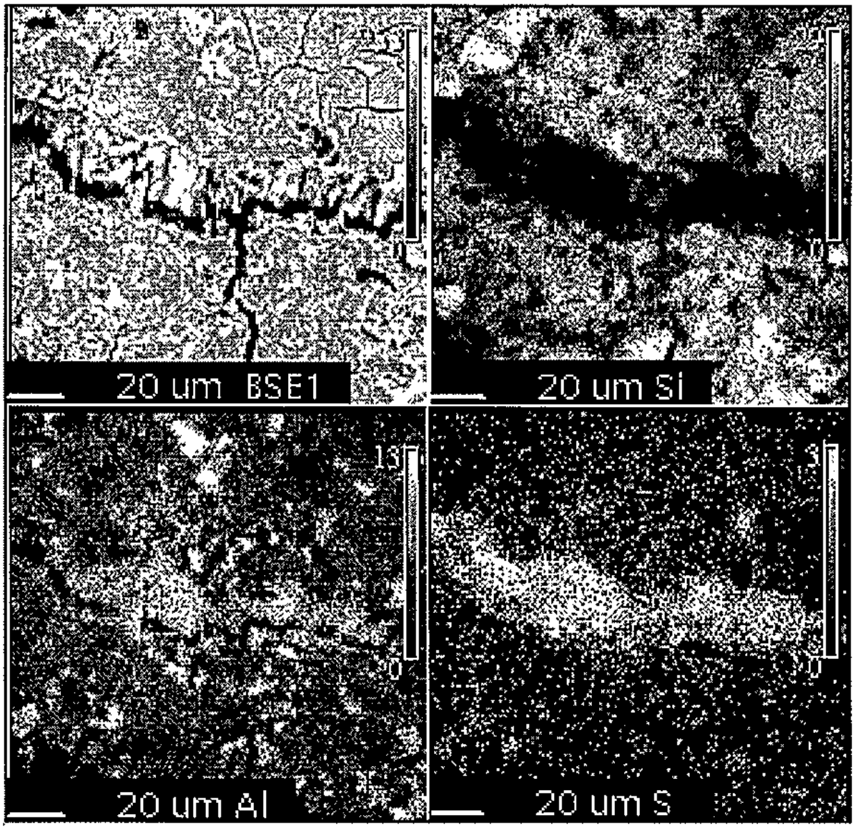

Figure 1. Ettingite lining a crack in sample KC04. BSE image (upper left) and element maps of silica, aluminum, and sulfur are included. Lighter areas in the element maps indicate more counts of the element.

Several areas of a gel-like mass were identified using the SEM, but elemental mapping and the WDS scanning did not positively identify the gel as alkali silica reaction (ASR) gel. In Figure 4 (same as Fig. 1), an example of gel is present in the upper right hand corner of the BSE image. If this is the destructive ASR gel, element mapping should indicate a significant concentration of potassium in the gel area, but this was not observed. The gel area did contain substantial calcium and silica, and therefore was identified as normal calcium silicate hydrate (C-S-H) gel.

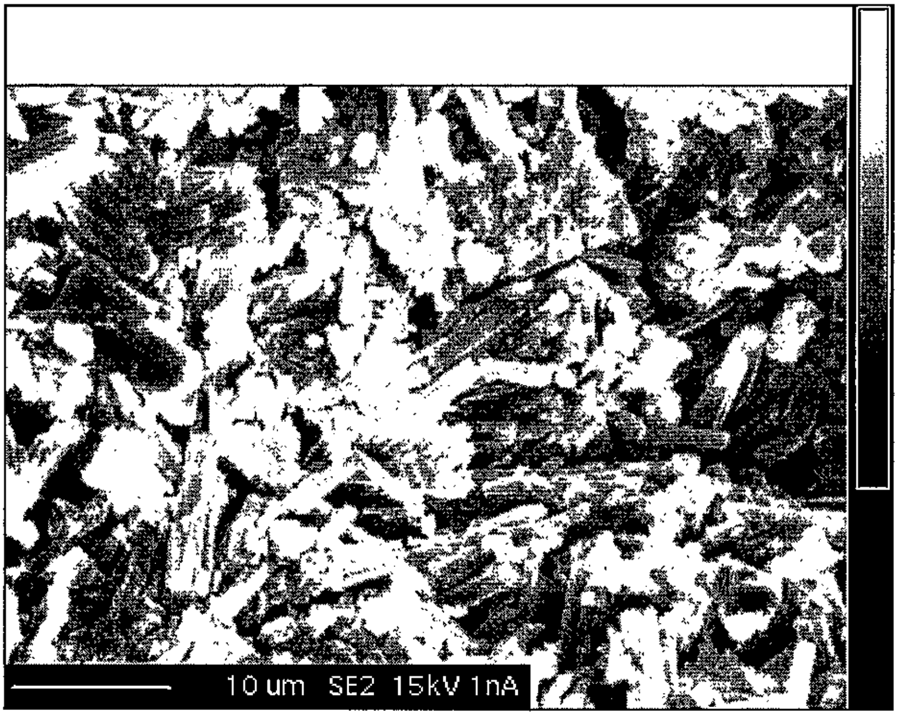

Figure 2. Secondary electron image of elongate ettringite in an air void of sample KC04.

Although ettringite has been identified with the SEM, its presence did not appear to correlate with concrete soundness. This confirms statements that if ettringite occurs as partly filling voids, it does not contribute to concrete deterioration (Anon, 1996). Delayed ettringite formation (DEF) is considered the cause of some concrete deterioration because growing ettringite crystals cause stress that cracks hardened concrete. However, this occurs at temperatures over about 70°C during curing. In most cases, the ettringite we observed did not appear to cause any distress because it is growing into open air-void spaces. The only exception was sample KC04 in which the ettringite was found lining a crack. Even then, it cannot be said whether the crack was existing prior to the ettringite forming in it or the ettringite formation caused the crack. It is also possible that the ettringite replaced ASR gel that developed earlier and caused the crack. In any case, the growing ettringite crystals now have the potential to further split the crack, causing further distress in the concrete.

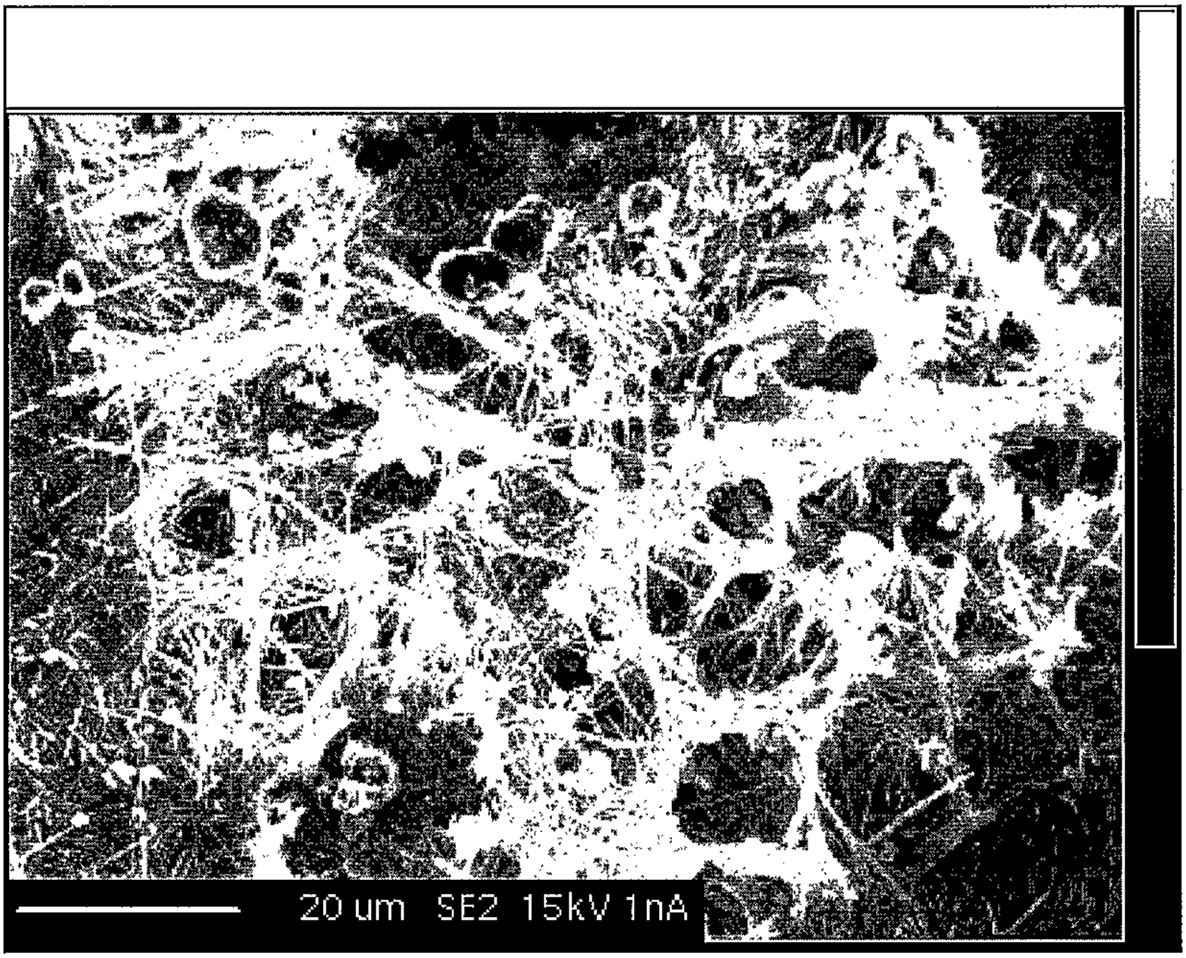

Figure 3. SEM image of fibrous ettringite in an air void of sample KC12. The concrete was placed in 1923.

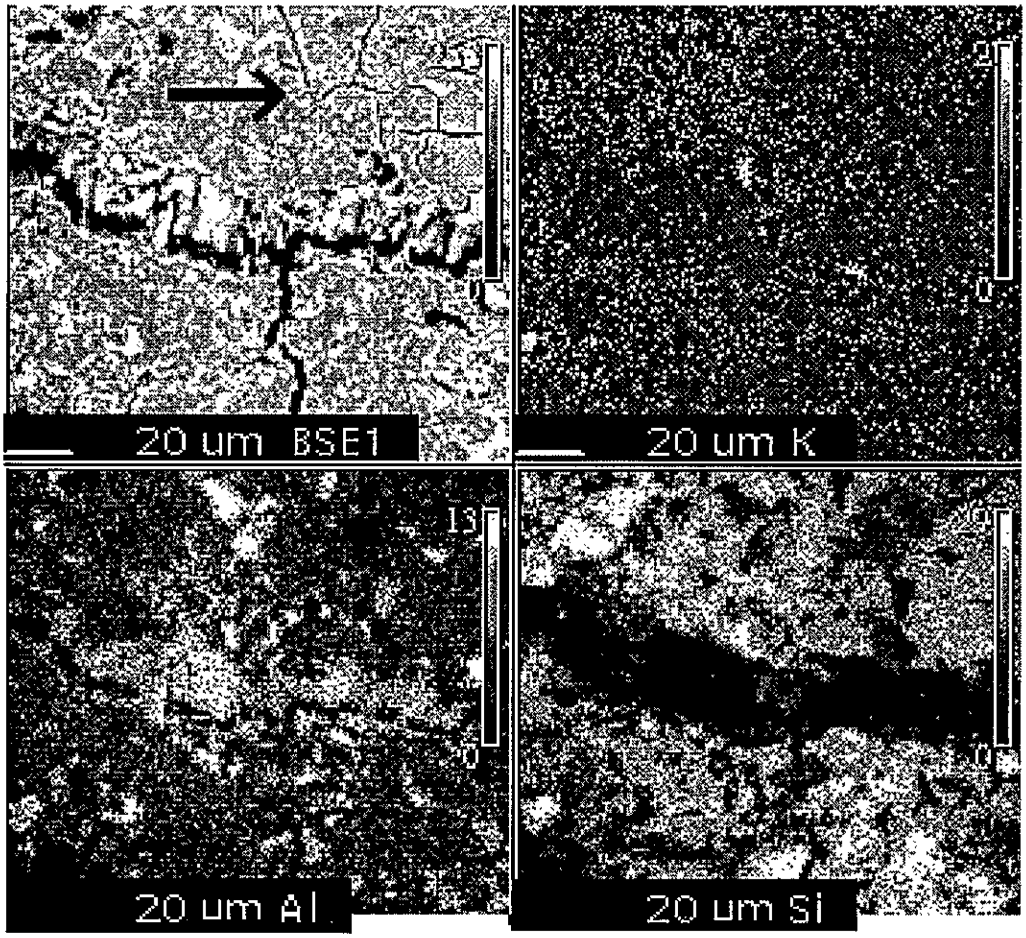

Figure 4. C-S-H gel with cracks is present in the upper right corner of BSE image (arrow). This is the same area of sample KC04 as Figure 1. Element maps of potassium, aluminum, and silica are included indicating that this gel is not ASR gel.

Analyses of sampled aggregate pits

Mineralogic analyses of material washed from aggregate samples

The material washed from aggregate we collected at several New Mexico aggregate pits was first separated into sand-, silt-, and clay-size fractions and then analyzed with the Rigaku Geigerflex D/Max 1 XRD unit at the New Mexico Bureau of Mines and Mineral Resources. Many New Mexico aggregate pits do not wash their products and thus this material would be incorporated into concrete that uses them. The analyses of material washed from aggregate collected in November 1997 are displayed in Table 5. To test if any seasonal changes occurred in the washings, we collected additional samples from four pits in May 1998 and repeated the tests (Table 6).

Table 5. XRD analyses for minerals by size of material washed from aggregate collected in November 1997. Aggregate is identified by pit names and size or product designation. C-33 is the designation for concrete sand. I/S is the designation for mixed-layer illite and smectite.

	Edgewood 3/8”	**Edgewood 1”**	**Placitas C-33**	**Placitas 1”**	**Tinaja 1”**	**Mimbres 1”**	**Santa Ana 1”**
Clay-size mineralogy (in parts of 10)							
Illite	4	4	2	2	4	0	3
Kaolinite	4	2	3	5	5	0	4
Smectite	2	0	2	1	0	4	1
I/S	0	4	3	2	1	6	2
	10	10	10	10	10	10	10
Other (in decreasing abundance)							
	albite	calcite	calcite	calcite	calcite	microcline	calcite
	calcite	quartz	quartz	feldspar	dolomite		quartz
Coarse silt-size mineralogy (in decreasing abundance)							
	quartz	calcite	quartz	quartz	calcite	quartz	quartz
	albite	quartz	albite	albite	sanidine	albite	calcite
	calcite	feldspar		calcite	dolomite	plagioclase	albite
						dolomite	
Sand-size mineralogy (in decreasing abundance)							
	none	calcite	none	albite	calcite	quartz	quartz
		feldspar		quartz	sanidine	albite	calcite
		quartz			dolomite	plagioclase	albite

The data in Tables 5 and 6 (mineralogic analyses of material washed from aggregate collected in November 1997 and May 1998) clearly show the variability of this material from pit to pit and from time to time. One might expect major differences between the Placitas C-33, Placitas 1”, and the Edgewood 3/8” (a blend material from the Edgewood pit with material from the Placitas operation). Similar differences should also be expected between the Santa Ana 1” and Mimbres 1” pits because of the heterogeneity of the material present in these aggregates. However, even aggregate from the Tinaja and Edgewood (Edgewood 1”) quarries contain non-carbonate minerals (quartz, feldspar, and sanidine—a high-temperature orthoclase feldspar) in the silt- and sand-size fraction. Clay minerals washed from the Tinaja aggregate consist of illite (the high-potassium clay mineral group) and kaolinite, while the November 1997 sample from the Edgewood pit contained I/S as well.

Because the material removed by our washing represents the loosely attached particles, the products of weathering may be more tightly held. It is possible that an active scrubbing circuit would remove these weathering products and improve aggregate performance. This would be especially true of aggregates that contain a significant amount of shales and iron-stained and deeply weathered particles.

Table 6. XRD Mineralogic analyses by size of material washed from aggregate collected in May 1998. Aggregate is identified by pit names and size or product designation

	Edgewood 3/8”	**Edgewood 1”**	**Placitas 1”**	**Tinaja 1”**	**Santa Ana 1”**
Clay-size mineralogy (in parts of 10)					
Illite	3	10	4	2	0
Kaolinite	4	0	4	8	10
Smectite	2	0	2	0	0
I/S	1	0	0	0	0
	10	10	10	10	10
Other (in decreasing abundance)	feldspar calcite	calcite quartz	quartz feldspar calcite	calcite dolomite quartz	calcite quartz
Coarse silt-size mineralogy (in decreasing abundance)	quartz feldspar calcite	calcite quartz feldspar	quartz feldspar calcite	calcite quartz dolomite feldspar	quartz calcite feldspar
Sand-size mineralogy (in decreasing abundance)	none	calcite quartz feldspar	quartz feldspar	calcite dolomite quartz feldspar	quartz calcite feldspar

All of the non-carbonate material in the limestone quarries represents impurities in an unwashed limestone aggregate that may cause expansion in concrete, but because of the preponderance of limestone, composed predominantly of the mineral calcite ($CaCO_3$), expansion should be small. Impurities in limestone can consist of all of the non-carbonate minerals listed in Tables 5 and 6, but sand- and silt-size feldspar is rare in high-purity limestone. If they are not found in a petrographic analysis of the limestone (see following analyses), the source or sources probably is external to the limestone.

Analyses of washed aggregate samples

Petrographic analysis. After being washed, the collected aggregate was crushed with a large mill crusher and a smaller pulverizer in the NMBMMR Metallurgical Laboratory. It was then separated into five size fractions using industrial sieves. The sizes of the material include: passing a No. 4 (4.75 mm) and retained on a No. 8 (2.36 mm) sieve, passing a No. 8 and retained on a No. 16 (1.18 mm) sieve, passing a No. 16 and retained on a No. 30 (600 μm) sieve, passing a No. 30 and retained on a No. 50 (300 μm) sieve, passing a No. 50 and retained on a No. 100 (150 μm) sieve. A split of each size fraction of each sample was sent to Spectrum Petrographics for the preparation of petrographic thin sections (Tables 7 and 8).

Table 7. Petrographic analysis of aggregate samples at the five pits collected in November 1997 as part of this project. The procedure used was ASTM C 295-90, *Standard guide for petrographic analysis examination of aggregate for concrete* (Anon., 1995b). The samples are identified by pit and the size of the material or product designation collected. C-33 is the designation for concrete sand at the Placitas pit. Reactive minerals and rocks include chalcedony/chert, rhyolite/trachyte, and andesite. Weathered particles include those exhibiting color and/or texture alteration, iron-staining, and similar modifications.

Counts	**Edgewood 3/8”**	**Edgewood 1”**	**Placitas C-33**	**Placitas 1”**	**Tinaja 1”**	**Mimbres 1”**	**Santa Ana 1”**
Rhyolite/trachyte	69	0	61	87	0	23	49
Andesite	1	0	21	15	0	50	1
Dacite/basalt	119	0	116	191	0	280	60
Chert/chalcedony	105	3	145	222	1	252	65
Quartz	95	3	136	190	1	19	88
Feldspar	165	0	198	87	0	38	71
Ferromagnesian	3	0	4	3	0	2	0
Opaque	2	0	7	3	0	2	20
Limestone/dolomite	197	669	6	1	685	6	408
Subtotal	756	675	694	799	687	672	742
Weathered	132	47	63	97	10	55	94

Percent	**Edgewood 3/8”**	**Edgewood 1”**	**Placitas C-33**	**Placitas 1”**	**Tinaja 1”**	**Mimbres 1”**	**Santa Ana 1”**
Rhyolite/trachyte	9.1	0.0	8.8	10.9	0.0	3.4	6.6
Andesite	0.1	0.0	3.0	1.9	0.0	7.4	0.1
Dacite/basalt	15.7	0.0	16.7	23.9	0.0	41.7	8.1
Chert/chalcedony	13.9	0.4	20.9	27.8	0.4	37.5	8.8
Quartz	12.6	0.4	19.6	23.8	0.4	2.8	11.9
Feldspar	21.8	0.0	28.5	10.9	0.0	5.7	9.6
Ferromagnesian	0.4	0.0	0.6	0.4	0.0	0.3	0.0
Opaque	0.3	0.0	1.0	0.4	0.0	0.3	0.0
Limestone/dolomite	26.1	99.1	0.9	0.1	99.1	0.9	55.0
Total	100	100	100	100	100	100	100
Reactive	23.1	0.4	32.7	40.6	0.1	48.3	15.5
Weathered	17.5	7.0	9.1	12.1	7.0	8.2	12.7
Percent of total	40.6	7.4	41.8	52.7	7.1	56.5	28.2

Reactive minerals and rocks and weathered particles comprise a large amount of the aggregate from all tested gravel pits, but not the limestone quarries (Edgewood and Tinaja). In both quarries the quantity of reactive minerals was very low, with Tinaja slightly lower than Edgewood. Of the gravel pits, Santa Ana has the lowest percentage of reactive and weathered material and the highest percent of non-reactive limestone.

The heterogeneity of the material in the Placitas and Santa Ana pits with a large size range of particles, both reactive and non-reactive, means that it would be difficult to get a narrow range of results with multiple mortar bar expansion tests. This heterogeneity is further illustrated by comparing percentages in the Placitas C-33 and Placitas 1” petrographic analyses. Our samples indicate these pits contain weathered and unweathered igneous, sedimentary, and metamorphic material in all size fractions.

Table 8. Petrographic analysis of aggregate samples at the four pits collected in May 1998 as part of this project. The procedure and specifications were the same as in Table 7.

Counts	**Edgewood 3/8”**	**Edgewood 1”**	**Placitas 1”**	**Tinaja 1”**	**Santa Ana 1”**
Rhyolite/trachyte	17	0	44	0	34
Andesite	24	0	43	0	11
Dacite/basalt	121	0	197	0	82
Chert/chalcedony	89	4	136	1	51
Quartz	88	3	129	1	152
Feldspar	180	0	145	2	108
Ferromagnesian	8	0	36	0	4
Opaque	6	0	3	0	2
Limestone/dolomite	120	671	1	684	285
Total	653	675	704	688	729
Weathered	73	53	65	13	91

Percent	**Edgewood 3/8”**	**Edgewood 1”**	**Placitas 1”**	**Tinaja 1”**	**Santa Ana 1”**
Rhyolite/trachyte	2.6	0.0	6.3	0.0	4.7
Andesite	3.7	0.0	6.1	0.0	1.5
Dacite/basalt	18.5	0.0	28.0	0.0	11.2
Chert/chalcedony	13.6	0.6	19.3	0.1	7.0
Quartz	13.5	0.0	18.3	0.1	20.9
Feldspar	27.6	0.0	20.6	0.3	14.8
Ferromagnesian	1.2	0.0	0.9	0.0	0.5
Opaque	0.9	0.0	0.4	0.0	0.3
Limestone/dolomite	18.4	99.4	0.1	99.4	39.1
Total	100	100	100	100	100
Reactive	19.9	0.6	31.7	0.1	13.2
Weathered	11.2	7.9	9.2	1.9	12.5
Percent of whole	31.1	8.5	10.9	2.0	25.7

Only quartz and chert/chalcedony were found by the petrographic microscope in the limestone aggregate from the Edgewood and Tinaja quarries. Most likely the feldspar, and perhaps some of the quartz and clay minerals washed from the aggregate (Tables 5 and 6), represents wind-blown dust. The wind-blown nature of these loosely attached impurities may also reflect the variability of these materials with time, as presented by the different composition in the various size fractions between the November and May samples. It is clear from the analyses in Tables 5 and 6 that unless the aggregate from all pits tested is washed, the aggregate will contain minerals that may contribute to expansion problems.

In order to see how repeatable the results would be, we collected a second set of samples from four of the same aggregate operations in May 1998. We processed the samples in the same manner as before and results are shown in Table 8.

Leming (1996) considers ASTM C 295-90, *Standard guide for petrographic analysis examination of aggregate for concrete* (Anon., 1995b), to be a guide rather than a standard test method. He states that it is limited to the extent that it can identify only minerals or aggregates that have been shown to be reactive. He continues, "many silica-based aggregates could, under the right conditions, show signs of alkali-silica reactivity…." Thus, not only must the aggregates contain reactive minerals and rocks, but also the environment must be such as to produce ASR reactions. Leming states that "Many aggregates of practical interest can only be classified as 'potentially' deleterious expansive, because they contain minerals that are known to be reactive in other situations." Thus, the mere presence of known deleteriously reactive minerals is not is not adequate to state positively that concrete made with this aggregate will rapidly deteriorate.

It appears to us that it is difficult to use the ASTM C 295 method to get an accurate mineralogic content for mixed aggregates similar to the Placitas pit. In this test, the aggregate is crushed and sieved into five size fractions. Each fraction is mounted in an epoxy and is then analyzed under the petrographic microscope. Point counts are made across slides, each containing a different size fraction. Counts from the same material in all five slides are added together and used to determine the mineral or rock percentage in the whole aggregate. By using the coarser splits of the aggregate, one tends to over-emphasize particles that the cross hairs intersect while under-emphasizing particles that are not intersected. This problem grows more pronounced as particle sizes increase. We suggest that the finer fractions of the crushed aggregate should be the most representative of the total aggregate.

Expansion tests. Splits from these washed aggregate samples also were sent to the NMSHTD Central Lab in Santa Fe for mortar bar tests (Table 9). In this test, an expansion of <0.10% is considered innocuous and >0.10% is deleterious expansion (Barela, 1997). Stark and others (1993) noted that other researchers use <0.10% as innocuous, 0.10–0.20% as uncertain for deleterious expansion, and >0.20% is potentially deleterious expansion. The modification of ASTM C 227 by Stark and others (1993) included soaking mortar bars in 1 N NaOH at approximately 80°C for 14 days after one-day storage in water. In this test, only <0.08% expansion was considered innocuous.

Table 9. Results of expansion tests on aggregate from five New Mexico pits. C-33 is the designation for concrete sand at the Placitas pit.

Pit/size	1997 expansion[1]	Nov. 1997 expansion[2]	May 1998 expansion[2]	1998 expansion[3]	1998 rerun expansion[3]	Average
Edgewood 3/8"	NA	0.973	0.882	NA	NA	0.93
Edgewood 1"	NA	0.373	0.407	NA	NA	0.39
Placitas C-33	NA	0.880	NA	NA	NA	0.88
Placitas 1"	1.34	0.998	0.986	0.806	0.785	0.98
Tinaja 1"	0.00	0.014	0.009	0.003	0.022	0.01
Mimbres 1"	0.52	0.567	NA	0.492	0.495	0.52
Santa Ana 1"	0.24	0.848	0.792	0.534	0.417	0.57

[1]NMSHTD data pre-November 1997; [2]we collected and processed samples, but tests are by NMSHTD; [3]samples collected, processed, and tested by UNM; NA = not available

Clearly, of the aggregate pits and quarries sampled, only the Tinaja quarry produces aggregate that has non-deleterious expansion. All of the other aggregates tested, including the Edgewood 1" limestone aggregate, should be considered to have deleterious expansion in mortar bar tests and that must be corrected with admixtures. As was predicted from the petrographic analyses, several aggregate pits have a range of values from the mortar bar expansion test. In particular, this is illustrated by the data from the analyses of Placitas aggregate (1" and C-33). Six mortar bar expansion test results in Table 9 show the average expansion of 0.98 with a standard deviation of 0.18. Santa Ana 1" aggregate has a lower but still deleterious expansion average of 0.57 for five tests with a standard deviation of 0.23. Similar heterogeneity in mineral content is shown by aggregate collected at different times (Tables 7 and 8). Mineral heterogeneity of samples collected and of samples collected at different times explains the range of expansion test values for the Placitas and Santa Ana aggregates.

We had adequate data to examine the variability of expansion tests for two other aggregate operations. The Mimbres pit produces aggregate with deleterious expansion (Table 9). With four tests, the Mimbres pit had an average expansion of 0.52 but the standard deviation was only 0.03. With five tests, the Tinaja quarry yielded an average expansion of 0.01 and a standard deviation of 0.01. It is interesting that although the average expansion for the Mimbres pit was nearly the same as the Santa Ana pit, the standard deviation was much smaller. Consequently, it is much easier to obtain a precise expansion value from the Mimbres pit than from the Santa Ana pit. Presumably, the number is also more accurate.

Another item to consider is the reaction rate of silica and alkalis in the aggregate. Stark and others (1993) note the slow reactivity of granite gneiss and quartzite. Similarly, if the alkalis in the cement is extremely low (<0.6%), then the cement is not the main source of an ASR problem. Limestone aggregates, especially that from the Tinaja quarry, have a very small amount of alkalis and silica and will give good results on ASR tests. However, even if silica and alkalis are present in the aggregate, as is true with material from the Placitas and Santa Ana pits, they may or may not be present in forms that may generate ASR gel. Quartz in granite is considered much less reactive than strained quartz in granite gneiss or silica as chert or chalcedony (Kosmatka and Panarese, 1988). Clearly, potassium present in the chloride form (the mineral sylvite, KCl) is far more soluble than potassium present in the silicate form (the mineral microcline/orthoclase, $KAlSi_3O_8$).

Microcline feldspar is the most abundant mineral in granite, which is very common in the Santa Ana and Placitas aggregates. Orthoclase feldspar is the most abundant mineral in rhyolites. The grain size and the permeability of alkali volcanics make them highly reactive in contrast to the slowly reactive granites. Weathering, which increases surface area and breaks down even resistant minerals like microcline, makes weathered granite more susceptible to ASR than unweathered granite. Thus the solubility of alkali-bearing minerals is highly significant in evaluating an aggregate in mortar bar tests and the ASTM C 295 analysis procedure for aggregates takes into account whether or not the grains are weathered. Thus, the bulk chemistry of aggregate alone is not always a good predictor of ASR problems.

As indicated above, the solubility of alkali-bearing minerals is affected by the particle size, and particle size is measured by surface area per gram. The surface area of a gram of unweathered microcline is essentially the outer surface of the particles. If the microcline particles are weathered, surface area goes up dramatically because pits, cracks, channels, twining planes, etc., in the particles are enlarged. In addition to very small particles of orthoclase feldspar, alkali volcanics commonly are permeable and may contain numerous pores of all sizes due to expanding gases during solidification. Other examples of minerals with extremely large surface areas are the clay minerals in which surface areas are measured in square meters per gram (Table 10). The alkali content of most clay minerals in shales and siltstones is relatively low, but they are silicates and their very high surface area makes them suspect in contributing to ASR problems.

In Table 10, the clay minerals, kaolinite and halloysite, and the clay materials, ball clay and fireclay, are members of the kaolin group ($Al_4Si_4O_{10}OH_8$) and contain very minor amounts of alkalis. Montmorillonite is a member of in the smectite group, which are known to contain a large and variable number of cations, including alkalis. Fullers earth is a clay material used because it absorbs oil and grease. It also contains a large and variable number of cations including alkalis. New Mexico's clay material, both present in sedimentary rocks like shales and siltstones and as materials near the surface such as weathered rock and soils, contain these minerals. Another clay mineral group common in New Mexico's clay material is illite with the approximate formula of $KAl_2(AlSi_3O_{10})(OH)_2$. Illite is the potassium-rich clay mineral group.

Table 10. Surface area values of clay material measured by gas absorption (after Grimshaw, 1971).

Material	Surface area in m^2/g
Kaolinite (Cornwall)	13.2
Montmorillonite (Wyoming)	85.0
Fullers earth	310.0
Halloysite	14.2
Ball clay (Dorset)	19.3
Better bed fireclay	10.1
Silica gel	520.0

Silica gel (Table 10) is not present in rock materials. It is a manufactured product, but it has been used in ASR tests (Helmuth and others, 1993). However, there are several natural materials that have similar but smaller surface areas. Among these are the microcrystalline water-bearing varieties of quartz (chert, chalcedony, flint, and opal). These minerals are nearly always included in the lists of reactive rock materials, and are common in the aggregates of the Rio Grande valley (Table 4, samples 6, 8, 9, 10, 11, 14, 16; and Table 8, Edgewood 3/8", Placitas C-33 and 1", Santa Ana 1") and other aggregate derived from igneous areas (Table 8, Mimbres 1").

Microcrystalline opal, chalcedony, and flint have a disordered intergrowth structure composed of cristobalite and tridymite domains in opal, and quartz and moganite (a disordered SiO_2 mineral) domains in chalcedony and flint (Graetsch et al., 1987). Each constituent phase has different cell dimensions and symmetry. Impurities enter the structure because of the substitution of Al^{3+} for Si^{4+}. Electro-neutrality is achieved by the addition of monovalent cations at interstices close to the substitutional defects. The main impurity is water, which is enriched at the intergrowth interfaces. Dehydration of loosely hydrogen-bonded molecule water, which is bonded to surface silanols (SiOH), begins to occur at temperatures <200°C and even as low as 50°C (Yamagishi et al., 1997). The pH of a good quality noncarbonated concrete without admixtures is usually greater than 12.5 (Kosmatka and Panarese, 1988). In the highly alkaline concrete environment, these highly porous phases of quartz react quickly forming expansive gels.

The particle-size problem even carries over to the testing of aggregate. If particle size is important in that the surface area—the reacting surface—is larger for smaller particles, then we increase reactivity by crushing and grinding aggregate. To accurately judge how reactive an aggregate will be, we should measure the reactivity of aggregate in the size it is used in concrete. This means that the complete size range of reactive minerals should be considered in the evaluation. According to Taylor (1997), the greatest expansion appears to be in the range of 0.1–1.0 mm and decreases both in larger particles and smaller ones. He states that expansion is zero or negligible if the particle size is below about 10 µm, but does not indicate if mineralogy is significant. Clay minerals most commonly occur as particles of less than 2 µm and are known to produce expansion problems. Perhaps Taylor (1997) is only considering the non-clay minerals such as chert, chalcedony, and orthoclase as producing virtually no ASR problems if they are smaller than 10 µm.

An examination of the two limestone aggregate quarries points out why the Tinaja pit produces aggregate that ranks better than the Edgewood pit. Very little overburden is present at the Tinaja pit and what is there is stripped away from the limestone. The limestone appears to be very pure and there is little evidence of clay material. In contrast, overburden at the Edgewood pit is not cleanly stripped and stockpiled away. In addition, the quarried limestone has many large fractures that are filled with debris, not only clay material, but larger particles as well. Without washing, the limestone aggregate appears to have some clay material. Even with washing, the aggregate appears to have some foreign material, but weathered grains are more common in the Edgewood quarry (Tables 7 and 8). Finally, there appears to be some shaly partings in the limestone near the top of the pit. It is conceivable that all these factors contribute to greater expansion of mortar bars made of Edgewood aggregate than bars made of Tinaja aggregate.

CONCLUSIONS

New Mexico's abundance of fluvial sand and gravel deposits in the highly populated Rio Grande valley means that this material is going to be used in concrete structures and highways. Admixtures, such as air entrainers, water reducers, and setting-time accelerators and retarders, are necessary to control deterioration due to abundant reactive particles.

Our study of hardened concretes of various ages leads us to several conclusions: (1) There appears to be no less use of reactive aggregate earlier in this century than now and therefore reactive aggregate is not the cause of the perceived more durable older concretes and less durable recently produced concretes. (2) We speculate the reasons are: (a) the modern tendency to use cement formulated to set up in a relatively short time; (b) the care, or lack of it, taken during hydration of concrete; (c) the long-term effects of additives and admixtures that initially modify cement durability and setting positively, but are detrimental over extended periods of time; or (d) a combination of these factors and others of which we are unaware. (3) Delayed ettringite formation (DEF) does not appear to be the chief cause of concrete deterioration in the state. (4) Reactive aggregate is very common in many areas. (5) Chert, chalcedony, flint, and high-alkali volcanic rocks (rhyolite, trachyte, and andesite) as aggregate appear responsible for most of the problems of concrete durability.

Our examination of aggregate from several pits and quarries resulted in several additional conclusions: (1) Microcrystalline silica as chert and chalcedony, and sheared and strained quartz (in gneiss and schist) appear to be some of the principal reactive minerals in the fluvial sediments that supply aggregate in many parts of the state. (2) Abundant alkali-rich feldspar, both in volcanic and intrusive rocks, is present in all sizes in the fluvial sands and gravels. Depending on the mineralogy, particle size, drainage, and environment with the concrete, these minerals react fast or slow, producing ASR gels through time. (3) Weathering products and effects in both aggregate pits and aggregate quarries contribute to ASR difficulties. (4) Alternatives to the fluvial sediments include bedrock units, such as the Madera and San Andres limestones, that are quarried near Edgewood and Grants, respectively. However, these limestones are not always pure and can not be assumed to produce only innocuous expansion characteristics. (5) One simple method of lowering expansion is washing the aggregate to remove finer particles including reactive sand-, silt-, and clay-size material, clay minerals, and weathering products.

RECOMMENDATIONS FOR ADDITIONAL WORK

1. Analyze additional dated New Mexico concretes to determine if the use of a wide range of aggregates, both reactive and non-reactive, is as wide spread as we believe.
2. When sampling additional concretes, use a large-scale coring devise to secure about an 8-inch deep, 6-inch-diameter core and characterize the concrete with multiple thin sections.
3. Characterize the environment of the sampled concretes as well-drained or poorly drained, load bearing (constant or periodic) or not, and subject to a wide range of temperatures, humidity, etc.
4. Characterize “distress” in hardened concretes as “shallow distress” if deterioration effects only the upper 1–2 inches, as is observed with only popouts, or “deep distress” if the effects continue deeper into the concrete, as can be observed in map and longitudinal cracking.
5. Make an effort to sample concretes for which complete records are available, including which additive and admixtures were used and, if possible, what care was taken in its emplacement. If

this type of data is not available, it should be required for New Mexico State Highway & Transportation Department projects.

6. The value of washed versus unwashed aggregate should be determined and the value of washed versus scrubbed aggregate should be tested.
7. When testing a given aggregate for expansion in the laboratory, use material directly from the product pile without crushing, which would increase expansion by decreasing particle size.
8. Characterize pits and quarries with expansion data only after a sizeable number of analyses have been made to determine an average value and the standard deviation of the data.
9. Determine the long-term effects of additives and admixtures used in New Mexico on the durability of concretes in the many climates of the state.

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